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## The impact of light source spectral power distribution on sky glow

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### ABSTRACT

The effect of light source spectral power distribution on the visual brightness of anthropogenic sky glow is described. Under visual adaptation levels relevant to observing the night sky, namely with dark-adapted (scotopic) vision, blue-rich (“white”) sources produce a dramatically greater sky brightness than yellow-rich sources. High correlated color temperature LEDs and metal halide sources produce a visual brightness up to  $8 \times$  brighter than low-pressure sodium and  $3 \times$  brighter than high-pressure sodium when matched lumen-for-lumen and observed nearby. Though the sky brightness arising from blue-rich sources decreases more strongly with distance, the visual sky glow resulting from such sources remains significantly brighter than from yellow sources out to the limits of this study at 300 km.

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### 1. Introduction

Outdoor lighting is an increasingly pervasive aspect of the human nocturnal environment. Yet beyond the intended effects for human vision and information conveyance, a variety of collateral impacts arise from its use – these impacts are often referred to as “light pollution” (e.g. [1] and references therein). Though there are a number of aspects of light pollution such as glare, disturbance to biological systems, and “light trespass,” one of the principal impacts is increased night sky brightness (“anthropogenic sky glow”) arising from light scattered by atmospheric molecules and aerosols. Beginning as early as the 1930s, when a site was being chosen for the 200 in. Hale telescope,

astronomers have been concerned about the impact of this increased sky brightness on the observability of faint astronomical sources. In the past 50 years protection has been sought through civil regulations that require shielding of light fixtures to prevent light emanation above the horizontal plane; in the last 25 years these efforts have extended in some cases to limits on both the total amount of light and the spectral characteristics of the light sources.

Garstang developed the first comprehensive model [2,3] that treats the scattering of light from molecules and aerosols in clear (cloudless) air, and accurately accounts for varying locations of light source and observer, Earth (and atmospheric) curvature, and varying levels of atmospheric aerosol. This model, extended to account for blocking of light rays by objects in the near-ground environment [4] has been successfully used to predict the sky brightness arising from artificial light sources (e.g. [4,5]).

In recent years there has been an increasing interest in the use of solid-state lighting sources (LEDs) with a broad and relatively blue-rich spectral power distribution compared to the previously dominant technology, high-pressure sodium (HPS) (see, for example, discussions of

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many LED lighting projects undertaken in collaboration with the US Department of Energy Gateway Program [6]). The question arises as to the impacts on anthropogenic sky glow of such a shift in light source spectrum. In this contribution we present an extension of the Garstang model to include the wavelength dependence of molecular and aerosol scattering, to allow the treatment of light sources with different spectral power distributions. An initial study [7] has examined the impact of a variety of light sources on the radiant sky glow in different parts of the visible spectrum. The goal of this study is to examine the impacts on the visual or luminous sky glow as observed by the human eye under both photopic and, more importantly, scotopic conditions.

## 2. Model

To examine these effects, an implementation of Garstang's [2,3] monochromatic model has been generalized to allow the calculation of sky brightness arising from polychromatic light sources. Along a given path through the atmosphere, Garstang's model calculates the amount of light removed due to extinction, as well as added due to scattering. Single and double scatterings are treated; higher order scattering is neglected. This is done for a two-component atmosphere consisting of molecules and aerosols. Each of these two components is defined by a number density at height  $h$  above ground level and a scattering cross-section. The amount of aerosol is defined through a parameter  $K$  (see Eq. (3) below) which sets the ratio of total molecular to aerosol scattering.

Generalization of Garstang's model for wavelength dependence requires specification of the wavelength dependence of the scattering cross-sections. The scattering by molecules is assumed to be Rayleigh scattering, where the cross-section scales with  $\lambda^{-4}$ . The aerosol scattering cross-section, on the other hand, scales with  $\lambda^{-1}$  for aerosol particle sizes most relevant to clear atmospheres (see, for example, [8] for experimental measurements). Referenced to the center of the astronomical Johnson  $V$  band at 550 nm, the wavelength-dependent aerosol and molecular scattering cross-sections  $\sigma_a$  and  $\sigma_R$  can be written as

$$\sigma_a(\lambda) = \sigma_a(550 \text{ nm}) \left( \frac{550 \text{ nm}}{\lambda} \right) \quad (1)$$

$$\sigma_R(\lambda) = \sigma_R(550 \text{ nm}) \left( \frac{550 \text{ nm}}{\lambda} \right)^4 \quad (2)$$

These wavelength-dependent definitions of the scattering cross-sections can then be substituted into the model equations given by Garstang [2,3]. However, it is important to note that particular care needs to be taken with the aerosol component; as in the Garstang approach the aerosol scattering cross-section is defined relative to the amount of molecular scattering at ground level at the center of the  $V$  band ([2], Eq. (4)). Consequently, the wavelength-dependent form of this relation is

$$N_a \sigma_a(\lambda) = \left( \frac{550 \text{ nm}}{\lambda} \right) 11.11 K N_m \sigma_R(550 \text{ nm}) \exp(-cH) \quad (3)$$

where  $c$  is the reciprocal scale height for the molecular atmosphere and  $H$  is the height of the light source above sea level, which is consistent with the original definition when  $\lambda=550$  nm. The rest of the Garstang's model equations can then be generalized for wavelength dependence by replacing  $\sigma_a$  and  $\sigma_R$  with the relations in Eqs. (1) and (2).

To determine the visible sky glow resulting from polychromatic light sources used for outdoor lighting, the spectrum of a light source is first scaled such that the spectrum, multiplied by the CIE  $V(\lambda)$  (photopic) response [9] yields a fixed luminous output (in lumens). We next perform the radiometric calculations on the scaled lamp spectrum within 20 nm wide wavelength bins, using the prescription described above, to compute the mean sky radiance  $\bar{I}_e^{(i)}$  in each wavelength bin  $i$ . The physical quantity calculated is the luminance  $L_v$ , which we define in terms of the mean radiance in each wavelength bin as

$$L_v = \sum_i \bar{I}_e^{(i)} \int_{\lambda_i}^{\lambda_{i+1}} V(\lambda) d\lambda \quad (4)$$

when the sky brightness evaluation is intended to apply to scotopic vision, we substitute the CIE  $V(\lambda)$  response [10] in place of the  $V(\lambda)$  response, and refer to the results as “scotopic” luminance<sup>1</sup> or luminance ratios.

### 2.1. Light sources

#### 2.1.1. Lamps

Six lamp types were examined in this study: low-pressure sodium (LPS); high-pressure sodium (HPS); two types of white light emitting diodes with correlated color temperature (CCT) of 2400 K (LED2400K) and 5100 K (LED5100K); ceramic metal halide with CCT of 4100 K (MH4100K); a white LED (3000 K CCT) filtered with a 500 nm short cutoff filter (FLED). Spectra for the sources are shown in Fig. 1. In the analysis all light sources were balanced for equal luminous output (measured in lumens).

#### 2.1.2. Uplight angular distribution

Light propagating upward into the atmosphere consists of two components: light emitted directly upward from incompletely shielded fixtures, and light reflected upward from illuminated surfaces. We use the angular descriptions for these components as defined by Garstang ([2], Eq. (1)) assuming direct upward component  $F=0.10$  and a horizontal ground surface with average reflectance  $G=0.15$ . To account for blocking of upward rays by objects in the near-ground environment, we follow the treatment of Luginbuhl et al. ([4], Eq. (2)) assuming a vertical “blocking extinction”  $E_b=0.3$  magnitudes, with an overall unblocked fraction  $\beta=0.10$ .

### 2.2. Atmosphere

A “moderately clear” atmosphere characterized by a total aerosol to molecular scattering ratio of 11:1 (following Garstang [2]) is adopted for the majority of the

<sup>1</sup> Strictly speaking, the term “luminance” is defined only in terms of photopic vision.

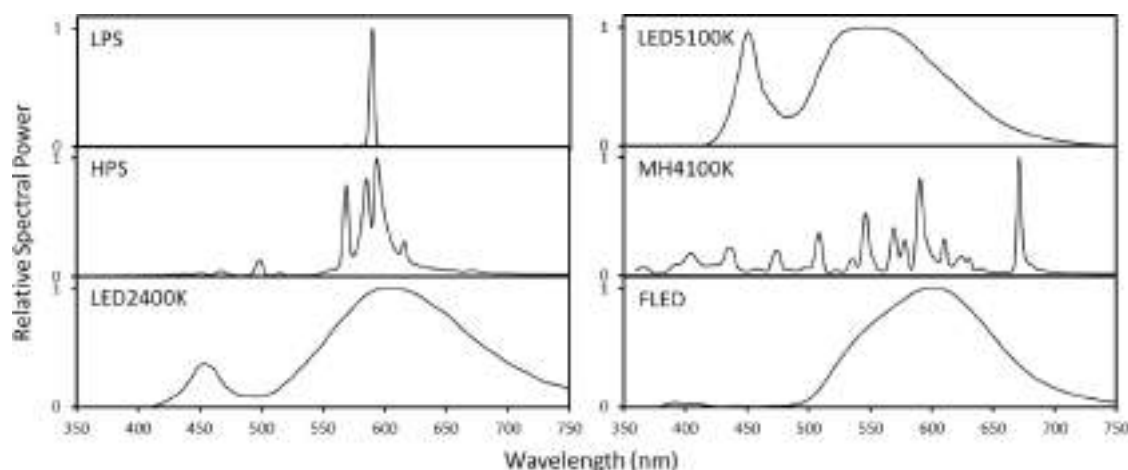


Fig. 1. Spectral power distribution of the six lamp types evaluated in this study. The lamp type abbreviations are explained in the text.

analyses. This is equivalent to a visual range at sea level of 26 km and an astronomical  $V$ -band extinction of 0.33 magnitudes per airmass; the Garstang  $K$  parameter for this condition is 1.0. To examine the influence of aerosols, models with  $K=0.3$  and 2.0 were also examined, corresponding to visual ranges of 74 and 14 km, respectively.

### 2.3. Light source and observer locations

The altitude for both the observer and the light source was set at 500 m, and observer – light source distances of 0.1–300 km were evaluated.

### 2.4. Sky glow measures

Overhead and near-horizon sky brightness was determined as follows. For overhead measures, we used the measure described by Luginbuhl et al. [11], where the sky brightness was calculated at the zenith and four points at zenith angle  $60^\circ$  at  $90^\circ$  intervals in azimuth, one at the azimuth toward the light source. The overhead sky brightness is calculated as the average of these five points, with the zenith value receiving double weight. Measures of the sky brightness near the horizon are the average of three values calculated on the azimuth toward the light source and at zenith angle  $80^\circ$ ,  $84^\circ$  and  $88^\circ$ . We note that these measures do not represent a strict average of any particular portion of the sky: they are used to give values representative at the positions described and to keep the computation time at a minimum.

## 3. Results

### 3.1. Scotopic sky brightness

The luminance of a naturally dark and unpolluted night sky in the absence of moonlight ranges from  $\sim 0.2$  mcd/m<sup>2</sup> ( $22.0$  V magnitudes per square arc second (mag/arcsec<sup>2</sup>)) at the zenith to  $\sim 3$  mcd/m<sup>2</sup> ( $19.0$  V mag/arcsec<sup>2</sup>) in the brighter parts of the Milky Way [12,13]. In 1988, the sky at Lowell Observatory, 1.5 km from Flagstaff (AZ, USA, 1990 population

Table 1

Overhead scotopic sky luminance ratios, relative to LPS.

| Dist. (km) | LPS | HPS  | LED2400K | LED5100K | MH4100K | FLED |
|------------|-----|------|----------|----------|---------|------|
| 0.1        | 1   | 2.47 | 4.39     | 8.12     | 6.60    | 3.66 |
| 0.3        | 1   | 2.45 | 4.34     | 8.02     | 6.53    | 3.63 |
| 1          | 1   | 2.42 | 4.26     | 7.86     | 6.39    | 3.59 |
| 3          | 1   | 2.35 | 4.11     | 7.55     | 6.13    | 3.51 |
| 10         | 1   | 2.20 | 3.75     | 6.82     | 5.51    | 3.32 |
| 30         | 1   | 2.00 | 3.28     | 5.85     | 4.72    | 3.04 |
| 100        | 1   | 1.83 | 2.88     | 4.99     | 4.03    | 2.78 |
| 300        | 1   | 1.58 | 2.30     | 3.78     | 3.08    | 2.34 |

$\sim 47,000$ ) city hall, was  $\sim 1$  mcd/m<sup>2</sup> ( $20.4$  mag/arcsec<sup>2</sup>) at zenith and  $\sim 2$  mcd/m<sup>2</sup> ( $19.5$  mag/arcsec<sup>2</sup>) at zenith angle  $60^\circ$  [14]; in 2002 (population  $\sim 55,000$ ) a measure from the same location shows  $\sim 2$  mcd/m<sup>2</sup> ( $19.6$  mag/arcsec<sup>2</sup>) at zenith angle  $70^\circ$  [15]. As the scotopic-to-mesopic transition is generally accepted to be near  $10$ – $30$  mcd/m<sup>2</sup> [16], even near the center of a town of 55,000 residents the eye is essentially completely scotopic when observing the majority of the night sky (though the mesopic threshold is likely to be crossed at very high zenith angles). This means that the brightness of the night sky when observed by humans under naturally dark conditions, and even into urban areas of moderate sizes, is primarily a scotopic response. Thus, sources richer in short wavelengths are more effective in stimulating vision, producing an artificial sky luminance that appears brighter.

To examine the brightness of the anthropogenic sky glow produced by the light sources shown in Fig. 1 and observed at the low luminance of the night sky, the scattered spectral radiances were weighted as shown in Eq. (3) using the CIE  $V(\lambda)$  scotopic response, producing what we term here “scotopic luminances.” At the eight distances analyzed in this study, from 0.1 to 300 km, the calculated overhead scotopic luminances were divided by the scotopic luminance produced by LPS. The results are summarized in Table 1 and Fig. 2. At the low luminances observed in the night sky, the bluer sources produce dramatically (up to  $8\times$ ) brighter visual sky brightness



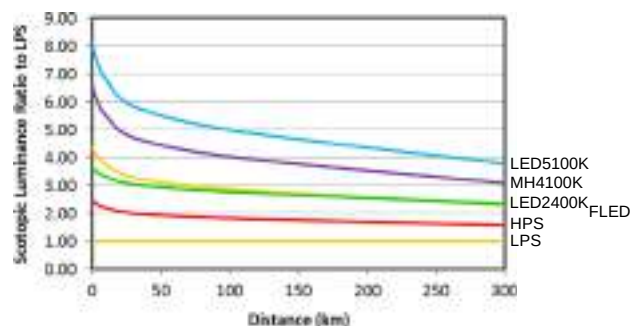


Fig. 2. Overhead scotopic sky brightness ratio, compared to LPS.

Table 2

Near horizon scotopic sky luminance ratios, relative to LPS.

| Dist. (km) | LPS | HPS  | LED2400K | LED5100K | MH4100K | FLED |
|------------|-----|------|----------|----------|---------|------|
| 0.1        | 1   | 2.51 | 4.50     | 8.34     | 6.79    | 3.72 |
| 0.3        | 1   | 2.51 | 4.48     | 8.30     | 6.75    | 3.71 |
| 1          | 1   | 2.48 | 4.41     | 8.16     | 6.64    | 3.67 |
| 3          | 1   | 2.41 | 4.24     | 7.81     | 5.34    | 3.58 |
| 10         | 1   | 2.19 | 3.74     | 6.79     | 5.49    | 3.31 |
| 30         | 1   | 1.83 | 2.89     | 5.02     | 4.05    | 2.78 |
| 100        | 1   | 1.55 | 2.24     | 3.66     | 2.99    | 2.29 |
| 300        | 1   | 1.33 | 1.72     | 2.55     | 2.15    | 1.82 |

than the yellow sources; the effect persists to the largest distance analyzed in this study despite their stronger falloff with distance. Even HPS is  $2.5 \times$  brighter than LPS when observed from nearby.

Scotopic sky luminance ratios observed near the horizon (i.e. from  $80^\circ$  to  $88^\circ$  zenith angle) are summarized in Table 2 and Fig. 3. When observed near the horizon the scotopic sky luminance diminishes more strongly with distance than when observed overhead, though nearby the ratios are essentially the same as observed in the overhead sky.

### 3.2. Effect of aerosols

The effect of differing aerosol loads was examined by running the models with Garstang  $K$  parameters of 2.0 and 0.3, representing hazier and clearer conditions. We note that the characteristics of the aerosols, in particular the dependence of the scattered intensity on scattered angle, are unchanged. The scotopic luminance ratios, divided by that for the  $K=1.0$  condition, are shown in Fig. 4. Under hazier conditions, the increased scattering leads to a greater overhead scotopic luminance when observed from less than about 6 km from the light source, and fainter when further, reaching a value about one quarter that of the  $K=1.0$  condition at 300 km. The opposite effect occurs under clear conditions, where overhead scotopic luminance nearby is decreased when observed from closer than about 10 km, and greater when observed from farther away, increasing to more than  $3 \times$  greater than observed under  $K=1.0$  conditions at 300 km. These results are essentially independent of light source spectrum.

### 3.3. Photopic sky brightness

Though not generally relevant to the brightness of the night sky as observed by humans, as discussed in Section 3.1, it is instructive to examine the effects of lamp spectrum on the standard or photopic luminance of the night sky. The overhead photopic sky brightness ratios, referenced to that for LPS, are shown in Table 3 and Fig. 5. As the light sources were balanced for equal luminous output, the photopic sky luminance ratios near the sources are approximately equal. The bluer sources produce slightly greater luminance when compared to the yellow sources (LPS and HPS) nearby, but the effect is not large, less than 6% for the bluest sources. The reason for this weak effect of lamp spectrum is that, though the shorter wavelengths suffer increased scattering by molecules and aerosols, this increased scattering also gives rise to increased extinction: the effects approximately balance when the observation point is near the light source. The sky luminance decreases more dramatically with distance for the bluer sources due to the increasing path length through the atmosphere and therefore extinction suffered by the shorter wavelengths. At distances greater than 10 km, the photopic luminance from all broad-spectrum sources is less than that for the yellow sources. For the bluest source (LED5100K), the photopic luminance falls to 0.78 that from LPS by 300 km.

## 4. Discussion and conclusions

When observing the night sky, the adaptation level of the human eye, even under moderately light polluted skies, is essentially completely scotopic. As outdoor lighting installations are generally specified in terms of photopic units (lumens, lux,  $\text{cd}/\text{m}^2$ ), the differing spectral sensitivity of photopic and scotopic vision means that the brightness of sky glow is strongly affected by the spectral characteristics of the light source. When the light sources are matched for equal photopic output, scotopic visual sky glow from sources with increased short wavelength emission such as white LED and metal halide appears dramatically brighter. The higher CCT LED and metal halide sources produce  $6\text{--}8 \times$  the scotopic luminance of low-pressure sodium (LPS), and  $3 \times$  that from high-pressure sodium (HPS), when observed from nearby. At 300 km the ratios decrease due to the greater extinction

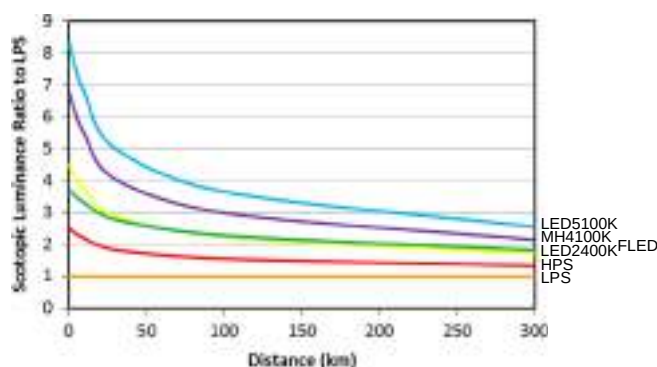


Fig. 3. Near-horizon scotopic sky brightness ratio, compared to LPS.

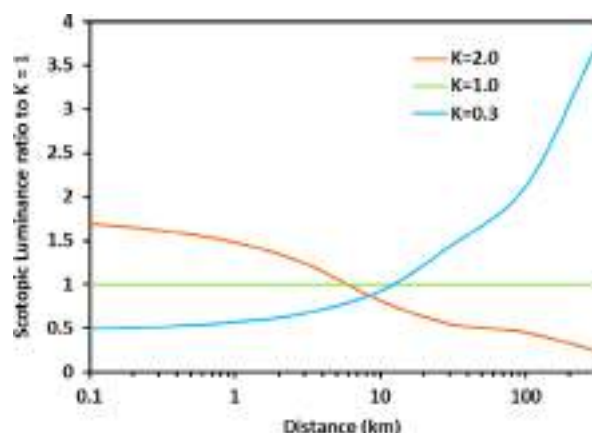


Fig. 4. The effect of varying aerosol content on overhead scotopic sky brightness.

Table 3

Overhead photopic sky luminance ratio, relative to LPS.

| Dist. (km) | LPS | HPS   | LED2400K | LED5100K | MH4100K | FLED  |
|------------|-----|-------|----------|----------|---------|-------|
| 0.1        | 1   | 1.022 | 1.031    | 1.053    | 1.055   | 1.030 |
| 0.3        | 1   | 1.022 | 1.029    | 1.048    | 1.051   | 1.028 |
| 1          | 1   | 1.020 | 1.025    | 1.039    | 1.045   | 1.024 |
| 3          | 1   | 1.017 | 1.019    | 1.022    | 1.033   | 1.016 |
| 10         | 1   | 1.010 | 1.003    | 0.981    | 1.004   | 0.997 |
| 30         | 1   | 1.000 | 0.982    | 0.924    | 0.964   | 0.971 |
| 100        | 1   | 0.991 | 0.965    | 0.869    | 0.926   | 0.947 |
| 300        | 1   | 0.980 | 0.943    | 0.784    | 0.869   | 0.912 |

of the bluer sources, but remain  $3\text{--}4\times$  that from LPS and  $1.6\text{--}2.4\times$  that from HPS.

Recent literature from the lighting industry [17,18] recognizes the effect of the shifting spectral sensitivity for mesopic vision, appropriate to lighting levels specified for applications such as roadways and parking areas. Procedures for adjusting the lighting level downward for blue-rich sources are described. Yet these reductions, if applied to industry-recommended average lighting levels,<sup>2</sup> are at the most 32% – i.e., when considering the *faintest*

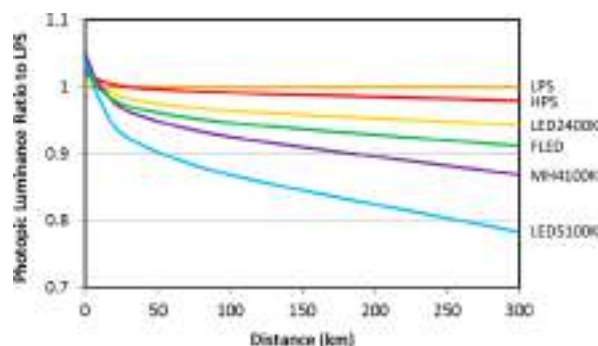


Fig. 5. Overhead photopic sky luminance ratio, compared to LPS.

lighting level, illumination using the *bluest* source (here taken as the 5100 K CCT LED) might be reduced to 68% of the lighting level with the *reddest* source (LPS).<sup>3</sup> Thus, even in the most extreme case, this reduction is insufficient to compensate for the  $1.6\text{--}8\times$  factor expected for the visual increase in sky glow brightness.

Increasing aerosol loading in the atmosphere causes sky glow near the sources (within about 10 km and less) to increase, while sky glow at more distant locations decreases. The reverse happens under clearer conditions, where sky glow nearby decreases and at greater distances increases. These variations show very little influence arising from the lamp spectral characteristics.

If sky glow is measured in photopic units (i.e.  $\text{cd}/\text{m}^2$ ) and within about 10 km of the light source, increased scattering from blue-rich sources is approximately balanced by the increased extinction arising from the same process. Here we intentionally use the term “measured” (as by a radiometer or standard luminance meter) rather than “observed” (as by the eye), as human vision will not become fully light-adapted (photopic) when viewing any but perhaps the brightest urban skies. Compared to LPS, sky glow from the bluest sources would measure only 5–6% brighter when the light sources are matched for equal luminous output. At larger distances,

<sup>2</sup> These adjustments are specifically *not* recommended in [17] for application to most roadways.

<sup>3</sup> If applied to the *faintest point* (rather than the average), the minimum recommended levels are  $6\times$  lower [17] – but applying the larger mesopic adjustment factors implied would bring the *average* lighting considerably below the recommendation.

the increased extinction of the blue-rich sources results in a significantly lower sky luminance than from LPS, with the bluest source analyzed producing less than 80% the luminance from LPS at 300 km. Yet, under nearly all (cloudless) nighttime conditions, particularly at larger distances from light sources, the low sky luminance means that photopic measures do not describe visual sensation. As a consequence the dramatically increased sensitivity of the scotopically adapted eye to blue-rich sources will overwhelm the modestly decreased radiance from such sources due to extinction.

Recent work by Bierman [19] examined sky glow expected from LED sources as compared to HPS. The analysis included approximate treatment of molecular and aerosol scattering, using radiometric and photopic measures, but neglected extinction. Though mentioning the potential effect of the spectral shift between photopic and scotopic vision, the analysis neglected the effect. Thus Bierman concluded that blue-rich LED light sources would cause only 10–20% increases in photopic sky brightness, and thus that concerns raised about the deleterious effects of blue-rich LED lighting (e.g. [1,20]) were overestimated. Though Bierman's photopic result is qualitatively confirmed here (though found to be smaller due primarily to the effects of extinction), the spectral shift cannot be neglected when describing the stimulus to human visual perception, as the photopic response is not appropriate to luminance levels in the night sky. Further, the scotopic increase compared to HPS is shown here to be significant for all LED sources, including low CCT. The net effect found in this study thus underscores and confirms the concerns about LED and blue-rich lighting [1,20,24], and directly contradicts Bierman's results.

Given the dramatically greater scotopic visual sky luminance arising from blue-rich sources, the recent interest in installing white LED lighting to replace the currently predominant HPS presents the prospect of a dramatic increase in visual sky glow, in nearly all locations from naturally dark areas to areas within towns and cities. As these sources increase the scotopic brightness of sky glow by factors of 2–3 or more compared to HPS, the estimate that over 70% of Americans and over 50% of Europeans live under skies where they cannot see the Milky Way [21] will have to be revised significantly upward, unless total lighting amounts are reduced to one half or less of the current amounts. As many other biological systems (including the human circadian response [22]) have response functions more sensitive to blue light than the CIE  $V(\lambda)$  function [23], increased impacts on these systems may also be expected.

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# The relation of outdoor lighting characteristics to sky glow from distant cities

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Five cities in the southwest United States were selected for an analysis of the impact of outdoor lighting practices on nighttime sky glow as observed from distances of 8–67 km. Data from the Suomi National Polar-orbiting Partnership (NPP) satellite visible infrared imaging radiometer suite day/night band were used to identify light sources for input to an atmospheric sky glow model. Total lumens of outdoor lighting were estimated by matching modelled to observed anthropogenic sky luminance at ground locations. The results of two conservative treatments were then modelled for each city: all outdoor luminaires fully shielded with the current lumen amount, and fully shielded luminaires with a lumen amount scaled to 2075 lm capita<sup>-1</sup>, matching Flagstaff, Arizona. The results indicate 42–88% reductions in average all-sky glow utilizing these ‘best practices’ for environmental conservation.

## 1. Introduction

Areas of sparse population exist in the western United States that combine with dry climate and clear air to generate excellent night sky quality. Night sky quality is explicitly recognized as a protected resource for many national parks and natural areas in this region. Sky glow from cities and towns often appears as isolated domes of light along the horizon at these sites. This situation creates opportunities for exploring the relationship between outdoor lighting practices and the amount of atmospheric sky glow produced. Photometric observations of anthropogenic sky glow may be correlated with the results from a sky glow model. Worldwide sky glow predictions have been constructed using the location and intensity of upward

anthropogenic light measured from satellite observations of the earth at night.<sup>1</sup>

The Suomi NPP satellite has been operational since 2011 and carries a scanning radiometer on board known as VIIRS (visible infrared imaging radiometer suite). The device includes a broadband imaging detector with high sensitivity, suitable for detecting anthropogenic sources of light on the earth's surface with high precision and accuracy, known as the VIIRS day/night band (DNB).<sup>2,3</sup> A preliminary product was released in December 2012 which presented a cloud-free composite of the earth at night from 75° north to 65° south latitude.<sup>4</sup> The radiance calibrated data are at a resolution of 15 arc seconds of longitude and latitude, or 463 m at the equator, and were compiled from data acquired in April and October of 2012. The data are single channel, high dynamic range, but with a spectral response biased towards the red end of the visible spectrum compared to the photopic or scotopic luminous

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efficiency functions established by the Commission Internationale de l'Éclairage (CIE). The methods used to construct the composite are described by Baugh *et al.*<sup>5</sup>

A sky glow model developed by Garstang may be used to predict the effects of outdoor lighting on sky brightness (luminance) as seen from an observing site some distance from the city centre.<sup>6–8</sup> Along a given path through the atmosphere, the model estimates the amount of light added through scattering, as well as removed by extinction (arising from both scattering and true absorption). Garstang's treatment uses an effective wavelength of 550 nm and a two-component atmosphere consisting of molecules and aerosols. The amount of aerosol is defined through a parameter *K* which sets the ratio of total molecular to aerosol scattering. It has been used successfully to predict and evaluate the effects of outdoor lighting on sky quality at astronomical observatories.<sup>9</sup>

Photoelectric photometers and charge-coupled device (CCD) detectors have been used to quantify night sky luminance in the absence of moonlight to evaluate the impacts of sky glow on astronomical observations.<sup>10–12</sup> Most of these site evaluation efforts focus on the region of the sky with a zenith angle less than 60°, ignoring the portions of the sky most affected by anthropogenic sky glow. Recently, all-sky fisheye cameras capable of calibrated sky luminance measurements have provided a rapid means of evaluating the entire sky.<sup>13–15</sup>

The U.S. National Park Service has collected all-sky luminance data with a 0.05° resolution mosaicking CCD camera system since 2001.<sup>16</sup> Improved accuracy in estimating the anthropogenic component of sky luminance is achieved using an all-sky subtraction of a natural sky luminance model.<sup>17</sup> These data are photometrically calibrated in a broadband system approximating the Johnson–Cousins Astronomical V band and the CIE photopic curve. Both observations

and modelling demonstrate that the amount and shielding of outdoor lighting has strong effects on sky glow. In this study we explore the potential reductions in sky glow that would be achieved with environmentally protective lighting design – conservative amounts in fully shielded luminaires. We use the term 'best practices' in this context and make no attempt to investigate details of outdoor lighting design to meet certain illuminance, uniformity, energy conservation, or human vision specifications. We emphasize that certain communities, such as Flagstaff, Arizona, have chosen to install outdoor lighting that limits sky glow, and this example is applied to other cities. Beginning with light geographic distribution and amount derived from the VIIRS DNB data and calibrated using a study of Flagstaff lighting published by Luginbuhl *et al.*,<sup>18</sup> supplemented by conservative assumptions of shielding, upright angular distribution intensity, and near-ground blocking, we develop models to match observed sky luminance profiles. We then predict the effects on sky glow of both fully shielded lighting and conservative outdoor lighting amounts as reflected by the practices in Flagstaff, Arizona.

## 2. Methods

### 2.1. Analytical approach

We begin with three sources of data for the city of Flagstaff, Arizona: (1) photometrically calibrated CCD camera observations of sky glow from a site at some distance from the city, (2) a complete outdoor lighting inventory including lumen output and average per cent upright, and (3) observations of upward radiance from the VIIRS DNB orbiting detector. The summed radiance for Flagstaff is compared to the total inventoried luminous output, determining the ratio between VIIRS DNB and luminous flux. We distribute the total inventoried lumen output over the land according to the observed VIIRS distribution. Using each

lumen-calibrated VIIRS grid cell as lighting amount input to a sky glow model, we compare the modelled result to ground-based CCD camera observations for verification. We then apply the radiance-to-lumen calibration ratio on a cell-by-cell basis to the VIIRS database over the southwest United States to estimate lumen output over this region. Data from the location of four other cities are each used as lighting amount input, and a model of sky glow as seen from observation sites near these cities is produced. Again, the modelled result for each city is compared to CCD camera observations for verification. If a significant discrepancy is observed, the difference is assumed to result from a different relationship between VIIRS radiance measurements and lumen output for that city. The calibration ratio is scaled in these cases to achieve agreement. After this adjustment, estimates of current lumen output for each of the four cities are calculated. Finally, we use the derived descriptions of current lumen output for all five cities as input to the sky glow model as a baseline to estimate the effects of two treatments: Changing the uplight fraction to zero, and changing the lumen amount to match that of Flagstaff as measured in lumens per capita. We consider Flagstaff's lumens per capita amount resulting from a sustained community effort to protect night sky quality and representing a 'best practices' target for other cities. The predicted sky glow amount and distribution for each treatment is compared to current baseline conditions.

## 2.2. Study area and cities selected

The study area includes a portion of the southwest United States. This region often experiences cloudless atmospheric conditions and low concentrations of atmospheric aerosols, which improve the quality of both observed sky glow data and results from sky glow modelling. A map of the region is shown in Figure 1.

The cities (or metropolitan areas) selected for analysis, including population size, latitude and longitude, observing site name, and the distance and azimuth from the observing site to the city centre, are given in Table 1. Flagstaff, Arizona, the 'First International Dark-Sky City' was selected as an example of best practices because of its efforts to protect dark night skies. Also, a complete outdoor lighting inventory was available for this city, allowing a calibration point for sky glow model inputs and for comparing the satellite data radiance values to known on-the-ground installations. Winslow, Arizona; Page, Arizona; and Moab, Utah were selected as relatively isolated small cities that illustrate sky glow impacts to an area of otherwise near-pristine night skies. Finally, Las Vegas, Nevada was included because of its regional significance to the night skies of the desert southwest. Analysis of Las Vegas included seven conterminous communities: Las Vegas, North Las Vegas, Henderson, Spring Valley, Paradise, Sunrise Manor, and Enterprise.

## 2.3. Upward light estimate based upon VIIRS DNB

The location on the earth's surface and relative intensity of upward light sources within cities were estimated using information from VIIRS DNB satellite data. False colour renderings of the pattern of upward light as detected by the VIIRS instrument are shown for the each study city in Figure 2(a)–(e).

The VIIRS DNB data exhibit varying background levels at values of approximately  $0.3 \text{ nW cm}^{-2} \text{ sr}^{-1}$ . The cumulative contribution of this background over a wide area can represent a significant contribution to the total radiant flux. After examining the areas of interest for each city, we decided to reset the zero point of the data at  $0.3 \text{ nW cm}^{-2} \text{ sr}^{-1}$  to effectively screen out radiance not associated with outdoor lighting.

We extracted and analysed VIIRS DNB data in ESRI ArcGIS<sup>TM</sup> software. Besides



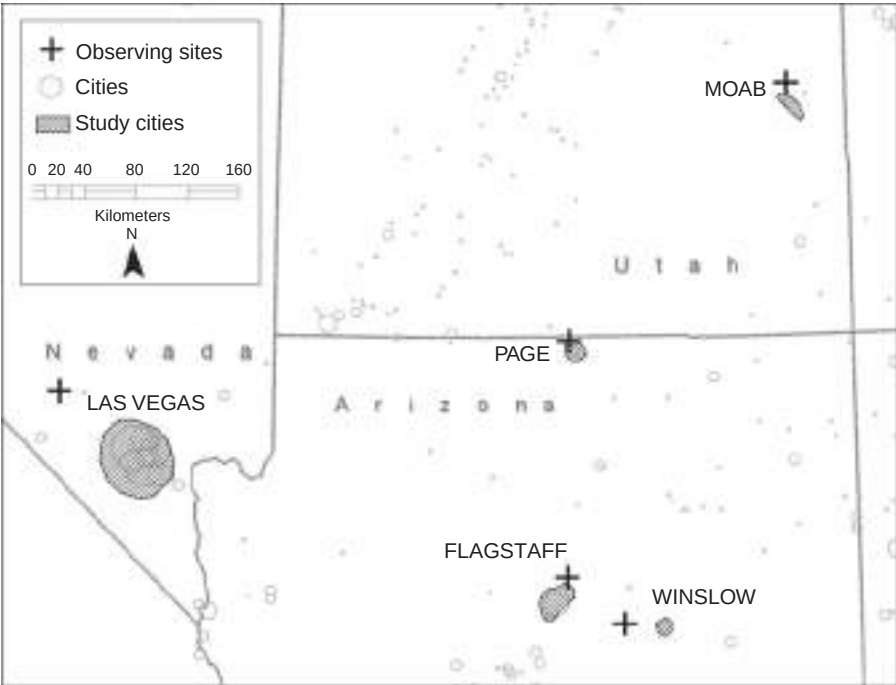


**Figure 1.** Map of a region in the southwest United States showing cities selected for analysis and the observing sites

**Table 1.** Cities and observing sites used in the analysis

| City name           | Population<br>2010 Census | Observing<br>site name | Distance to city<br>centre (km) | Azimuth<br>(site to city) |
|---------------------|---------------------------|------------------------|---------------------------------|---------------------------|
| Flagstaff, AZ, area | 76000                     | Sunset Crater          | 21.8                            | 205                       |
| Winslow, AZ         | 9652                      | Meteor Crater          | 29.9                            | 93                        |
| Page, AZ            | 7652                      | Wahweap Overlook       | 8.1                             | 150                       |
| Moab, UT            | 5101                      | Balanced Rock          | 14.6                            | 174                       |
| Las Vegas, NV, area | 1951269                   | FS Road 535            | 67.0                            | 125                       |

subtracting the background, we effectively defined the city limits by zeroing the adjacent undeveloped areas. The census data ‘populated place’ boundary was superimposed to define the population of each metropolitan area. An average and a sum of radiant flux for all cells within each city’s defined limits were then computed. These statistics form the basis for upward radiance and installed lumens estimates for each city.

#### 2.4. Calibration to Flagstaff lighting inventory

A comprehensive inventory of outdoor lighting for Flagstaff for 2003 was available, including lamp types, luminaire shielding, and luminaire lumen output (i.e. luminous flux escaping from luminaires, accounting for luminaire losses).<sup>19</sup> The late-night lumen output of Flagstaff (140 000 000 lm) estimated in this study was adjusted to account for growth between 2003 and 2012. We also

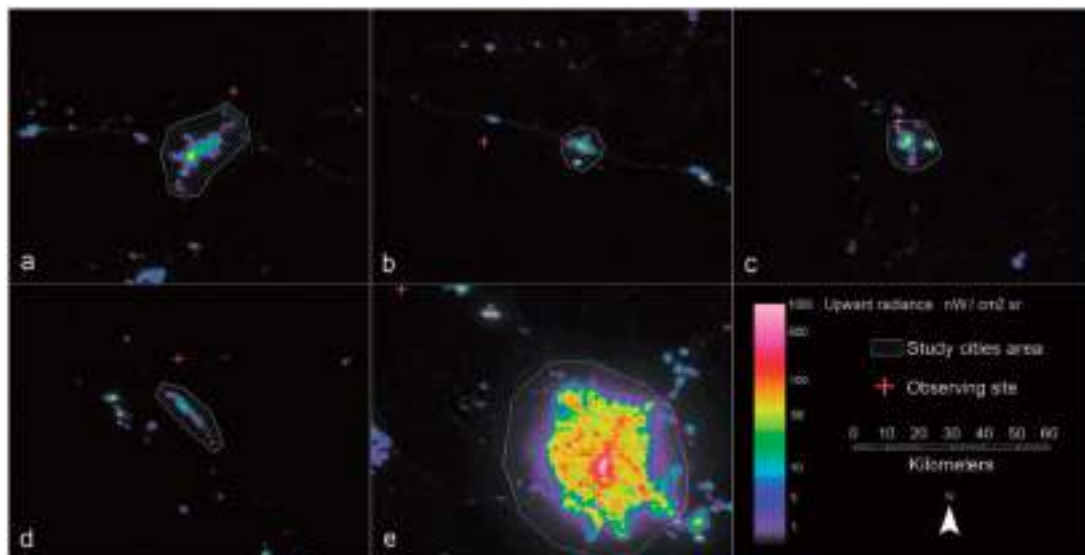


**Figure 2.** Maps of each study city: (a) Flagstaff, (b) Winslow, (c) Page, (d) Moab, and (e) Las Vegas showing the upward radiance observed by the VIIRS day/night band sensor in false colour and the observing site location (red '+') from which the field data of sky glow were collected. Outlined areas indicate approximate city boundaries (available in colour online)

included the adjacent communities of Dorney Park, Fort Valley, and Belmont, using an estimate based upon the number of residents, an estimated number of residents per house, and the per house lighting output (604 lm) and shielding (38% up) from the Flagstaff study. These adjustments brought the total installed luminaire lumens to 158 000 000 lm. The total radiant intensity from the Flagstaff area was measured at  $42725 \text{ W sr}^{-1}$  by summing the radiance from each cell in the DNB grid and multiplying by the total land area in  $\text{cm}^2$ . The ratio of total inventoried installed lumens to total upward radiant intensity observed by DNB yields a value of  $3698 \text{ lm W}^{-1} \text{sr}$ . We make the assumption that the DNB radiance is a useful measure of the upward luminous flux. The accuracy of predictions using this scale factor for other cities will thus depend upon their similarity to Flagstaff in terms of near-ground blocking, albedo characteristics, and light source

spectrum. We use the observed sky glow data to verify that the upward flux estimates for cities other than Flagstaff represent accurate estimates of the true amount, given the sky glow model assumptions. This is an important objective of this work and represents the first such exploration of the VIIRS database.

## 2.5. Observed sky glow from cities

Figure 3 shows sky glow from each city as observed by the NPS mosaicking camera. Anthropogenic sky glow (i.e. observed minus modelled natural) in micro-candela per metre squared ( $\mu\text{cd m}^{-2}$ ) was extracted from the observed sky glow mosaic at a  $1^\circ$  of zenith angle interval along a meridian through the sky aligned with the city centre. These observed values were compared to output from the sky glow model (Section 2.6) to adjust the initial estimate of luminaire lumens for each city determined from the VIIRS

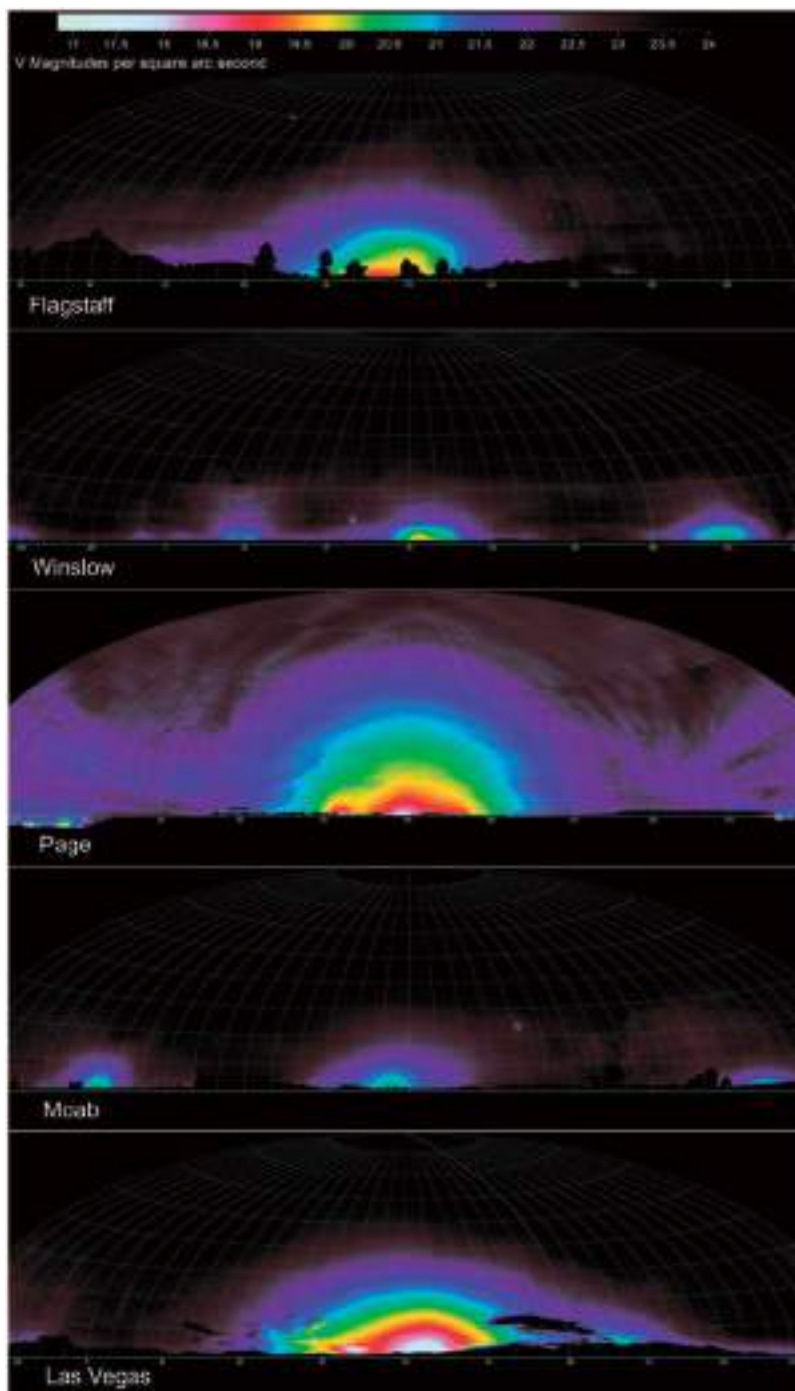


**Figure 3.** Observed anthropogenic sky glow for the five cities investigated (in Hammer-Aitoff equal area projection; grid lines are at 10° intervals) (available in colour online)

DNB radiance and Flagstaff scale factor described in Section 2.4.

## 2.6. Sky glow model parameters

A sky glow model developed by Garstang<sup>6-8</sup> was used to predict the sky luminance for comparison to the observations described in Section 2.5, as well as all-sky maps shown in Section 3. Inputs to the sky glow model include: (1) the location of the centre of each DNB grid cell in latitude, longitude, and elevation; (2) the estimated luminaire lumens obtained from the DNB radiance for each cell multiplied by the Flagstaff calibration scale factor (Section 2.4); (3) the angular distribution of upward emitted light as defined by Garstang,<sup>6</sup> with a ground reflection of 0.15<sup>6</sup> and direct uplight fraction of 0.10;<sup>19</sup> (4) a blocking profile (blocking parameters  $E_b = 0.3$  and  $\beta = 0.1$ ) arising from the blocking of light rays by objects in the near-ground environment as described by Luginbuhl *et al.*;<sup>18</sup> (5) the aerosol content of the atmosphere, calculated from the atmospheric extinction coefficient measured from observations of standard stars in the data for each observation; and (6) the altitude of the observer and the light source, determined from a digital elevation model.

Outputs from the model included predicted anthropogenic sky luminance in  $\mu\text{cd m}^{-2}$  along the meridian through the centre of the city in  $1^\circ$  zenith angle increments and predicted sky luminance over the entire sky. The all-sky predictions were fitted to a contour surface using a spline algorithm and this surface displayed with the same colour ramp as the observed data in ArcGIS software for direct visual comparison.

## 3. Results

### 3.1. Sky glow model for Flagstaff

The VIIRS DNB per pixel radiance measures were used to geographically distribute

the 158 000 000 lm determined from the corrected Flagstaff lighting inventory described in Section 2.3. The modelled and observed profiles for Flagstaff are shown in Figure 4. This result represents a successful corroboration of four separate components used to measure and predict sky glow impacts from a city: The photometric measurements from Sunset Crater and subsequent natural sky subtraction, the on-the-ground lighting inventory, the distribution of aggregate lumens from the inventory according to the VIIRS DNB relative upward radiance data, and the modified Garstang modelling process.

### 3.2. Sky glow model fit to observations for other cities and adjusted lumens per capita

The VIIRS DNB radiance maps were converted to luminous flux using the Flagstaff scale factor described in Section 2.4 and the resulting anthropogenic sky glow predictions compared with the observations. The predicted sky glow from the city of Winslow, Arizona fits the observed data well. However, for the other three cities, the luminous fluxes derived using the Flagstaff scale factor produced sky luminance predictions slightly to significantly greater than those observed. Table 2 summarizes these results. The need for this correction reveals that the VIIRS DNB measures cannot be immediately translated into on-the-ground fixture lumens given the sky glow model assumptions, which are the same for each city. Possible reasons for this include different surface albedos, different near-ground blocking from vegetation or buildings, or a higher fraction of unshielded light reaching the VIIRS DNB detector. Also, the reader is cautioned to not immediately infer that the sky glow models representing 'current conditions' for each city other than Flagstaff accurately portray the existing lighting practices. They are approximate representations and therefore essentially become hypothetical

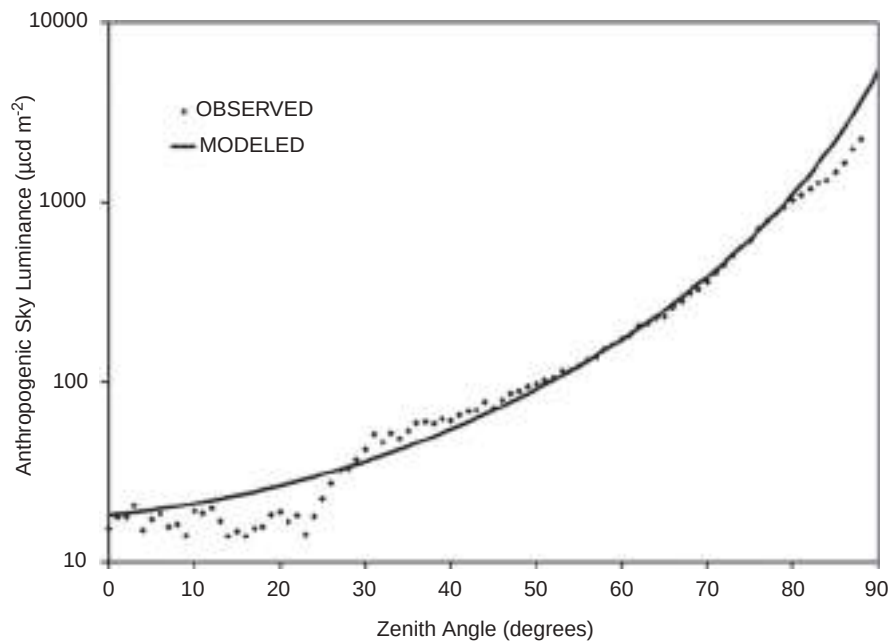


**Figure 4.** Observed and modelled luminance profiles for Flagstaff as seen from Sunset Crater National Monument, 21.8 km from the city centre

**Table 2.** Lumens per capita predicted by VIIRS DNB measures and measured by a model fitted to observed anthropogenic sky glow

| City name     | Predicted lumens per capita from DNB | Predicted lumens per capita from sky glow model fit | Adjustment resulting from Flagstaff model fit | Calculated lumens per capita ratio (city to Flagstaff) based on sky glow model fit |
|---------------|--------------------------------------|-----------------------------------------------------|-----------------------------------------------|------------------------------------------------------------------------------------|
| Flagstaff, AZ | 2075 <sup>a</sup>                    | 2075                                                | 1                                             | 1                                                                                  |
| Winslow, AZ   | 6275                                 | 6275                                                | 1.00                                          | 3.02                                                                               |
| Page, AZ      | 10368                                | 5702                                                | 0.55                                          | 2.75                                                                               |
| Moab, UT      | 7655                                 | 3828                                                | 0.50                                          | 1.84                                                                               |
| Las Vegas, NV | 7680                                 | 6528                                                | 0.85                                          | 3.15                                                                               |

<sup>a</sup>Calibration point derived from on-the-ground inventory

cities, given that certain model parameters are held constant for all cities.

### 3.3. Sky glow predictions for fully shielded and best practices lighting

Revised models for each city were developed to explore the consequences of improved lighting practice on sky glow. The first, developed for all five cities in the study, maintained the lumen output determined in

Section 3.3 but converted all lighting to zero upright or fully shielded luminaires. The second, developed for all cities except Flagstaff, reduced the luminous output per capita to that measured for Flagstaff (2075 lm capita<sup>-1</sup>). Figure 5 shows the results of the models (column 2 for fully shielded, column 3 for shielded plus 2075 lm capita<sup>-1</sup>) compared to the model of current conditions (column 1) as sky luminance maps. The all-sky average



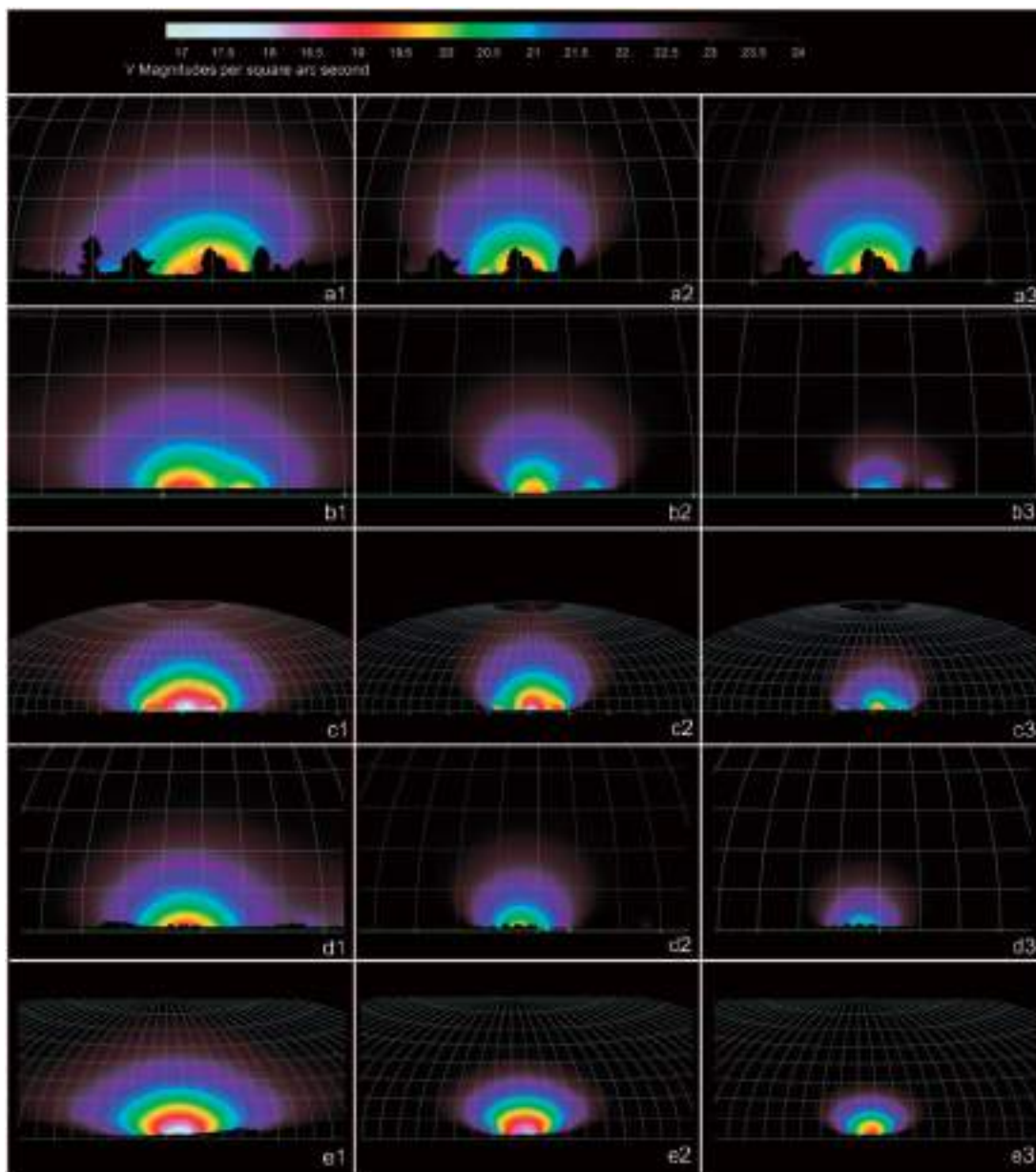


**Figure 5.** False colour representations of predicted sky glow from outdoor lighting as seen at each observing site in Hammer–Aitoff projection with  $10^\circ$  grid overlay (horizon at bottom, zenith at top) for each of the cities investigated with three outdoor lighting scenarios. Cities are arranged in rows: (a) Flagstaff, (b) Winslow, (c) Page, (d) Moab, and (e) Las Vegas. Lighting scenarios are in columns; column 1 = current conditions, column 2 = current lighting amount with full shielding, and column 3 = lighting amount same as Flagstaff ( $2075 \text{ lm capita}^{-1}$ ) + full shielding ('best practice') (available in colour online)

accurately represents the predicted total photon flux from anthropogenic sky glow arriving at the observer's location from all directions in the sky and is therefore a good indicator of environmental impact. Note that the scale is different for each city, indicated by the varying separation in the  $10^\circ$  grid lines, depending on the light dome overall size in the sky. The predicted reductions in sky glow over the meridian from zenith to horizon through the centre of each city light dome are shown in Figure 6 as a ratio to current conditions with zenith angle. In addition, three all-sky luminance indicators are presented in Table 3. Zenith luminance will affect astronomical observations, average all-sky luminance is the most unbiased indicator of light escaping into the environment, and the area of brightest luminance is a good indicator of human visual impact, since in a relatively dark environment the eye will be attracted to the brightest area of the sky.

These results reveal that merely shielding outdoor lighting produces very significant reductions in sky glow. This effect is most pronounced when the observer is at a greater distance from the city and in areas near the zenith. The shielded models for Las Vegas and Winslow (67 and 30 km from the observer, respectively) predict reductions to 28 and 55% of current conditions at the zenith, while Page (8 km distant) shows a reduction in zenith sky luminance to 79% of the current situation. Note, however, the large reductions in sky glow nearer the horizon ('Brightest area luminance' in Table 3) predicted for Page resulting from shielding. A reduction in installed lighting amount produces a directly proportional reduction in sky glow. Therefore, cities that are currently calculated to have much higher lumens per capita installed than our best practices standard of Flagstaff (such as Winslow, Page, and Las Vegas, see Table 2) could realize significant improvements in sky glow over all zenith angles at observing sites located any distance from the city centre.

The all-sky statistics shown in Figure 5 and Table 3 indicate potential dramatic reductions in overall environmental impact for the shielded + 2075 lm capita<sup>-1</sup> models, to 12–25% of current conditions.

## 4. Discussion

### 4.1. Use of VIIRS DNB data for measuring luminous output

We found that the VIIRS DNB cloud-free mosaic provided an excellent source for the geographical position and relative amount of escaped anthropogenic light over the surface of the earth for the cities we investigated. However, the conversion of VIIRS DNB radiance to absolute luminous flux appears to be uncertain within as much as a factor of two in the cities we examined. We believe this may be influenced by the following factors: (1) the vertical distribution of escaped light may be highly variable from city to city and is not available from the VIIRS DNB cloud-free composite, (2) the albedo of the ground surface may vary from city to city or even within cities, and (3) for large cities like Las Vegas, Nevada, near vertically upward-directed building facade lighting may be recorded strongly by the DNB sensor but may not lead to a proportional amount of sky glow when observed from a distant location on the ground.

These results do not imply that the uncertainties found in applying unadjusted VIIRS DNB data to a sky glow model render the data unusable for landscape scale analyses. They do indicate, however, the need for ground truthing of this type of remotely sensed data. For future work, the detailed Flagstaff inventory/VIIRS correlation provides a starting point. Methods employing a combination of remotely sensed and on-the-ground measures will minimize errors and may be required on a city-by-city basis to achieve an acceptable level of precision.

#### 4.2. Use of VIIRS DNB data for measuring energy waste

A gross measure of the efficiency of outdoor lighting use in cities may be obtained by calculating their total upward radiant flux

(watts). These numbers result from measures of DNB radiant intensity (see Section 2.3) times the effective solid angle into which the radiant flux emits. We assumed isotropic emission from the land surface into the

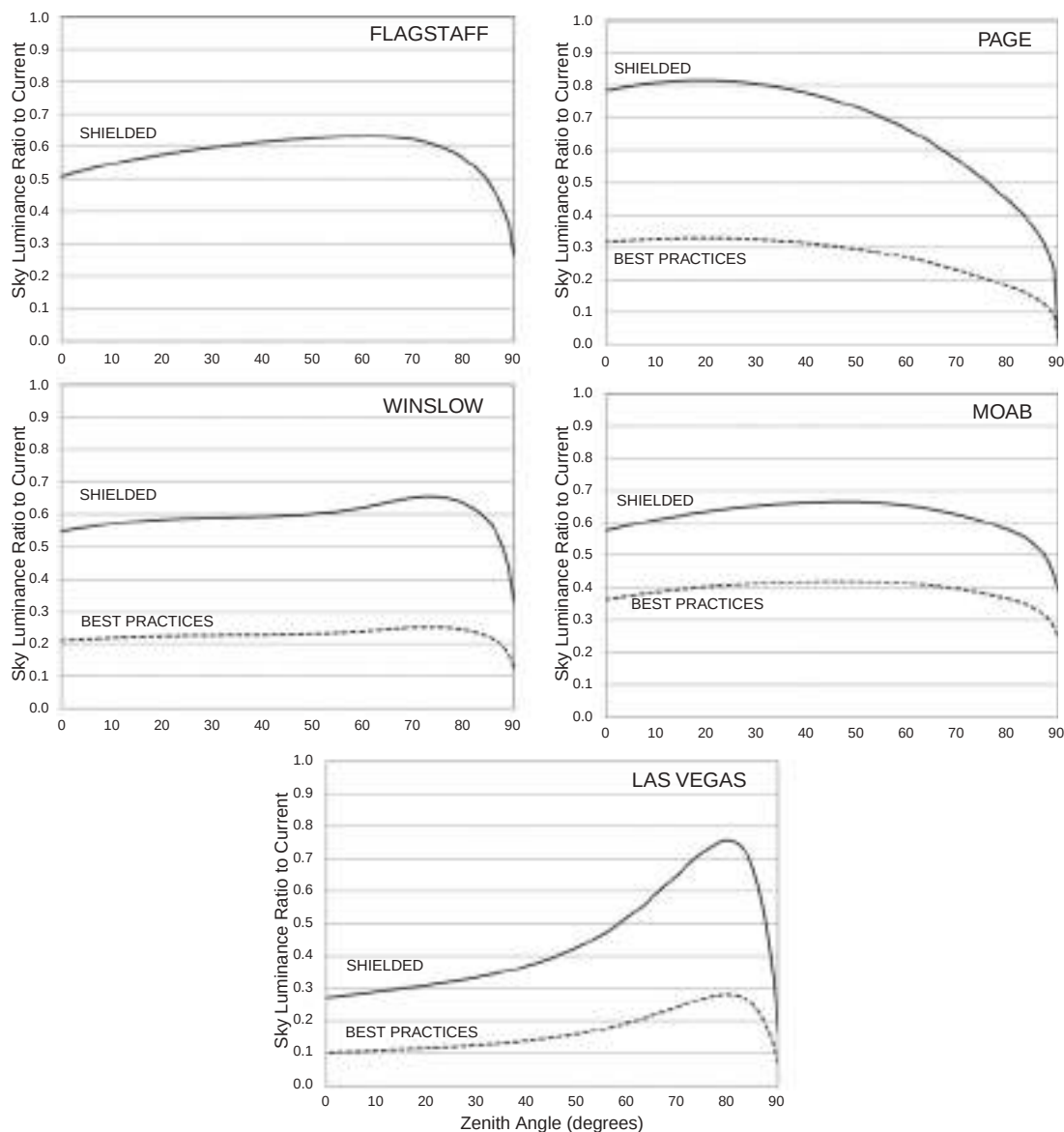


**Figure 6.** Sky glow reduction ratio along the meridian from zenith (zenith angle  $0^\circ$ ) to horizon (zenith angle  $90^\circ$ ) resulting from implementation of fully shielded luminaires (solid line) and fully shielded + lighting amount reduced to  $2075 \text{ lm capita}^{-1}$ , referenced to current conditions, for each of the cities investigated

**Table 3.** Predicted sky glow indicators for each observing site and treatment, luminance in  $\mu\text{cd m}^{-2}$ 

| Site (City)               | Zenith luminance<br>( $\mu\text{cd m}^{-2}$ ) |          |                | Average all-sky luminance<br>( $\mu\text{cd m}^{-2}$ ) |          |                | Brightest area luminance<br>( $\mu\text{cd m}^{-2}$ ) |          |                |
|---------------------------|-----------------------------------------------|----------|----------------|--------------------------------------------------------|----------|----------------|-------------------------------------------------------|----------|----------------|
|                           | Current                                       | Shielded | Best practices | Current                                                | Shielded | Best practices | Current                                               | Shielded | Best practices |
| Sunset Crater (Flagstaff) | 13                                            | 8        | 8              | 63                                                     | 37       | 37             | 6840                                                  | 4930     | 4930           |
| Meteor Crater (Winslow)   | 6                                             | 4        | 1              | 31                                                     | 14       | 5              | 3880                                                  | 2500     | 828            |
| Wahweap Overlook (Page)   | 65                                            | 52       | 21             | 331                                                    | 143      | 48             | 44600                                                 | 20800    | 5480           |
| Arches N.P. (Moab)        | 7                                             | 4        | 3              | 35                                                     | 16       | 9              | 3010                                                  | 2170     | 786            |
| FS Rd. 535 (Las Vegas)    | 37                                            | 10       | 3              | 239                                                    | 89       | 28             | 22300                                                 | 6910     | 2500           |

hemisphere above it, or  $2\pi$  steradians. Assuming isotropic emission, the radiant flux in watts is computed from the radiant intensity summed over the area of the city, multiplied by  $2\pi$  steradians. DNB radiant watts per person and per square kilometre were also calculated and the results are presented in Table 4. These results imply that Flagstaff is significantly more energy efficient and protective of night skies than the other cities, measured in both watts per person and watts per square kilometre. The total upward watts measured from the Las Vegas, Nevada area is overwhelmingly larger than the other cities, though the watts per capita appears moderate: roughly four times that of Flagstaff and comparable to Winslow and Moab. The calculated upward watts per unit land area of Las Vegas is massive, however, nearly 12 times that of Flagstaff. The calculated lumens per capita, using the Flagstaff scale factor, suggests that Page has higher outdoor lighting amounts per person than the other cities, including Las Vegas.

We found that the absolute upward radiant flux measured by VIIRS DNB drastically underestimated a measure derived from the Flagstaff on-the-ground inventory. Assuming an average of  $50 \text{ lm W}^{-1}$  for the lighting in Flagstaff, the VIIRS DNB estimate compares to about one-fifth the estimate deduced from the lighting inventory. Therefore, we cannot recommend the use of the DNB data to

directly calculate energy waste from outdoor lighting in absolute units. Some potential reasons for the observed discrepancy include: Upward radiant flux is unlikely to be an isotropic function of zenith angle, and this function may vary among cities; absorption and scattering reduce the number of photons reaching the satellite.

#### 4.3. Estimating upward light from each city resulting in sky glow

The significant adjustments often required to predict luminous flux based on VIIRS DNB radiance and the Flagstaff radiant flux-luminous flux calibration lead us to conclude that the use of a model fit to the actual observed sky glow pattern from a city produces a more accurate estimate of the total upward lumens. The last column in Table 2 represents our best estimate of the relative installed lighting amounts on a per capita basis. The most important part of our investigation is the effects of outdoor lighting on sky luminance as observed from the ground, and we consider field observations a must for accurate verification of any model based upon remotely sensed upward flux.

#### 4.4. Effects of best practices outdoor lighting on sky glow

We have defined best practice for outdoor lighting in cities in terms of the use of a conservative number of lumens per capita and

**Table 4.** Upward radiant flux for the cities investigated in this study

| City name     | Population | 2010 Illuminated city area (km <sup>2</sup> ) | Total upward radiant flux from VIIRS (W) | Upward radiant flux per capita (W person <sup>-1</sup> ) | Upward radiant flux per unit area (W km <sup>-2</sup> ) | Calculated fixture lumens per capita from VIIRS |
|---------------|------------|-----------------------------------------------|------------------------------------------|----------------------------------------------------------|---------------------------------------------------------|-------------------------------------------------|
| Flagstaff, AZ | 76000      | 164.3                                         | 42700                                    | 0.56                                                     | 260.1                                                   | 2075 <sup>a</sup>                               |
| Winslow, AZ   | 9652       | 52.8                                          | 17823                                    | 1.84                                                     | 337.7                                                   | 6275                                            |
| Page, AZ      | 7252       | 51.0                                          | 20373                                    | 2.80                                                     | 399.3                                                   | 10368                                           |
| Moab, UT      | 5101       | 59.2                                          | 10581                                    | 2.07                                                     | 178.5                                                   | 7655                                            |
| Las Vegas, NV | 1951269    | 1288.7                                        | 3783955                                  | 1.93                                                     | 3114.7                                                  | 7680                                            |

<sup>a</sup>Calibration point derived from on-the-ground inventory

100% fully shielded luminaires. The combination of lower amounts of light with the elimination of direct uplight is shown to be a very effective solution producing significant reductions in sky glow. We should also consider the application of adaptive lighting for both public and private applications, which would lower the after-hours lumens per capita even further.

We can interpret the results presented in Table 4 further given the knowledge that the sky glow model predicts a linear decrease in sky luminance with a given decrease in lighting amount. While we suggest that the example of Flagstaff at about 2000 lm capita<sup>-1</sup> represents ‘best’ practices, by dimming streetlights and/or businesses shutting down outdoor lighting after hours, this amount might be reduced to 1000 lm or lower in the early morning hours, resulting in proportional anthropogenic sky glow reductions. For cities like Winslow, or Las Vegas, which we estimate currently at over 6000 lm capita<sup>-1</sup>, a reduction to 1000 combined with full shielding is predicted to result in a more than 90% reduction in anthropogenic sky glow near the zenith as observed from a distant location (see the Las Vegas graph in Figure 6).

While not analysed in this paper, the third leg of night sky quality protection is the use of amber or yellow light sources such as high-pressure sodium, low-pressure sodium, or amber LED. Recent research has identified that scotopic vision (significantly more blue-sensitive and red-insensitive than photopic) must be addressed in sky glow analysis as whatever adaptation level is most applicable to on-the-ground lighting practices (photopic or mesopic); scotopic is clearly the proper response to consider when observing night skies in most situations.<sup>20</sup> If sky glow has a redder (or yellower) colour, it will be significantly less bright to the dark-adapted (scotopic) human eye, effectively reducing visual impacts, particularly at sites more remote



from cities such as national parks and other protected areas where complete dark adaptation is possible and desirable. Outdoor light that both dims and shifts in colour from white in the evening to yellow or amber in the early morning is an excellent mitigation strategy.<sup>21</sup> In future, analyses comparing traditional photopic (555 nm peak) to scotopic (507 nm peak) wavelengths may reveal more accurately the effects of the spectral component of outdoor lighting practices on visually observed sky glow.

## 5. Conclusions

The use of full shielding and conservative lighting amounts are outdoor lighting practices that will obviously reduce sky glow. This paper presents a quantitative estimate of the resulting magnitude of sky glow mitigation which may be achieved when entire cities employ these practices. The corroboration of predicted and observed sky glow measures reported for the case of Flagstaff, Arizona represents a validation of the methods employed to derive these estimates. Extrapolation to other cities is possible using VIIRS DNB satellite data if ground-based observations of sky glow are available. This analysis provides land managers and city planners a tool for estimating impacts of outdoor lighting on protected areas near cities and the benefits of improved shielding and total output limits.

This study shows that responsible best practice lighting installations reduce sky glow at the zenith 20–90% and 42–82% over the entire sky when viewed from a distant location. These reductions will significantly mitigate the impacts of outdoor lighting on visual sky quality. Protected areas (wilderness, national parks, wildlife preserves) are set aside for their natural characteristics and ecosystem processes. The design of outdoor lighting in cities located outside of these areas has rarely considered potential conflict

with the intent of such preserves. However, as light escaping from our urban environments travels great distances through the atmosphere,<sup>22</sup> and especially as human infrastructure and development is built to the very boundaries of such areas, light reflected and scattered by the atmosphere will erode environmental quality. Through the widespread use of shielding, reductions in lighting amounts, and yellow or amber colour, it is possible to maintain the natural nocturnal character of areas near cities.

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# Outdoor Lighting Retrofits

Folio N° 2897

A guide for the National Park Service and other federal agencies



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This guide was prepared by the California Lighting Technology Center (CLTC) at the University of California, Davis, for the National Park Service. CLTC is a research, development and demonstration facility dedicated to accelerating the development and commercialization of energy-efficient lighting and daylighting technologies. The center develops technological innovations, conducts demonstrations of new and emerging technologies, and carries out education and outreach activities in partnership with utilities, lighting manufacturers, end users, builders, designers, researchers, academics, and government agencies.

July 2014

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**Lighting constitutes a large portion of energy use at national parks. This guide provides assistance to facility managers who want to reduce lighting energy use while making parks safer and more visually appealing for visitors.**

Proper outdoor lighting increases safety and security, minimizes light pollution, and makes visitors' experience of national parks more memorable. Illuminating key attractions with the right luminaires, equipped with the right lighting controls, can also reduce energy consumption. This guide is intended to make the selection of appropriate, energy-efficient outdoor lighting solutions easier and improve project outcomes.

This guide provides an overview of outdoor lighting best practices as well as information on lighting technologies that can optimize energy, cost and maintenance savings. It offers guidance for evaluating light sources, performing a lighting audit, and pairing lamps with lighting controls. In many cases, following best practices allows facilities to exceed federal standards for outdoor lighting energy efficiency.

While some traditional outdoor lighting products are relatively energy-efficient, most sacrifice light quality and control for the sake of energy savings. This compromise is no longer necessary. Many new types of high-quality, outdoor lighting solutions are both highly energy-efficient and compatible with advanced lighting controls. Lighting retrofits that utilize these new technologies can reduce lighting energy use immediately, often by 50% or more as compared to traditional solutions.

Photo: Nimish Gogri





## Part 1

# Reasons for Outdoor Lighting Retrofits





After the sun sets, people rely on outdoor lighting for safety, security, wayfinding, and recreational activities, but excessive lighting often obstructs views of the night sky and can negatively impact ecosystems. Recent advances in light sources, controls and luminaires have made it possible to focus lighting only where and when it is needed, reducing light pollution.

Advances in outdoor lighting technologies are also increasing energy savings, reducing maintenance costs, improving visual environments, and enhancing safety. These improvements, coupled with a nationwide push to increase energy efficiency, have prompted the development and deployment of many lighting retrofit programs.

## Energy Efficiency

Lighting retrofits can lower energy use and costs without sacrificing light levels or quality. Switching to more advanced technologies may also allow users to implement lighting controls more successfully, which further increases energy savings.

Outdoor lighting presents an excellent opportunity for national parks to reduce their energy use. Case study summaries presented throughout this guide illustrate the energy savings that can be achieved with outdoor lighting retrofits.

When replacing older technologies, it is important to select fixtures, light sources and controls suited to each site. Proper selection requires consideration of many factors. This guide is intended to assist facility managers during the process. It includes instructions for conducting a lighting audit and guidelines for determining which lighting system components might be best suited to different applications.

**Figure 1.** Satellite imagery of the Earth at night reveals the density of electric lighting in developed areas.

## Reduced Maintenance Costs

A lighting retrofit can often deliver reduced maintenance costs over the life of the new lighting system as compared to costs to maintain old or outdated components. For example, improvements in lighting technologies have led to increased lifetimes for many types of products. This lengthens the time between maintenance tasks such as lamp replacement, which reduces labor costs and other expenses. In addition, implementing a routine maintenance program simplifies maintenance and further reduces operational costs associated with sustaining lighting systems.

Maintenance savings may also help offset some the initial cost of a lighting retrofit project. For example, prices for LED sources continue to decrease, as their efficacy continues to increase, resulting in greater energy savings and a better return on investment.

## Improved Visual Environments

Lighting retrofits can help address general lighting quality problems. For example, new technologies can offer lighting with better color rendering characteristics and reduced flicker and audible noise. When discussing outdoor lighting characteristics, two metrics are commonly used: correlated color temperature (CCT) and color rendering index (CRI). In addition, surrounding visual conditions influence the way we perceive light in the outdoor environment.

## Correlated Color Temperature (CCT)

Correlated color temperature (CCT) indicates the color appearance of a light source and is measured in Kelvin (K). CCT is calculated by measuring the apparent color of light emitted by a source then correlating that color to that of an idealized reference light source, called a blackbody radiator.

The color of light emitted by a blackbody radiator depends exclusively on its temperature. As a blackbody radiator heats up or cools down, the color appearance of the light it emits varies. The higher the temperature of the blackbody radiator, the “cooler” the color appearance of the light it emits (see figure 2). High-pressure sodium lamps, for example, have a relatively low CCT (~2000K), and deliver orange-yellow light. In contrast, most general illumination LED sources have high CCTs (5000–6000 K) and deliver white light that is relatively cooler in appearance.

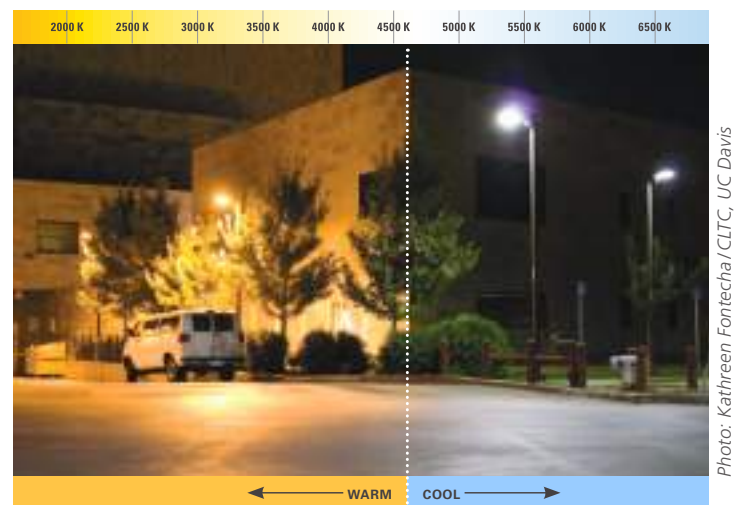
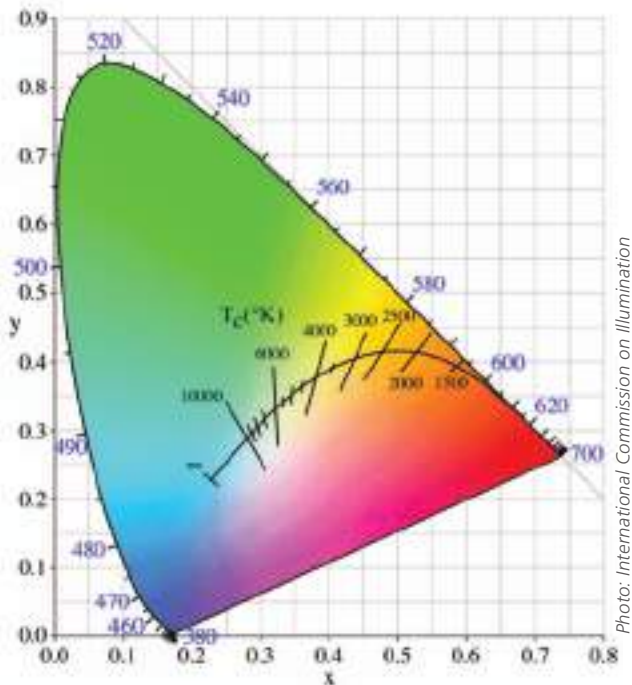


Photo: Kathreen Fontecha/CLTC, UC Davis

**Figure 2.** CCT indicates the warmth or coolness of a light’s apparent color. Note how the high-pressure sodium light on the left in this photo has a warm CCT while the metal halide lighting on the right has a cooler CCT.



**Figure 3.** CIE 1931 x,y chromaticity (color) space, with the chromaticities of blackbody light sources of various temperatures shown as the locus plot.



A more in-depth perspective on color specification uses the International Commission on Illumination (CIE) 1931 x,y chromaticity diagram (figure 3). Here, specific color matching can be achieved by plotting the chromaticity coordinates of light sources and comparing how close those points are to the reference light source (represented by the black line cutting through the middle of figure 3).

### Color Rendering Index (CRI)

The color rendering index is used to describe how accurately a light source renders colors. CRI uses eight standard color samples to compare the color rendering ability of a light source (such as a fluorescent or HID lamp, etc.) to that of a reference light source. The color of each sample is measured under the test light source and the reference light source, both with the same CCT. The degree of color shift between the two sets of measurements is calculated and grouped as an average. This average is subtracted from 100 to produce the CRI value. CRI is expressed as a number on a scale with no units. CRI ratings range from 1 to 100. A CRI rating (above 80) denotes more accurate color rendering ability.

Any light source appears to emit a single color, but in reality, a light source emits a broad range of colors that the eye blends together. This spectrum deconstructed into its individual colors is called spectral power distribution, or SPD. SPD is usually represented as wavelengths in the visible spectrum. The visible spectrum of light wavelengths ranges from approximately 380–780 nm. CCT and CRI are two ways of distilling a light source's SPD into a single number.

**Figure 4.** These photos were taken before and after a streetlight retrofit in San Jose, CA. The pre-retrofit low-pressure sodium lights (top) have a low CRI while the post-retrofit LED lights (bottom) have a high CRI.

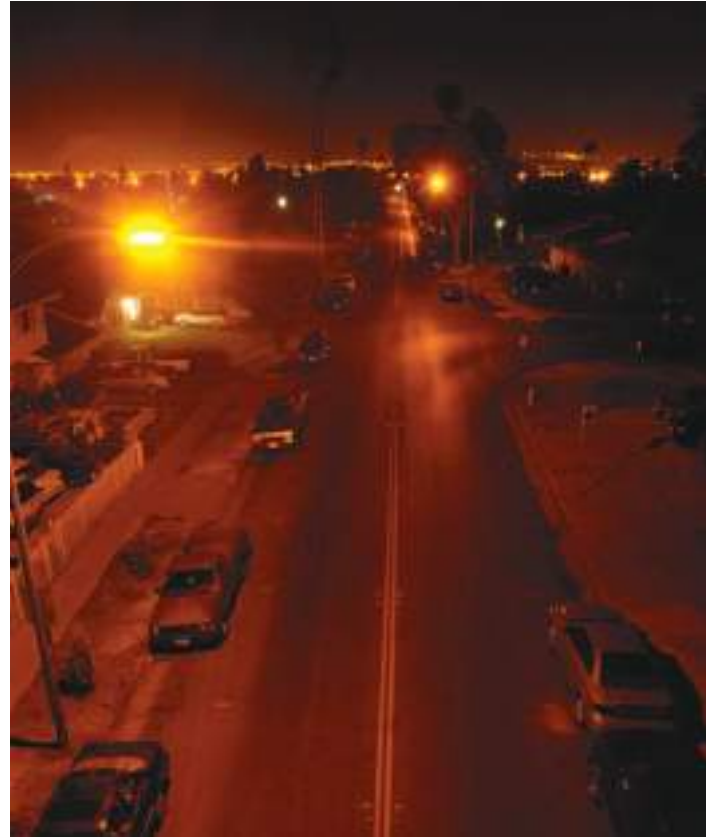


Photo: Pacific Gas and Electric; Energy Solutions

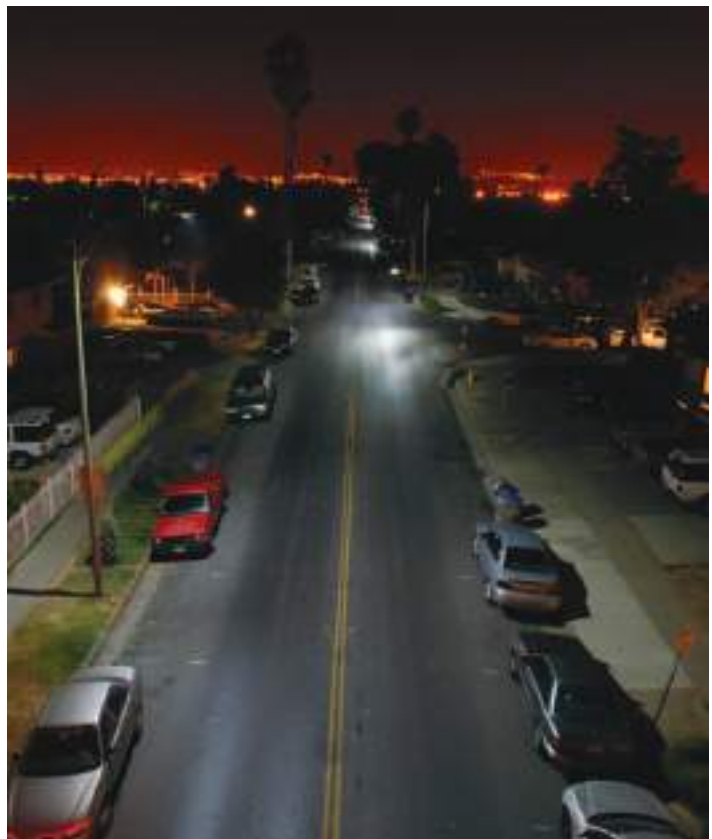


Photo: Pacific Gas and Electric; Energy Solutions



## Visual Conditions: Scotopic, Photopic and Mesopic Efficiency Functions

How the human eye perceives the SPD of a light source is also critical. This perception is, in part, dependent on the SPD of the source and the surrounding visual conditions. There are three general types of visual conditions: photopic, scotopic and mesopic conditions.

Photopic conditions account for the majority of applications, including all applications occurring under moderate to well-lit conditions; scotopic conditions occur at very low light levels, such as occur in a forest on a cloudy night; and mesopic conditions occur somewhere in between. Mesopic conditions account for the majority of nighttime lighting conditions in suburban and urban outdoor environments.

Viewing-condition effects are captured through a luminous efficiency function, which is applied to the SPD to get a representation of what the human eye actually sees under real-world conditions. There are three different luminous efficiency functions, one for each of the three different visual conditions.

Photopic and scotopic luminous efficiency functions are well defined, although the photopic luminous efficiency function is the only function accepted for use in standard lighting practice. The mesopic luminous efficiency function is more complex. Work is ongoing to better define and account for visual conditions in the mesopic range.

Light level measurements are calculated based upon application of the luminous efficiency function to the SPD of a particular light source. Application of one function or the other has the effect of biasing the measured light level; thus, it is important to understand which function has been applied to obtain a particular light output value. The lighting industry usually provides light output values using the photopic luminous efficiency function. Figure 5 shows the scotopic and photopic luminous efficiency functions.

## Safer Outdoor Areas

An outdoor lighting retrofit can improve the visual environment and make outdoor spaces feel safer and more secure. Many people assume that “brighter is safer,” but studies have shown that increased illuminance is not always beneficial.

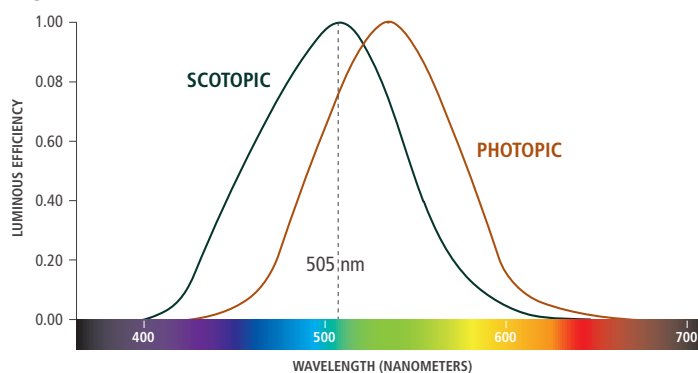
Too often, excessive lighting can lead to glare and overillumination. When designing outdoor lighting systems, the quality of light, not just the quantity of light, is important for safety. Outdoor lighting designs should aim to reduce glare, employ appropriate contrast ratios, and create “zones of recognition” in order to increase safety and perceived security.

The visual needs of the area’s intended occupants should also determine what type of illumination is installed. The color temperature and quality of different light sources can also affect people’s perception of brightness. As a result, it is important to understand who will use the space being lit, when they will use it and for what tasks or purposes.

## Minimal Light Pollution and Light Trespass

Light pollution and light trespass occur when nighttime lighting strays from its intended target, spreading into the sky or intruding on surrounding areas. Research continues to indicate the adverse effects of light pollution on people and wildlife. An important reason for completing an outdoor lighting retrofit is to reduce the negative environmental impacts of an existing lighting system. More on this topic, and the important role that national parks can play in reducing light pollution, is provided in the section on “Preserving Dark Skies,” presented in Part 6 of this guide.

**Figure 5.** Scotopic and photopic luminous efficiency functions



Source: *The Lighting Handbook*, 10<sup>th</sup> edition, Illuminating Engineering Society, Figure 5.5



Photo: Jeremy Stanley

**Figure 6.** The constellation Orion, as viewed under dark-sky conditions near Mammoth, Utah (left) and amid the urban sky glow of Orem, Utah (right).

## Part 2

## Best Practice Strategies



*A successful lighting installation delivers the right light, in the right amount, only where and when it is needed.*

## Basic Steps for a Lighting System Retrofit or New Lighting Installation

### 1. Perform a lighting audit of existing systems.

Before beginning a lighting system retrofit, a lighting audit of the existing system should be performed to determine the system's performance, how it meets the area's lighting needs, opportunities for improvement, and requirements for replacement technologies. The lighting audit will also establish the physical dimensions of the space, as well as the mounting heights and locations of existing luminaires and lighting controls; this is essential information for a lighting retrofit project. Guidelines for performing a lighting audit are provided later in this guide.

### 2. Establish goals for the retrofit or new lighting system design.

The results of the lighting audit will help identify which aspects of the existing system need improvement. These needs, in turn, will clarify the goals of the retrofit, e.g., to improve energy efficiency, reduce maintenance needs, reduce light pollution, etc.

### 3. Identify appropriate light sources and lighting controls.

The needs of the outdoor space and the retrofit goals will determine which lamps, luminaires or lighting controls are best suited to the project. A section on light sources, light fixtures and lighting controls is provided in this guide. Federal codes and standards, as well as professional lighting resources, should also guide product selection.

### 4. Obtain a code-compliant lighting design.

Lighting plans must meet, or exceed, the federally mandated standards set forth by ASHRAE 90.1–2010. Whether installing a new lighting system in a previously dark area or retrofitting an existing system, the new lighting design should be obtained through one of the following:

- A reputable lighting system supplier
- A professional computer-aided design package (e.g., AGI 32, Radiance, or Visual Pro)
- IES Recommended Practice appendix calculations

### 5. Verify application-specific light levels and distribution patterns meet best-practice guidelines.

Consult the Recommended Practice guides published by the Illuminating Engineering Society (IES) for each lighting application to ensure designed light levels and other lighting characteristics are sufficient without being excessive.

### 6. Perform a lifecycle cost-benefit analysis.

Evaluate the long-term costs and benefits of different systems under consideration. Remember to factor in projected increases in energy costs, estimated energy savings from lighting controls, replacement and disposal costs, and environmental impact.



## Lighting Design and Retrofit Elements

There are several elements that are common to both the design of a new lighting system as well as to the retrofit of an existing system. These elements are specific to both the object or space being illuminated and the intended use of the space. Factors such as illuminance, luminance, surface reflectance, and the lighting zone of the site should be considered before beginning any lighting project. In addition, for every new lighting design, a lifecycle cost analysis should be performed for each potential technology, to evaluate its payback based on initial costs such as design, materials, installation, and commissioning. Annual energy savings and maintenance cost savings should also be compared to existing lighting or alternative options.

### Illuminance (E)

Illuminance refers to the amount of light that strikes a surface from a light source. Illuminance is measured in footcandles (fc), or lumens per square foot (lm/ft<sup>2</sup>). Typically, the IES provides recommended, maintained illuminance values for specific applications. Illuminance values are also specified as minimum horizontal and vertical values for some applications.

### Luminance (L)

Luminance is the measure of light reflected from a surface in a given direction. It indicates the intensity, or brightness, of lighting in that direction and is measured in candelas per square foot (cd/ft<sup>2</sup>). Luminance measurements indicate, for example, how much light is reflected from the paved surface of a road in the direction of a driver. The IES provides recommended luminance values for use with roadway lighting.

### Surface Reflectance

Surface reflectance classifications are required to determine luminance. In the case of pavement reflectance, the IES follows CIE guidelines for the Four Class System (Table 1).

### Lighting Zones

The IES and the International Dark-Sky Association (IDA) developed the Model Lighting Ordinance (MLO) to minimize light pollution and keep light levels appropriate to the surrounding area. Released in 2011, the MLO classifies areas into five lighting zones, with guidelines for outdoor lighting in each of these zones. It is important to know which lighting zone a given project falls in, whether it is a new monument being installed in an urban setting or a retrofit of an existing wilderness area. This topic is discussed in more detail in Part 6 of this guide, on Preserving Dark Skies.

**Table 1. Road Surface Reflectance**

| Class     | Description                                                                                                                                                           | Mode of Reflectance          |
|-----------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------|
| <b>R1</b> | Portland cement, concrete road surface. Asphalt road surface with a minimum of 12% of the aggregates composed of artificial brightener and aggregates.                | Mostly diffuse               |
| <b>R2</b> | Asphalt road surface with an aggregate composed of a minimum 60% gravel (size greater than 1 cm, or 0.4 in).                                                          | Mixed (diffuse and specular) |
| <b>R3</b> | Asphalt road surface (regular and carpet seal) with dark aggregates (e.g., trap rock, blast furnace slag); rough texture after some months of use (typical highways). | Slightly specular            |
| <b>R4</b> | Asphalt road surface with very smooth texture.                                                                                                                        | Mostly specular              |

**Figure 7.** LED luminaire installation at UC Davis



### Luminaire Choice and Positioning

When replacing or retrofitting luminaires, the following are important characteristics to keep in mind:

- The energy efficiency of the light source technology
- Potential maintenance cost savings
- Distribution / beam width
- Compatibility with existing poles or other mounting apparatus
- Fixture aesthetic and consistency with the surrounding environment
- Opportunity to reduce light pollution (BUG rating)

See IES Recommended Practices or other reputable lighting guides for recommended spacing/aiming ratios applicable to the outdoor space. Factors to consider include:

- Setback
- Spacing
- Vertical/horizontal aiming

It is recommended that all lighting designs be modeled in a computer-based scenario program to validate the light levels and uniformity.

**Figure 8.** The Vietnam Veterans Memorial and Washington Monument illuminated at night (Washington, D.C.).



### Structures and Monuments

Some structures or monuments call for uniform illumination, while others need a more striking approach to accentuate focal points. In general, uniform illumination leads to more light pollution, so this approach should be used for limited applications. Structures are typically lit through one of the following strategies:

- Floodlighting
- Outlining
- Spotlighting
- Silhouetting

More information on lighting design for outdoor monuments may be found in "Lighting for Exterior Environments," IES Recommended Practice 33 (RP-33).

## Softscape

Softscape lighting incorporates illumination of surrounding plants and natural landscaping materials into one unified lighting design. It is typically used for parks, gardens, entry markers, yards, or natural structures. When implementing a softscape lighting design:

### 1. Identify focal points to be highlighted in the landscape and their material characteristics

- Shape
- Height
- Width
- Age
- Color
- Reflectance
- Texture
- Density

For trees, branching pattern, bark condition, root depth and spread, growth rate, and whether the tree is evergreen or deciduous, can inform luminaire selection and placement.

### 2. Choose appropriate luminaires to suit material characteristics and project goals

Consider the following when making selections:

- Light source choice for maximum energy efficiency benefits and lower maintenance costs
- Cutoff visors and shielding to reduce light pollution
- Beam width / distribution

### 3. Determine best-practice guidelines for spacing

For each point of interest, refer to IES Recommended Practices or other reputable lighting design sources for specific guidelines and best-practice recommendations.

## Hardscape

Hardscape lighting applies to man-made elements of landscape, but involves similar considerations as softscape lighting.

### 1. Identify whether the focal point is a structure or water

#### Structure (sculpture, flat display, gazebo, etc.)

Considering critical viewing angles and position luminaire(s) to accentuate the structure from these vantage points.

- Incorporate colored lighting so it is not dominated by other light sources
- Use shadows and highlights to emphasize surface texture and shape
- Avoid glare and “hot spots” by lighting the structure with IES recommendations in mind, from both above and below
- Use shielded luminaires and correct beam shape

#### Water feature (fountain, pool, etc.)

Take the properties of light and water into consideration when positioning luminaires for this type of application.

- Refraction: Known to cause rainbows in rough water
- Reflection: Angle of incidence determines luminaire location
- Diffusion: May add desired effects or obscure focal points under water with certain conditions

### 2. Choose appropriate luminaires

- Choose technologies that increase energy efficiency and lower maintenance costs
- Use cutoff visors and shielding to reduce light pollution
- Consider beam width and distribution

### 3. Determine luminaire spacing for each point of interest

Refer to IES's Recommended Practices or other authoritative sources for guidelines.

## Vehicle Spaces

Good lighting for outdoor areas serving vehicle traffic allows both motorists and pedestrians to safely navigate the space. Roadways, tunnels, parking lots, and parking garages all have different lighting needs. Considerations for lighting each of these applications are explored below.

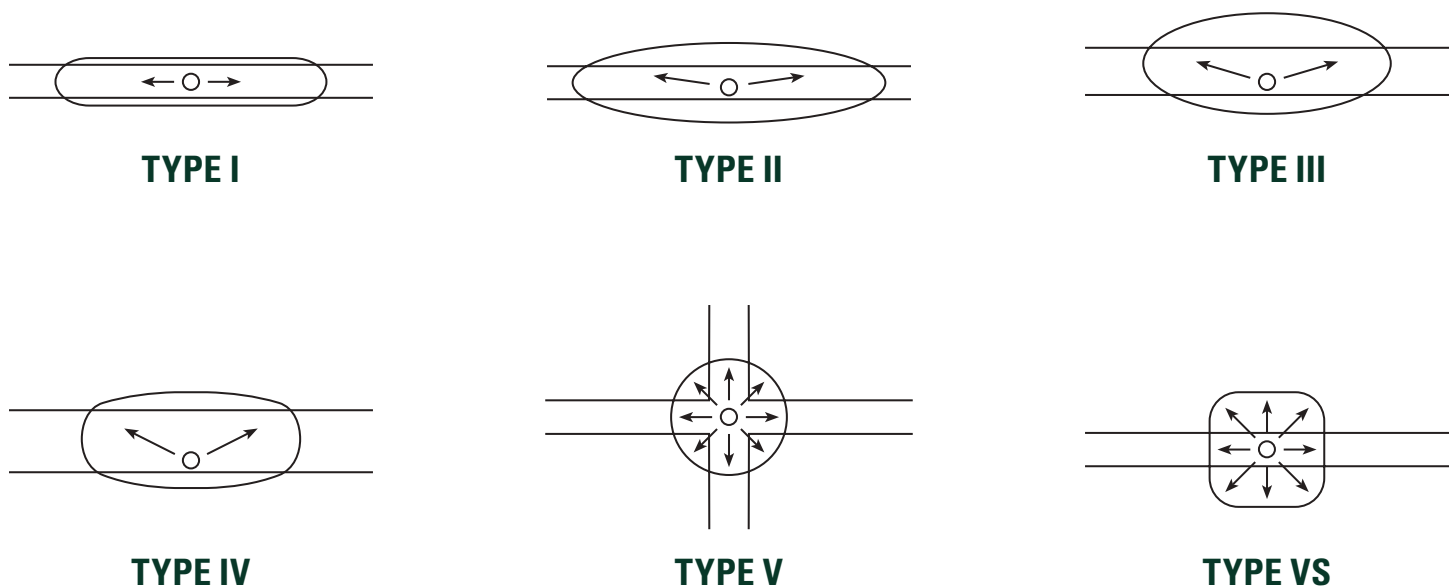
### Roadways

Designing a roadway lighting system requires evaluating many factors, including: visibility, economics, aesthetics, safety, environmental conditions, materials, space geometry (roadway width, curb location, etc.), the pavement's reflective properties, extreme grades and curves, intersections, and landscaping.

Roadway lighting designs are implemented following these basic steps:

1. Determine the classification of the roadway, area and pavement (see table 1)
2. Based on the roadway classification, determine the lighting codes and standards that must be met, including local ordinances
3. Choose luminaires that will satisfy lighting standards and provide appropriate distribution patterns for each area type along the roadway (see figure 9)
4. Implement lighting controls where appropriate to further improve energy savings and minimize light pollution

**Figure 9.** IES outdoor luminaire and light distribution patterns



*IESNA Lighting Handbook, 10th ed. 8.10*



**Figure 10.** Adaptive parking garage lighting at UC Davis employs both occupancy and daylighting controls. In California, there are now requirements for both to be included in most lighting alterations for parking garages.



## Parking Lots and Garages

Lighting in both parking lots and garages should provide ample lighting for safety and security while minimizing glare and light trespass. Parking garages are classified as indoor spaces under federal lighting regulations, but they utilize many of the same lighting technologies as outdoor parking lots, and they often provide excellent opportunities to reduce lighting energy waste. Unlike lots, parking garages have special lighting requirements for illuminating entrances and exits, ramps, perimeters, and stairways.

Follow these general guidelines when designing a lighting system for a parking lot or garage:

- Maintain illuminance levels at entrances to at least match surrounding public lighting. For parking garages, a daylight contribution is suggested
- Select appropriate shielding / reflectors to reduce glare and obtrusive light
- Choose adaptive luminaires with motion sensors to save energy and alert occupants when another person enters an area
- Choose a luminaire with appropriate color rendering capabilities (i.e., high CRI where helpful to promote a sense of safety and security in the space)
- Design the geometry of the lighting system, including mounting height and spacing, according to the distribution of the luminaire selected and in order to achieve required uniformity levels
- Incorporate safety lighting to abide by federal building ordinances (and any applicable at state or local codes and standards)
- Incorporate daylighting controls along parking garage perimeters, where daylight can supplement electric lighting, to reduce electricity use

## Tunnels

Vehicle tunnels are typically exempt from energy efficiency codes and standards. Several important factors influence tunnel lighting design:

- **Length and geometry of the tunnel:** These are the two primary factors to consider, as both will determine the spacing and mounting height of luminaires during installation
- **Geographic location:** Surrounding area, type of landscape surrounding the tunnel, and the solar altitude / azimuth
- **Climate factors:** Temperature, humidity, seasonal changes in landscape growth, type and levels of precipitation, and average cloud coverage

## Pedestrian Spaces

Adequate lighting along walkways and other pedestrian paths can help to prevent accidents, assist police protection, and facilitate wayfinding. Energy-efficient lighting designs can support all these lighting goals. Table 2 provides illuminance recommendations for different areas with pedestrian traffic.

**Table 2. Recommended Maintained Illuminance Levels for Pedestrians and Cyclists**

|                                                           | <b>Minimum average horizontal illuminance levels on pavement (lux / footcandles)</b> | <b>Average vertical illuminance levels for special pedestrian security (lux / footcandles)</b> |
|-----------------------------------------------------------|--------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------|
| <b>SIDEWALKS (ROADSIDE) AND TYPE A BIKEWAYS</b>           |                                                                                      |                                                                                                |
| Commercial Areas                                          | 10/1                                                                                 | 20/2                                                                                           |
| Intermediate Areas                                        | 5/0.5                                                                                | 10/1                                                                                           |
| Residential Areas                                         | 2/0.2                                                                                | 5/0.5                                                                                          |
| <b>WALKWAYS DISTANT FROM ROADWAYS AND TYPE B BIKEWAYS</b> |                                                                                      |                                                                                                |
| Commercial Areas                                          | 5/0.5                                                                                | 5/0.5                                                                                          |
| Intermediate Areas                                        | 5/0.5                                                                                | 10/1                                                                                           |
| Residential Areas                                         | 20/2                                                                                 | 55/0.5                                                                                         |

## Outdoor Sports and Recreation Areas

Different guidelines apply, depending on the type of space and the specific activities it is designed to support (whether that space is a track, bike path, tennis court, ski run, etc.). In general, outdoor sports lighting should be designed to minimize sky glow, using luminaires with the appropriate BUG ratings for the site and the proper placement for the application. Countdown timers, timeclocks, and other control devices ensure lighting operates only when it is needed.

### Sidewalks

Sidewalk spaces are typically paved areas for pedestrians that extend along roadways.

### Walkways

Pedestrian walkways are within the right of way for vehicular traffic and include skywalks, subwalks, walkways for access to parks or block interiors, and midblock street crossings.

### Bikeways

A bikeway is any path specifically designated for bicycle travel.

## Part 3

## Light Sources and Controls



## Best Practices for Selecting Products

For over a century, electric light was mainly produced by a glowing filament in a glass bulb or by the fluorescence of a gas-filled tube. Now, solid-state lighting is providing viable alternatives for general illumination. Selecting the right type of light source and the right lighting controls for a given application means comparing lumen output, efficacy, color quality, and spectral output. Factors such as cost, lamp life and controls compatibility are also important.

When selecting a light source, keep in mind that each technology will be paired with other elements to create an effective system. The source should be selected in combination with the proper luminaire and controls for the specific application. When considering various lighting products, lumen output, efficacies, light quality, lifetimes, and cost all should be considered.

The following guidelines are helpful to keep in mind when selecting light sources and lighting controls:

- Luminaires should use long-life sources to reduce maintenance and recycling requirements
- Luminaires with the lowest appropriate BUG rating for controlling backlight, uplight and glare should be used whenever possible
- Sources should have a maximum CCT of 6000 K (or 4000 K in residential areas)
- Luminaires bearing the “IDA-approved Dark Sky Friendly” Fixture Seal of Approval (FSA) will help minimize light pollution
- Amber, orange or red light sources are available for sensitive habitats, such as coastal regions where sea turtles or threatened seabird populations nest, and spectrally tunable luminaires for use at different times of the year, such as migration seasons, may soon be more widely available
- Photocontrols and/or time clock devices should switch luminaires off entirely when sufficient daylight is available and operate lights at reduced power during dusk and dawn
- Occupancy controls should reduce luminaire power during vacant periods



Photo: National Park Service

### **The Statue of Liberty: Temporary LED solution speeds restoration while reducing energy consumption 65%**

The National Park Foundation and the National Park Service partnered with Musco Lighting to relight the Statue of Liberty in the wake of Hurricane Sandy. Musco developed and installed a system of LED light fixtures powered by small generators and mounted on moveable structures that could be easily relocated as needed during restoration work. The LED lighting system reduced the energy used to light the iconic statue by an estimated 65% or more.

[nationalparks.org/connect/npf-news/musco-lighting-and-national-park-foundation-join-national-park-service-relight](https://nationalparks.org/connect/npf-news/musco-lighting-and-national-park-foundation-join-national-park-service-relight)

## Light Sources

When planning a retrofit, keep in mind that not all sources are interchangeable. The new source may not perform the same way as the older source. For example, CFLs typically do not perform well in cold environments, and LED replacement lamps may not last as long as intended when operated for prolonged periods at very high temperatures.

Carefully evaluate the long-term goals of the retrofit. In some cases, replacing the whole luminaire is more cost-effective overall than replacing lamps, even though the up-front costs may be higher. It may be tempting to remove controls or dimmable luminaires from the purchasing plan to reduce initial project costs, but doing so will mean sacrificing the long-term savings associated with these measures. Understanding the benefits and limitations of light sources makes it easier to select the right technology for the application. Table 3 compares common source types used for outdoor lighting.

**Table 3. Common Light Sources Used in Outdoor Applications**

| LAMP TYPE            | DEMAND (W)* | SOURCE EFFICACY (LPW)** | CCT (K)     | CRI   | LIFETIME (HOURS)     | PRICE       |
|----------------------|-------------|-------------------------|-------------|-------|----------------------|-------------|
| High pressure sodium | 70–400      | 80–120                  | 1,900–2,200 | 22–70 | 20,000–40,000        | \$\$        |
| Low pressure sodium  | 55–180      | 130–170                 | 1,700–1,800 | —     | 16,000–20,000        | \$\$        |
| Ceramic metal halide | 20–400      | 75–110                  | 3,000–4,200 | 80–94 | 10,000–30,000        | \$\$–\$\$\$ |
| Metal halide         | 70–400      | 40–70                   | 3,000–4,200 | 60–80 | 10,000–20,000        | \$\$        |
| Mercury vapor***     | 75–1,000    | 20–40                   | 4,000–6,000 | 15–50 | 16,000–24,000        | \$\$        |
| CFL                  | 20–70       | 80–85                   | 2,700–5,000 | 80–85 | 6,000–12,000         | \$          |
| Induction            | 70–250      | 50–85                   | 3,500–5,000 | 80–85 | 100,000              | \$\$–\$\$\$ |
| LED                  | 40–250****  | up to 130               | 2,700–6,000 | 50–85 | up to 35,000 or more | \$\$–\$\$\$ |

*Note: The ranges listed in this table reflect typical values for light sources commonly used in outdoor lighting applications. These numbers were compiled when this guide was created and are subject to change as technologies improve.*

*Selection of a particular product should be made only after carefully considering the lighting needs of the site. Some outdoor applications may be best served by products with characteristics that fall outside of the ranges listed in this table.*

\* Typical size of lamps used in exterior applications.

\*\* Based on initial lumens, system efficacy should be determined and is dependent on the specific luminaire style, as well as the ballasts or drivers employed.

\*\*\* Manufacture and import of mercury vapor lamp ballasts and luminaires has been banned since 2008; this is included for comparison purposes only.

\*\*\*\* Typical size of LED luminaires used in exterior applications, luminaire contains multiple LEDs.



## Filament-Based Light Sources

Filament-based light sources produce light by passing current through a fine filament wire, causing it to glow. Incandescent and halogen lamps are both filament-based light sources, but they have unique differences.

**INCANDESCENT** sources produce light from a filament heated by an electric current to the point of incandescence. Traditionally, incandescent lamps have been used in nearly every application. These sources are known for their warm color appearance and high color rendering ability. Incandescent lamps are available in many different lamp shapes and sizes to fit almost any application, although they are one of the least efficient sources available.

**HALOGEN** lamps, sometimes called tungsten halogen or quartz halogen, are another type of incandescent, filament-based light source. This lamp uses halogen gas inside a small quartz capsule that encloses the filament. The gas provides some protection for the filament and redirects filament particles back to the filament itself, which results in a longer lamp life than standard incandescent lamps and allows the lamps to burn hotter and brighter. Higher operating temperatures can pose a fire hazard in some applications.

**HALOGEN INFRARED REFLECTING (HIR)** Lamp is a type of halogen parabolic aluminized reflector (PAR) lamp with a coating on the inside of the lamp. The coating not only absorbs ultraviolet (UV) radiation but also redirects heat (infrared radiation) back onto the filament, which allows for a slight increase in efficacy over standard halogen lamps.

## Fluorescent Light Sources

A fluorescent lamp is a type of low-pressure gas discharge lamp. Visible light is produced by phosphor coatings on the inside of the glass tube. The entire light-production process involves many reactions and requires proper voltage and current regulation.

A variety of phosphors can be used to provide fluorescent lamps in various color temperatures and with various color rendering qualities. Fluorescent lamps are also available in many shapes, sizes, wattages, and colors. Ballasts are essential to the operation of fluorescent lamps. Ballasts are electrical devices that provide proper starting voltage to initiate the arc between the electrodes and then control and modulate the current during operation.

**PREHEAT LAMP AND BALLAST** lamps are designed to operate in a circuit requiring a manual or automatic starting switch to preheat the electrodes to start the arc. Preheat lamp and ballast circuits heat the cathode using a variety of starter mechanisms before high voltage is applied. The preheating takes a few seconds and then the ballast attempts to strike the lamp; if the lamp does not strike, the preheating process starts over. When using a starter that cannot recognize a lamp failure, it is important to remove the lamp as soon as possible, or the ballast will continue to attempt to strike the lamp until the ballast and/or starter fail. Lamp flicker is usually an indication of lamp failure.

**INSTANT-START LAMP AND BALLAST** is designed to start by a very high voltage without preheating the electrodes. The high voltage in instant-start lamp and ballast circuits causes the electrodes to discharge electrons through field emission.

**RAPID-START LAMP AND BALLAST** is designed to operate with a ballast that uses low-voltage windings to preheat the electrodes and initiate the arc. This is done without a starting switch or the application of high voltage. Rapid-start lamps require a bi-pin configuration.

**PROGRAM-START BALLAST** warm the electrodes before high voltage is applied. Once the arc is struck, the ballast stops the warming circuit.

**MAGNETIC AND ELECTRONIC FLUORESCENT BALLASTS** provide the proper starting voltage and regulate the amount of current flowing through the lamp. The magnetic ballast is an older technology that uses coiled wire as an inductor to regulate current. It is less efficient and larger than an electronic ballast, and may create a humming noise during operation. The magnetic fluorescent ballast is currently being phased out of the market because electronic ballasts deliver higher efficacy than magnetic ballasts and use improved electronic components to control the current more precisely. Electronic ballasts do not emit a notable humming noise, but they may have shorter lifespans than magnetic ballasts.

**COMPACT FLUORESCENT LAMPS (CFLS)** are a type of fluorescent lamp designed to replace incandescent A-lamps. CFLs are available in three base types with many different geometries, wattages, and color temperatures. Most CFLs are designed for use with a standard screw-base socket. These are commonly known as screw-in or screw-base CFLs. Screw-in CFLs are also known as self-ballasted CFLs because the ballast is integrated into the base of the lamp.

Pin-base CFLs have small, plastic bases that do not contain integrated ballasts. Pin-base CFLs are designed with two or four pins and are used with specially designed fluorescent luminaires that have the ballast remotely mounted to part of the housing.

The third type of CFL has a GU-24 base. GU-24 CFL lamps are installed using the same screw-in motion as a screw-base CFL but with a modified twist-and-lock connector instead of threads. Some lamp styles contain integrated ballasts while others have separate, detachable ballasts that allow for replacement.

**INDUCTION LAMPS** are a type of fluorescent lamp and generate light in the same way: The flow of electricity creates a gas discharge that is converted into visible light by the white phosphor inside the lamp. Instead of using the standard ballast and electrode system, induction systems use a high-frequency electromagnetic wave produced by a special ballast (also called a generator) to induce a current in the lamp. Fluorescent lamps have electrodes that degrade over time and eventually fail, but because induction lamps do not have electrodes, they have much longer lifetimes. Because of their longevity, induction luminaires are well suited for outdoor areas where reducing lamp replacement and maintenance would provide an advantage.

## High-Intensity Discharge (HID) Lamps

HID lamps are a type of gaseous discharge lamp. Typical HID lamps contain an electrode within an inner arc tube that is mounted on a supporting frame. The frame and support assembly are connected to a base, which provides the electrical contact. The entire assembly is surrounded by a hard glass outer jacket that has been exhausted of air to protect the arc tube and lamp components from contamination and oxidation.

**MERCURY VAPOR (MV) LAMPS** are an older technology that generally underperforms in efficacy and lamp life compared with metal halide or sodium lamps. For this reason, sales of mercury vapor lamp ballasts were banned in the United States in 2008. Metal halide and high-pressure sodium (HPS) sources have replaced many MV lamps.

**METAL HALIDE (MH) LAMPS**, similar in construction to mercury vapor lamps, provide white light at higher efficacies and have longer lifetimes. Metal halides in the arc tube contribute to the improved light output over time. MH lamps are commonly used for commercial, industrial, sport, building façade, and high-ceiling architectural purposes. MH is the most suitable HID source when good color rendering is required.

Probe-start metal halide lamps contain a special “starting” electrode within the lamp to initiate the arc when the lamp is first lit. This generates a slight flicker when the lamp is turned on. Pulse-start metal halide lamps do not require a starting electrode and instead use a special starting circuit, called an igniter, to generate a high-voltage pulse to the operating electrodes.

**CERAMIC METAL HALIDE (CMH) LAMPS** are similar to pulse-start MH lamps, except the arc tube is made of aluminum oxide instead of quartz. These lamps have better color rendering, lumen maintenance, and color consistency over their lifetimes than metal halide lamps because of the improved arc tube material.

**HIGH-PRESSURE SODIUM (HPS) LAMPS** produce light by exciting sodium atoms contained in the arc tube. The outer glass of an HPS lamp is made of borosilicate hard glass to withstand high operating temperatures. The arc discharge is produced by a mixture of xenon and sodium-mercury amalgam in the arc tube. HPS lamps are available with clear and diffuse coatings. They produce an amber light and are widely used in outdoor and industrial applications where color appearance and color rendering are not critical. The lamps' long life and high efficacy have made them popular for parking lots, street lighting, and other outdoor lighting applications.

**LOW-PRESSURE SODIUM (LPS) LAMPS**, similar to HPS sources, produce light from sodium vapor. This arc discharge produces a monochromatic yellow light (CCT 1800K); the lamps are not CRI rated. Not only does the light appear yellow, but also any object whose color is not yellow appears yellow or gray under this source. LPS lamps deliver extremely high efficacy, but because of their poor color characteristics, LPS lamps are rarely used except near astronomical observatories, where their limited spectral output causes minimal interference with analysis of cosmic radiation.

### Light Emitting Diodes (LEDs)

A wide number of LED replacement options are now available to suit a variety of outdoor lighting applications. Long-life, energy-efficient LED luminaires and lamp replacement kits are achieving considerable energy and maintenance savings as a growing number of sites replace incandescent and HID sources with LED options. LEDs have also long been a popular source for exit signs and traffic signals. As the most rapidly developing type of source technology today, LED efficacy and quality continue to improve, and the technology continues to become more affordable.

Made from solid-state materials that emit light when a current is passed through them, the light output and characteristics of LEDs depend on the specific material, chemistry, size, color, and thermal environment used for their production. The color of the emitted light depends on the chemical composition of the material used and can be near-ultraviolet, visible, or infrared. Red LEDs are the most efficient at producing light in the visible spectrum. LEDs can be monochromatic, emitting primarily one wavelength on the visible spectrum.

To make white light, there are two general approaches: color mixing or phosphors. Color mixing is typically denoted as RGB (Red-Green-Blue). The RGB LEDs are placed close together, typically with a diffusing lens. This configuration effectively combines the light emissions on the different spectra to make white light. The other approach to making white light with LEDs requires a yellowish phosphor coating over the top of a blue LED. The resulting mix gives the appearance of white light.

**Figure 11.** LED pathway lighting at UC Davis



Photo: Kathleen Fontecha / CLTC, UC Davis

## Lighting Controls

Lighting controls can prolong lamp life, lower maintenance costs, increase energy savings, and reduce light pollution. There are several types of outdoor lighting controls, including photosensors, time clocks, motion sensors, and energy management systems. These technologies can be used to automatically dim lights or turn them off when doing so will not compromise safety or comfort.

Some lighting manufacturers offer luminaires with integrated controls, and many light sources can be paired with external control options. Controls can be implemented with a variety of sources, including LED, induction, fluorescent, and HID lamps. The end result is a smart lighting system that optimizes energy use, offers the right amount of light output for the application, and reduces operating costs.

Some lighting controls, such as photosensors, are useful in all outdoor areas. Others, such as bi-level motion sensor controls, are appropriate only for certain spaces, such as those that must remain illuminated after dark but have low, intermittent occupancy rates. National parks and other federal properties with after-hours parking lots, garages, pathways, or outdoor security lighting are ideal sites for motion sensors.

The first step in any lighting controls project is to define control zones and control resolution within each zone. Exterior lighting control zones can vary depending on the application and occupancy patterns.

Control can be as layered as luminaire-integrated photosensors and motion sensors for all area luminaires, with a networked control system employed to monitor and adjust lighting, or it can be as basic as one time-clock for an entire facility. Lighting controls are often installed at the circuit or luminaire level, and specific configurations will vary according to each system type and manufacturer.

## Daylighting Control Systems

Daylighting control systems detect available sunlight and adjust electric light output accordingly. Electric lights may dim or turn off completely, depending on the amount of daylight available and the type of daylighting controls used. Daylighting control systems may include time scheduling, which can maximize energy savings.

A photosensor is an electronic component that detects the presence of visible light, infrared (IR), and/or ultraviolet (UV) energy. Used in conjunction with lighting controllers (i.e., dimmers and switches), photosensors can help reduce the number of operating hours for outdoor lighting. If the amount of light that strikes the photosensor is greater than the preset threshold, a signal is sent to lighting controllers to dim or shut off the electric light. A photosensor is often integrated in the luminaire, or placed in a location free from shadows or direct sunlight. Properly installed photosensors will require little maintenance, perhaps just occasional dusting of the surface to keep operation optimal.

## Time Clocks and Energy Management Control Systems

An energy management control system (EMCS) or a time-clock can be used to limit lighting to specific scheduled hours. An EMCS is often used to control lighting both indoors and outdoors at a site such as a visitor center with an adjacent parking lot. Energy management control systems can also be used to monitor energy use, adjust luminaire light levels remotely, and indicate when repairs are needed.

Pairing or layering controls usually achieves the best results. For example, daylight controls or photosensors can adjust lights as the sky darkens and more light is needed; a time-clock or EMCS can then increase or decrease their power later in the evening depending on scheduling needs.

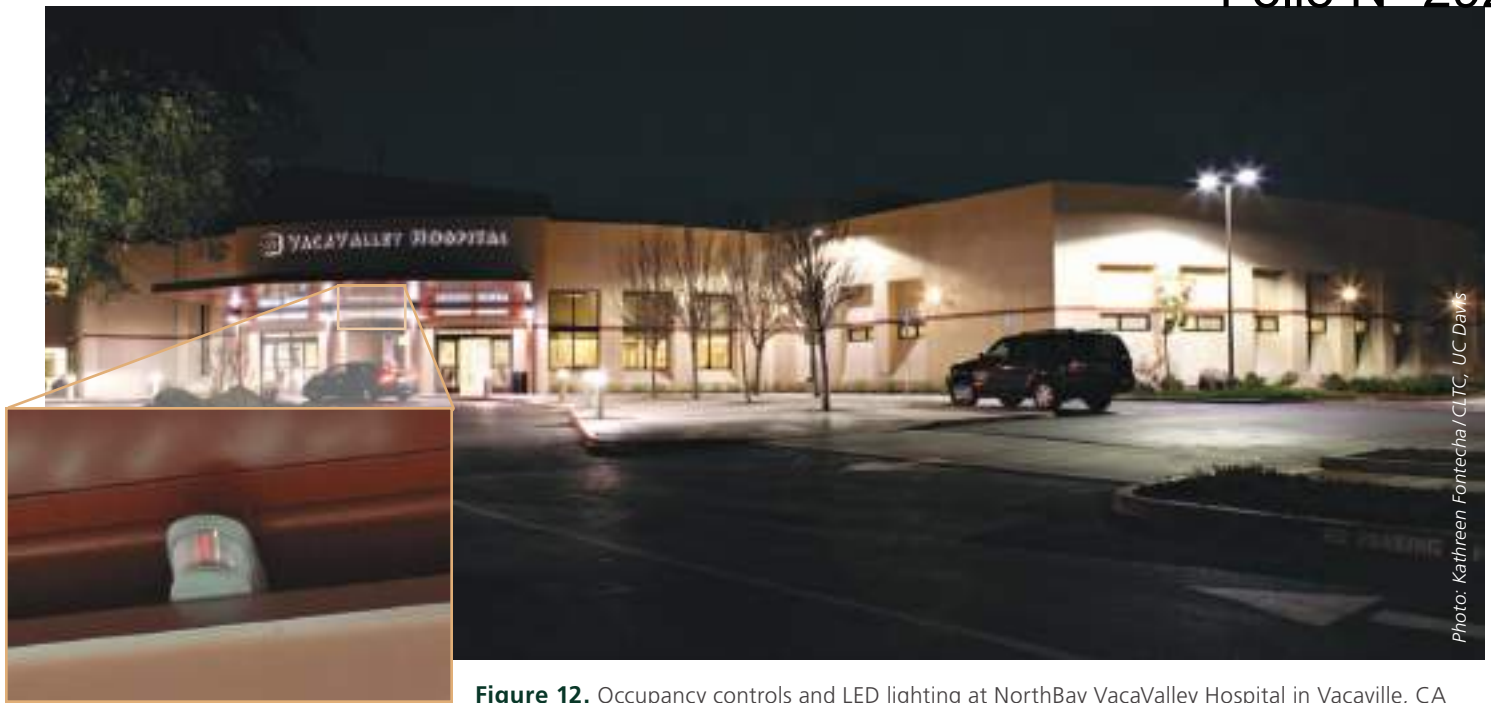


**Figure 12.** Occupancy controls and LED lighting at NorthBay VacaValley Hospital in Vacaville, CA

### Occupancy Controls (Motion Sensors)

Passive infrared (PIR) and microwave technologies are the primary types of occupancy control devices used in outdoor applications. Ultrasonic and audio-based occupancy sensor technologies are inappropriate for outdoor use because they can be triggered unintentionally by small animals, wind, rain, etc.

Standard (on/off) occupancy controls enable lighting systems to operate at full power and light output when an area is occupied and shut lights off completely when the area is unoccupied. This strategy is best suited to secondary-use areas where lighting is rarely needed at night.

Step-dimming occupancy controls consist of a lighting system that operates at multiple steps, or dimming levels. Luminaires operate at full power and light output when the space is occupied and at a reduced power level and light output when unoccupied. Dimming levels can often be adjusted to increase energy savings or increase light based on the needs of the site. This design method balances energy savings with safety, security and comfort. It is a suitable solution for primary-use areas and yields the greatest savings where occupancy rates are low or occupancy patterns are irregular.

Care should be taken when installing lighting control systems as most sensors are visible to the public and can potentially be manipulated, damaged or stolen. To function correctly, sensors must also be carefully positioned and commissioned. Follow these steps to ensure sensors are properly installed and maintained:

1. Refer to the sensor manufacturer's instructions for proper installation
2. Include building personnel in planning stages
3. Position sensors to minimize false triggers
4. Train staff on sensor maintenance

When adding controls to existing lighting:

- Assess the needs and usage patterns of occupants to determine the best lighting control system
- Evaluate sensor upgrade costs versus estimated energy savings using first- and second-level economic analyses
- Ensure the sensor is physically compatible with the space, considering sensor ranges, ambient light and sensor delays



## Emerging Technologies

### Networked Lighting

Several network lighting control systems are now commercially available. These allow authorized users to remotely access a system's detailed energy-use profile, receive automated maintenance alerts as soon as an outage occurs, and view or edit operating schedules, from a desktop or laptop computer with the system software. Networked lighting control systems are quickly expanding to incorporate new features and improved technologies.

Networked lighting is a fundamental improvement in how lights are managed. Because automated monitoring and instant control of every light is now possible, maintenance issues can be quickly and precisely addressed, saving money and energy. Some of the features of networked lighting include:

- Remote monitoring and data assessment, including maintenance tracking and outage detection, via Web connection
- Demand response (DR) control
- Power metering to take advantage of power savings from dimming
- Compatibility with motion sensors for increased energy savings
- Easily adjustable light dimming profiles
- Scheduling, as an alternative to photocell control

### Plasma Lighting

Plasma technology has the potential for high efficacy, high lumen density, and long life. These characteristics, combined with plasma's small form factor, show promise for a future high-performance light source. Plasma lighting systems use an electrodeless lamp that emits light as a result of an interaction of gas inside the lamp and precisely focused radio frequency power. Because there is no electrode, which is a common cause of failure for many HID lamps, plasma lighting systems have the potential for longer lifetimes.

Because of their high power density, plasma systems are currently being developed for exterior lighting applications typically illuminated with HID lamps, such as roadways, parking lots and outdoor sports facilities. With further performance and cost validation, plasma lighting could potentially increase the energy efficiency of lighting in these outdoor applications.

### Photovoltaic (PV) Systems

A photovoltaic (PV) system may serve as a stand-alone source of energy or be connected to a utility-owned electricity grid. Grid-connected PV systems are less costly and require less maintenance than stand-alone systems. In some areas, grid-connected systems qualify for more government incentives. For these reasons, grid-connected PV systems are more common in North America.

When a grid-connected PV system generates more power than the customer can use, the surplus power is fed to the utility grid, and the customer earns credit for that unused electricity. When power use exceeds what the system can produce, the customer draws electricity from the grid and is charged for that power.

Lighting loads installed underneath PV structures, such as solar-paneled carports, should be minimized by pairing high-efficacy sources with photosensors and motion sensors.

Stand-alone PV systems are less common than grid-connected systems. These are not connected to the electrical grid; instead, they store excess electricity in batteries, which are then used for power when the sun is not shining. Batteries, however, incur additional initial costs and maintenance costs, and they must be replaced every few years.

Solar street and area lights can be used in stand-alone outdoor lighting applications where wiring, trenching, or metering is not feasible. The solar panel and battery pack can be placed in many locations on the luminaire — at the top, middle, bottom, or with the battery pack underground—and several options are available for pole height and lamp style.

Additionally, PV bollards are well suited for stand-alone systems. PV bollards can be programmed to turn on at dusk and off when the sun rises. A solar panel on the luminaire converts solar energy into electricity, which is stored in a battery to be used during the night. Bollards have a variety of uses, including marking pathways, increasing security and serving as traffic barriers.

## Networked Adaptive LED Wall Packs at UC Davis

In 2012, the University of California, Davis, upgraded 101 of its wall packs as part of a campus-wide outdoor lighting retrofit. The campus selected full-cutoff, dimmable LED fixtures, controlled by motion sensors and wireless network control modules that integrated the wall packs into a campus-wide networked lighting control system. These replaced 56 high-pressure sodium (HPS) fixtures and 45 metal halide (MH) fixtures. The networked system was a first-of-its-kind, best-practice solution.

The California Lighting Technology Center (CLTC) participated in the project and conducted a case study of the wall packs to measure results. Occupancy rates averaged just 20% during the nighttime hours when the fixtures were on. The LED fixtures use 45 watts at full brightness and just 14 watts for the nine and a half hours or so that they are not needed; this is compared to the 189 watts consumed throughout the night by the HPS fixtures that lacked motion-sensing lighting controls. Electricity use and electricity costs for the wall packs were reduced 89%.

The fixtures emit a white light (4100K) with a CRI of 70, factors that improved visibility and lighting quality on campus. The network control system allows facility managers to create pre-set lighting profiles, adjust lighting schedules, directly control individual fixtures or groups of fixtures, monitor energy use patterns, and receive automatic alerts when a fixture needs maintenance.

**More information on this project is available online:**  
[cltc.ucdavis.edu/sites/default/files/files/publication/speed-case-study-ucd-wall-packs.pdf](http://cltc.ucdavis.edu/sites/default/files/files/publication/speed-case-study-ucd-wall-packs.pdf)



Photo: Kathreen Fontecha / CLTC, UC Davis



Photo: Kathreen Fontecha / CLTC, UC Davis



Photo: Luxim



## Part 4

## Project Planning



## Lighting Evaluation Basics

Whether retrofitting an existing lighting system or designing a new one, certain issues should be addressed before any new lighting components are selected:

- Where will the luminaires be located, and what lighting control measures are required for the site, in terms of limiting light pollution, light trespass and glare?
- How will the lighting system operate, and what control schemes are best for the application?  
Can lights be fully extinguished during certain parts of the night?
- What measures can be taken to minimize the impact of nighttime lighting on any wildlife in the surrounding ecosystem?
- How important is accurate color rendering, relative to other factors, within the given area?
- What technologies are available to achieve the desired design?
- What are the costs and benefits associated with different options?

## Conducting a Lighting Audit

Lighting audits are essential to efficiently determine the current state of a lighting system and the need, if any, for a new one. An audit of the existing lighting system can determine what type of retrofit is best suited to the site, and it will allow for an accurate economic evaluation and light level comparison of the pre-retrofit and post-retrofit systems. The measurements gathered through an audit often play an important role in funding and financing lighting retrofit projects.

## Lighting Audit Guidelines

Many organizations provide professional services for large-scale lighting system audits. The process varies for each individual audit, but a thorough evaluation of the existing lighting system will include assessment of the following:

- Age, condition and quality of the existing luminaires (e.g., lens discoloration, lens cracking, paint cracking, or burn marks)
- Model and manufacturer of the existing lighting system, to obtain photometrics
- Lamp wattage and ballast type
- Operational environment of the lighting system, noting the possibility of particulate, moisture, or dirt buildup in or around luminaires
- Activities and type of work being conducted in the area, as well as any special visual requirements
- Lighting system controls and time of use
- Colors of objects within the space (to characterize color rendering)
- Physical layout of the existing lighting system, including luminaire height, spacing and number

Use an illuminance meter to measure the light intensity of the existing system during dark-sky conditions to determine if the existing design is appropriate for the space. Readings and measurements should be taken on the ground and at even intervals, following a grid pattern. These illuminance levels can then be compared to IES recommended levels for the application.

Once all this basic information has been recorded, it is possible to draw conclusions about the existing lighting system and answer some important questions:

- Does the lighting system meet the original or proposed lighting needs of the area and its occupants?
- How cost-effective is the lighting system, given its operational costs for energy use and maintenance?
- Calculate the system efficacy of each type of luminaire. How efficient is each system at delivering light to its target surface?
- Calculate the theoretical system illumination, determined from a rough lumen method or point-to-point calculation. Use lighting design software to determine if the theoretical measurements match the measured illumination values from the site. This will help determine the level of deterioration of the existing lighting system and if the system meets code requirements.
- Calculate the existing lighting power density and determine if it meets the applicable codes or energy standards.



|                    |                                                  |  |  |  |  |  |
|--------------------|--------------------------------------------------|--|--|--|--|--|
|                    | Item Number                                      |  |  |  |  |  |
|                    | Location, Description                            |  |  |  |  |  |
| LUMINAIRE / LENSES | Age                                              |  |  |  |  |  |
|                    | Condition<br>(soiled, cracked, etc.)             |  |  |  |  |  |
| LAMP               | Age                                              |  |  |  |  |  |
|                    | Condition<br>(soiled, cracked, etc.)             |  |  |  |  |  |
|                    | System Power (W)                                 |  |  |  |  |  |
|                    | Model Number                                     |  |  |  |  |  |
|                    | Manufacturer                                     |  |  |  |  |  |
|                    | Perceived Color Quality<br>(good, poor, etc.)    |  |  |  |  |  |
|                    | Occupants, Tasks<br>(age, work activities, etc.) |  |  |  |  |  |

## Relamping and Maintenance

There are two strategies for addressing this aspect of lighting maintenance: group and spot relamping. Each has its own advantages, but scheduled group relamping has generally proven to be more cost effective than spot relamping.

### Group Relamping

Using this strategy, lamp replacement occurs on a fixed schedule, minimizing lamp outages. Depending on the size of the lighting installation and amount of time the relamping would take, group relamping normally occurs in phases. This strategy saves labor costs by reducing setup time and luminaire cleaning. Group relamping is also easy to delegate to outside contractors who have special equipment and training, further increasing labor efficiency.

### Spot Relamping

Lamps are replaced as they fail with this strategy. This approach saves material costs since lamps run until the end of their useful lives, but it entails higher labor costs as a technician must replace and clean lamps according to their individual life-cycles rather than systematically. Spot relamping can also result in inconsistent light levels with delays between lamp failure and replacement.

### Tracking Maintenance

Keeping a maintenance log allows facilities to track relamping, regardless of which strategy is selected. Logs should allow employees performing relamping or other maintenance tasks to note their names, identify the item number addressed, its location, the date the maintenance was performed and the action taken. See the example provided on this page.

## Maintenance Log

| Item Number         |  |  |  |  |  |
|---------------------|--|--|--|--|--|
| Location of Fixture |  |  |  |  |  |
| Date of Relamp      |  |  |  |  |  |
| Action Taken        |  |  |  |  |  |
| Employee Name       |  |  |  |  |  |

## Recycling

### Fluorescent lamps and CFLs

Fluorescent lamps contain a small amount of mercury and therefore require careful disposal. The vast majority of lamps that contain mercury are considered hazardous waste under federal regulations and cannot simply be thrown in the trash. Fluorescent ballasts manufactured before 1978 might contain polychlorinated biphenyls; these must also be disposed of as hazardous waste. Lamps not tested and proven non-hazardous must be assumed hazardous and handled accordingly.<sup>1</sup> State requirements may also apply.

A growing number of home improvement stores recycle CFLs, including Home Depot and IKEA. For more information on specific state regulations, contact the appropriate state environmental agency. These agencies are listed on the EPA's website.<sup>2</sup>

### HID lamps

High-intensity discharge lamps—including mercury vapor, metal halide, and high-pressure sodium sources—contain various amounts of mercury. Fewer disposal sites and stricter laws exist regarding disposal or recycling of these lamps. Two sets of laws govern the disposal of HID lamps: Section C of the Resource Conservation and Recovery Act, and each state's hazardous waste regulations. To find out more about both, visit [www.epa.gov](http://www.epa.gov).

### LED sources

LED lighting products must be treated as electronic waste. A DOE study released in March 2013 stresses the importance of properly recycling this equipment, as one would do with cell phones, computer equipment or other e-waste. A report on the research concludes that the hazardous materials in these products come mainly from components other than the LEDs themselves. The same report indicates the recycling of aluminum components would be particularly effective in reducing the environmental impact of LED lighting products, many of which contain aluminum heat sinks. Study results also indicated that the value of recovering aluminum can offset the cost of recycling.

Reports on all three parts of the DOE study, and guidelines for meeting stringent regulations for hazardous waste disposal, are available at [www.ssl.energy.gov/tech\\_reports.html](http://www.ssl.energy.gov/tech_reports.html).

<sup>1</sup> EPA. FAQs about Lamps: <http://www.epa.gov/osw/hazard/wastetypes/universal/lamps/faqs.htm>

<sup>2</sup> EPA: <http://www2.epa.gov/home/state-and-territorial-environmental-agencies>

## Cost-benefit Analysis

### Funding Sources

Agencies can look to federal, state and local sources to fund outdoor lighting projects. Sources of assistance include:

- Federal grants
- The National Park Foundation, charitable partner of the National Park Service
- Local utilities offering incentives and rebates
- Lighting manufacturers or distributors with information on financing programs and incentives

In addition to securing outside funding, weighing the costs and benefits of various retrofit options makes planning a successful project easier.

### Simple Payback

Simple payback is defined as the incremental cost of a new system over the existing system, divided by the incremental annual energy and maintenance cost savings gained from the new system.

Initial costs vary by lighting project but typically include:

- Design
- Installation
- Materials
- Commissioning

Simple payback often drives project decisions, but this can yield poor results in the long term. Following best practices means looking beyond short-term payback opportunities and focusing on strategies and technologies that will produce deeper, more sustained energy savings as well as greater economic benefits in the long term. Forward-thinking project planners base their decisions on a cost-benefit analysis that spans the full life of the lighting system and includes projected rises in the cost of energy and the cost of maintenance.

### Lifecycle Analysis (LCA)

A lifecycle analysis attempts to capture all costs and benefits for the entire life of a product, cradle to grave. This differs from simple payback, which only considers the initial costs and the savings from energy and maintenance cost reductions. A true LCA starts with manufacturing and ends at disposal, including transportation costs and the related pollution effects. There are different approaches for implementing an LCA, depending on the project.

The following worksheet provides for a simplified economic analysis of outdoor lighting systems. It does not include equations for factoring in inflation or calculating the present value of future costs or benefits. Chapter 18 of the *IES Lighting Handbook, 10th edition*, covers economic analysis in more detail and provides tables that support more complex calculations. The IES's Recommended Practice for the Economic Analysis of Lighting (IES RP-31-96) is also helpful.

## Economic Analysis Worksheet

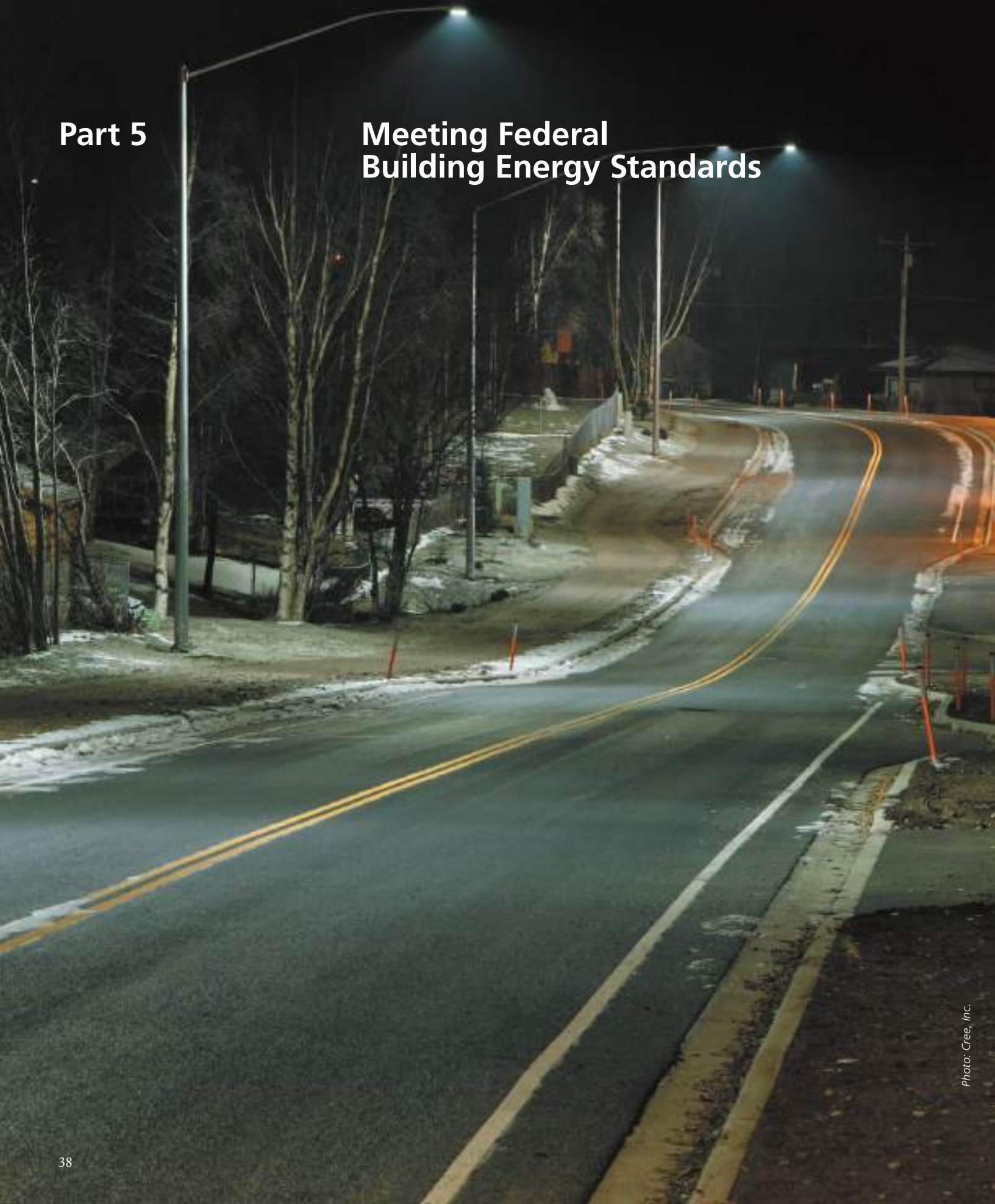
| PROJECT METRICS                                                                                                                                                                 | System 1 | System 2 | System 3 |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------|----------|----------|
| 1. <b>Total power used by each lighting system (kW)</b><br>Note connected load, including any ballasts and transformers.                                                        |          |          |          |
| 2. <b>System life (years)</b>                                                                                                                                                   |          |          |          |
| 3. <b>Interest rate (%)</b><br>Determine the interest rate associated with borrowing funds, alternative investments, or simple escalation over the life of the lighting system. |          |          |          |
| INITIAL COSTS                                                                                                                                                                   | System 1 | System 2 | System 3 |
| 4. <b>Equipment</b><br>Sources for cost estimates might include: RSMeans, contractors, manufacturers, distributors, and past projects.                                          |          |          |          |
| 5. <b>Labor</b>                                                                                                                                                                 |          |          |          |
| 6. <b>Utility rebates</b><br>Utilities sometimes offer incentives for energy-efficient lighting retrofits or installations. Enter rebates as negative numbers.                  |          |          |          |
| 7. <b>Other first costs</b><br>Include differential costs, such as design fees or tax credits.                                                                                  |          |          |          |
| 8. <b>Initial taxes</b><br>Usually 6–8.5% of initial material and equipment costs (line 4).<br>Include taxes for labor if not included in line 5.                               |          |          |          |
| 9. <b>Total initial costs</b><br>Enter the sum of lines 4–8.                                                                                                                    |          |          |          |

| ANNUAL COSTS                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | System 1 | System 2 | System 3 |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------|----------|----------|
| <b>10. Energy costs (annual kWh x \$ / kWh)</b><br>Annual energy use depends on operating hours, lighting controls, and occupancy rates. Multiply the annual energy use for each system by the average utility rate.                                                                                                                                                                                                                                                                                                                                                              |          |          |          |
| <b>11. Maintenance costs (equipment and labor)</b><br>Annual maintenance costs for SSL luminaires will reflect longer lifetimes. For HID and fluorescent sources, include both lamp and ballast replacement costs, and consider whether a group or spot relamping strategy will be followed. Annual relamping costs can be calculated as follows:<br><br><u>cost for replacement (number of replacements required)</u><br><u>lamp life / annual operating hours</u><br><br>Annual ballast replacement costs can be calculated similarly, with ballast life in place of lamp life. |          |          |          |
| <b>12. Cleaning costs</b><br>Estimate average costs per year. If cleaning will occur only during lamp replacement, these costs may be included in line 11.                                                                                                                                                                                                                                                                                                                                                                                                                        |          |          |          |
| <b>13. Other annual costs</b>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |          |          |          |
| <b>14. Total annual costs</b><br>Enter the sum of lines 10–13.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |          |          |          |
| FINAL COSTS                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | System 1 | System 2 | System 3 |
| <b>15. Residual (salvage) value at end of economic life</b><br>This value is negative if money is received for the salvage; it is positive if a cost is incurred to dispose of the system.                                                                                                                                                                                                                                                                                                                                                                                        |          |          |          |
| <b>16. Final total for system costs</b><br>Enter the sum of lines 9, 14 and 15.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |          |          |          |



## Part 5

## Meeting Federal Building Energy Standards



The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) develops technical standards and performance criteria for building systems. Federal buildings designed on or after July 9, 2013 must meet the requirements of ASHRAE Standard 90.1-2010: Energy Standard for Buildings Except Low-Rise Residential Buildings. To comply, outdoor lighting systems and equipment must meet the requirements specified in Section 9 of the ASHRAE 90.1-2010 Standard and summarized in this part of the guide.

By following best practices, facilities can often exceed the minimum lighting requirements listed in ASHRAE Standard 90.1-2010 and the updated ASHRAE Standard 90.1-2013, released in October, 2013.

## General Outdoor Lighting Guidelines

The standards for outdoor lighting apply to exterior building features, including facades, illuminated roofs, architectural features, entrances, exits, loading docks, and illuminated canopies, as well as lighting for outdoor building grounds supplied through the building's electrical service.

The exceptions to this are:

- Emergency lighting that is automatically off during normal building operation
- Lighting that is specifically required by a health or life safety statute, ordinance or regulation
- Decorative gas lighting systems

## Lighting Alterations

Alterations to lighting systems in any outdoor area must comply with the lighting power density (LPD) requirements applicable to that area and the automatic shutoff requirements of Section 9.4.1.1. Alterations include the addition, replacement and removal of luminaires, as well as replacement of lamps and ballasts.

Alterations do not include:

- Routine maintenance or repairs
- Alterations involving less than 10% of the connected lighting load in an area, provided that such alterations do not increase the installed LPD

## Installed Lighting Power

ASHRAE Standard 90.1-2010, Section 9.1.3 states luminaire power (total watts) for outdoor lighting applications is calculated as all power used by the luminaires, including:

- Lamps
- Transformers
- Ballasts
- Control devices

Exceptions include those previously noted (emergency lighting, etc.) and those specified in Section 9.4.3, Exterior Building Lighting Power. If two or more independently operating lighting systems in an area are capable of being controlled to prevent simultaneous user operation, the installed lighting power is based on whichever lighting system uses the most power.

## Luminaire Power

To calculate installed outdoor lighting power, determine luminaire power (watts) based on the manufacturer's maximum labeled wattage for the luminaire. For luminaires with permanently installed or remote ballasts, transformers, or similar devices, the operating input power of the maximum lamp/auxiliary combination may also be used (this is based on values from the auxiliary manufacturers' literature or recognized testing laboratories).

Lighting power calculations for ballasts with adjustable ballast factors are the exception. These are based on the ballast factor that will be used in the space, provided that the ballast factor is not user changeable.

## Miscellaneous Lighting Equipment Power

Refer to the specified power (watts) of the lighting equipment for all other lighting equipment.



Photo: Kathleen Fontecha/CLTC, UC Davis

**Figure 13.** Outdoor lighting at the University of California, Davis, campus is controlled by a state-of-the-art network system that maximizes energy savings based on occupancy patterns and allows facility managers to track occupancy data, monitor energy use, adjust lighting schedules, and receive automated maintenance alerts.

## Lighting Controls Requirements

The following requirements are based on those listed under Section 9.4.1.7 of ASHRAE 90.1-2010. They apply to building exteriors and grounds lighting:

- Lights must be equipped with a device that automatically turns them off when sufficient daylight is available
- Building façade and landscape lighting must automatically shut off between the hours of midnight or business closing, whichever is later, and 6 a.m. or business opening, whichever is earlier (or alternate times established by the authority with jurisdiction)
- Other outdoor lighting, including sign lighting, must have controls that automatically reduce lighting power at least 30% during the same period described above or any time the surrounding area is vacant (with sensor switching set up to a maximum of 15 minutes)
- Time-switch controls must be able to retain programming for at least 10 hours in the event of a power failure, using a back-up battery or other means

## Functional Testing

Commissioning and testing are absolutely necessary if lighting control devices are to function properly and perform as intended. ASHRAE 90.1-2010, Section 9.4.4 lists requirements designed to ensure that control hardware and software are calibrated, adjusted, programmed, and in proper working condition in accordance with manufacturers' installation instructions and any construction documents for the project.

When the following controls are installed, these minimum procedures are required:

- **Photosensors:** Confirm that photosensor controls reduce electric light levels based on the amount of usable daylight in the space as specified.
- **Occupant sensors:** Confirm placement, sensitivity and time-out adjustments for occupant sensors yield acceptable performance; lights should turn off only after the space is vacated and should not turn on unless the space is occupied.
- **Time switches and programmable schedule controls:** Confirm devices are programmed to turn the lights off and function as programmed.

## Certification

Construction documents must state who will conduct and certify the functional testing. The party responsible for testing must not be directly involved in either the design or construction of the project. The responsible party must also provide documentation certifying exactly how the installed lighting controls meet or exceed all documented performance criteria.



## Lighting Power Allowances

To comply with Section 9 of ASHRAE 90.1–2010, the total installed outdoor lighting power must not exceed the outdoor lighting power allowance specified by the standards. Lighting power allowances for building exteriors are determined by lighting zone (described below). Many national parks are located in zones designated as LZ-0 or LZ-1. In some areas, local lighting ordinances may limit outdoor lighting power allowances more than ASHRAE standards.



### Lighting Zone 0

LZ-0 requirements preserve dark skies in wilderness areas, parks and preserves, forest land, rural regions, areas near astronomical observatories, and other undeveloped areas.



### Lighting Zone 1

LZ-1 pertains to parks and preserves in developed areas, low-density residential districts, and developed rural areas.



### Lighting Zone 2

LZ-2 applies to areas predominantly consisting of residential zoning, neighborhood business districts, light industrial with limited nighttime use and residential mixed-use areas.



### Lighting Zone 3

LZ-3 pertains to areas with moderately high lighting levels. It is the recommended default zone for business districts in large cities.



### Lighting Zone 4

LZ-4 is not a default zone. It should only apply in dense commercial districts of major metropolitan areas or heavy industrial zones.

**Figure 14.** UC Davis parking lot with adaptive induction lighting

Photo: Kathleen Fontecha/CLTC, UC Davis

The total outdoor lighting power allowance for all outdoor building applications is the sum of the base site allowance plus the individual allowances for areas listed in Table 9.4.3B (see pages 44 and 45). These allowances are determined according to the site's lighting zone designation.

### Tradable Surfaces

Trade-offs are allowed for the following outdoor lighting applications (listed in Table 9.4.3B as "Tradable Surfaces"):

- Uncovered parking areas
- Building grounds
- Building entrances and exits
- Canopies and overhangs

**Exceptions:** Lighting used for the following exterior applications is exempt when it is controlled independently from the nonexempt lighting and complies with the lighting controls requirements discussed earlier (Section 9.4.1.7):

- Specialized signal, directional, and marker lighting associated with transportation
- Lighting integral to equipment or instrumentation and installed by the manufacturer
- Advertising signage or directional signage

### Parking Garages

Lighting for parking garages must comply with indoor lighting requirements specified in Section 9.4.1.1, but guidelines are included here because retrofits for these spaces can yield deep energy savings and they are often included in outdoor lighting retrofit projects.

### Automatic shutoff controls

One of the following is required:

- Time-of-day operated control device that turns lighting off at specific programmed times
- Occupant sensor that turns lighting off within 30 minutes of an occupant leaving
- A signal from another control or alarm system that indicates the area is unoccupied

**Exceptions:** Exceptions include spaces where 24-hour lighting is required or where automatic shutoff would endanger the safety or security of occupants.

### Automatic dimming controls

Lighting must be controlled by one or more devices that automatically reduce the lighting power of each luminaire by at least 30% when there is no activity detected within a lighting zone for a set period of time (maximum: 30 minutes). Lighting zones for this requirement shall be no larger than 3,600 ft<sup>2</sup>.

**Exceptions:** Daylight transition zones and applications using induction lamps or HID sources of 150 W or less are exempt from this requirement.

### Automatic daylighting controls

Power must be automatically reduced in response to daylight for luminaires within 20 ft of any perimeter wall structure that has a net opening-to-wall ratio of at least 40% and no exterior obstructions within 20 ft.

**Exception:** Daylight transitions zones are exempt from this requirement.

### Transition lighting zones

Lighting in parking garage transition zones (not to exceed 50 ft in width and a depth of 66 ft) must be separately controlled by a device that automatically turns lighting on during daylight hours and off at sunset. This helps visitors' eyes to adjust as they enter or exit the parking garage.





## ASHRAE Standard 90.1-2010

Table 9.4.3B: Individual Lighting Power Allowances for Building Exteriors

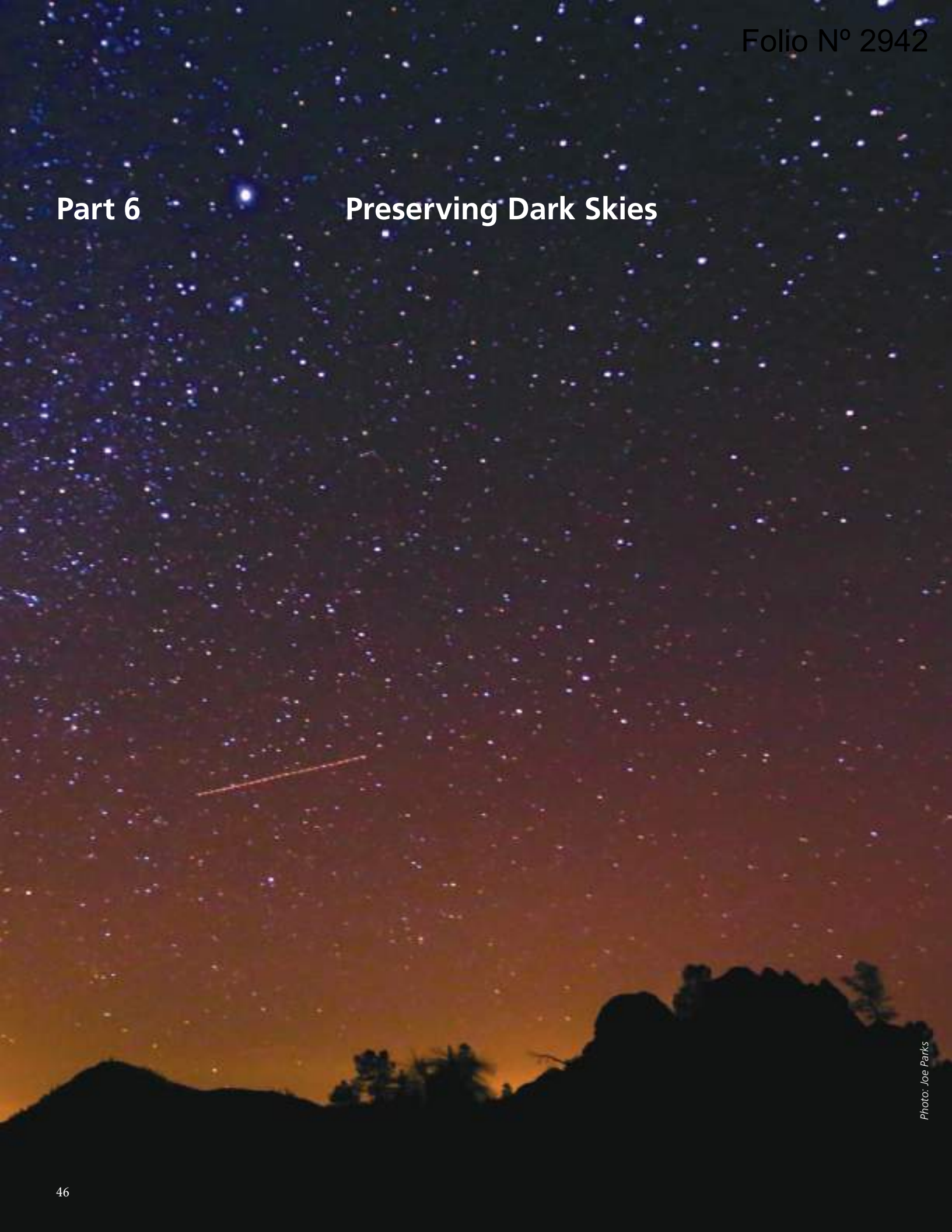
|                                                                                                                                                                             | Zone 0                 | Zone 1                         | Zone 2                         | Zone 3                         | Zone 4                         |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|
| <b>BASE SITE ALLOWANCE</b> (base allowance may be used in tradable or non-tradable surfaces)                                                                                |                        |                                |                                |                                |                                |
|                                                                                                                                                                             | No Base Site in Zone 0 | 500W                           | 600W                           | 750W                           | 1,300W                         |
| <b>TRADABLE SURFACES</b> (LPDs for uncovered parking areas, building grounds, building entrances and exits, canopies and overhangs, and outdoor sales areas may be traded.) |                        |                                |                                |                                |                                |
| <b>Uncovered parking areas</b>                                                                                                                                              |                        |                                |                                |                                |                                |
| Parking areas and drives                                                                                                                                                    | No allowance           | 0.04 W/ft <sup>2</sup>         | 0.06 W/ft <sup>2</sup>         | 0.10 W/ft <sup>2</sup>         | 0.13 W/ft <sup>2</sup>         |
| <b>Building grounds</b>                                                                                                                                                     |                        |                                |                                |                                |                                |
| Walkways less than 10 ft wide                                                                                                                                               | No allowance           | 0.7 W/linear foot              | 0.7 W/linear foot              | 0.8 W/linear foot              | 1.0 W/linear foot              |
| Walkways 10 ft wide or greater<br>Plaza areas<br>Special feature areas                                                                                                      | No allowance           | 0.14 W/ft <sup>2</sup>         | 0.14 W/ft <sup>2</sup>         | 0.16 W/ft <sup>2</sup>         | 0.2 W/ft <sup>2</sup>          |
| Stairways                                                                                                                                                                   | No allowance           | 0.75 W/ft <sup>2</sup>         | 1.0 W/ft <sup>2</sup>          | 1.0 W/ft <sup>2</sup>          | 1.0 W/ft <sup>2</sup>          |
| Pedestrian tunnels                                                                                                                                                          | No allowance           | 0.15 W/ft <sup>2</sup>         | 0.15 W/ft <sup>2</sup>         | 0.2 W/ft <sup>2</sup>          | 0.3 W/ft <sup>2</sup>          |
| Landscaping                                                                                                                                                                 | No allowance           | 0.04 W/ft <sup>2</sup>         | 0.05 W/ft <sup>2</sup>         | 0.05 W/ft <sup>2</sup>         | 0.05 W/ft <sup>2</sup>         |
| <b>Building entrances and exits</b>                                                                                                                                         |                        |                                |                                |                                |                                |
| Main entries                                                                                                                                                                | No allowance           | 20 W/linear foot of door width | 20 W/linear foot of door width | 30 W/linear foot of door width | 30 W/linear foot of door width |
| Other doors                                                                                                                                                                 | No allowance           | 20 W/linear foot of door width | 20 W/linear foot of door width | 20 W/linear foot of door width | 20 W/linear foot of door width |
| Entry canopies                                                                                                                                                              | No allowance           | 0.25 W/ft <sup>2</sup>         | 0.25 W/ft <sup>2</sup>         | 0.4 W/ft <sup>2</sup>          | 0.4 W/ft <sup>2</sup>          |
| <b>Sales canopies</b>                                                                                                                                                       |                        |                                |                                |                                |                                |
| Free standing and attached                                                                                                                                                  | No allowance           | 0.6 W/ft <sup>2</sup>          | 0.6 W/ft <sup>2</sup>          | 0.8 W/ft <sup>2</sup>          | 1.0 W/ft <sup>2</sup>          |
| <b>Outdoor sales</b>                                                                                                                                                        |                        |                                |                                |                                |                                |
| Open areas<br>(including vehicle sales lots)                                                                                                                                | No allowance           | 0.25 W/ft <sup>2</sup>         | 0.25 W/ft <sup>2</sup>         | 0.5 W/ft <sup>2</sup>          | 0.7 W/ft <sup>2</sup>          |
| Street frontage for vehicle sales lots in addition to "open area" allowances                                                                                                | No allowance           | No allowance                   | 10 W/linear foot               | 10 W/linear foot               | 30 W/linear foot               |

|                                                                                                                                                                                                                                                                                                                                    | Zone 0                                                                                                                                                                                | Zone 1                                                                                                                               | Zone 2                                                                                                                   | Zone 3                                                                                                                     | Zone 4                                                                                                                   |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------|
| <b>NONTRADABLE SURFACES</b> (LPD calculations for the following applications can be used only for the specific application and cannot be traded between surfaces or with other exterior lighting. The following allowances are in addition to any allowance otherwise permitted in the “Tradable surfaces” section of this table.) |                                                                                                                                                                                       |                                                                                                                                      |                                                                                                                          |                                                                                                                            |                                                                                                                          |
| Building facades                                                                                                                                                                                                                                                                                                                   | No allowance                                                                                                                                                                          | No allowance                                                                                                                         | 0.1 W/ft <sup>2</sup> for each illuminated wall or surface 2.5 W/linear foot for each illuminated wall or surface length | 0.15 W/ft <sup>2</sup> for each illuminated wall or surface 3.75 W/linear foot for each illuminated wall or surface length | 0.2 W/ft <sup>2</sup> for each illuminated wall or surface 5.0 W/linear foot for each illuminated wall or surface length |
| Automated teller machines and night depositories                                                                                                                                                                                                                                                                                   | No allowance                                                                                                                                                                          | 270 W per location plus 90 W per additional ATM per location                                                                         |                                                                                                                          |                                                                                                                            |                                                                                                                          |
| Entrances and gatehouse inspection stations at guarded facilities                                                                                                                                                                                                                                                                  | No allowance                                                                                                                                                                          | 0.75 W/ft <sup>2</sup> of uncovered area (covered areas are included in the “Canopies and overhangs” section of “Tradable surfaces”) |                                                                                                                          |                                                                                                                            |                                                                                                                          |
| Loading areas for law enforcement, fire, ambulance, and other emergency service vehicles                                                                                                                                                                                                                                           | No allowance                                                                                                                                                                          | 0.5 W/ft <sup>2</sup> of uncovered area (covered areas are included in the “Canopies and overhangs” section of “Tradable surfaces”)  |                                                                                                                          |                                                                                                                            |                                                                                                                          |
| Drive-through windows/doors                                                                                                                                                                                                                                                                                                        | No allowance                                                                                                                                                                          | 400 W per drive-through                                                                                                              |                                                                                                                          |                                                                                                                            |                                                                                                                          |
| Parking near 24-hour retail entrances                                                                                                                                                                                                                                                                                              | No allowance                                                                                                                                                                          | 800 W per main entry                                                                                                                 |                                                                                                                          |                                                                                                                            |                                                                                                                          |
| Roadway/parking entry, trail head, and toilet facility, or other locations approved by the authority having jurisdiction                                                                                                                                                                                                           | A single luminaire of 60 W or less may be installed for each roadway/parking entry, trail head, and toilet facility, or other locations approved by the authority having jurisdiction | No allowance                                                                                                                         |                                                                                                                          |                                                                                                                            |                                                                                                                          |

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## Part 6

## Preserving Dark Skies



In the United States today, most residents seldom experience truly dark skies, no matter what time of night they find themselves outdoors. This is because light pollution is now a common problem around cities and towns. The expansion of urban environments has made the problem more acute in recent decades, diminishing the visibility of stars and planets in the night sky for astronomers and casual observers alike. Light pollution can also adversely affect the health and well-being of people and animals.

Light pollution is arguably the easiest environmental hazard to remedy. Simple retrofits and changes to lighting designs can dramatically limit the amount of light spilling into the atmosphere and surrounding ecosystem—with immediate results. And advanced lighting controls make it easy to further minimize light pollution without compromising safety or security.

## Light Pollution

Outdoor light pollution occurs when electric lighting alters the photic habitat of an outdoor environment. Light pollution is also commonly defined as any excessive, misdirected or obtrusive light emitted by a man-made source. Sky glow is one form of light pollution. It occurs when light is projected into the sky and spreads, causing a glow above populated areas. The sky glow above some cities is visible from as far as 100 miles away. Consequently, more than two-thirds of the U.S. population can no longer see the Milky Way with the naked eye,<sup>3</sup> and anyone interested in an unobstructed view of the night sky must travel well beyond city limits. Sky glow is also a serious impediment to astronomical research. The annual cost of all these negative effects, including energy waste, has been estimated at nearly \$7 billion in the U.S.<sup>4</sup>

## Light Trespass

As with light pollution, light trespass results when luminaires shine light beyond their intended target areas. This potentially disruptive light can fall into neighboring buildings, inhibiting people's ability to sleep. Likewise, nighttime lighting that spreads into surrounding ecosystems or across migratory paths can impact the health of a variety of species and even endanger populations.

A variety of species have evolved in sync with the diurnal patterns of light and darkness characteristic of our planet. Insects, fish, reptiles, amphibians, birds, and mammals—including humans—all depend on dark night skies to keep their circadian systems in alignment and support patterns of rest and activity. A number of species also depend on dark skies to provide cover from predators and allow for nighttime navigation by natural light sources such as the moon and stars.

In an effort to eliminate light pollution and light trespass, the International Dark-Sky Association (IDA) recommends preventing light from projecting above the horizon. More guidance on how to select dark sky-friendly luminaires is provided at the end of this section.

### Light Pollution Defined

According to the International Dark-Sky Association (IDA), "light pollution is any adverse effect of artificial light, including sky glow, glare, light trespass, light clutter, decreased visibility at night, and energy waste."

### Dark Skies: A Precious Resource

The sky glow from many cities can be seen as far as 100 miles away. Consequently, 66% of the United States can no longer see the Milky Way at night (Cinzano et al., 2001).

[www.sciencedirect.com/science/article/pii/S0921800909004121](http://www.sciencedirect.com/science/article/pii/S0921800909004121)

### An Impact Grant Helps Redwood National Park Protect Dark Skies

Redwood National and State Parks are retrofitting existing lights, thanks in large part to a 2012 Impact Grant from the National Park Foundation.

Park staff will work with two Northern California school districts to produce short educational videos promoting best practices for outdoor lighting and the appreciation and protection of dark skies.

[www.nationalparks.org/our-work/success-stories/redwood-national-park-impact-grant](http://www.nationalparks.org/our-work/success-stories/redwood-national-park-impact-grant)

<sup>3</sup> Cinzano, P., Falchi, F., and Elvidge, C.D. "The First World Atlas of the Artificial Night Sky Brightness." *Monthly Notices of the Royal Astronomical Society* 328 (2001): 689–707. Print.

<sup>4</sup> Gallaway, T., Olsen, R.N., and Mitchell, D.M. 2010. "The Economics of Global Light Pollution." *Ecological Economics*, Vol. 69, Issue 3 (2010): 658–665. Print.



## Spectral Power Distribution

In addition to the intensity and directionality of light, the spectral characteristics of light emitted from different sources can impact biological function to greater or lesser degrees. Research indicates shorter wavelengths of light, particularly in the 400–550nm range, are more disruptive to circadian function, with wavelengths shorter than 500nm having particularly adverse impacts. This light would fall along part of the green band and across the entire blue, indigo and violet bands of the visible light spectrum.

While correlated color temperature (CCT) is useful for describing the color quality of white light as our eyes perceive it, CCT does not indicate how much energy a white light source emits along each aspect of the spectrum. This is why an metal halide (MH) source and an LED source could have identical CCTs, yet the spectral power distribution of one might be significantly higher in the range below 500nm, compared to the other.

It is important to understand that a light source can emit a strong concentration of short-wave radiation, often referred to as “blue-rich light,” but when mixed with other wavelengths of light energy, the blue-rich character of the light is not discernible to the naked eye. Nevertheless, it can still have a physiological impact.

HPS light sources (550–650nm) are still the most prevalent type of light source installed for roadway and area lighting in the U.S., but a growing number of facilities are replacing HPS lamps with solid-state white light sources, including LEDs.

Along with energy efficiency and improved life, white-light LEDs provide better color rendering than HPS sources. This is because the spectral output of white light sources differs from that of HPS sources. Facilities undergoing retrofits should examine the spectral power distribution of potential replacement lamps and weigh any potential ecological impact along with the advantages of broad-spectrum lighting.

Not all LED sources are the same. Some LED manufacturers offer LED products with reduced blue content for outdoor lighting. Amber LEDs designed for sensitive habitats are also available.

Broad-spectrum electric light emissions, often produced by white light sources, can also interfere with astronomical research and activities at observatories. This is because some emissions from broad-spectrum sources match the wavelengths of cosmic radiation often studied by astronomers. It is difficult to selectively filter this electric light from starlight.

Low-pressure sodium (LPS) sources emit yellow light in a narrow range of wavelengths that are easier for astronomers to filter out during research. For this reason, LPS sources are often preferred in areas near observatories. If broad-spectrum sources must be used, the problem can be mitigated by dimming lights whenever possible and limiting light sources' spectral output to shorter wavelength content, which is less likely to reflect off of surfaces.

### Big Bend National Park: A park-wide relight project restores dark skies and cuts lighting energy use 98%

In February 2012, Big Bend National Park in Texas was designated a Dark Sky Park by the International Dark-Sky Association. It is only the second national park in the U.S. (after Natural Bridges National Monument in Utah) to earn the distinction, thanks to a four-phase, park-wide retrofit project that has improved outdoor lighting and drastically reduced light pollution in the area.

Phase two of the project introduced LED lighting along park buildings and outdoor paths within the Chisos Basin. Estimated annual energy cost savings so far total \$3,130. The project has also reduced energy consumption and cut greenhouse gas emissions for lighting by 98%.

Appropriately shielded to limit light trespass, the new light fixtures have improved the quality of lighting along paths and walkways while reducing sky glow so effectively that the spectacular night skies over Big Bend are once again visible. In fact, Big Bend is now thought to have one of the darkest measured skies in the lower 48 states, conditions which also benefit the McDonald Observatory, a leading center for astronomical research located just 150 miles from the park.

The collaborative effort was undertaken with support from the National Park Service, funding from the American Recovery and Reinvestment Act, and a grant from the Friends of Big Bend National Park. A Best Lighting Practices Grant also aided the effort. The grant is administered through the National Park Foundation and the National Park Service's Denver Service Center. Musco Lighting provided services and Forever Resorts, Inc. also made contributions.

More information, photos and video of the project are available online: [www.nps.gov/bibe/parknews/upload/Chisos\\_Basin\\_Best\\_Lighting\\_Practices\\_Release.pdf](http://www.nps.gov/bibe/parknews/upload/Chisos_Basin_Best_Lighting_Practices_Release.pdf)

**Figure 15.** Light trespass can disrupt rest and sleep cycles, impacting long-term health and wellness. Glare can pose an immediate safety hazard.



## Human Factors

Outdoor lighting allows us to safely and comfortably navigate at night. Like any light processed through the optic nerve, nighttime lighting also elicits a physiological response in the human brain and body. The same bright, white light that helps people feel alert and awake during the day can potentially disrupt sleep cycles at night and, over time, impair metabolic function.

In June 2012, the American Medical Association (AMA) adopted a new policy recognizing the adverse health effects of nighttime lighting. The AMA concluded: “Exposure to excessive light at night, and blue-rich light in particular, has been linked to sleep disturbances and sleep disorders, impaired metabolic function, and suppression of the hormone melatonin.”<sup>5</sup> The most adverse health effects are more common among those who experience chronic and long-term exposure to excessive light at night, such as overnight shift workers.

The AMA also stated its support for lighting technologies that minimize circadian disruption. Park facilities can do this by selecting light sources with limited blue-rich spectral content, by selecting dark sky-friendly luminaires, and by further reducing light pollution through the use of lighting controls that enable scheduling, tuning and automatic dimming when lights are not in use.

<sup>5</sup> The Council on Science and Public Health. “Light Pollution: Adverse Health Effects of Nighttime Lighting.” American Medical Association, Rep. 4-A-12. AMA, 19 June 2012.

## Protecting Wildlife

Circadian science continues to reveal the ways that light exposure and dark periods influence hormone production and even affect gene expression. Researchers have observed light pollution disrupting feeding, migration, reproduction, and other behaviors essential to species' health and survival.

Outdoor lighting can disorient migrating species, spur wakeful behavior when animals should be resting, inhibit activities associated with feeding and reproduction, and otherwise disturb normal, healthy behavior patterns, increasing animals' risk of exhaustion and death. Insofar as light pollution inhibits successful reproduction, it can even result in extinction for small, isolated populations. For all these reasons, lighting that preserves dark skies is vital to the protection of wildlife.

### Mammals

Research shows light pollution affects both diurnal and nocturnal mammals, including bats, raccoons, deer, moose, coyotes, and mountain lions. The endangered lesser long-nosed bat is just one example of mammal species that favor areas managed for lower light intensity, such as national parks. Research has demonstrated the bats avoid zones where light intensity is greater, favoring relatively darker flight paths instead.<sup>6</sup> The endangered species is a primary pollinator in Arizona's Organ Pipe Cactus National Monument, located west of Tucson in the Sonoran Desert. The bat species' flight corridors and foraging areas encompass other parts of the state as well, where state and local agencies are working together to minimize light pollution and protect populations.



Photo: National Park Service

**Figure 16.** A lesser long-nosed bat, covered in pollen from Sonoran Desert flowers. Data shows the endangered species favors low lighting zones.

<sup>6</sup> Lowery, S.F., Blackman, S.T., Abbate, D. "Urban Movement Patterns of Lesser Long-nosed Bats (*Leptonycteris curasoae*): Management implications for the habitat conservation plan within the city of Tucson and the town of Marana." Research Branch, Arizona Game and Fish Department, 2009.

Outdoor lighting can also impact mammals' natural movement patterns. A study of juvenile mountain lions in urban Southern California concluded that highway lighting hinders young lions' attempts to find and establish their own territories away from densely populated areas.<sup>7</sup> The animals were observed bedding down for the night when highway lighting crossed their direction of travel and effectively obscured their view of the landscape beyond. After sunrise, the mountain lions would assess the terrain beyond the highway and either attempt to cross, if the terrain was wild, or change direction, if it was industrial. This delay comes at a biological cost insofar as it inhibits hunting or diminishes the animals' ability to find suitable habitat more quickly.

### Birds

Outdoor light sources can also disrupt bird migration patterns, and because birds often become fixated on bright light beams, improperly shielded lights can make birds vulnerable to predators. Some birds will circle certain light sources to the point of exhaustion and collapse. One million birds die every year throughout North America from collisions with lighted towers and buildings, according to the International Dark-Sky Association (IDA).<sup>8</sup> During stormy weather, in particular, when low cloud ceilings obscure the moon and stars, birds are more likely to be negatively impacted by nighttime lighting.

### Fish

Research shows light and darkness affect every aspect of fish species' lifecycle, from egg development, hatching and emergence to feeding, migration and spawning. Controlled aquarium research published in 2013 demonstrated that ecologically relevant light intensity levels from broad-spectrum street lamps can delay the emergence and dispersal of Atlantic salmon fry. This disruption desynchronized the population's emergence and caused a significant proportion to disperse during daylight hours. In the wild, these factors would leave young salmon more vulnerable to predation and at a disadvantage to establish feeding territories among other species. The weight of salmon fry exposed to street-lit conditions was also significantly lower.

Field research confirms that bright light at night near rivers and streams can slow, stop or alter the migration patterns of young salmon. Light avoidance behaviors have been observed as some fish seek cover from predators in darker parts of the water. For other species, bright lighting along water ways acts as a fish trap, attracting predators and arresting movement along rivers and streams.

<sup>7</sup> Beier, P. "Dispersal of Juvenile Cougars in Fragmented Habitat." *Journal of Wildlife Management* 59 (1995) : 228-237.

<sup>8</sup> International Dark-Sky Association. "Light Pollution and Wildlife," 2008.



**Figure 17.** Bright lights from bridges or waterfront paths can adversely affect the feeding, migration and spawning of fish. Simple solutions, such as redirecting lamps and installing shields and lighting controls, can prevent this type of light pollution.



Washington researchers who have contributed to these observations recommend keeping light levels on rivers and other water habitats below 0.1 lux and implementing shielding and motion controls, so lighting is limited to where and when it is needed. Other requirements and guidelines may apply where state measures, such as the California Environmental Quality Act (CEQA), and local ordinances apply.

## Amphibians and Reptiles

Sea turtle hatchlings are perhaps the most famous example of reptile species adversely affected by light pollution. For millions of years, young turtles could follow the white glow of the surf and the moonlight reflected in the waves to find their way to the ocean, where they are protected from predation by sea birds and mammals. In the last century, as lighting became denser in turtle habitats, the glow of broad-spectrum lamps along the shore has drawn hatchlings off course, with adverse effects on the population.<sup>9</sup>

Lizards and other reptiles are also affected by excessive light at night, and amphibians also exhibit unusual behavior in areas where the night never approaches natural levels of darkness. Salamanders, having evolved to forage and mate at night to avoid predators, will forage less and reproduce in smaller numbers where nighttime lighting interferes. Canadian scientists have also found male green frogs make fewer mating calls in brightly lit areas, affecting selection for females and potentially changing the dynamics and genetic diversity of the entire population.<sup>10</sup>

## Insects

In 2013 a research team published its findings that dung beetles navigate using the sun, the moon, and, on moonless nights, the Milky Way.<sup>11</sup> The team's experiments were the first to conclusively demonstrate insects' use of the starry night sky for orientation, and they underscore the importance of dark night skies for all aspects of the animal kingdom.

In addition to allowing for navigation by celestial markers, dark night skies provide cover for many insects. Nighttime lighting attracts and distracts insects, interfering with their ability to evade detection and capture by predators. In this way, lights can effectively act as bird and bat feeders, disrupting the natural hunting and foraging behaviors of predators. Naturalists have observed that spiders, frogs, and toads also take advantage of insects' vulnerability in lit areas.

Researchers have found nighttime lighting can also interfere with insects' reproduction. A study of male moths found outdoor lights compete with females for the males' attention, thus inhibiting the insects' reproductive success.<sup>12</sup> Nighttime lighting also inhibits pheromone release in female moths. Light sources that arrest and kill pregnant females before they can lay their eggs further diminish populations. Naturally, any impact on insect populations also impacts the species that depend on insects for food and the pollination of plants that provide sustenance.

Lighting manufacturers design light sources that minimize light output in the UV spectrum, for example, or otherwise limit the light's attractiveness to most insect species. Selecting appropriate sources, and implementing proper shielding and lighting controls can protect ecosystems without compromising human safety or comfort. Fewer swarms around luminaires can also reduce maintenance needs.

## Plant Life

Older studies have found many plant species are unaffected by continuous lighting, but certain species, including geranium and tomato plants require natural light-and-dark cycles to thrive and stay alive.

A more recent 2013 study by biologists from Rice University in Texas and the University of California, Davis, found that plants exposed to light-and-dark cycles (circadian entrainment) even after harvesting had higher levels of phytochemicals, including antioxidants. These phytochemicals bolstered the plants' resistance to herbivores and enhanced their nutritional value.<sup>13</sup> The team demonstrated that the first phenomenon, of naturally enhanced pest resistance, is widespread among diverse crops.

<sup>9</sup> Salmon, M., Tolbert, M.G., Painter, D. P., Goff, M., and Reiners, R., 1995. "Behavior of Loggerhead Sea Turtles on an Urban Beach. II. Hatchling Orientation," *Journal of Herpetology*, Dec. 1995, Vol. 29, No. 4: 568-576.

<sup>10</sup> Baker, B.J., Richardson, J.M.L., 2006. "The Effect of Artificial Light on Male Breeding-season Behaviour in Green Frogs (*Rana clamitans melanota*)."  
*Canadian Journal of Zoology*, 84: 1528-1532.

<sup>11</sup> Dacke, Marie, E. Baird, M. Byrne, B. C.H. Scholtz, and E.J. Warrant, 2013. "Dung Beetles Use the Milky Way for Orientation." *Current Biology*, Vol. 23, Issue 4: 658-665.

<sup>12</sup> Rich, Catherine and T. Longcore (eds.). *Ecological Consequences of Artificial Night Lighting*, Island Press. 305-344. 2006.

<sup>13</sup> Goodspeed, D., Liu, J.D., Wassim Chehab, E., Sheng, Z., Francisco, M., Kliebenstein, D.J., and Braam, J., 2013. "Postharvest Circadian Entrainment Enhances Crop Pest Resistance and Phytochemical Cycling." *Current Biology*, Volume 23, Issue 13: 1235-1241.

## Selecting Dark Sky-Friendly Luminaires

Many new light luminaire designs optimize light output while reducing glare, light pollution and light trespass. Specifications developed by the lighting industry help lighting designers and installers select outdoor luminaires with the appropriate distribution for sites in different lighting zones (the same zones listed in Table 9.4.3A of the ANSI/ASHRAE/IES Standard 90.1-2010).

### The BUG System

The Illuminating Engineering Society of North America (IES) developed the Backlight-Uplight-Glare (BUG) rating system to evaluate luminaires' performance in relation to light trespass, sky glow, and high-angle brightness (see figure 18).<sup>14</sup>

A BUG system rating consists of a three-part code that indicates how well the luminaire controls backlight, uplight and glare. A code for a luminaire may look something like this:

# B0-U2-G1

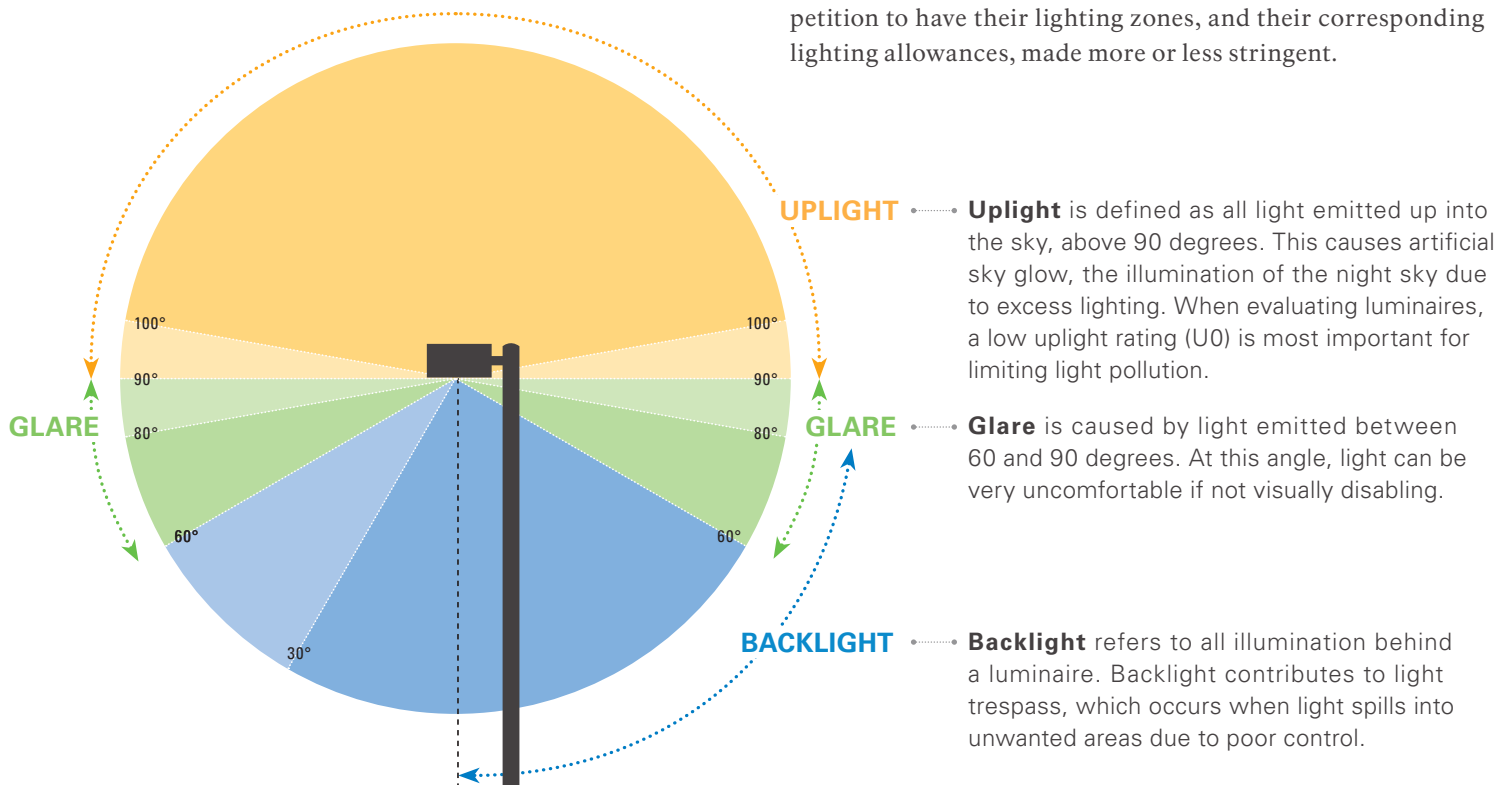
The numbers in the rating represent how well the luminaire performed in photometric testing, with 0 representing the best control and 5 indicating poorest performance. A luminaire rated with the example code above (B0-U2-G1) offers excellent control of backlight, mediocre control of uplight, and fairly good control of glare.

Today, a growing number of manufacturers will provide BUG-rated zonal lumen distributions for their outdoor luminaires. The appendix of this guide includes a demonstration exercise, "Finding the BUG Rating for a Type II Outdoor Lighting Fixture," which explains in more detail how BUG ratings can be determined using the information in a standard photometric report.

The Model Lighting Ordinance (MLO) jointly developed by the IES and the International Dark-Sky Association (IDA) lists maximum allowable BUG ratings for various lighting zones (see table 4).

Parks, preserves, wilderness areas, and protected wildlife corridors are classified as Lighting Zone 0 (LZ-0) under the MLO. Dark periods constitute a critical part of the habitat in this category, so LZ-0 environments require the most stringent control of outdoor lighting. The MLO recommends luminaires match the following backlight-uplight-glare (BUG) rating: B0 or B1, U0, G0. (A maximum rating of B1 is recommended for certain applications over 1 mounting height.) Some sites may be in more populated zones where greater general illumination levels are appropriate. Local jurisdictions can petition to have their lighting zones, and their corresponding lighting allowances, made more or less stringent.

**Figure 18.** Backlight, Uplight and Glare (BUG) rating system



<sup>14</sup> IES Luminaire Classification System for Outdoor Fixtures, IES TM-15-11.



Table 4. Maximum Allowable BUG Ratings

|                                                                                                 | LZ-0 | LZ-1 | LZ-2 | LZ-3 | LZ-4 |
|-------------------------------------------------------------------------------------------------|------|------|------|------|------|
| <b>BACKLIGHT RATING</b>                                                                         |      |      |      |      |      |
| >2 mounting heights from property line                                                          | B1   | B3   | B4   | B5   | B5   |
| 1 – <2 mounting heights from property line and ideally oriented                                 | B1   | B2   | B3   | B4   | B4   |
| 0.5 – 1 mounting heights from property line and ideally oriented                                | B0   | B1   | B2   | B3   | B3   |
| <0.5 mounting height to property line and properly oriented                                     | B0   | B0   | B0   | B1   | B2   |
| <b>UPLIGHT RATING</b>                                                                           | U0   | U1   | U2   | U3   | U4   |
| Allowed % light emission above 90° for street or area lighting                                  | 0%   | 0%   | 0%   | 0%   | 0%   |
| <b>GLARE RATING</b>                                                                             | G0   | G2   | G2   | G3   | G4   |
| Any luminaire not ideally oriented with 1 – <2 mounting height to any property line of concern  | G0   | G0   | G1   | G1   | G2   |
| Any luminaire not ideally oriented with 0.5 – 1 mounting height to any property line of concern | G0   | G0   | G0   | G1   | G1   |
| Any luminaire not ideally oriented with <0.5 mounting height to any property line of concern    | G0   | G0   | G0   | G0   | G1   |

Joint IDA–IES Model Lighting Ordinance (MLO), 2011.

## Resources & Glossary



Photo: Kathleen Fontecha/CLTC, UC Davis

The resources included in this section are intended to serve as preliminary sources for information on outdoor lighting. Though it is not a complete list, each resource listed here provides links to a wide range of useful materials. The information contained here is up to date at the time this guide was created.

## **U.S. Department of Energy**

**energy.gov**

The Department of Energy's overarching mission is to advance the national, economic, and energy security of the United States; to promote scientific and technological innovation in support of that mission; and to ensure the environmental cleanup of the national nuclear weapons complex.

## **U.S. National Park Service**

**nps.gov**

Since 1916, the American people have entrusted the National Park Service with the care of their national parks. With the help of volunteers and park partners, the National Park Service is proud to safeguard these nearly 400 places and to share their stories with more than 275 million visitors every year.

## **NPS Night Skies Resources**

**nature.nps.gov/night**

The National Park Service website has helpful pages on the "Science of Light," "Light Pollution," "Managing Lightscapes," "Making a Difference," and more.

## **Lawrence Berkeley National Laboratory**

**lbl.gov**

Berkeley Lab is a member of the National Laboratory System supported by the U.S. Department of Energy through its Office of Science. It is managed by the University of California (UC) and is charged with conducting unclassified research across a wide range of scientific disciplines.

## **California Lighting Technology Center**

**cltc.ucdavis.edu**

The California Lighting Technology Center (CLTC) is a not-for-profit research, development and demonstration center dedicated to accelerating the development and commercialization of energy-efficient lighting and daylighting technologies. Part of the University of California, Davis, CLTC includes laboratories for technology testing, development and prototyping. CLTC also conducts education and outreach activities. The center works in partnership with utilities, lighting manufacturers, end users, builders, designers, researchers, academics, and government agencies.

## **Illuminating Engineering Society**

**ies.org**

The Illuminating Engineering Society seeks to improve the lighted environment by bringing together those with lighting knowledge and by translating that knowledge into actions that benefit the public.

## **International Dark-Sky Association**

**darksky.org**

IDA is a nonprofit member organization that teaches others how to preserve the night sky. It provides resources, including fact sheets, photos and guides. IDA co-developed the Model Lighting Ordinance (MLO) with the Illuminating Engineering Society, and it recognizes national and state parks that protect dark-sky environments.

**Dark Sky Society****darksksociety.org**

The Dark Sky Society supports educational and legislative efforts to eliminate light pollution.

**National Renewable Energy Laboratory****nrel.gov**

National Renewable Energy Laboratory (NREL) is the only federal laboratory dedicated to the research, development, commercialization, and deployment of renewable energy and energy-efficiency technologies. Backed by 32 years of achievement, NREL leads the way in helping meet the growing demand for clean energy.

**Pacific Northwest National Laboratory****pnl.gov**

Pacific Northwest National Laboratory (PNNL) is one of the U.S. Department of Energy's (DOE) 10 National Laboratories, managed by DOE's Office of Science. PNNL also performs research for other DOE offices as well as government agencies, universities, and industry to deliver breakthrough science and technology to meet today's key national needs.

**Rensselaer Polytechnic Institute****lrc.rpi.edu**

The Lighting Research Center is the world's leading university-based research and education organization devoted to lighting—from technologies to applications and energy use, from design to health and vision.

**National Electrical Manufacturers Association****nema.org**

NEMA is the trade association of choice for the electrical manufacturing industry. Founded in 1926 and based near Washington, D.C., its approximately 450 member companies manufacture products used in the generation, transmission and distribution, control, and end-use of electricity.

**Reports and Guides**

**LED Exterior Lighting: Above Ground Parking Garage | [www.etcc-ca.com/images/stories/pdf/ETCC\\_](http://www.etcc-ca.com/images/stories/pdf/ETCC_)**

**Case Studies****Lighting of Thomas Jefferson Memorial****[nps.gov/partnerships/lighting\\_jefferson\\_memorial.htm](http://nps.gov/partnerships/lighting_jefferson_memorial.htm)**

The National Park Service retrofitted the exterior and portions of the interior of the Thomas Jefferson Memorial, one of Washington's most recognized landmarks.

**UC Davis Smart Energy Initiative****[cltc.ucdavis.edu/project/uc-davis-smart-lighting-initiative](http://cltc.ucdavis.edu/project/uc-davis-smart-lighting-initiative)**

The California Lighting Technology Center, Energy Efficiency Center, and Facilities Management at UC Davis launched the California Parking Garage Lighting Project as part of the UC Davis Smart Energy Initiative. This project is directed at increasing safety, reducing maintenance costs, and achieving 50% or greater energy savings in standard parking garage lighting applications.

**International Dark-Sky Association  
Exterior Lighting****[www1.eere.energy.gov/femp/pdfs/29267-5.4.5.pdf](http://www1.eere.energy.gov/femp/pdfs/29267-5.4.5.pdf)**

Outdoor lighting improves security, enhances safety, and directs pedestrians and vehicles. IDA gives tips on how to improve outdoor lighting and provides information and guidance to help facilities choose sustainable, ecologically responsible solutions.

**Lansing Board of Water & Light  
and Midwest Circuits****[www.philipslumileds.com/pdfs/CS11.pdf](http://www.philipslumileds.com/pdfs/CS11.pdf)**

The Lansing Board of Water & Light provides outdoor area lighting for its customers, and installs, operates, and maintains about 34,000 street lights throughout the greater Lansing area.

**City of Los Angeles LED Street Lighting****[www.mwcog.org/environment/streetlights/downloads/](http://www.mwcog.org/environment/streetlights/downloads/)****CCI Case Study Los Angeles LED Retrofit.pdf**

Los Angeles' street lighting system is owned and maintained by the Los Angeles Bureau of Street Lighting — part of the Los Angeles Department of Public Works. With more than 209,000 street lights in its control, the city boasts the second largest municipally owned street lighting system in the United States. The goal is to replace 140,000 city street luminaires with LED luminaires and install a remote monitoring system.

**Report\_435.pdf**

Light-emitting diode (LED) lights are emerging as a viable



alternative for outdoor locations such as parking lots, parking garages, and streets, which typically use wallpacks and bollards lit with high wattage, high intensity discharge (HID) or fluorescent lights. In addition to increased energy efficiency, LEDs offer longer bulb life, reliability, and cool operating temperatures. LED sources are currently considerably more expensive than fluorescent, but prices are expected to drop as demand increases.

### **Oregon DOE Outdoor Lighting Report**

[www.oregon.gov/ENERGY/CONS/Codes/docs/MLO\\_report.pdf](http://www.oregon.gov/ENERGY/CONS/Codes/docs/MLO_report.pdf)

Excessive outdoor lighting can have a number of harmful consequences. Glare from high intensity light sources can be hazardous, light pollution can be disruptive to the nighttime aesthetic, and unnecessary artificial light is a waste of natural resources. There are simple measures that can be implemented to mitigate these problems. Use of shielded outdoor lighting fixtures that direct light appropriately is a simple remediation of the adverse consequences of excessive outdoor lighting.

### **LED Low-Bay Garage Lighting**

**South San Francisco, CA | [www.etcc-ca.com/images/stories/pdf/ETCC\\_Report\\_435.pdf](http://www.etcc-ca.com/images/stories/pdf/ETCC_Report_435.pdf)**

Energy Solutions provided monitoring, data collection, and data analysis services for an LED Low-Bay Garage Lighting Demonstration project under contract to the Emerging Technologies Program of Pacific Gas and Electric Company. The project replaced low-bay metal halide luminaires of 175 W lamps with new low-bay LED Luminaires from Lighting Science Group Corporation of nominal 85 W and 6,000 K color temperature.

### **LED Fixtures for Exterior, Porch, and Perimeter Lighting | [www.etcc-ca.com/component/content/article/33/2567-light-emitting-diode-led-fixtures-for-exterior-porch-and-perimeter-lighting](http://www.etcc-ca.com/component/content/article/33/2567-light-emitting-diode-led-fixtures-for-exterior-porch-and-perimeter-lighting)**

The overall goal of this project is to reduce energy consumption by researching and developing a series of high-performance, energy-efficient, LED-based alternatives to incandescent exterior, porch, and perimeter lighting in residential, commercial, and institutional applications.

### **Action Energy: Energy Efficiency in Lighting — an Overview**

[www.cibse.org/pdfs/energylight.pdf](http://www.cibse.org/pdfs/energylight.pdf)

This publication provides an overview of energy efficiency in lighting considering all the elements and how they interrelate with one another. It is aimed at people who are concerned with improving lighting energy efficiency without inhibiting the quality of the lit environment. This includes architects, lighting designers, and installers as well as building developers, facility managers, and building users.

### **LED Street Lighting - Phase III Continuation, Oakland, CA | [www.etcc-ca.com/index.php?option=com\\_content&task=view&id=2422&Itemid=72](http://www.etcc-ca.com/index.php?option=com_content&task=view&id=2422&Itemid=72)**

This report summarizes the third phase of an LED street lighting assessment project conducted to study the applicability of LED luminaires in a street lighting application. In Phase II, fifteen 78 W LED luminaires replaced 121 W high pressure sodium (HPS) luminaires (nominal 100 W) in a residential area of Oakland. In Phase III, the luminaires on one of the Phase II streets were replaced with next generation LED luminaires (58 W) from the same manufacturer. Four of the LED luminaires installed in Phase II were replaced. The same suite of lighting performance, electrical power measurements, and economic analyses performed in Phase II were performed for the Phase III LED luminaires.

### **Section 5.4.5 Exterior Lighting: Greening Federal Facilities; Second Edition | [www1.eere.energy.gov/femp/pdfs/29267-5.4.5.pdf](http://www1.eere.energy.gov/femp/pdfs/29267-5.4.5.pdf)**

Federal Energy Management Program (FEMP) Greening Guidebook: This section discusses exterior lighting as it relates to greening federal facilities.

### **Lighting Fundamentals Handbook: Lighting Fundamentals and Principals for Utility Personnel | [my.epri.com/portal/server.pt?Abstract\\_id=TR-101710](http://my.epri.com/portal/server.pt?Abstract_id=TR-101710)**

This comprehensive EPRI handbook provides basic information on lighting principles, lighting equipment, and issues related to lighting design. It is intended as a primer and reference for utility personnel involved in commercial and industrial lighting programs as well as customer assistance.



## Articles

### **Fort Benning Saves Energy with Wireless Control of Outdoor lights | [www.lonmark.org/connection/case\\_studies/documents/FortBenning\\_OutdoorLights.pdf](http://www.lonmark.org/connection/case_studies/documents/FortBenning_OutdoorLights.pdf)**

Fort Benning, GA, updates its Energy Management and Control System to improve performance and reliability and, ultimately, to save on energy costs.

### **Guidance Notes for the Reduction of Obtrusive Light**

**[www.britastro.org/dark-skies/pdfs/ile.pdf](http://www.britastro.org/dark-skies/pdfs/ile.pdf)**

All living things adjust their behavior according to natural light. Man's invention of artificial light has done much to enhance the nighttime environment but, if not properly controlled, obtrusive light (commonly referred to as light pollution) can present serious physiological and ecological problems.

### **Light Done Right**

**[www.libraryjournal.com/article/CA6696205.html](http://www.libraryjournal.com/article/CA6696205.html)**

The haphazard lighting currently used to support 24 / 7 lifestyles affects humans' natural rhythm, physical and spiritual well-being, and the ability to see and study the stars. Continuous illumination also relates to the natural rhythms of animals, birds, reptiles, bugs, and plants. More conscious lighting design can help address these issues.

### **LEDs, Centralized Control Illuminate Anchorage's Green Initiatives**

**[www.govtech.com/gt/583194?topic=290183](http://www.govtech.com/gt/583194?topic=290183)**

Anchorage, Alaska, sought a way to make its 16,500 streetlights more energy efficient. What the city found was a plan to replace current streetlights — or high pressure sodium (HPS) lamps — with light-emitting diodes (LEDs) that are connected to a centralized control system.

### **Light Emitting Diode Streetlight Systems Help Cities Save Energy**

**[www.govtech.com/gt/628240](http://www.govtech.com/gt/628240)**

State and local governments looking to improve efficiency and cut costs are casting their gaze skyward—at streetlights—for an answer.

### **LED Exterior Lighting: Above Ground Parking Garage | [www.etcc-ca.com/images/stories/pdf/ETCC\\_Report\\_435.pdf](http://www.etcc-ca.com/images/stories/pdf/ETCC_Report_435.pdf)**

Light-emitting diode (LED) lights are emerging as a viable alternative for outdoor locations such as parking lots, parking garages, and streets, which typically use wallpacks and bollards lit with high wattage, high intensity discharge (HID) or fluorescent lights. In addition to increased energy efficiency, LEDs offer longer bulb life, reliability, and cool operating temperatures. LED sources are currently considerably more expensive than fluorescent, but prices are expected to drop as demand increases.

### **Oregon DOE Outdoor Lighting Report | [www.oregon.gov/ENERGY/CONS/Codes/docs/MLO\\_report.pdf](http://www.oregon.gov/ENERGY/CONS/Codes/docs/MLO_report.pdf)**

Excessive outdoor lighting can have a number of harmful consequences. Glare from high intensity light sources can be hazardous, light pollution can be disruptive to the nighttime aesthetic, and unnecessary artificial light is a waste of natural resources. There are simple measures that can be implemented to mitigate these problems. Use of shielded outdoor lighting luminaires that direct light appropriately is a simple remediation of the adverse consequences of excessive outdoor lighting.

### **LED Low-Bay Garage Lighting South San Francisco, CA | [www.etcc-ca.com/images/stories/pdf/ETCC\\_Report\\_435.pdf](http://www.etcc-ca.com/images/stories/pdf/ETCC_Report_435.pdf)**

Energy Solutions provided monitoring, data collection, and data analysis services for an LED Low-Bay Garage Lighting Demonstration project under contract to the Emerging Technologies Program of Pacific Gas and Electric Company. The project replaced low-bay metal halide luminaires of 175 W lamps with new low-bay LED luminaires from Lighting Science Group Corporation of nominal 85 W and 6,000 K color temperature.

### **LED Fixtures for Exterior, Porch, and Perimeter Lighting | [www.etcc-ca.com/component/content/article/33/2567-light-emitting-diode-led-fixtures-for-exterior-porch-and-perimeter-lighting](http://www.etcc-ca.com/component/content/article/33/2567-light-emitting-diode-led-fixtures-for-exterior-porch-and-perimeter-lighting)**

The overall goal of this project is to reduce energy consumption by researching and developing a series of high-performance, energy-efficient, LED-based alternatives to incandescent exterior, porch, and perimeter lighting in residential, commercial, and institutional applications.

## Demonstration Exercise: Finding the BUG Rating for a Type II Outdoor Lighting Luminaire

### Step 1. Locate Photometric Information

Search the manufacturer's website for the photometric report or summary on the luminaire in question.

### Step 2. Consult IES for BUG Ratings

Next, find the most recent version of the BUG ratings. For this example, we will use the ratings from Addendum A for *IESNA TM-15-07*. Check the IESNA website, [www.iesna.org](http://www.iesna.org), for the most recent rating available.

### Step 3: Determine the Backlight Rating

To find the backlight ('B') classification of this luminaire, we must first identify the lumen output for the secondary solid angles of BH, BM and BL. Our photometric report includes this data:

BH: 375.8 lumens  
BM: 1034.8 lumens  
BL: 508.3 lumens

These values are then compared to the backlight ratings in Table A-1 of Addendum A for *IESNA TM-15-07* in order to determine which rating each secondary solid angle receives. In this example, the secondary angles are classified as follows:

BH: B1 ( $375.8 < 500$  lumens)  
BM: B2 ( $1034.8 < 2500$  lumens)  
BL: B2 ( $508.3 < 1000$  lumens)

The highest rating for the three secondary angles is then selected as the backlight rating for the luminaire. In this case, B2 is the highest rating the secondary angles received, so for this luminaire, the **Backlight Rating is B2**.

### Step 4: Determine the Uplight Rating

The same process is used to determine the Uplight ('U') rating of the luminaire.

UH: 0.0 lumens = U0      BVH: 11.6 lumens = U1  
UL: 0.0 lumens = U0      **Uplight Rating is U1**  
FVH: 16.7 lumens = U1

### Step 4: Determine the Glare Rating

The process for finding the glare ('G') rating depends on the IES classification of the luminaire. Glare ratings differ for asymmetrical luminaire types (Type I, II, III, and IV) and symmetrical luminaire types (Type V, V Square). The manufacturer usually provides the IES Classification for a luminaire.

Our example is a Type II luminaire, so we will use Table A-3: Glare Ratings of *ESNA TM-15-07*, using the same process used to determine the backlight rating.

FVH: 16.7 lumens = G1      BH: 375.8 lumens = G1  
BVH: 11.6 lumens = G1      **Glare Rating is G1**  
FH: 1062.5 lumens = G1

### Step 5: BUG Rating

Finally, we can determine that this luminaire has the following BUG rating:

**B2-U1-G1**

# Glossary

## A

**Accent lighting:** Lighting used to emphasize a building's architectural features or draw visitors' attention to certain objects.

**Ambient lighting:** See "general lighting" and "lighting zones."

**Astronomical time-switch:** An automatic lighting control device that switches lights on or off at specified times of the day, or during astronomical events such as sunset and sunrise, to prevent energy waste during periods when daylight is available. These devices can account for geographic location and calendar date. Multi-level astronomical time switch controls reduce lighting power in multiple steps between full light output and their off setting.

## B

**Baffle:** An opaque or translucent element to shield a light source from direct view.

**Ballast:** A device used with a discharge lamp to obtain the necessary voltage, current, and /or wave form for starting and operating the lamp.

**Beam spread:** The angle created by two points of equal light intensity on either side of the beam's axis and the point where the axis and lamp surface intersect.

**Brightness:** Strength of the sensation that results from viewing surfaces from which the light comes to the eye.

**BUG rating system:** System created by IES based on TM-15-07 to rate the amount of light emitted from a luminaire in unwanted directions, i.e., backlight, uplight and glare. The methodology represents a comprehensive system that limits lamp lumens to values appropriate

for various lighting zones. The BUG rating system replaces the older IES cutoff classification system.

## C

**Candela (cd):** Standard SI unit of luminous intensity, or candle power. One candela is one lumen per steradian (lm/sr). A candle flame emits light with a luminous intensity of approximately one candela.

**Candlepower distribution:** The plot graph representation of the variation in light spread and intensity of a lamp or luminaire.

**Center beam candlepower (CBCP):** The intensity of light produced at the center of a reflector lamp; expressed in candelas.

**CIE:** Commission Internationale de l'Eclairage (the International Commission on Illumination), an independent nonprofit organization that determines most lighting standards.

**Coefficient of utilization (CU):** Ratio of luminous flux (lumens) from a luminaire received on the work plane to the lumens emitted by the luminaire.

**Color Rendering Index (CRI):** The standard scale used in the lighting industry to measure how accurately a light source renders colors in comparison to an ideal source (known as a blackbody radiator). The rating system uses eight specific test colors. The apparent shifting of these test colors is measured to determine a light source's average color rendering ability. The greater the apparent shift, the lower the CRI. The CRI scale ranges from 0 (poorest) to 100 (color rendition matching that of the ideal source). A CRI of 80 or higher provides good color rendering for outdoor

applications where color rendering is important. If color rendering is less important, a CRI in the mid-70s may suffice.

**Compact fluorescent lamp (CFL):** See "fluorescent lamp." CFLs are a type of fluorescent lamp with ballasts incorporated in the base. The fluorescent tube of a CFL is curved into a more compact shape to allow for direct replacement of incandescent lamps.

**Cones and rods:** Retinal receptors that allow humans and animals to see. The cones in the eye enable color perception and sharper focus. Cones are most active when light levels are high (photopic vision). Rods dominate at low light levels (scotopic vision); they detect motion well but perceive less detail and do not allow for the perception of colors. At intermediate light levels, both cones and rods actively contribute to vision by varying degrees (mesopic vision).

**Correlated color temperature (CCT):** Measured in Kelvins (K), CCT describes the color appearance of light emitted from a lamp. Low CCT indicates a warmer (more red) cast while high CCT denotes a cooler (more blue) appearance. Light sources with a CCT of 2700–3000K emit incandescent-like light. Lamps with cooler color temperatures, within the range of 5000–6500K emit light that more closely resembles bright daylight on a clear afternoon. A CCT diagram is included in the first section of this guide.

**Cutoff fixture:** A luminaire that provides a cutoff (shielding) for the light it emits. The old cutoff system of luminaire classification has been replaced by the more precise BUG (backlight, uplight and glare) rating system.

## D

**Dark adaptation:** The process by which the eye becomes adapted to a luminance less than about 0.03 candela per square meter (0.01 footlambert).

**Daylight control:** An automatic lighting control device that uses one or more photosensors to detect changes in daylight contribution and automatically adjust electric lighting levels accordingly. A multi-level daylight control adjusts the light output (luminous flux) of the electric lighting system in either a series of steps or by continuous dimming in response to available daylight.

**Dimmer:** A lighting control device that varies the light output (luminous flux) of the electric lighting system by changing the power delivered to that system. Step dimmers decrease power by one or more distinct, predetermined steps between maximum and minimum light output. Continuous dimmers operate over a continuous range, from maximum to minimum light output, allowing for subtle, granular transitions between light levels.

**Disability glare:** See “glare.”

**Discomfort glare:** Glare that produces discomfort but does not necessarily diminish visual performance.

## E

**Efficacy:** Also called “luminous efficacy,” this is the ratio of visible light emitted by a lamp relative to the amount of power it consumes. This is measured in lumens per watt (lm / W). A lamp that consumes 100 W of power and produces 2000 lm would have an efficacy of 2000 lm / 100 W or 20 lm / W. A lamp’s efficacy is calculated by dividing its rated initial lumens (lm) by the rated lamp power (watts) without including auxiliaries such as ballasts, transformers or drivers.

**Efficiency:** A measure of the effective or useful output of a system compared to the input of the system, also called “luminaire efficiency.” Often expressed

as a percentage of how much energy a system provides compared to the amount of energy supplied to it.

**Electromagnetic (EM) spectrum:** The distribution of energy emitted by a radiant source, arranged in order of wavelength or frequency. Includes gamma-ray, X-ray, ultraviolet, visible, infrared, and radio regions.

**Energy management control system (EMCS):** A computerized control system designed to regulate energy consumption by controlling the operation of one or more building systems, such as lighting and HVAC. An EMCS can also monitor environmental and system loads, adjust system operations, optimize energy usage, and respond to demand response signals..

## F

**Fixture:** See “luminaire.”

**Floodlight:** A luminaire designed to “flood” a well-defined area with light with a beam angle of 30% or more.

**Fluorescent lamp:** A low-pressure mercury electric discharge lamp in which a phosphor coating transforms some of the UV energy into visible light.

**Flux:** The flow rate of visible light emitted from a source over time (see also “luminous flux”).

**Footcandle:** Illuminance produced on a surface one foot from a uniform point source of one candela.

**Footlambert:** The average luminance of a surface emitting or reflecting light at a rate of one lumen per square foot (lm/ft<sup>2</sup>).

**Full-cutoff fixture:** A luminaire that allows no light emission above a horizontal plane. See “cutoff.”

## G

**General illumination:** In outdoor lighting, this term describes lighting designed to generally enhance visibility throughout an area, as distinguished from decorative lighting, task lighting, or

lighting designed to illuminate objects such as statues, monuments or signs.

**Glare:** Intense and blinding light resulting in reduced visual performance and visibility, often accompanied by discomfort.

**Group relamping:** Practice of replacing lamps on a routine scheduled basis determined by a percentage of estimated lamp life.

## H

**High-intensity discharge (HID):** A class of lamps that emit light by passing an electric current through a gas. Types of HID lamps include mercury, metal halide, and high-pressure sodium (HPS) lamps. Other discharge lamps are low-pressure sodium and fluorescent. Some such lamps have internal coatings to convert some of the ultraviolet energy emitted by the gas discharge into visual output.

**High-pressure sodium (HPS):** A type of high-intensity discharge (HID) lamp that uses sodium in an excited state, along with other elements, to generate light. HPS lamps produce light with a yellow or amber color and provide poor color rendering.

## I

**Illuminance:** The amount of visible light that falls on a surface, measured in lumens per square foot or footcandles (fc). The metric units for illuminance are lumens per square meter or lux. One fc is equal to 10.76 lux. Different illuminance levels are recommended for different visual activities and environments.

**Illuminating Engineering Society of North America (IES):** The professional society of lighting engineers, IES is the authority on lighting design and specification for lighting professionals. IES produces print and electronic publications, including The Lighting Handbook, the Model Lighting Ordinance (MLO) for outdoor lighting, and Recommended Practice manuals.

**Incandescent:** A type of lamp with a



filament that gives off light when heated by an electric current.

**Indirect fixture:** A luminaire that directs the majority of its luminous flux in an upward direction.

**Induction:** A type of lamp that uses a special ballast or a generator to create the initial electrical current, much like fluorescent lamps. Induction lamps have a long lifespan due to the fact that they do not require electrodes to start.

**Infrared radiation:** Electromagnetic radiation on the long wavelength side of the visual spectrum.

**Intensity:** The degree or amount of energy or light.

### **International Dark-Sky Association**

**(IDA):** A nonprofit organization dedicated to reducing light pollution and energy waste, building awareness of the value of dark skies, and supporting lighting ordinances that conserve and protect dark-sky ecosystems.

**Infrared (IR) lamp:** A type of lamp with a coating that recycles the wasted heat generated by the filament. This coating allows visible light to pass through it while reflecting infrared heat back to the filament, making the lamp more efficient.

## **K**

**Kilowatt-hour (kWh):** A unit of energy equal to the work done by one kilowatt (1000 W) of power acting for one hour.

## **L**

**Lamp:** The lighting industry term for an electric light source, as distinguished from the whole assembly (see “luminaire”). Lamps are commonly referred to as “bulbs.”

**Light pollution:** Any adverse effect of manmade light. Often used to denote urban sky glow.

**Light trespass:** Light falling where it is not wanted or needed; spill light; obtrusive light.

**Light emitting diode (LED):** An LED

is a semiconducting device made of inorganic material that produces light when an electric current flows through it. The acronym is often used to describe a component, device or package that incorporates an array of light emitting diodes.

**Lighting zone (LZ):** One of the five zones identified for distinct light-level limits by the IES and IDA. Lighting zones are designed to curtail light pollution. They range from LZ-0, the most stringent, to LZ-3, the least stringent, or LZ-4 in some rare cases where even higher light levels are deemed necessary. Lighting zone requirements are determined by ASHRAE or the authority with jurisdiction, based on the environment and activities within each area.

**Low-pressure sodium (LPS):** A discharge lamp where the light is produced by radiation from sodium vapor at a relatively low partial pressure (about 0.001 torr). LPS is a “tube source” that produces monochromatic light.

**Lumen depreciation factor:** Light loss of a luminaire with time because of the lamp’s decrease in efficiency, dirt accumulation, and any other factors that lower the effective output.

**Lumen maintenance:** Ability of a source to maintain a given percentage of its original lumen output expressed in percentage of total lifetime.

**Lumen:** Unit of measurement for the amount of light emitted from a light source. Higher lumen output generally indicates a brighter light source.

**Luminaire:** The lighting industry terms for what is commonly referred to as a “light fixture.” A luminaire is a complete lighting unit, consisting of lamp(s) and the parts that distribute light, position and protect the lamp(s), and connect them to a power supply.

**Luminance:** The intensity of light reflected from a surface in a given direction. Measured in candelas per area unit (generally, cd/ft<sup>2</sup> or cd/m<sup>2</sup>). Luminance (L) often varies depending

on the angle from which the reflected light is viewed.

**Luminous flux:** The intensity of light reflected from a surface in a given direction. Measured in candelas per area unit (generally, cd/ft<sup>2</sup> or cd/m<sup>2</sup>). Luminance (L) often varies depending on the angle from which the reflected light is viewed.

**Lux:** SI unit of illuminance, equal to one lumen per square meter.

## **M**

**Mercury vapor lamp:** An older type of HID lamp that emits a blue-green light. Sale of ballasts for these lamps has been banned in the U.S. since 2008, due to the fact that mercury vapor lamps are significantly less energy efficient than other HID sources, including metal halide and high-pressure sodium lamps.

**Mesopic vision:** Vision with fully adapted eyes at intermediate light levels, between photopic and scotopic conditions, or about 3.4 – 0.34 cd/m<sup>2</sup>.

**Metal halide (MH):** A type of HID lamp in which the majority of the light is generated through the radiation of metal halide vapors.

**Motion sensor:** A device that automatically turns lights off soon after an area is vacated. “Motion sensor” applies to outdoor lighting controls. When the device is used to control indoor lighting systems, it is called an occupant sensor, occupancy sensor, occupant-sensing device, or vacancy sensor.

**Mounting height:** The height of the luminaire or lamp above the ground.

## **N**

**National Park Foundation:** The official charity of America’s National Parks, the National Park Foundation raises private funds to support national park projects and programs.

## **O**

**Occupant sensor:** A lighting control



device that automatically turns lights off soon after an area is vacated. When used for outdoor lighting systems, this type of device is called a motion sensor.

## P

**PAR lamp:** Lamp with a parabolic aluminized reflector.

**Phosphor conversion:** A method used to generate white light with LEDs. A blue or near-ultraviolet LED is coated with a yellow or multichromatic phosphor, resulting in white light.

**Photocontrol:** A device that detects changes in daylight levels and controls electric lighting loads accordingly to maintain predetermined illumination levels (e.g., automatically turning luminaires on at dusk and off at dawn).

**Photometry:** The quantitative measurement of light level and distribution.

**Photopic vision:** Vision mediated essentially or exclusively by the cones. It is generally associated with adaptation to high light levels, a luminance of at least  $3.4 \text{ cd} / \text{m}^2$ .

## R

**Reflector lamp:** Lamp in which the outer blown glass bulb is coated with a reflecting material that helps direct the light.

**Reflector:** A component, such as a mirror, that controls light output by means of reflection.

**Refractor:** An object, such as a lens, that controls light output by means of refraction.

**RGB:** RGB stands for red, green and blue, the three primary colors of light. When the primaries are mixed, the resulting light appears white to the human eye. Mixing the light from red, green and blue in LEDs is one way to produce white light. The other approach is known as phosphor conversion.

## S

**Scotopic vision:** Visual function under very low light levels. The rod cells of the human eye are activated under scotopic conditions. Scotopic vision is associated with “night vision” and is characterized by high light sensitivity (as the eyes adapt to the darkness), poor spatial acuity, and a lack of color perception. It is generally associated with adaptation to light levels below  $0.034 \text{ cd} / \text{m}^2$ .

**Semi-cutoff fixture:** A luminaire that provides some cutoff, but less than a full-cutoff luminaire. The cutoff system has been replaced by the more precise BUG (backlight, uplight and glare) rating system.

**Spectral power distribution (SPD):** Radiant power emitted by a light source at each wavelength across the visible light spectrum, 380–760nm. SPD curves provide a visual profile of the color characteristics of a light source.

**Solid-state lighting (SSL):** Technology that uses semiconducting materials to convert electricity into light. SSL is an umbrella term encompassing both light emitting diodes (LEDs) and organic light emitting diodes (OLEDs).

**Spot relamping:** The practice of replacing lamps as they burn out, as distinguished from the strategy of group relamping.

**Spotlight:** A luminaire designed to light only a small, well-defined area with a beam angle of 12 degrees or less.

**Stray light:** Emitted light that falls away from the area where it is needed or wanted; light trespass.

## T

**T5, T8, T12:** Fluorescent lamp types. The T stands for tubular; the number indicates the diameter of the tube in 1/8-inch increments. A T8 lamp is 8 / 8 of an inch or one inch in diameter, a T12 lamp has a diameter of 12 / 8 or one and one-half inches. Fluorescent lamps 38 mm in diameter include specialized models

for work premises with low temperature applications, including exterior spaces.

## U

**Ultraviolet (UV) light:** Light energy output of shorter wavelengths than the human eye can see. Some animals, including insects, birds and reptiles, can see UV light.

**Urban sky glow:** The brightening of the night sky over urban areas as a result of dense electric lighting.

## V

**Vacancy sensor:** An occupant sensor that requires manual activation of lighting but automatically turns lights off soon after an area is vacated. The device also may be called a manual-on occupant sensor or manual-on/automatic-off sensor.

**Veiling luminance:** A luminance produced by bright sources in the field of view superimposed on the image in the eye, reducing contrast and hence decreasing visibility.

**Visibility:** The quality of being perceptible to those with typical vision. Effective nighttime lighting increases visibility.

**Visual acuity:** Acuteness or clearness of vision, especially form vision, which is dependent in part on the sharpness of the eye's retinal focus.

## W

**Watt:** Unit of measure for the electric power used by an appliance or device such as a lamp or luminaire.





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# The effect of reduced street lighting on road casualties and crime in England and Wales: controlled interrupted time series analysis

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## ABSTRACT

**Background** Many local authorities in England and Wales have reduced street lighting at night to save money and reduce carbon emissions. There is no evidence to date on whether these reductions impact on public health. We quantified the effect of 4 street lighting adaptation strategies (switch off, part-night lighting, dimming and white light) on casualties and crime in England and Wales.

**Methods** Observational study based on analysis of geographically coded police data on road traffic collisions and crime in 62 local authorities. Conditional Poisson models were used to analyse longitudinal changes in the counts of night-time collisions occurring on affected roads during 2000–2013, and crime within census Middle Super Output Areas during 2010–2013. Effect estimates were adjusted for regional temporal trends in casualties and crime.

**Results** There was no evidence that any street lighting adaptation strategy was associated with a change in collisions at night. There was significant statistical heterogeneity in the effects on crime estimated at police force level. Overall, there was no evidence for an association between the aggregate count of crime and switch off (RR 0.11; 95% CI 0.01 to 2.75) or part-night lighting (RR 0.96; 95% CI 0.86 to 1.06). There was weak evidence for a reduction in the aggregate count of crime and dimming (RR 0.84; 95% CI 0.70 to 1.02) and white light (RR 0.89; 95% CI 0.77 to 1.03).

**Conclusions** This study found little evidence of harmful effects of switch off, part-night lighting, dimming, or changes to white light/LEDs on road collisions or crime in England and Wales.

ultimately make their own assessment of the most appropriate lighting regime on each road for which they have responsibility. Three street light adaptation strategies reduce the amount of light: switching lights off permanently ('switch off'), reducing the number of hours that lamps are switched on at night ('part-night' lighting), and reducing the power or output of lamps ('dimming'). A fourth strategy is to replace traditional sodium lamps (orange/yellow light) with more energy efficient lamps or LEDs ('white light').

Each of these strategies has prompted public and media concerns about the negative effects that focus on risks of night-time road traffic collisions, crime, and fear of crime.<sup>3</sup> Road collisions have received particular attention, with a number of coroners concluding that reduced street lighting contributed to road deaths sparking inquests.<sup>4</sup> However, health and well-being benefits from reduced light pollution (eg, improved sleep and being able to see the night sky) have also been noted.<sup>5–6</sup> There are also putative benefits from reductions in artificial light at night, which have been linked to a range of health outcomes affected by disruptions to the circadian rhythms.<sup>7–9</sup>

Public concern that street lighting is necessary for road safety and crime prevention is, in part, supported by the literature: systematic reviews have identified some evidence for improved road safety<sup>10</sup> and an overall reduction in crime<sup>11</sup> with increased street lighting. However, with respect to crime, studies show that reductions in victimisation are observed during both hours of daylight and darkness,<sup>11</sup> calling into question the mechanism through which improvements to street lighting might influence crime. Moreover, there is to date, no empirical evidence on whether the implementation of reduced street lighting has had any negative effects on these important public health outcomes. National research on the effects of reduced street lighting on road traffic collisions and crime is, therefore, timely.

Theoretically, street light adaptation strategies might influence the risk of road traffic collisions and crime in a number of ways. Reducing lighting levels by switch off, part-night lighting, or dimming can reduce visibility in an area, which may increase the risk of collisions if road users are no longer able to detect hazards. Reduced visibility may also decrease mobility if fear of collisions, falling over in the dark, or fear of crime deters people from making some journeys. Fewer people on the streets might reduce road casualties by reducing the

## INTRODUCTION

Within a context of cost constraints and increasing local accountability for climate change mitigation, technological innovation is enabling changes to the provision of street lighting in England and Wales in ways that may have important implications for public health. Emerging technologies, such as LED lighting and computerised central management systems, have created opportunities for local authorities to adapt their street lighting strategies in ways that can reduce energy costs and contribute to reductions in carbon emissions. However, there is also concern that reductions in street light at night might increase road traffic injury, crime and fear of crime.

Local authorities are able to draw on national guidance on lighting<sup>1</sup> and professional standards<sup>2</sup> when making decisions about street lighting, but



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potential for collisions, but may decrease the 'natural surveillance' in an area, leading to an increase in crime. Reduced visibility may also reduce crime, such as theft from vehicles or robbery, if criminals are less able to identify potential targets. The introduction of energy efficient lamps, or LEDs, can change the quality and colour of lighting (eg, from yellow to white light) without reducing visibility. White light might improve visual acuity, and by improving closed circuit television (CCTV) images can make criminals feel more conspicuous, thus deterring certain types of crime.

The broader cultural meanings of street lighting as one component of modern (sub)urban life may also link switch off, part-night lighting and dimming strategies to crime. Residents and visitors may feel that areas targeted for lighting reductions have been devalued; this may lower levels of community pride, leading to behavioural changes that influence crime. Alternatively, introducing new technologies, such as white light/LEDs, in an area may signal increased investment in a community to local residents, which may increase community pride and a willingness to use, and to monitor, their neighbourhood, leading to a reduction in crime.

In summary, street light adaptation strategies may have different effects on two public health outcomes, casualties and crime. In light of a lack of evidence, we used the reduction of street lighting by local authorities in England and Wales as a natural experiment to examine whether it was associated with any changes in road traffic collisions and crime. The project was called the LANTERNS (Local Authority collaborators' National Evaluation of Reduced Night-time Streetlight) project.

## METHODS

We designed a controlled interrupted time series analysis to examine associations between reduced street lighting and road traffic collisions and crime, adjusting for regional trends. Analyses were conducted at road level for traffic collisions and at area level for crime. Analyses were based on the patterns of change in monthly counts of collisions and crimes within each street, or area.

### Data sources

**Street lighting**—all local authorities in England and Wales were invited to participate in the study (details of recruitment methods are reported elsewhere).<sup>3</sup> From local authorities who had made changes to street lighting provision at night, data were requested on the geographic location of each street lighting column, the change to lighting (eg, part-night lighting), and the date the change was introduced. All local authorities who provided usable data by October 2014 were included in the analysis.

**Traffic collisions**—data on traffic collisions were obtained from STATS19, the official dataset of collisions on public highways in the UK collected by the police. Data were obtained on the dates, times, geographical coordinates of collision locations, and severity of casualties for all collisions that occurred during the period 2000–2013.

**Crime**—data on crime were obtained from the *Police.uk* website from December 2010 (the earliest date for which the data are available) to December 2013. Data included type of crime, year, month, name of road where the crime occurred, and approximate geographical coordinates.

### Exposure variables

**Street lighting**—data were linked using a geographical information system (GIS) to a detailed road segment database derived

from the Ordnance Survey Mastermap Integrated Transport Network.<sup>12</sup> For each month between January 2000 and December 2013, road segments were categorised according to whether switch off, part-night lighting, dimming and white light had been implemented in the lighting columns along that segment. Where combinations of interventions had been implemented (eg, part-night lighting with white light), road segments were categorised as having both interventions. To facilitate area-level analyses, we also calculated the proportion of total kilometres of road in each area that had introduced switch off, part-night lighting, dimming and white light.

### Outcome variables

**Traffic collisions**—collisions recorded in STATS19 were classified as 'night-time' (occurring between sunset and sunrise) or 'day-time' (between sunrise and sunset) according to the time and date of the collision. For this, we obtained the daily timings of sunrise and sunset in each region of England and Wales between 1 January 2000 and 31 December 2013. Using data on injury severity, we classified each collision according to whether any casualties suffered a fatal or serious injury. A casualty is classified as fatal if the person dies within 30 days of the collision. A casualty is defined as serious if the person is admitted to hospital or has suffered fractures, concussion, internal injuries, crushing, non-friction burns, severe cuts and lacerations, or is in severe general shock requiring medical treatment. A GIS was used to link collisions to road segments using a combination of spatial overlay and analysis of the text descriptor of each road location. In brief, the algorithm assigned a collision to the nearest road segment of the type indicated in the STATS19 report. Collisions occurring over 50 m from a road segment of the appropriate type were excluded from analysis. We calculated counts of collisions in road segments for each month from January 2000 to December 2013.

**Crime**—to preserve victim anonymity, the publicly available *Police.uk* data only includes approximate geographical coordinates of offences, and does not detail the time of day of offences. A study of the spatial accuracy of the data suggests that it is very good for large areal units, such as census Middle Super Output Areas (MSOA), that contain around 7500 people,<sup>13</sup> but not for the postcode or street segment level. We therefore analysed crime at the MSOA level, assigning each offence to the relevant MSOA. We analysed offences most likely to occur during the evening or at night: burglary, theft of (or from) a vehicle, robbery, criminal damage, and violence, including sexual assault.<sup>14</sup> We calculated counts of each offence in MSOAs for each month from December 2010 to December 2013.

### Statistical methods

Our focus was to characterise the influence of changes in street lighting on collisions and crime after allowing for underlying trends over time. Analyses were based on the patterns of change in the monthly counts of collisions within each road segment, and in the monthly counts of crime within each MSOA. To control for confounding due to differences in areas chosen and not chosen for interventions, we analysed these road level (collision) and MSOA level (crime) counts as 'panel' studies, conditional on total counts in each road or MSOA, such that any of the factors that are constant over time (eg, road design) contribute no information to the analysis. Conditional Poisson regression models were used rather than standard Poisson models to allow variation in rates by road segment and MSOA without having to directly estimate a large number of nuisance parameters.<sup>15</sup> Further details of the models are given in web



appendix 1. We conducted sensitivity analyses by assuming a negative binomial, rather than Poisson model, by allowing for zero inflation and by fitting models without autoregression terms.

**Traffic collisions**—We estimated the association of each street lighting adaptation intervention with night-time collisions from a single model to avoid mutual confounding. To guard against bias due to changes concurrent with lighting interventions that impact on overall (ie, day and night) collisions, the data set included counts of daytime collisions and a binary variable indicating day/night. We estimated from our regression model the change in collision rate associated with each street lighting adaptation intervention during daytime as well as night-time, and the ratio of night-time and daytime changes. We consider this ‘daytime collision’ adjusted measure the most robust estimate of the change in night-time collisions following the lighting intervention. Models were adjusted for seasonal variation and temporal trends by fitting individual terms for year and month. Models were fitted for each region in England and Wales, and effect estimates were pooled in a fixed effects meta-analysis.

**Crime**—we estimated the association between changes in the proportion of total kilometres of road in each MSOA that had introduced each street lighting adaptation intervention, and counts of each criminal offence (and their aggregation), controlling for trends in crime over time. We fitted indicator variables for the number of months elapsed from the start of the study (ie, a step function for elapsed month, from December 2010). We fitted separate models for each police force in view of their different data collection systems and evidence for different background time patterns across these systems. We pooled effect estimates in a random effects meta-analysis. Given the large number of police forces and types of crime considered, we do not present forest plots of the meta-analyses in the main text, only the means for England and Wales.

## RESULTS

By October 2014, we had had direct contact with 125 (72%) of the 174 local authorities in England and Wales, resulting in data submissions from 71 local authorities of which 62 provided usable data (figure 1). Data for nine authorities were excluded due to missing information on dates of changes, and changes implemented after the end of the study. Local authorities from each region provided data. The participating local authorities were evenly distributed across deciles according to population density (persons per hectare), covered the range of deprivation levels as measured by the Index of Multiple Deprivation 2010, and covered each of the six urban–rural classifications of areas.

**Street lighting**—of the 62 local authorities with usable data, 5 (8%) had introduced switch off, 30 (48%) had introduced part-night lighting, 40 (65%) had introduced dimming, and 52 (84%) had introduced white light. The introduction of street lighting adaptation strategies increased steadily from 2009 (figure 2). By December 2013, the local authorities participating in this study had implemented white light on a total of 15 833 km of road (7% of total road km in the 62 participating local authorities); part-night lighting on 12 101 km of road (5%); dimming on 10 519 km of road (4%); and switch off on 946 km of road (0.4%). The proportions of total kilometres of road in each MSOA that had lights switched off ranged from 0% to 60% (median 0.03%; IQR 0.01–0.05%). For part-night lighting, the proportions ranged from 0 to 84% (median 0.2%; IQR 0.1–18%); for dimming, the proportions ranged from 0 to 93% (median 0.14%; IQR 0.07–5%); and for white light,

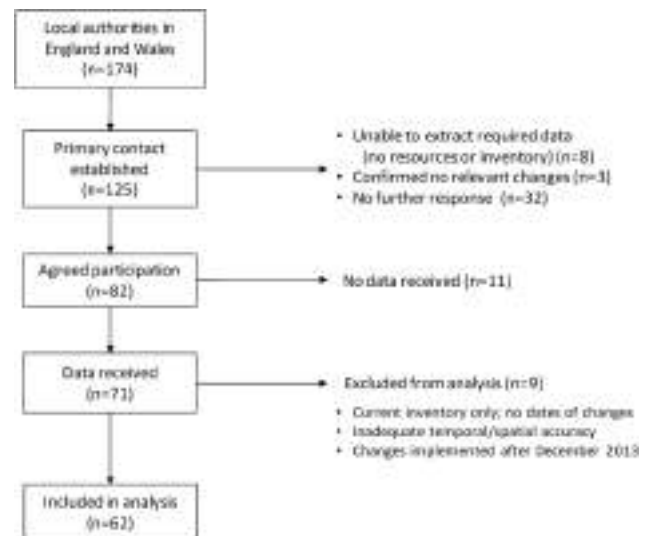


**Figure 1** Flow of local authority participants in the LANTERNS project.

the proportions ranged from 0 to 81% (median 1%; IQR 0.15–11%).

**Traffic collisions**—during 2000–2013 there were 859 935 collisions in the 62 local authorities included in the analysis; of these, 161 049 (19%) were night-time collisions; 153 442 (18%) collisions had resulted in a serious injury or fatality. Of the night-time collisions, 1202 (0.7%) occurred on roads along which switch off had been introduced by December 2013; 5670 (4%) were on roads with part-night lighting; 11 634 (7%) were on roads with dimming; and 12 423 (8%) were on roads with white light.

We found little evidence for any associations between street light adaptation strategies and day-adjusted night-time collision rates (figure 3). There was no evidence from any of the regional models, or the overall estimates, for an association between switch off (rate ratio (RR) 0.97; 95% CI 0.82 to 1.15), part-night lighting (RR 0.95; 95% CI 0.84 to 1.07); or dimming (RR 1.00; 95% CI 0.91 to 1.10). There was weak evidence in London for an association between the introduction of white light and increased night-time collisions (RR 1.30; 95% CI 1.03 to 1.65); however, the overall national estimate provides no evidence for such an association (RR 1.01; 95% CI 0.93 to 1.09).

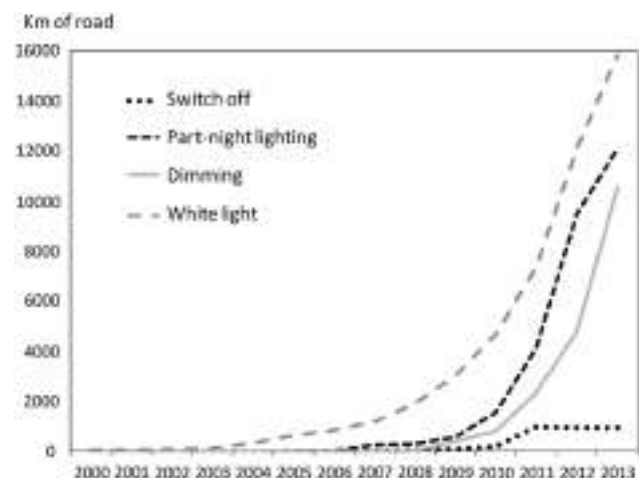


**Figure 2** Kilometres of road with lighting adaptation strategies implemented in participating local authorities.

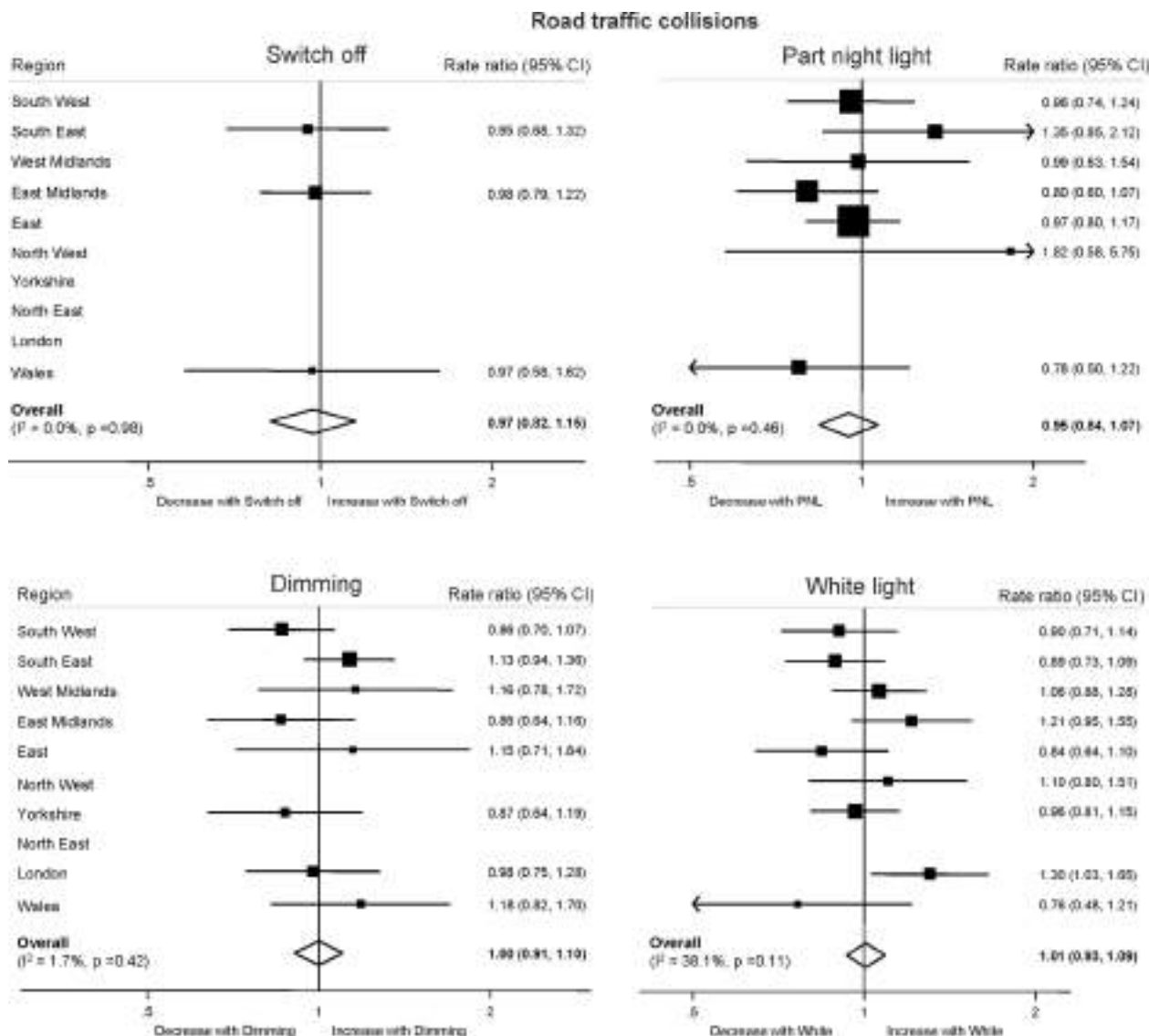


**Figure 3** Associations between street light adaptation strategies and night-time road traffic collisions.

Similarly, models estimating associations between street light adaptation strategies and collisions causing a serious injury or fatality found no evidence for associations with any lighting intervention (see web appendix 2).

**Crime**—across the 62 local authority areas there had been 581 837 burglaries; 475 657 thefts of or from a vehicle; 67 470 robberies; 486 367 criminal damage offences and 730 280 violence offences during the period December 2010 to December 2013.

Figure 4 shows the estimated mean associations between changes in the proportion of total kilometres of road in each MSOA that had introduced each street lighting adaptation intervention, and counts of each offence across England and Wales. The rate ratios indicate the expected change in crime if 100% of total kilometres of road in an area were to receive the lighting intervention.

There was no evidence from the overall estimates for an association between the aggregate count of crime and switch off (RR 0.11; 95% CI 0.01 to 2.75) or part-night lighting (RR 0.96; 95% CI 0.86 to 1.06). There was weak evidence for a reduction in the aggregate count of crime and dimming (RR 0.84; 95% CI 0.70 to 1.02), and white light (RR 0.89; 95% CI 0.77 to 1.03). We found

significant heterogeneity between the estimates at police force level (see web appendix 3); there was strong evidence for an association between part-night lighting, dimming and white light, and a decrease in crimes in some police forces, and strong evidence for an association between part-night lighting, dimming and white light, and an increase in crimes in others.

When specific offences were considered, the estimates provide suggestive evidence that part-night lighting may be associated with an increase in robbery (RR 1.48; 95% CI 0.99 to 2.21), and that dimming may be associated with a decrease in violence (RR 0.78; 95% CI 0.60 to 1.01). At the national level, we found consistency in the direction of the estimated associations between crime and dimming, with all point estimates indicating reductions in crime. There was similar consistency in the estimated associations with white light, all suggesting reductions in crime. Again, however, we found substantial statistical heterogeneity between estimates of associations between all lighting adaptations on all crime types at police force level (see web appendix 3).

Small differences were apparent in sensitivity analyses, but the results for collisions and crime were not materially different from the main results. We found no evidence for zero inflation.

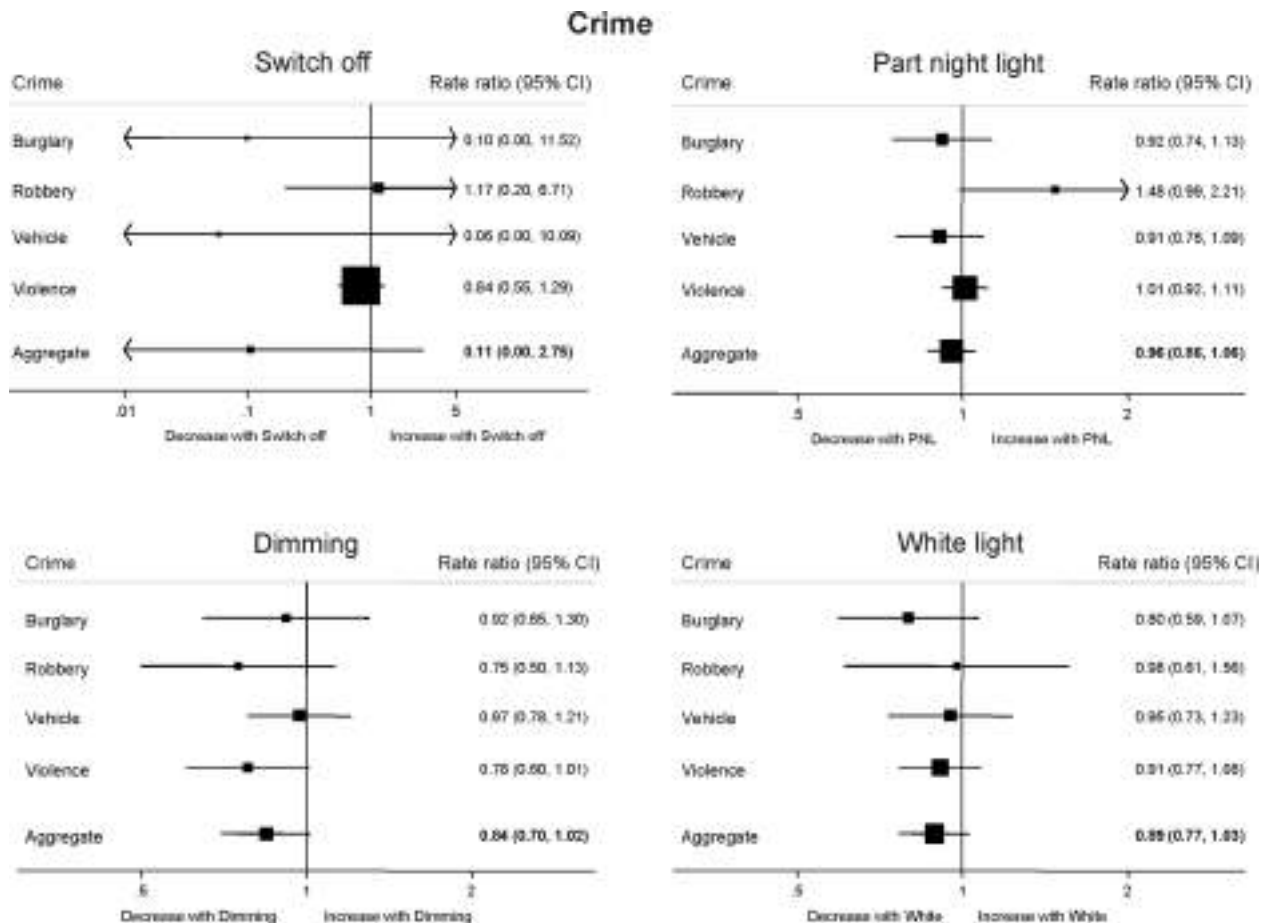


**Figure 4** Associations between street light adaptation strategies and crime.

## DISCUSSION

The results provide no evidence that switch off, part-night lighting, dimming, or white light adaptations to street lighting were associated with night-time traffic collisions. The results also provide no evidence that these lighting strategies are associated with an increase in crime at an area level. Results suggest that in the aggregate, dimming and white light regimes were associated with reductions in crime, though estimates were imprecise.

## Limitations

**Selection bias:** this study was able to obtain usable data on street lighting changes from 62 of 174 local authorities. It is possible that local authorities may have declined to participate because of expected or known increases in collisions or crime in their areas due to lighting changes. If changes in collisions or crime are greater in the non-participating authorities, our study may have underestimated the effects of reduced lighting on collisions and crime.

**Information bias:** our study used routine data sources on road traffic collisions and crime. These data sets have several limitations; in particular, they may be incomplete due to under-reporting of incidents. However, for under-reporting to affect the results of our analysis this would require differential changes over time in the recording of crime and collisions in the streets where lighting has been changed, compared with streets without changes to street lighting, which seems unlikely.

To address the potential for under-reporting to bias estimates of effect on collisions, we analysed separately those collisions where casualties were fatally or seriously injured, as these collisions are

more likely to be reported to the police. These analyses found no evidence for associations between street lighting changes and night-time collisions. We also analysed crimes that are more likely to be reported to the police (ie, burglary and vehicle theft reports are required for insurance claims). The estimated effects were not consistently larger for these two types of crime.

We were unable to specifically examine crime occurring at night using the *Police.uk* data. Our analyses were, however, limited to crimes that the crime survey of England and Wales suggests are more likely to occur in the evening or at night. It is unlikely that another data set would have been able to address this limitation, as the exact times of many offences (such as property or vehicle thefts) are unknown to victims. The *Police.uk* crime data have a further limitation: they are geographically obscured to protect the anonymity of victims. To address this, we analysed the data at an area level for which the spatial accuracy of the data is known to be good,<sup>13</sup> though this diminished statistical power.

**Confounding:** We did not take into account the potential impact of other road safety or crime prevention initiatives, such as improved road markings, policing interventions, or CCTV. If such measures have been introduced more often in streets where lighting has been changed than elsewhere, it is possible that some of the changes in crime in areas where lighting has been changed may be attributable to these other measures.

Despite the limitations of this study, we utilised two large publicly available data sets to provide evidence on the relationship between recent street lighting adaptation strategies, road traffic collisions and crime. Systematic reviews of the evidence on the effects of increased street lighting on road traffic collisions and

crime suggest relative reductions of 32% and 38%, respectively.<sup>10 11</sup> The current study showed CIs sufficiently narrow to exclude changes in collisions of such magnitude. The results for crime were highly heterogeneous and limited in power due to the need to aggregate to MSOA level, but the average effects estimated overall do not suggest any increase in crime at an area level with reduced lighting. Again, CIs were sufficiently narrow to exclude an increase in crime of such magnitude as may have been expected. The estimates for switch off, however, are imprecise because of the small number of areas in which switch off was implemented, and so should be treated with caution.

### Interpretation

Despite using 14 years of data on road traffic collisions in 62 local authorities, we found no convincing evidence for associations between street lighting adaptations and road traffic collisions. As we have no direct measures of the number of trips taken, or modes of travel before and after implementation of street lighting interventions, we cannot know whether this reflects reduced mobility or changes in mode (eg, from walking to car travel) in areas where either switch off or part-night lighting had been implemented. It is possible that the numbers of pedestrians, cyclists, motorcyclists and car drivers who travel within the streets where street lighting was reduced declined at the same time as the lighting was reduced, resulting in fewer collisions in those streets. If so, any increase in hazards to road users due to lower lighting conditions may have been obscured by a reduction in numbers of people exposed to road injury risk at night. However, qualitative and survey evidence<sup>3 16</sup> suggests that changes to mobility overall, and mode choice in areas affected were likely to be minimal.

This study did, however, suggest an association between some street lighting adaptations and crime. While there was significant statistical heterogeneity in effects estimated at police force level, results overall were suggestive of an association between dimming and reductions in crime, particularly for violent crime. These results may lend support to the hypothesis linking lower levels of visibility to difficulties in identifying 'suitable' targets from those on the street at night. Results also suggested an association between white light and reductions in crime, particularly burglary, which may provide support for the credibility of mechanisms linking increased visibility or increased investment in local communities to reductions in crime. If reduced street lighting displaces pedestrian activity to better-lit streets, this might reduce the risks of victimisation and interpersonal crime on those streets, and increase guardianship on the better-lit streets. Different causal mechanisms may apply in different contexts, and these need to be assessed by further research.

This study does not support concerns around impacts of switch-off, part-night lighting, dimming and white light on crime and road safety. Local authorities informally (and sometimes formally) assess risks when adapting street lighting in local areas, drawing on local experiments and trials,<sup>17</sup> and national and professional guidance on the selection of lighting classes.<sup>1 2</sup> Considerations of the appropriate 'lighting class' for roads reflect a number of factors, including speed limits, traffic volume, composition of motorised versus non-motorised traffic, junction density, presence of parked vehicles, ambient luminosity (lighting from other sources such as shops), and how easy the road is to navigate.<sup>1</sup> Results from this study suggest that when risks are carefully considered, local authorities can safely reduce street lighting saving both costs and energy using switch off, part-night lighting, dimming, and white light strategies without necessarily impacting negatively upon road traffic collisions and crime. The participating local authorities

included a good range of communities in terms of population density, geographic location, and economic resources. Our results may, therefore, be generalisable to other communities considering street lighting reduction strategies.

This study was able to shed light on the impact of reduced street lighting at night. More research is needed on how different lighting regimes affect opportunities for crime and crime prevention, and on other public health impacts of changes in light at night, given the suggestive evidence that artificial light may be linked to health outcomes as diverse as obesity,<sup>7</sup> sleep and cancer.<sup>8</sup>

### What is already known on this subject

- ▶ There is evidence that introducing street lighting at night is associated with reductions in road traffic crashes and crime.
- ▶ Many local authorities in England and Wales are reducing street lighting at night to save energy costs and reduce carbon emissions.

### What this study adds

- ▶ There is no evidence that reduced street lighting is associated with increases in road traffic collisions or crime.
- ▶ Dimming the amount of light or switching to white light/LEDs may reduce crime in an area.
- ▶ When risks are carefully considered, local authorities can safely reduce street lighting, saving energy costs and reducing carbon emissions, without impacting negatively on traffic collisions and crime.

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**Contributors** All authors contributed to the design of the study and the writing of the manuscript. RS, CP and LT collected, managed and linked the GIS and outcome data. CG provided advice on data management. RS, BA and PE conducted the statistical analysis. SJ advised on analysis of crime data.

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## Research

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One contribution of 14 to a theme issue 'The biological impacts of artificial light at night: from molecules to communities'.

**Subject Areas:**

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**Keywords:**

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## Physical behaviour of anthropogenic light propagation into the nocturnal environment

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Propagation of artificial light at night (ALAN) in the environment is now known to have non negligible consequences on fauna, flora and human health. These consequences depend on light levels and their spectral power distributions, which in turn rely on the efficiency of various physical processes involved in the radiative transfer of this light into the atmosphere and its interactions with the built and natural environment. ALAN can affect the living organisms by direct lighting and indirect lighting (scattered by the sky and clouds and/or reflected by local surfaces). This paper mainly focuses on the behaviour of the indirect light scattered under clear sky conditions. Various interaction processes between anthropogenic light sources and the natural environment are discussed. This work mostly relies on a sensitivity analysis conducted with the light pollution radiative transfer model, Illumina (Aubé *et al.* 2005 Light pollution modelling and detection in a heterogeneous environment: toward a night-time aerosol optical depth retrieval method. In *Proc. SPIE* 2005, vol. 5890, San Diego, California, USA). More specifically, the impact of (i) the molecular and aerosol scattering and absorption, (ii) the second order of scattering, (iii) the topography and obstacle blocking, (iv) the ground reflectance and (v) the spectrum of light devices and their angular emission functions are examined. This analysis considers different behaviour as a function of the distance from the city centre, along with different zenith viewing angles in the principal plane.

## 1. Introduction

The first studies regarding light pollution focused on its impact on the starry sky. The astrophysical research community began these studies in the 1970s. In recent years, however, the study of light pollution was updated due to the varied effects on the integrity of the nocturnal environment being discovered. These effects affect both the balance of the natural environment (flora and fauna) [1–10] and the social and economic activities of humans [11–15]. Light pollution even has significant impact on human health [16–18]. In order to study the consequences of artificial light at night (ALAN) on fauna, flora and human health, an understanding of how it depends on light levels and spectral power distributions is essential. The aim of this paper is to find relationships between the physical properties of the environment and the production of the anthropogenic spectral radiance of the night sky. The relationships will be obtained through one specific empirical experiment but mostly by using a light pollution radiative transfer model. A simple modelling scenario is suggested to achieve this goal. This scenario comprises a circular city with constant properties together with small-scale obstacles and a mountain outside the city.

To be able to characterize the relationship between ALAN and its impacts on biological organisms, one must first be able to understand the physics of its propagation. This understanding is usually conducted both by field measurements and by a theoretical approach that exploits the numerical modelling. The interaction of ALAN with the environment shows an extremely complex and nonlinear behaviour, which cannot be analytically solved so far. To overcome this limitation, several numerical models of radiative transfer have been developed in recent

years [19–23]. These new developments were made possible thanks to the increasing availability of high-performance computing resources, as well as to the availability of geographical datasets, such as night-time satellite data. Such datasets greatly simplify the production of inputs to model over large territories.

Multiple variables that affect the propagation of light pollution in the environment include:

- (1) The optical properties of the atmosphere that involve the behaviour of the scattering and absorption of molecules, as well as those caused by aerosols. Some atmospheric constituents, such as water vapour, ozone, aerosols and CO<sub>2</sub>, show significant spatial and temporal variability, which complicate the propagation of anthropogenic light in the atmosphere. For example, a greater presence of weakly absorbing aerosols will have the effect of increasing the scattering probability of the atmosphere which fosters a greater level of radiance from the sky near the light sources. At the same time, this will increase the attenuation of light over long distances for observers located away from sources;
- (2) The spectral reflectance properties of the ground;
- (3) The presence of masking by terrain and obstacles (mountains, trees, buildings);
- (4) The characteristics of lighting devices (spectral power distributions, angular emission pattern (also known as light output pattern (LOP) function), spatial distribution of lighting power on the territory).

Light pollution can reach the environmental elements via three main paths: (i) direct illumination, (ii) scattered light by cloud cover and (iii) scattered light from a clear sky. Scattered light from a clear sky will be main topic for this paper. This complex process is prevalent in cases where there are long distances between the sources and the environment, but the process is also present for short distances when the direct illumination is blocked by obstacles or by the topography (i.e. in shadows as in dense canopies). Before discussing in more depth the scattered light from a clear sky process, let us introduce general considerations about the direct illumination and about light scattered by cloud cover.

Direct illumination generally has the highest light intensity. In that case, the light leaves the lighting device and hits the surface after very low alteration. The particles between the surface and the source scatter and absorb light but, in most cases, these processes are negligible compared with the intensity of the radiation and also because of the short optical paths. For example, in an urban environment, the mean free path of light to a surface is of the order of tens to hundreds of metres. The case of direct illumination is very simple to understand because it only involves geometrical effects, like the shape of the LOP, the source–surface distance and the angles. An estimation of direct lighting can be made with lighting simulation software (e.g. AGI32 or Radiance). For this reason, this process will not be discussed in this paper.

The second largest contributor is the scattering of artificial light by cloud cover. The importance of scattering by clouds in comparison with the scattering from the clear atmosphere is generally many times greater for sites near sources, such as urban and suburban environments. In the specific case of the Cabau Experimental Site for Atmospheric Research (CESAR), located in the western part of the Netherlands, Lolkema *et al.* [24] have determined that the night sky luminance can increase

by a factor of 5–9 compared with the clear sky conditions. Similarly, Kyba *et al.* [25] studied the effect of cloud fraction on the sky's brightness using Sky Quality Meter (SQM) measurements for urban and rural locations. According to their results, an overcast sky in an urban environment increases the value of the sky brightness by a factor of approximately 10, while in the rural environment this amplification factor is smaller. Very far from sources, the presence of clouds generally obscures the sky, hiding the natural radiance of the starry night. Our group observed this situation at the Mont-Mégantic International Dark Sky Reserve (Canada). Similar observations can be made at many world-class astronomical observatories. Although the process of light scattering by clouds is of considerable importance for the study of light pollution, it will not be specifically dealt with in this paper. The model Illumina does not yet allow this calculation. The implementation of clouds in the model is in progress, but has neither been completed nor validated.

## 2. Methodology

The methodology mostly involves a modelling sensitivity analysis using simplified properties of the geographical domain in order to infer the effect of the various physical variables involved. In one exceptional case, a combination of empirical and modelling methods was used to determine the relationship between the night sky radiance and the aerosol optical depth (AOD; e.g. §3*a*).

### (a) Model description

The radiative transfer model used for this study is called Illumina, v. 2 [19]. This model is distributed under Gnu Public License and is available for download from Google Code [26]. The main difference between v. 1 and v. 2 is that a statistical optimization has been added for the selection of ground-level pixels and gridded three-dimensional air elements (voxels) along the line of sight in order to reduce the computing time by a factor of approximately 50. Basically, Illumina acts as a ray-tracing software where a set of photons is thrown from light fixtures located above the ground-level pixels and then reaches the observer's field of view (FOV) following four different light paths: (i) first scattering by molecules and aerosols in voxels of the line of sight ( $I_1$ ), (ii) first scattering after Lambertian reflection on the ground ( $I_{r1}$ ), (iii) a second scattering in a voxel of the line of sight after a first scattering from atmospheric voxels contained in a surrounding volume ( $I_2$ ), and (iv) the same path as (iii) but after reflection on the ground pixel ( $I_{r2}$ ). The resulting approximation of the light spectral intensity ( $\text{W sr}^{-1} \text{nm}^{-1}$ )  $I_{\text{no}}$  is expressed in equation (2.1) and illustrated in figure 1*a*.

$$I_{\text{no}} \approx I_1 + I_{r1} + I_2 + I_{r2}. \quad (2.1)$$

The total spectral flux ( $\text{W nm}^{-1}$ ) as perceived by a simulated observer is modelled by equation (2.2):

$$\Phi_m = \sum_n I_{\text{no}} \Omega_{\text{no}} \frac{\Omega_{\text{FOV}}}{\Omega_{\text{on}}}. \quad (2.2)$$

The different solid angles involved in equation (2.2) are illustrated in figure 1*b*.

The scattering processes toward the observer and the extinction by aerosols (scattering and absorption) and molecules (scattering only) are computed for all the light paths considered. Illumina computes the first and second orders of scattering of light. The second order of scattering may have a significant impact on sky radiances, especially when the observer is far from the cities [27].

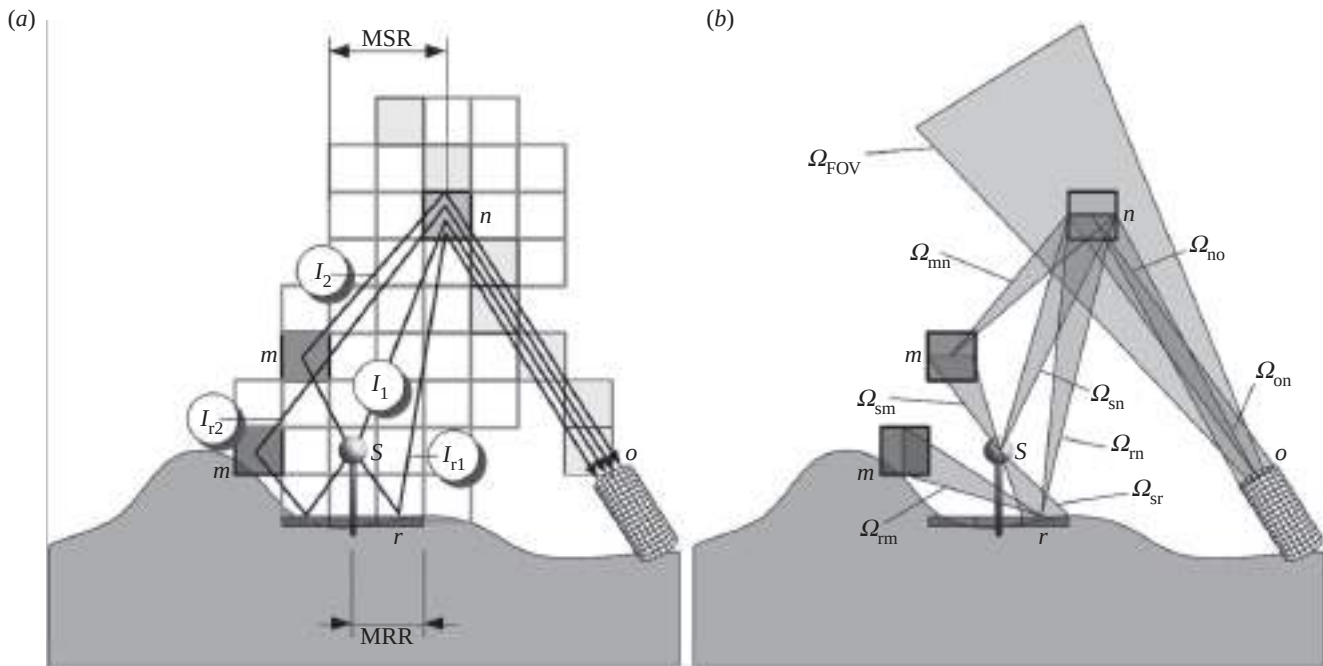


**Figure 1.** Modelling geometry and most important contributions to the flux perceived by an observer. MRR, maximum reflection radius which is equivalent to the average distance between obstacles; MSR, maximum radius for second order of scattering computation.

The case of the propagation of light pollution is, in fact, very different from the well-studied propagation of sunlight because the sources of light pollution are spread on a large surface in comparison with the distance from the observer. The importance of the second order of scattering in that case may be understood by the fact that the first scattering dome of light acts as an extended source for the second scattering process, and thus its reduction as a function of the distance is less steep when compared with point-like sources. In addition to the explicit treatment of the second order of scattering, the main advantage of Illumina is its gridded based concept, allowing for change to the light flux power, the spectrum, the LOP, the lamp height, the ground reflectance and the topography for each pixel independently. It is then possible to model complex situations as they appear in real cities and environments.

Generally, many gridded datasets are taken from satellite remote sensing data (MODIS, DMSP-OLS, SRTM). But there are still some limitations, especially those generated by the spatial uniformity of some variables. Indeed, the AOD, relative humidity, ground-level atmospheric pressure, obstacle height and the typical distance between obstacles are spatially uniform in the model. The chemical composition of the aerosol content and the size distributions are determined by using the complex refractive index and bimodal lognormal size distributions suggested by Shettle & Fenn [28]. Their corresponding optical impacts were calculated with a Mie theory code for spherical particles, originally developed by Evans [29]. The aerosol composition may be changed according to the geographical particularities of the modelling experiment or to account for specific events, like important biomass burning or Saharan sand storms. Many standard aerosol models are available (maritime, urban, rural), with each of them defining the chemical composition, size distribution and hygroscopic properties of aerosols, which have been translated in scattering and absorption cross sections, as well as in scattering phase functions for a variety of ambient relative humidities.

### (b) Standard modelling parameters set used

In this specific study, some simplifications of the geographical properties of the modelling domain are made as shown in figure 2. Actually, a hypothetical circular shaped city with a 10 km radius

and constant lamp properties is considered. Ground reflectance was made uniform over the modelling domain. The ground elevation was set to zero for most of the grid points, except for a 2000 m high three-dimensional Gaussian-shaped mountain located 30 km eastward from the city centre. The full width half maximum used for the Gaussian function was 10 km. The city has a small slope. The westernmost pixel of the city is elevated by only 1 m, while the elevation is gradually increasing to a height of 164 m at the easternmost pixel. This elevation change occurs over a distance of 20 km (equivalent to a mean slope of approx. 0.8%). The spatial resolution used for this study is 1 km per pixel, and the domain covers a surface of  $301 \times 301$  km, centred on the city. Light flux inside the city is set to 1000 W per pixel for each of the key spectral lines used. The idea was to study the spectral behaviour of light pollution while excluding the fact that the spectral line fluxes vary according to the mix of lamps installed. The five key spectral lines used are: 436, 498, 546, 569 and 616 nm. Each line corresponds to a common line for high pressure sodium, for metal halide, or for mercury vapour lamps. The spectral lines have been selected in such a way that they do not interfere with any important molecular absorption feature, and are only slightly impacted by the Fraunhofer and auroral lines.

The reference frame and set of standard parameters were defined in order to be able to efficiently compare any variation of a given variable. The reference frame is summarized in table 1. Note that the averaged distance between obstacles and averaged obstacle height has been determined from the average distance between buildings facades and average building height in typical European city centres. For the suburbs, the distance must be increased and the building height decreased, but as of now Illumina considers this distance as a constant value all over the modelling domain. In a future version, one may expect correction of this limitation.

To infer the impact of each identified variable, a set of values for each variable was defined, each combination corresponding to a distinct model computation. The set of values is given in table 2. This set resulted in 163 800 different calculations that needed to be solved. Calculations were made with the supercomputer Mammouth serial II, an infrastructure maintained by Compute Canada. On average, it requires a couple of weeks to complete the computations for approximately 1000 computing nodes using this equipment.

**Table 1.** Standard parameter set used as reference.

| parameter name                     | value | units |
|------------------------------------|-------|-------|
| aerosol model – Urban              |       |       |
| relative humidity                  | 70    | %     |
| ground-level pressure              | 101.3 | kPa   |
| mesh size                          | 1     | km    |
| aerosol optical depth              | 0.1   |       |
| ground reflectance                 | 0.1   |       |
| light fixture model – Cobrahead    |       |       |
| lamp height relative to ground     | 7     | m     |
| sub-grid obstacle height           | 10    | m     |
| average distance between obstacles | 15    | m     |
| reference wavelength               | 569   | nm    |
| distance from city centre          | 0     | km    |
| zenith angle                       | 0     | deg   |

### 3. Results and discussion

#### (a) Sky radiance as a function of aerosol loading

Very few studies have inferred the dependence of the sky brightness upon aerosol loading, but a modelling experiment conducted by Tian *et al.* [30] showed that for a constant light source the brightness of anthropogenic light sources observed from a distance (here, approx. 50 km) is strongly dependent on AOD with a negative slope. According to Tian *et al.*, for sites located in the suburbs or cities, the sky brightness becomes less dependent on AOD.

Pun & So [31] tried to find experimentally a relationship between the sky brightness and aerosol atmospheric content by comparing a huge database of SQM measurements taken around Hong Kong with ground-level particulate (PM<sub>2.5</sub>) concentration measurements. Note that there is a strong correlation between AOD measurements and ground-level PM<sub>2.5</sub> concentrations [32]. The data acquired by Pun & So do not show clear relationship between aerosol loading and sky brightness ( $R^2 = 0.0667$  with a very low slope). This low dependency is consistent with the results of Tian *et al.* [30] for cities and suburbs.

During the winter of 2009, I tried to find the AOD versus sky brightness relationship in Sherbrooke, Canada, by using the spectrometer for aerosol night detection (SAND) [33]. The methodology used compared night radiance of the 569 nm sodium line with AERONET AOD measurement (CARTEL site) which was the nearest in time (less than 6 h) [34]. Only the AERONET data which were stable were considered, and a first-order correction to the SAND data was applied to reduce the impact of temporal variations in snow cover during this period. This correction was made to account for the major impact of snow reflection on the sky radiance readings. In fact, the radiance was divided by the snow cover fraction. The SAND and the AERONET sunphotometer were located in the suburbs of Sherbrooke city and thus, according to Tian *et al.* [30], one must expect a weak relationship between sky radiance and AOD. This relationship, however, showed a significant increase in the AOD range 0–0.1, followed by a slow decrease. Tian *et al.*'s theoretical result is consistent with our observations presented in

figure 3. The grey curve on that figure is a lognormal fit of the data, which is only valid for that specific case.

Figure 4 shows the calculated distance relationship of the radiance at 569 nm obtained with the Illumina model. The relationship is steep (note the logarithmic vertical scale) and it gets steeper when the zenith angle decreases. Note that the curve for  $z = 0$  corresponds to the standard parameter set described in table 1. A power law was fitted on the data for distance larger than a city radius; a decreasing function with  $r^{-3.33}$  ( $R^2 = 0.9933$ ) was obtained. Figure 5 clearly shows how the ratio of the sky radiance at AOD = 1.0 (polluted atmosphere) over the sky radiance at AOD = 0.1 (clear atmosphere) is close to unity (between 0.96 and 1.10) inside the city but decreases rapidly outside city limits with increase of the distance from the city centre. As an example, at 50 km from the city centre the ratio is about 0.023. In other words, the zenith radiance is 44× larger with AOD = 0.1 compared with AOD = 1.0. This behaviour can be understood by the mechanism of extinction that reduces the light reaching the zenith direction when the observer is far from the source.

#### (b) Impact of second order of scattering and small obstacles

This study shows that the importance of the second order of scattering is highly dependent on the presence of blocking obstacles that are taller than light fixtures. This is consistent with the idea that obstacles block the light reaching the zenith line of sight in a remote site. Indeed, the light is more likely to reach this line of sight after one scattering process than it is directly. Figures 6 and 7 show, respectively, how the percentage contribution of the second order of scattering to the radiance varies with distance for AOD = 0.1 and AOD = 1.0. The curve with the black squares in figure 6 corresponds to our standard parameter set (table 1). Note that for both figures 6 and 7, the cases without obstacles and with obstacles lower than the light fixtures show very similar behaviour.

For low aerosol loadings (AOD = 0.1), the contribution of the second order of scattering is generally lower inside the city perimeter (approx. 7% with obstacles), but this percentage increases rapidly when exiting the city. The maximum contribution of the second order of scattering is obtained near the city limit, where it can reach 38% without the blocking effect generated by obstacles. By adding obstacles that are taller than light fixtures, this contribution drops to 14%. In any case, the contribution of the second order of scattering is not negligible and must be taken into consideration. When the AOD rises, the percentage of the second order of scattering next to the city limits increases (compare figure 7 with figure 6). In figure 7, the percentages obtained are 62% without obstacles taller than light fixtures, and 32% with obstacles taller than light fixtures. The importance of the second order of scattering decreases more rapidly with distance for highly polluted atmospheres.

Luginbuhl *et al.* [21] showed that omitting the effect of light blocking by objects, such as buildings and vegetation, could lead to an overestimation of the sky brightness by a factor of more than two. This discrepancy is more important for larger zenith angles. In their study, they tried two methods to correct for obstacle blocking: the first one was to define new upward intensity distributions with the help



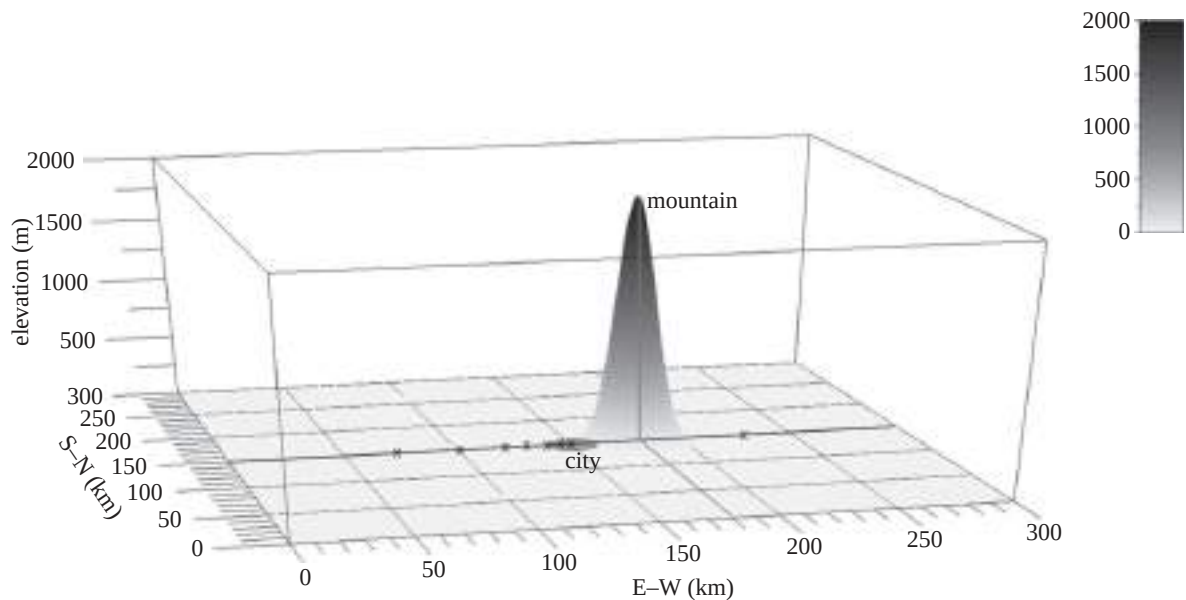


**Figure 2.** Three-dimensional representation of model elevation and of lighted area. The Gaussian shape is a mountain of 2000 m elevation; the grey disc centred at (150,150) is a city 10 km in radius. The simulated observers are marked by black crosses in the E–W direction.

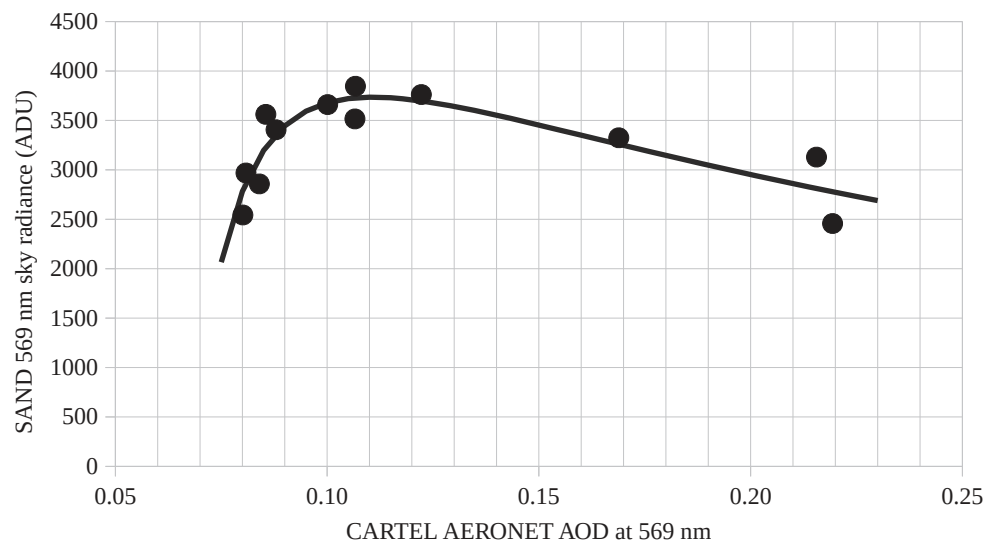


**Figure 3.** Relationship between the sky radiance in the 569 nm sodium line, as measured with the SAND and with the AERONET sunphotometer (CARTEL site) for Sherbrooke, Canada, during March 2009. SAND data are reported in analogue to digital units (ADU) and were determined by the surface of a Gaussian fit of the spectral line.

**Table 2.** Parameters used for sensitivity analysis.

| parameter name             | no. values | set of values                                         | units |
|----------------------------|------------|-------------------------------------------------------|-------|
| aerosol optical depth      | 5          | 0.05, 0.1, 0.2, 0.5, 1.0                              | —     |
| ground reflectance         | 3          | 0.1, 0.2, 0.8                                         | —     |
| light fixture model        | 2          | Cobrahead, Helios                                     | —     |
| sub-grid obstacle height   | 3          | 0, 5, 10                                              | m     |
| reference wavelength       | 5          | 436, 498, 546, 569, 616                               | nm    |
| distance from city centre  | 13         | −80, −50, −30, −20, −10, −5, 0, 5, 10, 20, 30, 50, 80 | km    |
| zenith angle               | 7          | 0, 30, 50, 60, 70, 75, 85                             | °     |
| azimuth angle              | 2          | 90, 270                                               | °     |
| second order of scattering | 2          | on, off                                               | —     |



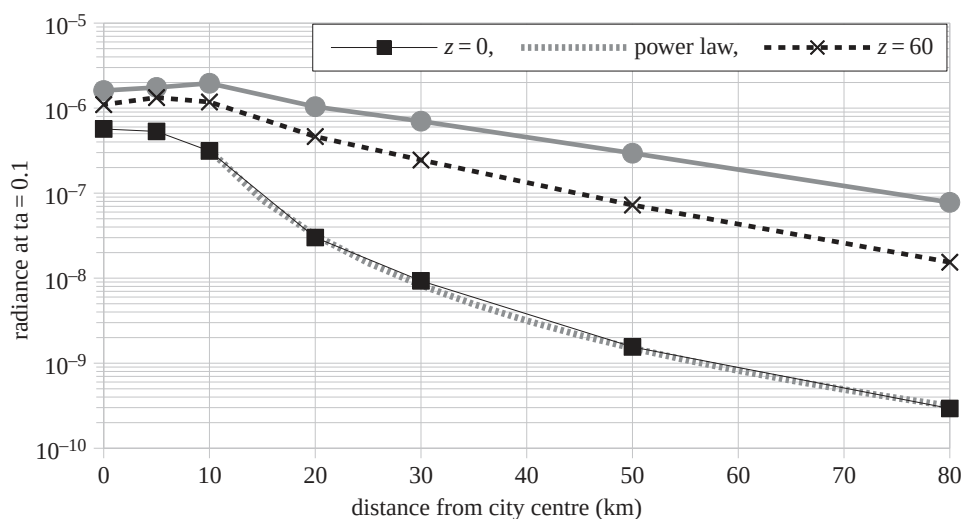


**Figure 4.** Distance relationship of 569 nm sky radiance as a function of distance from the city centre for three zenith angles with AOD = 0.1 as given by the model results.

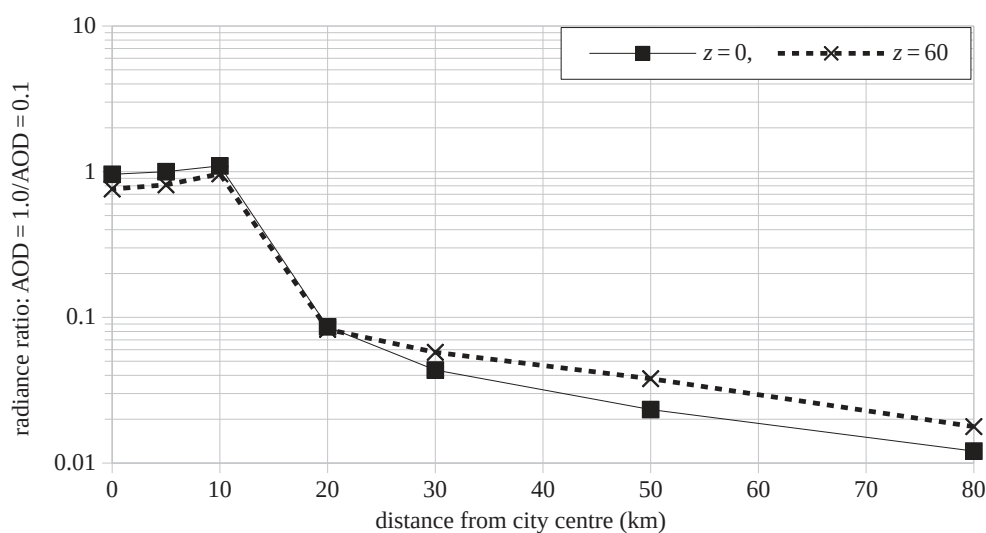


**Figure 5.** Ratio of 569 nm sky radiance with AOD = 1.0 over sky radiance with AOD = 0.1 as a function of distance from the city centre.

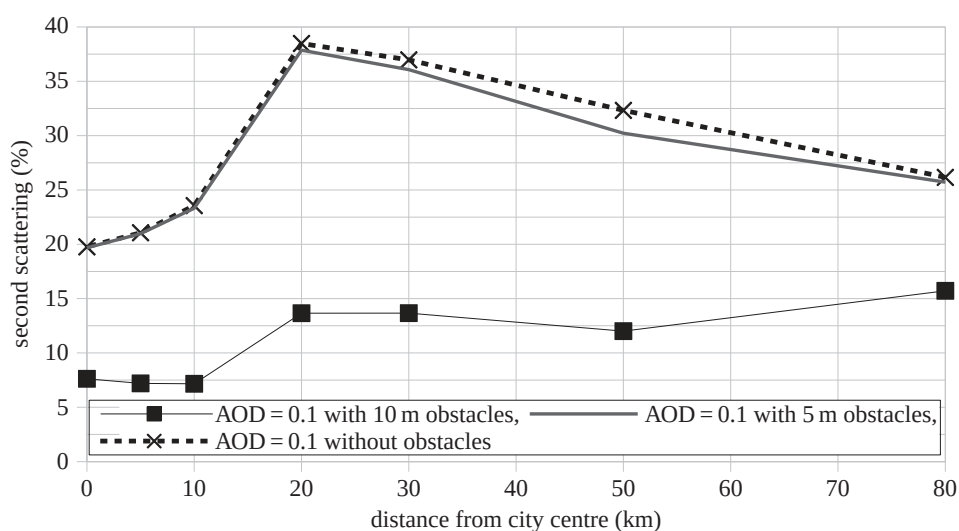


**Figure 6.** Contribution of the second order of scattering to total radiance as a function of distance from the city centre with AOD = 0.1 (clear).

of lighting simulation software, and the second method was to consider blocking as a process of extinction and as a function of distance (air mass).

As part of this study, the relative importance of the presence of obstacle blocking for AOD = 0.1 and AOD = 1.0 as a function of the distance from the city centre for the zenith

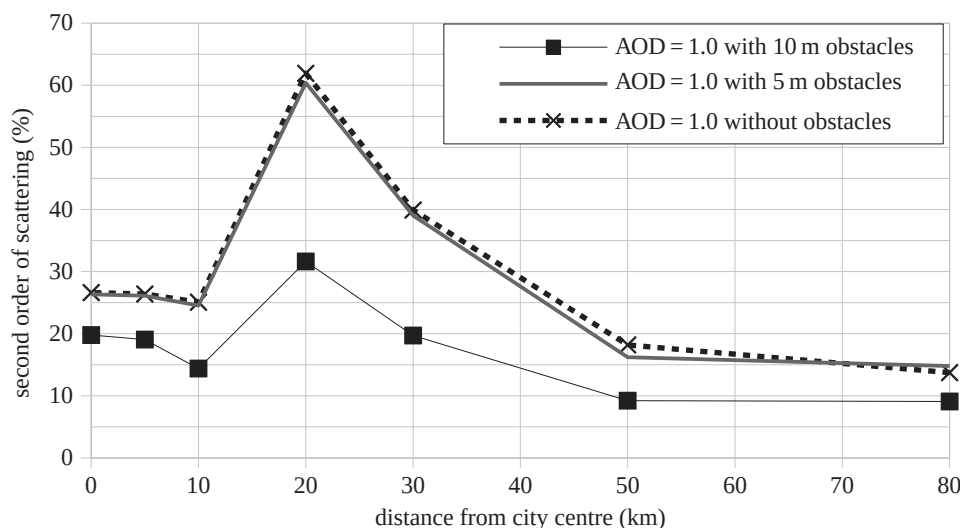


**Figure 7.** Contribution of the second order of scattering to total radiance as a function of distance from the city centre with AOD = 1.0 (polluted).

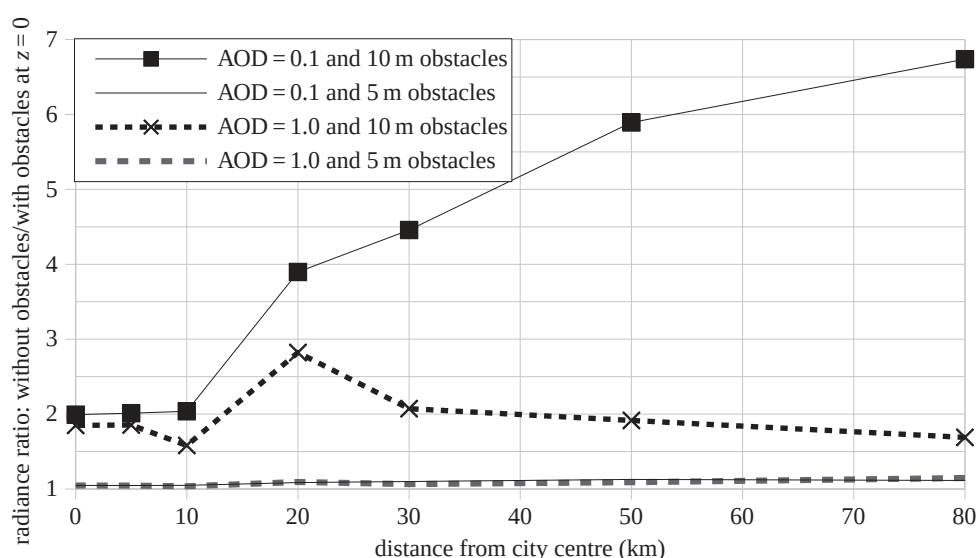


**Figure 8.** Ratio of zenith radiance without obstacles over zenith radiance with obstacles as a function of distance from the city centre.

radiance was inferred. Two obstacle heights were tested: 5 m and 10 m which were, respectively, smaller and taller than light fixtures (7 m). This experiment is illustrated in figure 8 which shows that inside the city perimeter the radiance without obstacles is almost twice the radiance with the obstacles when these are taller than the light fixtures. This result is consistent with the findings of Lughinbuhl *et al.* [21]. When obstacles are smaller than the light fixtures, their impact is very low (a ratio slightly above unity is observed). This latter case corresponds to most suburban regions. At AOD = 0.1 (figure 8, black squares), the radiance without obstacles rapidly increases outside the city compared with the radiance with obstacles taller than the light fixtures, and is still increasing 80 km from the city centre. When AOD = 1.0 (dotted line), the ratio without/with obstacles is maximal when exiting the city, and then decreases with distance, meaning that obstacles are many times more efficient in reducing sky brightness far from cities under a clear atmosphere.

Figures 9 and 10 show, respectively, the impact of having tall and small obstacles for various zenith angles at 30 km from the city centre for an AOD of 0.1 and 1.0. The case without obstacles at AOD = 0.1 (figure 9, dotted curve) is very similar to Garstang's [35] results. Garstang's data are plotted as grey

circles in figure 9; his original data were normalized to equal data at  $z = 0$  without obstacles because of the different light power per unit of ground elements used. In Garstang's calculations, Denver was assimilated as a circular city of 15 km radius and the results are for a distance of 40 km from the city centre, both of which are different from our standard parameter set ( $r = 10$  km and  $d = 30$  km), and thus one should be careful with this comparison. Illumina is, however, in good agreement with Garstang's model between  $z = -30^\circ$  and  $z = 40^\circ$ . Garstang's calculations show lower values of the sky radiance at large zenith angles. This can be explained, in part, by the difference in LOP used by Garstang who employed a much greater upward light output ratio (ULOR) of 15% compared with the LOPs used in this study which have ULOR = 1% (Helios) and ULOR = 7% (Cobrahead). A larger ULOR produces less variation at  $z = 0$  compared with high zenith angle radiances (see figure 12 below).

The first feature of the angular dependence of figure 9 is that, under a standard parameter set, the minimum radiance is obtained at reverse angles near the zenith. But the most striking feature is the inflection of the curve at high reverse zenith angles ( $z \leq -50^\circ$ ). Note that when  $z > 0$ , the observer looks toward the city (forward angles). Without obstacles,

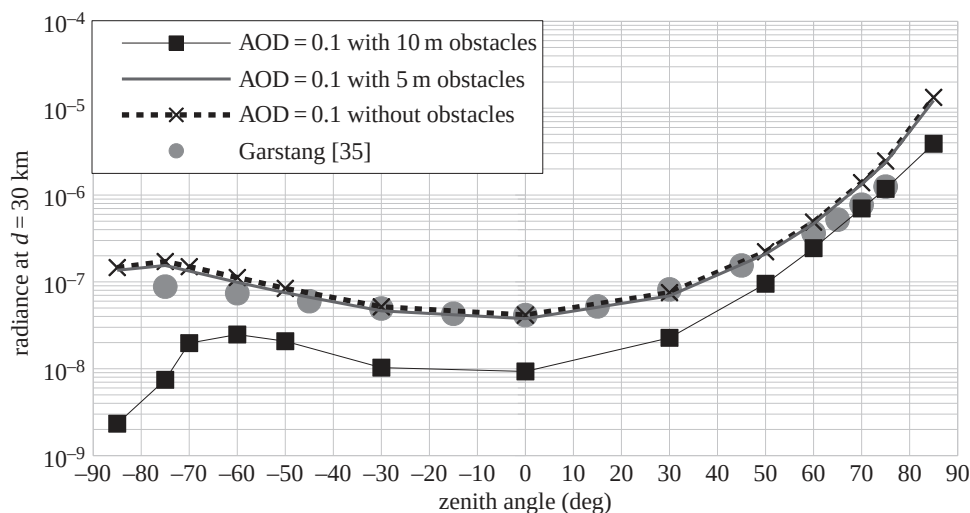


**Figure 9.** 569 nm sky radiance with AOD = 0.1 as a function of the zenith angle at 30 km from the city centre.

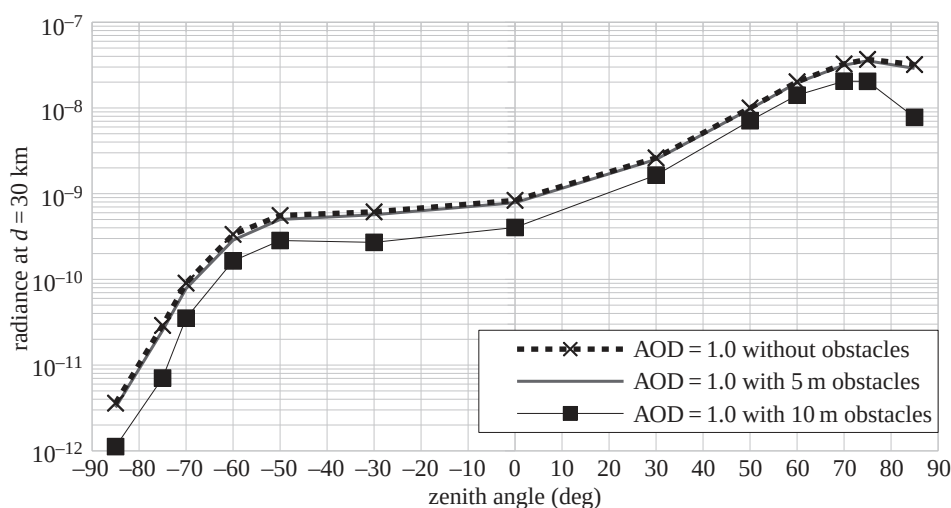


**Figure 10.** 569 nm sky radiance with AOD = 1.0 as a function of the zenith angle at 30 km from the city centre.

this inflection is small, but occurs around  $z = -75^\circ$ . With the obstacles, the inflection occurs at  $z = -60^\circ$  and is more important. This inflection is caused, in a large part, by the blocking of light by obstacles. According to the height and distance between obstacles that were used (10 m and 15 m, respectively), the upward light with  $|z| > 57^\circ$  does not reach the upper layers of the atmosphere at 30 km from city centre, hence reducing the sky's radiance. In addition, a significant part of the origin of the inflection is explained by the extinction of light that increases with increasing zenith angles. Indeed, if you look at figure 10 (AOD = 1.0), the inflection in the curve is more prominent than in figure 9 (AOD = 0.1), and it also occurs toward the city (at  $z = 75^\circ$ ). The relative importance of the second order of scattering coincides with the inflection in the curve (as shown in figure 11), but actually this feature is probably a consequence of the blocking of a part of the direct upward light by obstacles taller than light fixtures. Basically to have obstacles taller than light fixtures is more or less equivalent to a reduction of the net ULOR of the lamp. Note that in figure 9, when the obstacles are smaller than light fixtures, the inflection almost vanished. Also, figure 15 below, which shows the impact of changing the ULOR of the lamps,

indicates that the inflection is more important when the ULOR decreases.

### (c) Impact of light output pattern

This section addresses the impact of the angular distribution of light exiting the light fixture for obstacles taller and smaller than the light fixtures. As has been widely recognized by the dark sky protection community, the ULOR is of critical importance for generation of anthropogenic sky brightness. The fraction of light travelling near the horizon has also been historically identified as having a significant impact on sky brightness, especially for remote observers. Many of these concerns were identified with simplified models that had a very basic implementation of the second order of scattering. Moreover, the models did not account for blocking by obstacles or topography.

In 2007, Aubé [27] showed that light travelling near a horizon was not as critical as previously thought. Luginbuhl *et al.* [21] later confirmed this assertion. In 2011, Falchi [36] found that direct light (i.e. ULOR) was the main contributor to the zenith artificial sky brightness, at least for the sampled sites and that direct light contributes 75% of the

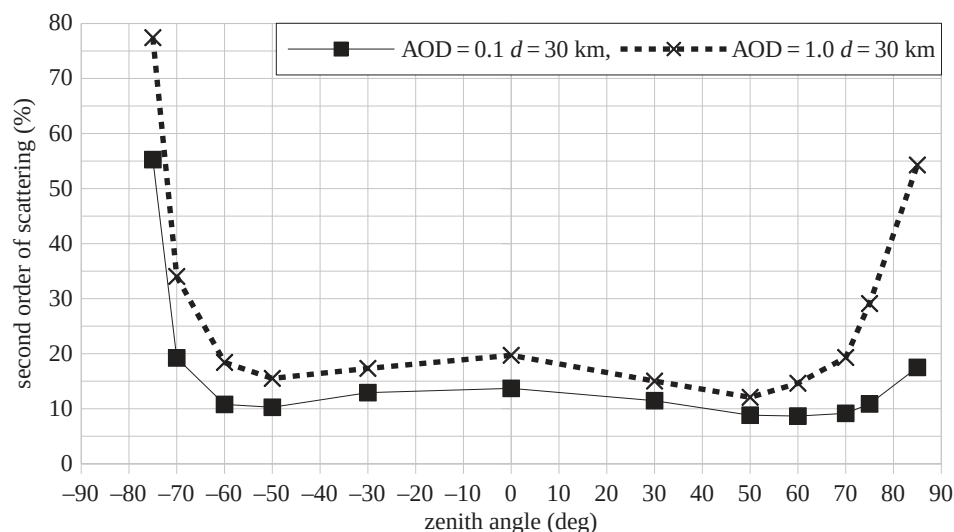


**Figure 11.** Contribution of the second order of scattering to total radiance as a function of the zenith angle at 30 km from city centre with AOD = 0.1 (clear) and AOD = 1.0 (polluted).

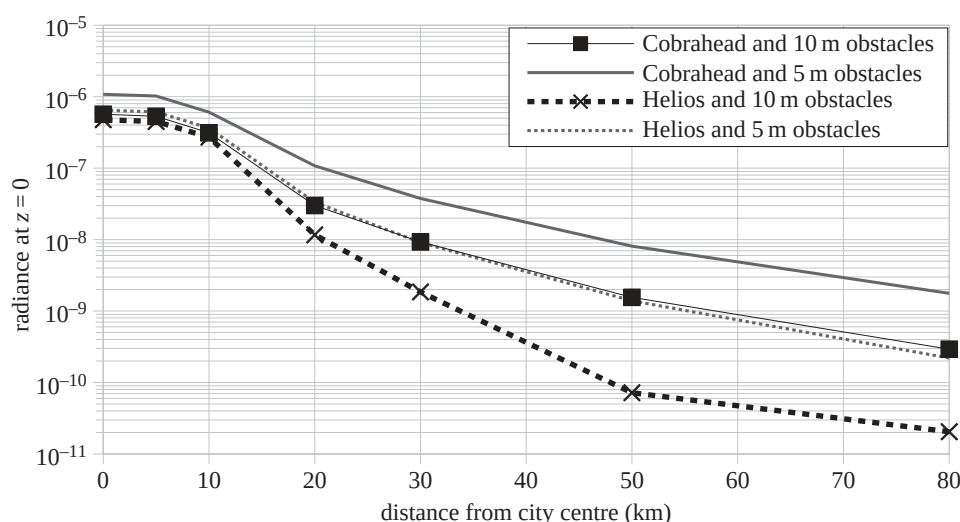


**Figure 12.** 569 nm zenith sky radiance as a function of distance from the city centre with two different light fixtures (Cobrahead ULOR = 7% and Helios ULOR = 1%) at AOD = 0.1.

artificial sky brightness. This paper explores the impact of the LOP, especially the difference in ULOR, while using the files provided by the manufacturers in the format defined by the Illuminating Engineering Society of North America. The two light fixtures used are very common in Canada: the Cooper Cobrahead fixture with type III distribution (IES file RY15H3AL.IES) and the Lumec-Schreder Helios type III fixture (IES file A210S2.IES). Basically, the Helios fixture has ULOR < 1%, while the Cobrahead has ULOR ~ 7%. Figures 12–14 show the distance relationships obtained at  $z = 0$  and  $z = 60^\circ$  and for obstacle heights of 5 m and 10 m. As expected, Cobrahead fixtures generally produce more sky brightness than Helios when obstacles are smaller than light fixtures, but obstacle height also plays an important role. As an example, when obstacles are taller than light fixtures, the Cobrahead becomes almost identical to the Helios because the Cobrahead ULOR is concentrated near the horizon and this part of the flux is efficiently blocked by obstacles. Figure 14 shows that the radiance ratio of Cobrahead over Helios is near unity in

the city, but can increase by one order of magnitude away from the city's border.

Figures 15 and 16 show similar results, but as a function of the zenith angle. The Cobrahead/Helios radiance ratio is given for two distances from the city centre (figure 16). As seen in figure 16, outside the city when obstacles are taller than light fixtures, one impact of having a larger ULOR is to have a radiance between five and 30 times higher between  $z = 0$  and  $z = -70^\circ$  (opposite to the city centre). When obstacles are smaller than light fixtures, a larger ULOR produces four- to eightfold a radiance increase for the same zenith angle interval and same observer position. In the direction of the city, the ULOR increase has a lower impact on the sky's radiance.

For an observer located in the city centre (figure 16, black squares and grey line), the ULOR increase produces a more important radiance increase at large zenith angles ( $z > 60^\circ$  and  $z < -60^\circ$ ). This is true for both obstacle heights. At  $z = 85^\circ$ , a change from Helios to Cobrahead increases the sky brightness by a factor of approximately three (10 m obstacles)

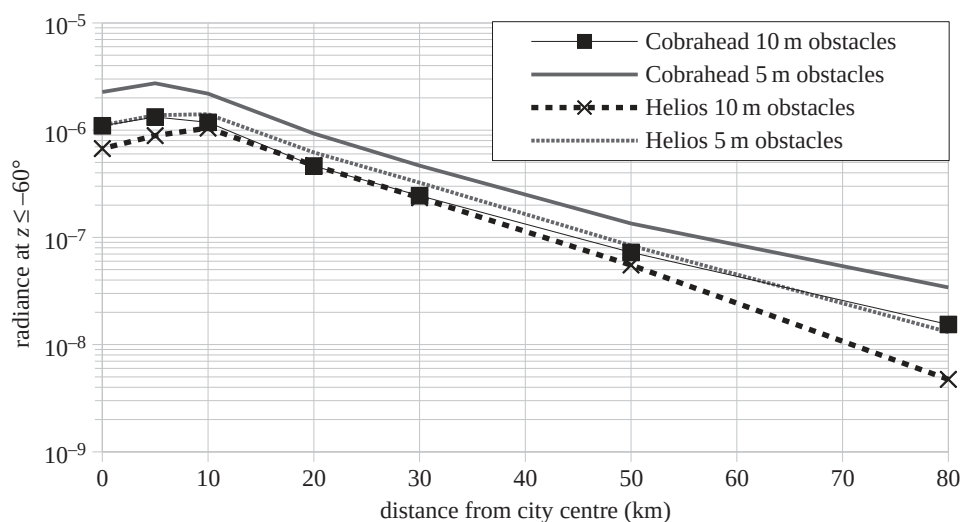


**Figure 13.** 569 nm sky radiance at  $z \leq -60^\circ$  as a function of the distance from the city centre with two different light fixtures (Cobrahead ULOR = 7% and Helios ULOR = 1%) at AOD = 0.1.

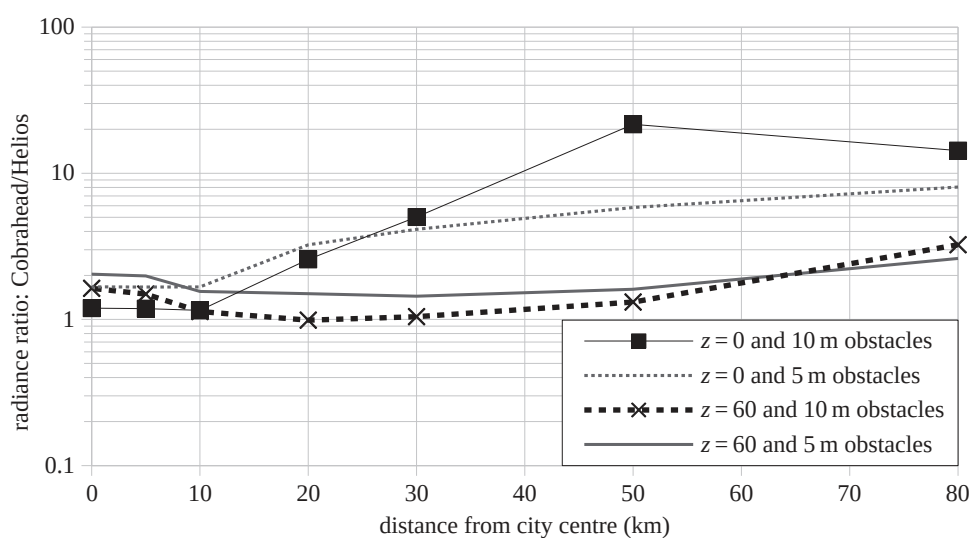


**Figure 14.** Ratio of radiance with Cobrahead over radiance with Helios as a function of distance from city centre for three different zenith angles.

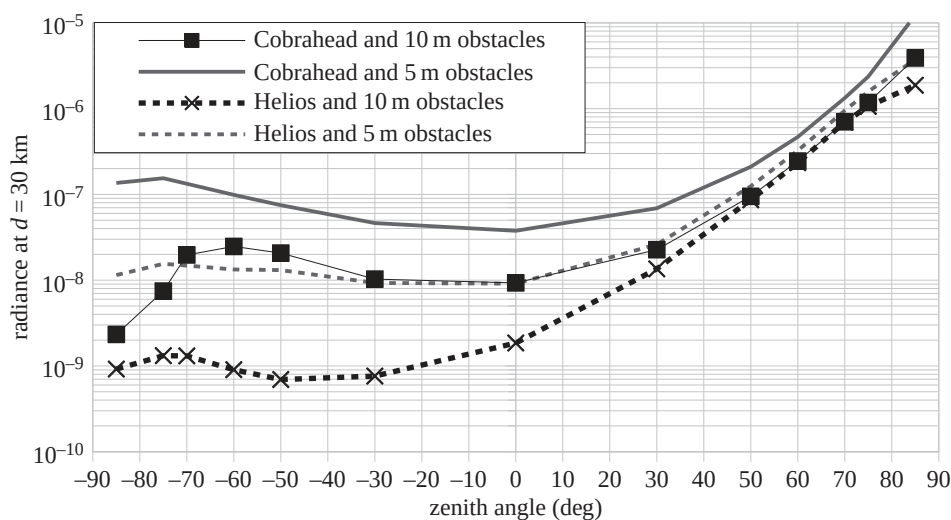


**Figure 15.** 569 nm sky radiance at 30 km from the city centre as a function of zenith angle with two different light fixtures (Cobrahead ULOR = 7% and Helios ULOR = 1%) at AOD = 0.1.



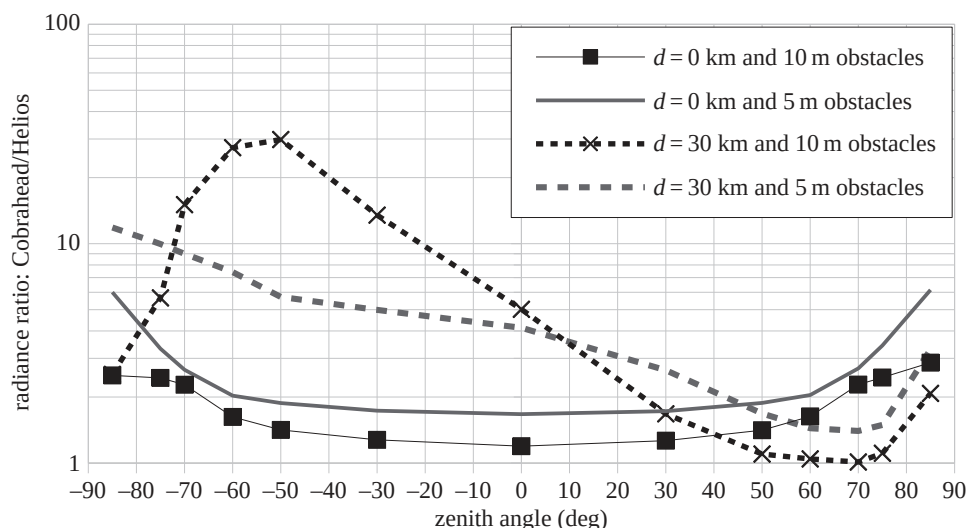


**Figure 16.** Ratio of zenith radiance with Cobrahead over radiance with Helios as a function of zenith angle for two different distances from the city centre.

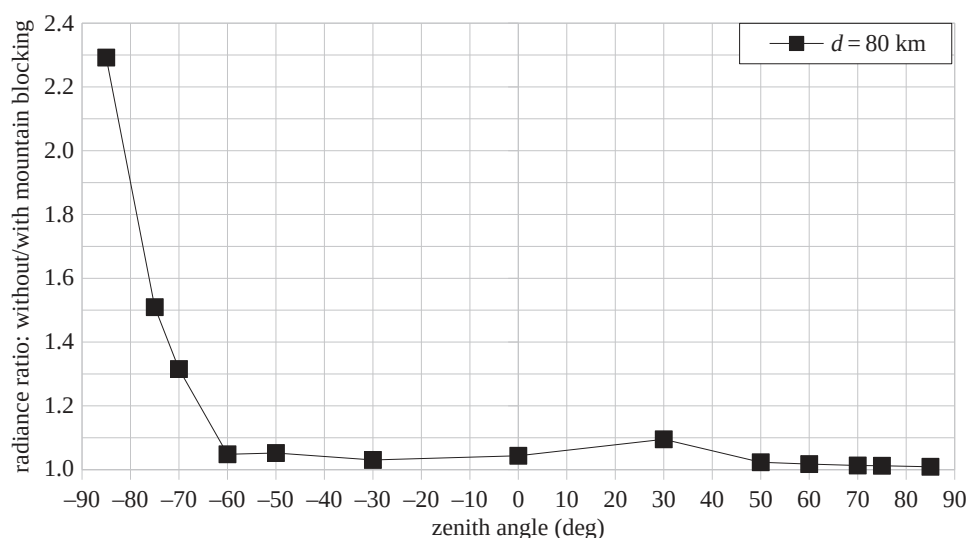


**Figure 17.** Ratio of sky radiance without mountain blocking to radiance with mountain blocking as a function of zenith angle 80 km from the city centre.

to approximately six (5 m obstacles), but by between one and two at the zenith.

#### (d) Impact of terrain masking

In 2001, Cinzano *et al.* [37] showed that the screening effect of mountains can influence significantly the sky brightness only when the mountain is near the observer. To infer the impact of masking by terrain in the present study, a mountain 2000 m high was placed eastward from the city. The summit of the mountain is located 30 km away from the city centre. Then, the observer was placed 80 km from the city centre at both sides of the city so that for the eastern observer, the mountain completely blocked the direct light from the city. The ratio of the radiance without blocking by the mountain over the radiance with blocking by the mountain as a function of the zenith angle is given in figure 17. This figure tells us that for most viewing angles, the terrain blocking only slightly reduces the sky's radiance. The radiance without the mountain is only 1.03 times the radiance with the mountain on average, from  $z = -60^\circ$  to  $z = 85^\circ$ . This factor increases rapidly for reverse angles larger than  $60^\circ$  ( $z \leq 60^\circ$ ). The highest factor, of approximately 2.3, is obtained at  $85^\circ$ , the highest zenith angle

computed. This rapid increase can be explained by the fact that at such angles, the observer's line of sight crosses the shadow of the mountain for most of its trajectory into the atmosphere.

#### (e) Impact of ground reflectance

The modelling experiment was repeated for three different values of ground reflectance, from 0.1 to 0.8. The first value roughly corresponds to the usual reflectance encountered underneath light fixtures, and 0.8 corresponds to the winter ground cover dominated by snow (full snow cover has a reflectance of approx. 0.97). Ground cover dominated by snow occurs in Canada immediately after a snow storm for asphalt surfaces and almost all the wintertime for dirt roads. Normally in Canada on asphalt roads, snow is removed with salt except when the temperature is lower than approximately  $-23^\circ\text{C}$ . In such cold conditions, snow does not melt and the snow cover can remain for many nights; the results are plotted in figure 18. The relationship between the sky's radiance at zenith and the ground reflectance is almost perfectly linear, both for the city centre and 30 km away. If one extrapolates the linear equation  $d = 0$  km for null reflectance, a radiance of  $2.07 \times 10^{-7}$  is

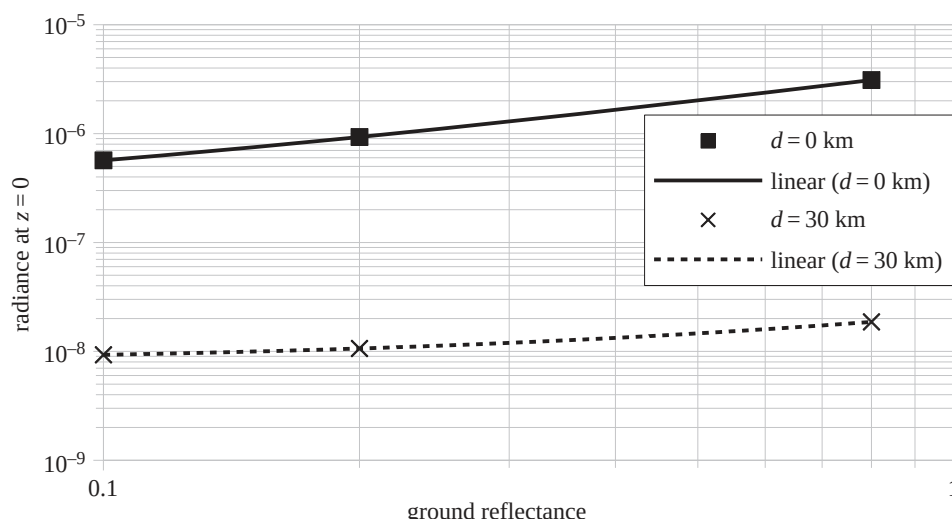


**Figure 18.** 569 nm zenith sky radiance as a function of ground reflectance in the city centre and 30 km from the city centre.

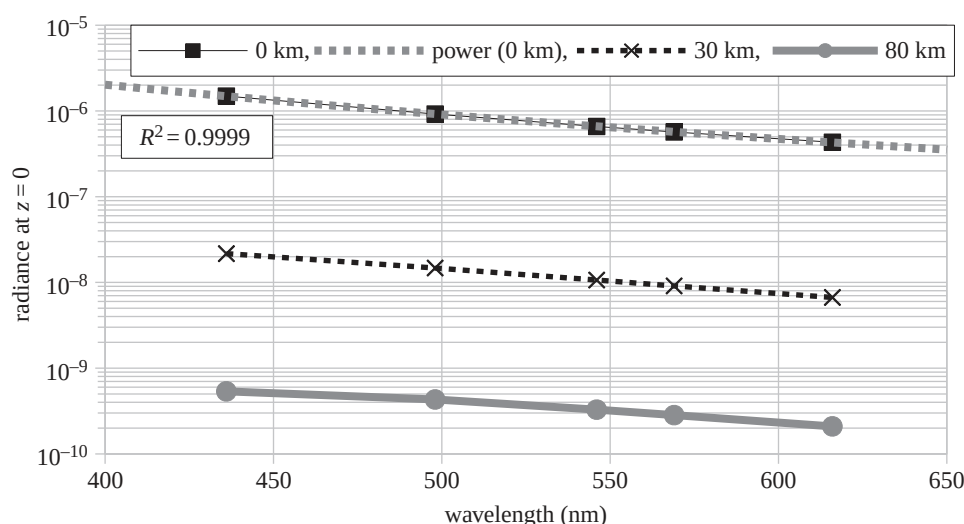


**Figure 19.** Zenith radiance as a function of wavelength for three distances from the city centre. The grey dotted line superimposed on the black squares is a power law fit of the data with a high correlation ( $R^2 = 0.9999$ ).

obtained, which represents the contribution of the upward flux of the light fixtures. This value is approximately 2.7 times lower than at a reflectance of 0.1 ( $5.68 \times 10^{-7}$ ). In other words, the direct upward light contributes to 36% of the zenith radiance for a downtown observer when using the Cobrahead fixtures and with obstacles 10 m high. When the reflectance is 0.8 (radiance of  $3.10 \times 10^{-6}$ ), the direct contribution in the upper hemisphere represents only 6.7% of the total radiance. Similarly, 30 km away from the city centre, extrapolation at a reflectance of zero gives a radiance of  $7.96 \times 10^{-9}$ . In that case, the upward direct light contributes to 86% of the zenith radiance at a reflectance of 0.1 ( $9.29 \times 10^{-9}$ ). When the reflectance is 0.8 (radiance of  $1.86 \times 10^{-8}$ ), the direct contribution in the upper hemisphere represents 43% of the total radiance. Basically, upward emission dominates the sky zenith radiance when the observer is located far from the city, but reflected light dominates the zenith sky radiance inside the city.

### (f) Impact of wavelength

It is well known that wavelength has a strong impact on the scattering process in the atmosphere. Thanks to the Rayleigh

theory, it is known that molecules scatter light with a probability proportional to  $\lambda^{-4}$ . However, aerosols, which are larger in size, scatter light with a probability proportional to  $\lambda^{-\alpha}$  with  $\alpha \approx 1$ , where  $\alpha$  is the Ångström exponent. The Ångström exponent varies with the size distribution of the aerosol population. As the AOD is dependent on the wavelength, the sensitivity analysis was conducted as a function of the wavelength by setting the AOD at 546 nm to 0.1, and using an Ångström exponent of 1.3 to determine AOD for the four remaining key wavelengths. Then, computations of the sky's radiance at each wavelength were made, assuming that the flux emitted by the light fixture in each key wavelength was the same. This is never the case, but allowed us to better discriminate the spectral variations originating from the atmospheric and environmental effects from variations originating from the lamps' spectral distributions.

The ground reflectance was considered independently of the wavelength and a value of 0.1 was adopted. Figure 19 shows the radiance versus wavelength relationship for the three distances from the city centre (0 km, 30 km, 80 km). But the calculation was also made for all the other distances listed in table 2. Then afterward, a power function of the wavelength was fitted to

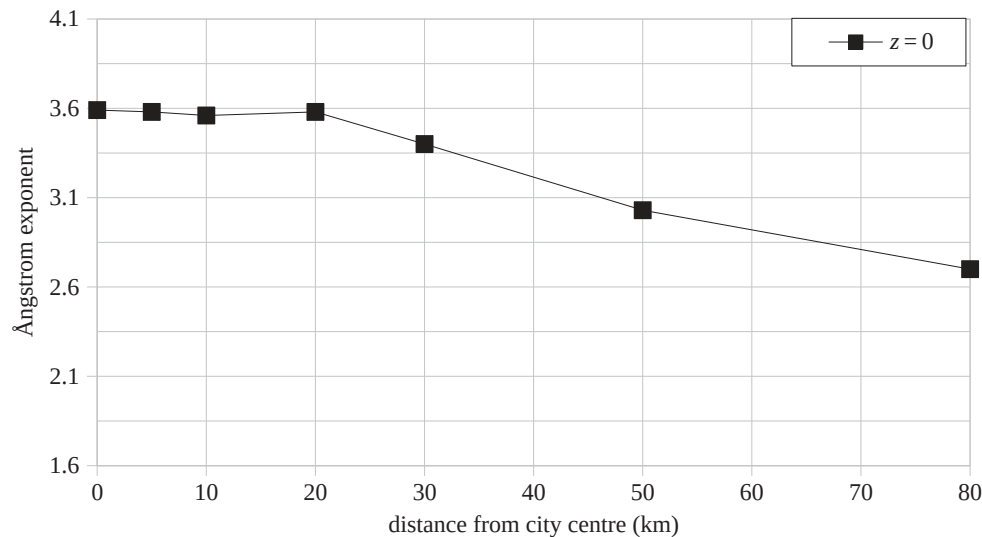


**Figure 20.** Ångström exponent determined by power law fits of radiance versus wavelength as a function of distance from the city centre.

each dataset. The fits showed very good correlations starting with  $R^2 = 0.9999$  for  $d = 0$  km, to  $R^2 = 0.9659$  for  $d = 80$  km. The power function fit of the data allowed us to track the Ångström exponent as a function of the distance from the city centre (figure 20). The Ångström exponent decreases gradually from a maximum of 3.59 at  $d = 0$  km to 2.70 for  $d = 80$  km. As expected, the exponent lies between the limits of the Mie and Rayleigh theories.

## 4. Conclusion

To investigate the consequences of ALAN on fauna, flora and human health it is important to understand how it depends upon light levels and spectral power distributions. The aim of this paper was to identify the variables that have a significant influence on the anthropogenic radiance of the night sky. We especially wanted to determine to what extent each of these variables could affect the spectral radiance of the night sky, while establishing interactions between these variables. To achieve this goal, a simple modelling scenario comprising a circular city with constant properties plus small-scale obstacles and a mountain outside the city, was defined. The standard parameter set was also defined, which gave a starting point for the sensitivity analysis. The variables that were investigated include: ground reflectance, the height of obstacles, the blocking effect by a mountain, the AOD, the angular photometry of the light fixtures and finally the impact of wavelength of the light. The analysis was performed as a function of distance from the city centre and as a function of the zenith viewing angle in the principal plane. The main results of the sensitivity analysis are summarized below:

- With standard parameters set (AOD = 0.1, wavelength = 569 nm, reflectance = 0.1, with 10 m obstacles), the zenith radiance decreases as a  $1/r^{3.33}$  function outside the city's perimeter.
- The zenith radiance is weakly dependent on AOD inside the city ( $R(\text{AOD} = 1)/R(\text{AOD} = 0.1)$  lies between 0.96 and 1.10), but is strongly dependent on AOD outside the city limits (e.g.  $R(\text{AOD} = 1)/R(\text{AOD} = 0.1) \approx 0.023$  at 80 km from the city centre). In other words, the zenith

radiance is rapidly attenuated with distance outside the city limits under high AOD.

- The second order of scattering is very important to accurately model the sky's radiance. The second order of scattering is even more important for high AOD and when the light is blocked by obstacles. Actually, under the standard parameter set, the second order of scattering contributes to approximately 7% of the zenith radiance inside and approximately 14% outside the city. For AOD = 1.0, the second order of scattering contributes to approximately 20% of the zenith radiance inside the city, but can reach more than 30% outside. The value decreases with increases in distance.
- Inside the city's perimeter, the zenith radiance without obstacles is almost twice the radiance obtained with obstacles taller than light fixtures (i.e. 10 m high). The relative importance of the radiance without obstacles in comparison with the radiance with 10 m obstacles increases with distance to reach approximately sevenfold at 80 km from the city centre, which indicates that blocking by obstacles becomes more and more efficient in reducing the zenith sky brightness when distances are increased. The case of obstacles smaller than light fixtures (e.g. 5 m tall) is almost equivalent to the case without obstacles inside and outside the city.
- Under the standard parameter set, the radiance as a function of the zenith angle in the principal plane, is lower near the zenith at low reverse angles and increases with the zenith angle, but also shows an inflection of the curve at high reverse zenith angles ( $z \leq -50^\circ$ ). This inflection is caused by (i) the reduction of the upward flux (which can be caused by a reduction of the lamp ULOR or by blocking by obstacles) and (ii) the increasing light extinction that occurs with increased zenith angle. The last effect is more important with a larger AOD.
- Having a larger ULOR (e.g. 7% in comparison with 1%) generates larger radiances in the reverse angles for an observer located outside the city. In the direction of the city, the ULOR increase has a low impact on the sky's radiance, especially when the obstacles are taller than the light fixtures. For an observer inside the city, the increase of ULOR with tall obstacles produces a modest increase of radiance (approx. 1.2-fold at  $z = 0$  and approx. threefold

at  $z = 85^\circ$ ), but with small obstacles the increase of the radiance is greater.

- Terrain masking has a very low impact on sky brightness for most zenith angles (approx. 1.03-fold), except for very high reverse zenith angles ( $z \leq -70^\circ$ ). The low impact observed is probably an effect of the relatively great distance of the mountain in comparison with its height.
- Zenith radiance is linearly related to the ground reflectance for a fixed set of light fixtures.
- Snow cover greatly reduces the relative impact of the ULOR.
- Upward emission dominates the sky radiance at zenith when the observer is located far from the city but reflected light dominates the sky radiance at zenith inside the city.
- Zenith radiance is a power function of the wavelength, with an Ångström exponent ranging from approximately 3.6 in

the city centre to approximately 2.7 at 80 km from the city centre. This indicates that the impact of blue light is more important at shorter distances from the city centre, but it is still large far from the city centre. This is a very important result in regard to the potential impact on biological systems. Indeed, scotopic vision is more sensitive in the blue part of the spectrum (approx. 500 nm). This is even more important for the melatonin suppression potential, because this process is more sensitive to the deep blue part of the spectrum (approx. 445 nm) [38].

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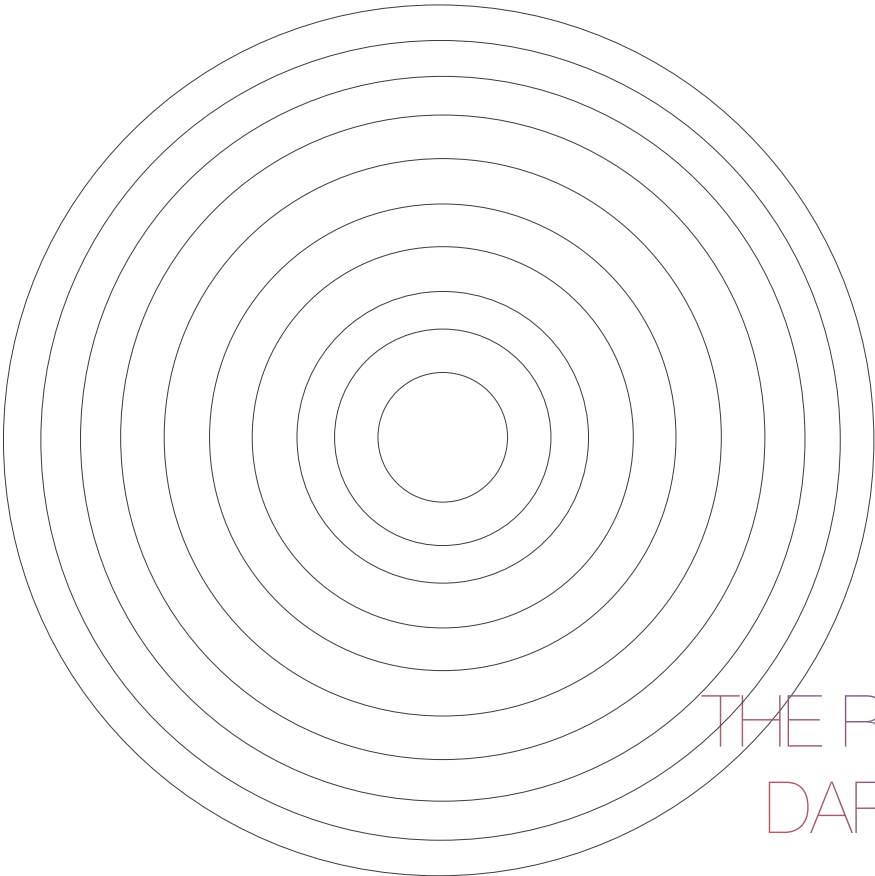
THE RIGHT TO  
DARK SKIES

EL DERECHO  
A LOS CIELOS  
OSCUROS



Organización  
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THE RIGHT TO  
DARK SKIES

EL DERECHO A LOS  
CIELOS OSCUROS



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THE RIGHT TO  
DARK SKIES

EL DERECHO A LOS  
CIELOS OSCUROS

Landscape showing geysers and the Milky Way. © J.M. Leclaire/  
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# Prologue

The Consejo Nacional de Ciencia y Tecnología (CONACYT) not only supports human resource training, research projects and links with industry, but is also committed to the communication of scientific research to the general public and the dissemination of knowledge between specialists. Reaching society and a knowledge economy cannot be achieved without the support of the community, nor without science becoming a part of citizen culture. Participating in thematic years is an excellent strategy to reach this goal of popularizing science, especially if the topic is related to our daily life, as is light.

The United Nations General Assembly proclaimed 2015 as the International Year of Light and Light-based Technologies (IYL 2015), with Mexico acting as one of the promoters of this initiative. CONACYT took advantage of this decision to promote the communication of science and technology on this subject and supported various activities designed to promote awareness of light and its applications. It may seem contradictory that, among the many projects carried out during the IYL2015 that highlighted the application of light across various disciplines, an international meeting on The Right to Dark Skies was organized by the

UNESCO Office in Mexico. Light should be a common good, but sometimes it is necessary to turn it off.

It is always a big surprise to children when they are taught that white light contains all colours, by demonstrating its diffraction through a prism. There is no museum of science in the world that doesn't have a disc, known as the Newton disc, with wedges of colour that appears to be white when spun. That all colour comes from something that is apparently colourless is one of the many wonders of nature. This decomposition of colours that we see in a rainbow was thought of as a serpent of light by our indigenous populations. Light that comes from the Sun and marks the difference between night and day is the basis of life on our planet. Another great surprise is that not all light is visible to the human eye. The electromagnetic spectrum also covers, among others, infrared and ultraviolet regions that we cannot see, but whose effects are equally important. Humans, who have always been curious, have studied not only the light of our stars, but also seek to learn about all the other objects in the universe that send us information in both visible and invisible light form.

The invention of electric power is undoubtedly one of humanity's most fundamental developments. The ability to apparently turn the Sun on and off at will, to be able to read at night and illuminate our cities, has defined our way of life. Of course electric power applications go far beyond just turning lights on, but what interests us here is precisely the fact that we can create light.

Unfortunately, the great advantage of illuminating our streets to return home at night, especially if the lighting is excessive, may conflict with the desire to study the confines of the universe. Excess night lighting prevents nearby telescopes from analysing the light coming from outer space. It is also a matter of biology and ecology as many species, both flora and fauna, are affected in their normal life cycles. What is the magnitude of this problem? How can it be resolved? It is not only a scientific issue; it is also about regulation.

The right to dark skies has been recognized by UNESCO as an implicit right in the conservation of cultural and natural heritage for future generations according to the Declaration in Defence of the Night Sky and the Right to Starlight (2007). It is therefore a measure that supports sustainable development.

All of these subjects were analysed with the vision and knowledge of experts at *The Right to Dark Skies* meeting. It was also significant that the venue of the meeting was the Centre of Digital Culture in Mexico City (Centro de Cultura Digital), for there is much art in dark skies. It is such a pleasure to see the Milky Way in the night sky!

The conclusions will undoubtedly have a very positive impact on astronomical and ecological challenges, and will also affect the issues of energy saving and rational energy use. Electric power should improve the quality of life for all, but must be consumed and managed sustainably.

CONACYT is proud to participate in activities that not only foster science and technology, but also have a positive social impact. We congratulate the UNESCO Office in Mexico for this initiative, as well as their co-organizers: the National Autonomous University of Mexico (UNAM in Spanish), the Mexican Academy of Sciences (AMC in Spanish) and the Scientific and Technological Consultative Forum (FCCyT in Spanish). It goes without saying that we send special congratulations to the researches who participated in the meeting for such a great job.

**Julia Tagüeña**

*Associate Director for Scientific Development  
Consejo Nacional de Ciencia y Tecnología*

## Prólogo

El Consejo Nacional de Ciencia y Tecnología (CONACYT) de México no solamente apoya la formación de recursos humanos, proyectos de investigación y vinculación con la empresa, sino que tiene un compromiso con la comunicación pública de la ciencia hacia la sociedad y la difusión del conocimiento entre especialistas. Alcanzar la sociedad y la economía del conocimiento no puede lograrse sin el acompañamiento de la comunidad, sin que la ciencia se vuelva parte de la cultura de los ciudadanos. Para caminar hacia esta meta, participar en los años temáticos es una excelente estrategia de divulgación de la ciencia, más aún si el tema es tan cercano a nuestra vida cotidiana, como lo es la luz.

La Asamblea General de las Naciones Unidas proclamó al año 2015 como el Año Internacional de la Luz y las Tecnologías basadas en la Luz, siendo México uno de los promotores de esta iniciativa. Así, el CONACYT aprovechó esta buena decisión para promover la comunicación de la ciencia y la tecnología alrededor de este tema y apoyó diversas actividades enfocadas a promover el conocimiento sobre la luz y sus aplicaciones. Parecería contradictorio que entre los muchos proyectos apoyados durante este Año de la Luz, que resaltan las aplicaciones del uso de la luz en muy diversas disciplinas, se apoyara una reunión internacional sobre “El derecho a los cielos

oscuros”, organizada por la Oficina en México de las Organización de las Naciones Unidas para la Educación, la Ciencia y la Cultura (UNESCO). La luz debe de ser un bien común, pero a veces es necesario apagarla.

Cuando se enseña a los niños que la luz blanca contiene todos los colores, mostrando su difracción a través de un prisma, es para ellos siempre una gran sorpresa. No hay museo de ciencias del mundo que no tenga un disco, conocido como disco de Newton, con franjas de colores que al girar se ve blanco. Que todo el color venga de algo que aparentemente no lo tiene es una de las muchas maravillas de la naturaleza. Esta descomposición en colores que vemos en el arcoíris hacía pensar a nuestros pueblos originales en una serpiente de luz. La luz que viene del Sol y que hace la diferencia del día y la noche es la base de la vida en nuestro planeta. Otra gran sorpresa de la luz es que no toda es visible al ojo humano. El espectro de radiación cubre también, entre otras, las regiones del infrarrojo y el ultravioleta, que no podemos ver, pero cuyos efectos son igualmente importantes. La humanidad, siempre curiosa, no sólo ha estudiado la luz de nuestra estrella, sino que queremos saber de todos los demás objetos del universo, que nos mandan información justamente en forma de luz, visible y no visible.

El invento de la luz eléctrica es sin duda uno de los más fundamentales del desarrollo de la humanidad. Que podamos aparentemente prender y apagar el Sol a nuestro gusto, para poder leer en la noche e iluminar nuestras ciudades, ha definido nuestra forma de vivir. Desde luego que las aplicaciones de la energía eléctrica van mucho más allá de prender la luz, pero lo que aquí nos interesa es justamente eso, que podemos crear luz.

Desafortunadamente la gran ventaja de iluminar nuestras calles para regresar de noche a la casa, sobre todo si se ilumina en exceso, puede entrar en contradicción con el deseo de estudiar los confines del universo. El exceso de iluminación nocturna impide que los telescopios cercanos analicen la luz que nos llega del espacio exterior. También es un tema de biología y ecología, pues muchas especies, tanto de flora como de fauna, son afectadas en sus ciclos normales de vida. ¿Cuál es la magnitud de este problema? ¿Cómo resolverlo? No es sólo un tema de ciencia, es también un tema de reglamentación.

El derecho a los cielos oscuros ha sido reconocido por la UNESCO como un derecho implícito en la conservación del patrimonio cultural y natural de las generaciones futuras, de acuerdo con la Declaración sobre la Defensa del Cielo Nocturno y el Derecho a la Luz de las Estrellas, en

el 2007. Es por lo tanto una medida que apoya al desarrollo sostenible. Todos estos aspectos fueron analizados con visión y conocimiento por expertos en la reunión llamada “El derecho a los cielos oscuros”. Fue también significativo que la sede haya sido el Centro de Cultura Digital de la Ciudad de México, pues hay mucho de arte en los cielos oscuros. ¡Qué placer es observar en el cielo nocturno la Vía Láctea!

Las conclusiones tendrán sin duda un impacto muy positivo en este gran reto de la astronomía y la biología, que además incide en el tema del ahorro y el uso racional de la energía. La energía eléctrica debe mejorar la calidad de vida de todos, pero debe ser consumida y administrada sosteniblemente.

Es para el CONACYT un orgullo participar en acciones que no sólo fomentan la ciencia y la tecnología, sino que además tienen una componente de impacto social positivo. Felicitamos a la UNESCO por esta iniciativa; también a sus coorganizadores: la Universidad Nacional Autónoma de México (UNAM), la Academia Mexicana de Ciencias (AMC) y el Foro Consultivo Científico y Tecnológico A. C. Por supuesto, una felicitación muy especial a los investigadores participantes en la reunión por un trabajo bien hecho.

**Julia Tagüeña**

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# Presentation

## **What Does it Mean to Preserve Dark Skies?**

Simply, or perhaps simplistically, the preservation of dark skies means retaining the ability to observe the sky in dark conditions similar to those that existed before the Industrial Age and the associated population explosion that followed. However, as the articles in this publication will reveal such preservation has many different aspects, which are all important individually and together, make this goal a common issue that can and should allow for greater interaction and scientific, cultural, educational and technological development, both locally and globally.

## **Why is Preserving Dark Skies Important?**

The most pressing reason to preserve dark skies could be the ability to continue making observations of the universe from the Earth. It may seem simple, but urban growth and associated night lighting in the last 50 years have made it impossible to carry out high-level astronomical research in many places in Europe and North America. On a more individual level, this implies that large

portions of the population are very disconnected from what it means to see the night sky and cannot appreciate our place in the universe. However, beyond astronomy, excessive night lighting has biological and ecological implications since it disrupts the life cycles of fauna (including humans); of the fauna, insects, birds and turtles have always used stars to navigate between different territories with the changing of the seasons.

## **What Can and Should We Do to Preserve Dark Skies?**

Limiting artificial night lighting in no way means relinquishing its benefits if it is carried out in a rational and planned manner, with high-level engineering and innovation. In fact, it implies a reduction in energy consumption and significant savings for the local and federal authorities of a country. The search for increased efficiency acts as a catalyst for the development of new technologies in renewable and sustainable energy, which would have favourable effects on the economy and the welfare of the population.

Education plays a key role in the preservation of dark skies and in the implementation of activities that support this goal. The best-case scenario is that children and young people have the relevant information to make informed decisions in the future and can appreciate for themselves the benefits of having an adequate, natural environment. In this sense, controlling light pollution is no different from controlling sound, air, water and land pollution; it is a matter of comprehensive conservation. Today, the best astronomical sites, favoured for their natural conditions for observation, are in emblematic places and in many cases are protected (such as national parks or ecological reserves). Several of these sites, such as in northern Chile, Hawaii, San Pedro Mártir and the Canary Islands are represented in this volume. They can and should be spearheading efforts to broaden initiatives that support and promote this conservation more generally.

### **A Common Heritage**

The subject of dark skies, above all, has a factor of prime importance that elevates it to and unifies it on an international

level: its cultural relevance. Astronomy and the determination of the seasons through the development of the first calendars is probably the activity with the oldest scientific roots in the history of humanity. Its importance is written in stone at many archaeological sites in China, Babylon, Egypt, Europe, Africa and the Americas. All cultures, absolutely all of them, developed some level of astronomy to measure the passage of time and to know when to migrate, plant, harvest and hunt. It is essential to preserve the ability to have dark skies over these sites where urban settlements were built to reflect this knowledge; if we don't reduce and take out of context what is below, the same must be said for the ability to see what is above on a clear night.

As a result of the meeting held in Mexico City in January 2016, the participants gave an account of both potential and current activities in order to include the right to dark skies on the global agenda. Who better than UNESCO to coordinate these efforts, as a part of its authentic mandate of working for Education, Science and Culture?

**William H. Lee**

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# Presentación

## ¿Qué significa preservar los cielos oscuros?

De manera sencilla, o quizás simplista, la preservación de los cielos oscuros significa retener la capacidad de observar el cielo en condiciones de oscuridad similares a las que existían antes de la era industrial y de la explosión demográfica asociada y subsecuente. Pero como se demuestra en este libro a través de sus muy diversas contribuciones, dicha preservación tiene muchas aristas diferentes, todas importantes por sí solas y que en conjunto convierten a dicho objetivo en un tema común que puede y debe permitir una mayor interacción y desarrollo científico, cultural, educativo y tecnológico, tanto a nivel local como global.

## ¿Por qué es importante su preservación?

La motivación más inmediata para contar con cielos oscuros podría ser la posibilidad de seguir haciendo observaciones del universo desde la superficie de la Tierra. Puede parecer algo simple, pero el crecimiento urbano y la luminosidad nocturna asociada en los últimos 50 años han hecho que en muchos sitios de Europa y Norteamérica ya no sea posible llevar a cabo investigación de alto nivel en astronomía. Mas a nivel individual, ello significa que grandes segmentos

de la población estén muy desconectados de lo que significa ver el cielo por la noche y que no puedan apreciar a nuestro lugar en el universo. Pero más allá de la astronomía, la luminosidad excesiva nocturna tiene implicaciones en la biología y en la ecología, porque perturba los ciclos de vida de la fauna (¡incluyendo a los humanos!), entre la que se hallan insectos, aves y tortugas que han usado siempre las estrellas para navegar entre distintos territorios con el cambio de las estaciones.

## ¿Qué podemos y debemos hacer para preservar los cielos oscuros?

Limitar la luz artificial nocturna de ninguna manera implica renunciar a sus beneficios si se lleva a cabo de manera racional y planeada, con ingeniería de alto nivel e innovación. Implica de hecho una reducción en el consumo de energía y ahorros importantes para las autoridades locales y federales de un país. Buscar esta mayor eficiencia produce directamente una motivación para nuevos desarrollos tecnológicos de energías renovables y sostenibles, que tendrían consecuencias favorables para la economía y el bienestar de una población por sí mismos.

La educación juega un papel fundamental en la preservación de los cielos oscuros y en la implementación de las acciones que llevan a ellos. La mejor opción es que los niños y jóvenes tengan información relevante para tomar las decisiones correctas a futuro y puedan apreciar por sí mismos los beneficios de contar con un entorno natural adecuado. En este sentido controlar la contaminación lumínica no es distinto de controlar la contaminación sonora, del aire, del agua y de los suelos. Es un asunto de conservación en el sentido integral. Hoy, los mejores sitios astronómicos favorecidos por sus condiciones naturales para la observación están en lugares emblemáticos, en muchos casos protegidos (como en parques nacionales o reservas ecológicas). Varios de ellos, como el norte de Chile, las Islas Hawái, San Pedro Mártir y las Islas Canarias, están representados en estas páginas. Pueden y deben ser entonces punta de lanza en los esfuerzos para iniciativas más generales que fomenten y promuevan esta conservación más generalmente.

### **Un patrimonio común**

Pero el tema de los cielos oscuros tiene además de todo lo anterior un factor de primera importancia que lo hace integrador a nivel

internacional: su relevancia cultural. La astronomía y la determinación de las estaciones a través de la elaboración de los primeros calendarios es probablemente la actividad con raíz científica más antigua de la humanidad. Su importancia está escrita en piedra en múltiples sitios arqueológicos, en China, Babilonia, Egipto, Europa, África y América. Todas las culturas, todas, desarrollaron algún nivel de astronomía para medir el paso del tiempo y saber cuándo migrar, cuándo plantar, cuándo cosechar y cuándo cazar. Los sitios donde se construyeron los asentamientos urbanos reflejan este conocimiento, y preservar la capacidad de tener cielos oscuros en ellos es primordial si no hemos de cercenar y sacar de contexto lo que esta abajo, por no poder ver lo que está arriba en una noche despejada.

Como resultado de la reunión llevada a cabo en la Ciudad de México en enero del 2016, los participantes hicieron un recuento de las acciones, tanto posibles como en curso, para poner en la agenda global el tema del derecho a los cielos oscuros. Qué mejor actor que la UNESCO para articular estos esfuerzos, en la auténtica misión de trabajar en pro de la Educación, la Ciencia y la Cultura.

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*Coordinador de la Investigación Científica de la  
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# Introduction

When we talk to friends or colleagues about dark and starry skies, we almost automatically think of places far from urban centres that are very distant and isolated. We are easily reminded of nights with celestial views that amazed us, of star filled skies in deserts, forests or beaches far from what we call civilization. Almost as if these forests, deserts and seas were the only places in the world where so many stars existed. . . . .

Nothing could be further from reality: stars abound and shine equally anywhere around our planet. Clearly, constellations change

with the seasons and between the Hemispheres, but the sky is essentially the same for everyone. We see this during the day, in the sunlight, but we literally lose sight of it at night when the greatest contrasts between urban and isolated or uninhabited areas occur.

The lights that illuminate the cities we live in have a huge impact on the skies. Effectively, street lighting, illuminated billboards, the powerful lighting of sports stadiums and car lights, among other light contaminants, emit a huge quantity of light into the sky. This light is dispersed by atmospheric gas and dust, and generates a



luminous halo around our urban centres, which ends up obscuring most of the stars. The Milky Way and faint stars become invisible due to light pollution.

In the same way that human activity has created increased pollution in our atmosphere and water resources (such as in rivers, lakes and seas), it has also produced sound and light pollution that have a high impact on our health and on the economy. Light pollution is not as evident as other forms of pollution and it not only affects human beings, but also has an impact on the life cycles of flora and

fauna. Moreover, its effects subvert the sources of cultural, historic and scientific values that have enabled us to understand our place in the universe. Light pollution is gradually depriving us of this extraordinary and intriguing window that reaffirms us as human beings; this excess of unnecessary night illumination takes away our right to enjoy the dark sky.

This international meeting, which brought together experts from all over the world, was conceived to reassess our role as a society in the recovery of our fundamental right to dark skies.

**Nuria Sanz**

*Head and Representative  
UNESCO Office in Mexico*

**José Franco**

*Coordinator  
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# Introducción

Cuando charlamos con amigos o colegas sobre cielos oscuros y llenos de estrellas, casi de manera automática pensamos en lugares lejanos a los centros urbanos, muy distantes y aislados. Con facilidad evocamos recuerdos de visiones celestes que nos maravillaron, con cielos repletos de estrellas, en desiertos, bosques o playas alejadas de esto que llamamos civilización. Como si esos bosques, desiertos y mares fueran los únicos lugares del mundo donde existieran tantas estrellas.....

Nada más lejano a la realidad: las estrellas abundan y brillan igual en cualquier lugar de nuestro planeta. Por supuesto, las configuracio-

nes estelares cambian con las estaciones y entre hemisferios, pero el cielo es en esencia el mismo para todos. Lo constatamos durante el día, a la luz del Sol, pero literalmente lo perdemos de vista en la noche, cuando se dan los grandes contrastes entre los sitios urbanos y los sitios no habitados o aislados.

La gran diferencia la hacen las luces que iluminan las ciudades donde vivimos. Efectivamente, el alumbrado público, los anuncios luminosos, la potente iluminación de los estadios deportivos y las luces de los automóviles, entre otros contaminantes lumíni-

cos, lanzan una enorme cantidad de luz hacia el cielo. Esta luz es dispersada por el gas y el polvo de la atmósfera y genera un halo luminoso alrededor de nuestros centros urbanos, el cual termina enmascarando a la mayoría de las estrellas. La Vía Láctea y las estrellas débiles se vuelven imperceptibles por la contaminación lumínica.

Sí, de la misma manera que la actividad humana ha generado una creciente contaminación en la atmósfera y en nuestros recursos hídricos en ríos, lagos y mares, también ha generado una contami-

nación sonora y luminosa que tiene un alto impacto en la salud y en la economía. Mucho más sutil que las otras, la contaminación lumínica no sólo afecta a los seres humanos, sino que además genera un impacto en los ciclos de vida de la fauna y la flora. Más aún, su efecto trastoca esa fuente de valores culturales, históricos y científicos que nos han permitido ubicarnos en el universo. Poco a poco, la contaminación lumínica nos despoja de esa ventana intrigante y extraordinaria que nos reafirma como seres humanos; ese exceso de iluminación nocturna innecesaria nos arrebató el derecho a disfrutar de los cielos oscuros.

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Chapter 1

# Astronomy and International Cooperation: UNESCO's Role

Capítulo 1

# Astronomía y cooperación internacional: el papel de la UNESCO



# Una reflexión polifónica

**Nuria Sanz**

*Directora y Representante de la Oficina de la UNESCO en México*

La admiración, valoración y placer de la contemplación celeste es consustancial a la vida humana desde hace por lo menos 2.6 millones de años de nuestra historia evolutiva como seres culturales; seguramente por aquel entonces las luces zodiacales formarían parte del cotidiano de los primeros homínidos africanos. Desde entonces las culturas han experimentado el cielo como forma de estar y dar sentido a su existir en la tierra. En nuestra historia civilizatoria los eventos astrológicos han pautado los ciclos productivos, la generación de los mitos de origen y las formas de medida espacio-temporales. La noche nos ha permitido entender el universo y seguir buscando respuestas en el cielo a algunas de las preguntas más antiguas de la humanidad. El cielo nos obliga a una poética y a una práctica de la cultura, especialmente ahora que sabemos que la astroingeniería y los megatelescopios son *instrumentalia* necesaria pero no suficiente para preservar nuestras formas de observación celeste, especialmente hoy, cuando estamos más seguros que nunca de que la contemplación tiene que seguir siendo un recurso cultural y científico duradero y seguro, a partir de las pocas ventanas privilegiadas al universo, desde donde continuar generando conocimiento.

Si el cielo es el paisaje cultural más común y universal a todas las culturas del mundo, es así como podemos entender que el verdadero Patrimonio de la Humanidad es que todos compartamos la pregunta sobre el origen y el destino del universo, y para ello la cooperación internacional debe de sentar las bases de otras formas de alfabetización científicas, tecnológicas y culturales que nos hagan valorar y comprender en términos de colaboración la mirada al cielo oscuro. A lo largo de estas jornadas de trabajo, declaramos que la comunidad científica no puede hacer frente a este enorme reto de forma independiente. Que es necesario y urgente proveer a las ciudadanías del mundo de las claves de comprensión de este derecho y de las formas de generación de alianzas para hacer del cielo un recurso esencial para cada uno de los habitantes del planeta.

Subrayamos que para ello es fundamental entender el significado de reconectar relaciones y de la necesidad de reflexionar sobre las formas de cooperación que exige este multipaís. El cielo oscuro nos obliga

a otra forma de entender el multilateralismo y de reflexionar sobre el significado del concepto de soberanía nacional en el ámbito de la investigación del universo. No podemos permitir que la oscuridad del cielo sea un recurso en vías de extinción. Las atmósferas estables, la nitidez del aire, el carácter de los vientos, repercuten en la calidad de las imágenes celestes y son muy pocas las plataformas de observación susceptibles de seguir generando la mejor comprensión de los fenómenos asociados a la observación nocturna de la bóveda astral. Una comunidad amigable, aun a sabiendas de que es fronteriza, es necesaria para construir juntos un discurso interpretativo polifónico, que incluya las diversas miradas que a lo largo de la historia ha suscitado la relación de la humanidad con el universo, lo ptolemaico, lo copernicano, lo olmeca, lo maya, lo islámico, lo escolástico...

Esta reflexión se interesa por amplificar la discusión en tres líneas de trabajo:

1. Entender la importancia de la astronomía y su papel en las agencias especializadas de la Organización de las Naciones Unidas como la UNESCO.
2. Continuar la investigación sobre las lecturas antropológicas del cielo como forma de coadyuvar a la preservación de nuestra diversidad cultural y por lo tanto creativa.
3. Esbozar las condiciones para el desarrollo de un multilateralismo astronómico exitoso.

## I. La astronomía en la historia de la UNESCO, algunos hitos que recordar

### Astronomía y Naciones Unidas. Conferencia de San Francisco y Conferencia de Londres, así como la creación de agencias especializadas, como la UNESCO

Pretendemos en este espacio generar una breve historiografía de la relación entre la astronomía y la Organización de las Naciones Unidas para la Educación, la Ciencia y la Cultura (UNESCO) en los ámbitos de la ciencia y la información. Creemos que se trata de un



recorrido poco conocido y que ayudará al lector a entender los procesos de reflexión internacional, las vinculaciones intersectoriales y los programas y proyectos contemporáneos que pueden servir para colaborar con nuestra causa desde múltiples plataformas multilaterales, directa o indirectamente relacionadas con nuestra institución.

Antes de adentrarse en los antecedentes de la astronomía en la UNESCO, conviene revisar justamente la historia de la inclusión de la emblemática sigla *S* (que se refiere a *Science*, ciencia) en el nombre de la Organización. La primera referencia se encuentra en la Conferencia de San Francisco, celebrada del 25 de abril al 26 de junio de 1945 y en la que, por propuesta de la Delegación francesa, se acordó no resolver ahí la creación de un organismo internacional de cooperación intelectual (es decir, la UNESCO), sino más bien convocar a una futura reunión específicamente dedicada a la fundación del mismo. De acuerdo con Gail Archibald (2006, p. 38), fue un astrónomo, el estadounidense Harlow Shapley, quien, desde la Conferencia de San Francisco, propuso que esta nueva organización incluyera la ciencia en su nombre. Sin embargo, la propuesta fue desechada en ese momento por la misma delegación de la que formaba parte el astrónomo, por considerar que el mandato contenía demasiados conceptos.

Posteriormente, y ya en la conferencia específica consensuada en San Francisco y celebrada en Londres, los Estados que participaron en ella (México entre ellos) decidieron crear la UNESCO el 16 de noviembre de 1945 e incluyeron a la Ciencia como uno de los ámbitos específicos de su acción, por lo que se agregó la *S* en su acrónimo. En Londres, Ellen Wilkinson, Ministra de Educación del Reino Unido y Presidenta de la Conferencia que le dio vida a la UNESCO, afirmó:

*Aunque en el nombre original de la Organización no figura la ciencia, la Delegación británica presentará una proposición para que se la incluya de modo que el nombre sea Organización para la Educación, la Ciencia y la Cultura. En esta época, cuando todos nos preguntamos, quizá con miedo, qué más van a hacernos los científicos, importa que éstos se mantengan estrechamente relacionados con las humanidades y tengan conciencia de su responsabilidad para con la humanidad por el resultado de sus trabajos. No creo que, tras la catástrofe mundial, haya científico alguno que pueda sostener todavía que no le interesan en*

*modo alguno las consecuencias sociales de sus descubrimientos. (Valderrama, 1991)*

Esta relación entre ciencia y cultura dotó a la astronomía de un papel ejemplar con respecto a su función social y económica. Por ende, la astronomía tiene, desde entonces y hasta ahora, la capacidad de establecerse como materia articuladora entre las diversas agencias de las Naciones Unidas.

### Los primeros pasos

En junio de 1946, el profesor Henri Laugier, Secretario General Adjunto de las Naciones Unidas para Asuntos Económicos y Sociales (de 1946 a 1952),<sup>1</sup> presentó ante las Naciones Unidas una propuesta para el establecimiento de un laboratorio internacional de investigación que fungiera como órgano coordinador entre las actividades científicas de las naciones, con el fin de compartir información y servir de enlace entre los científicos. De acuerdo con su propuesta, ésta sería una de las principales tareas del Consejo Económico y Social de las Naciones Unidas, así como de la UNESCO. Unos días después, el 19 de junio de 1946, el *New York Times* dedicó un artículo en su primera plana para comentar la propuesta. El encabezado claramente expresaba: “La Secretaría de la ONU está lista para formar científicos del mundo que trabajen por la paz, tal y como alguna vez lo hicieron para la guerra” (Petitjean, 2006, p. 52). De esta manera, el artículo explicaba que una gran parte de los científicos más relevantes a nivel mundial había sido consultada y que, en tiempos en de paz, la investigación debía centrarse en temas como la tuberculosis, el cáncer, la erosión del suelo, la urbanización y la astronomía (Petitjean, 2006). Así, con la enumeración de esta serie de prioridades, la propuesta de Laugier contribuyó a resaltar la función social y económica de la ciencia, así como la debilidad en la que se encontraban los sistemas de investigación científica a nivel nacional.

Paralelamente, la UNESCO se encontraba definiendo las prioridades de su primer programa de trabajo. Para este fin, se creó una Comisión Preparatoria que, dividida en subcomisiones, solicitaría a los Estados Miembros de la UNESCO propuestas en cada uno de los ámbitos de su mandato.<sup>2</sup> Una vez reunida la información, Joseph Needham, artífice de la propuesta británica para la inclusión

1. Y miembro fundador de la UNESCO, en noviembre de 1945, como parte de la Delegación francesa.

2. En el caso de las ciencias naturales, la Subcomisión fue presidida por el mexicano Manuel Martínez Báez.



de la ciencia en el mandato de la UNESCO y quien poco tiempo después fuera a convertirse en el primer director del programa científico de la UNESCO, entregó a la Primera Conferencia General de la Organización un proyecto de programa en el que, entre otras tantas propuestas (por ejemplo, el Instituto de la Hylea Amazónica, propuesto por Brasil; un Centro de Matemáticas Aplicadas, propuesto por Francia, o centros de salud de parasitología e inmunología, propuestos por México), se incluía la creación de observatorios astronómicos.<sup>3</sup> Al respecto, vale la pena concluir con el hecho de que, además de este proyecto de programa, durante la Primera Conferencia General, Needham también especificó la lista del personal que compondría al Departamento de Ciencias Naturales, agrupado por las disciplinas científicas que deberían dominar: agricultura (1), astronomía (2), bioquímica (3), botánica (2), química (2), ingeniería aeronáutica (1), ingeniería civil (2), geografía (2), matemáticas (1), metalurgia (1), neurología (1), parasitología (1), patología (1), física (3) y radiología (3). Según su visión, era necesario contar con un amplio rango de competencias si se quería disponer de un verdadero centro de intermediación en ciencias naturales (Hadley y Nuotio, 2006, p. 531).<sup>4</sup>

Posteriormente, y tras ser consultado sobre la posibilidad de que el Consejo Económico y Social de las Naciones Unidas estableciera un laboratorio internacional de investigación, el mismo Needham entregó un informe redactado por él con el cual la UNESCO subrayó la importancia de las ciencias naturales al afirmar que, de todas las actividades con las que puede comprometerse el ser humano, las ciencias naturales son la más internacional de todas: “La raza, el color, el credo o la nacionalidad —escribió Needham— han demostrado no tener ningún tipo de relación con la plausibilidad de una hipótesis. Los científicos se pueden entender entre sí sin importar de dónde provengan” (Petitjean, 2006, p. 55). Al mismo tiempo, Needham recaló la necesidad de una acción concertada para resolver los grandes problemas, señalando que el esfuerzo que estaban llevando a cabo los laboratorios nacionales en términos de disciplinas científicas universales (física, química, ingeniería) era encomiable. El informe definía tres principios por tomar en cuenta: primero, no duplicar los esfuerzos; segundo, que la materia a la cual se quisiera dedicar un laboratorio o centro de investiga-

ción hubiera llegado a un estado de madurez suficiente; tercero, la necesidad de que los laboratorios se establecieran ahí donde se encontraban los problemas a los cuales se les quería dar solución, particularmente en aquellos sitios con poca investigación al respecto. Con base en estos principios, Needham identificó, además, nueve áreas prioritarias, entre las cuales los observatorios astronómicos ocupaban el primer lugar.

### La divulgación de la ciencia, el caso de la astronomía

Una de las primeras acciones emprendidas por la UNESCO en el ámbito de las Ciencias Naturales fue la publicación, en 1948, de un manual titulado *Sugerencias para maestros que enseñan ciencias en países devastados*, el cual contenía 201 sugerencias para construir aparatos científicos y realizar experimentos de física, química, biología y astronomía.<sup>5</sup> Si bien la obra estaba pensada particularmente para su uso en las zonas devastadas por la guerra, rápidamente fue traducido al árabe, al chino, al español y al tailandés, pues resultó sumamente promisorio para aquellas regiones con poca o nula experiencia en la enseñanza práctica de la ciencia.<sup>6</sup>

En 1950, y ya bajo el mando del físico francés Pierre Auger, el entonces Departamento de Ciencias Naturales organizó, como parte de su programa de divulgación de la ciencia, una exposición científica itinerante para dar a conocer en América Latina los últimos descubrimientos científicos en física y astronomía.<sup>7</sup> De acuerdo con una nota publicada en octubre de 1950 en *El Correo de la UNESCO* (medio de difusión oficial de la información de la Organización):

*El Museo Científico Circulante demuestra lo que puede hacer un auténtico espíritu de cooperación, ya que, si bien la idea y el plan del mismo fueron de la UNESCO, la ejecución sólo ha sido posible gracias a la devoción de varias instituciones científicas [...] las que han puesto a su disposición, y para todo el tiempo que tarde en desarrollarse el itinerario previsto, algunos de los instrumentos principales que se exhiben en el Museo (el generador hipersónico, el aparato de control termostático, el aparato de televisión, el modelo en madera de betatrón, etc.) [...]*

*¿Qué fines se propone la UNESCO con esa obra? En primer término, desarrollar su programa de divulgación científica, brindando a la*

3. A solicitud, de acuerdo con el mismo Petitjean, de la Delegación estadounidense y de la Unión Astronómica Internacional.

4. UNESCO/Prep.Com./Nat.Sci.Com/12.Paris.

5. Por ejemplo, telescopios reflectores y refractores, astrolabios, cuadrantes solares, identificación de estrellas y constelaciones, etcétera.

6. Para 1962, el manual ya contaba con una segunda edición ampliada con sugerencias de los expertos de la UNESCO, se había reimpresso 24 veces y traducido a 30 idiomas.

7. Vale la pena recordar que, por aquel entonces, el mexicano Jaime Torres Bodet se desempeñaba como Director General de la UNESCO.



Figura 1. *El Correo de la UNESCO* (mayo de 1966), número especial sobre "El hombre y el espacio". © UNESCO.

*América de habla española un modelo de museo científico que podía y debía extenderse por esos países; y, en segundo lugar, fomentar la curiosidad de las juventudes latinoamericanas, no sólo mostrándoles los esfuerzos y las realizaciones de los Clubes Científicos Juveniles sino presentándoles también los elementos materiales necesarios para el estudio y evolución de la moderna ciencia física y astronómica. (El Correo de la UNESCO, 1950, p. 2)*

Así, y según la descripción de la exposición de Alain Gille (2006, p. 83): "En adición a los paneles con explicaciones, las ampliaciones

de dibujos e ilustraciones, los diagramas y las fotografías, la exposición incluía un vasto número de aparatos científicos que podían ser manipulados por los visitantes, así como una serie de experimentos que se podían realizar al momento". Sin lugar a dudas, el hecho de transportar y poner al alcance de las personas equipos de observación astronómica implicaba un riesgo, pero la exposición resultó todo un éxito pues en los dos años que duró la itinerancia, se montó en 13 países y fue vista por casi medio millón de personas, siendo así una de las primeras y más importantes campañas públicas sobre astronomía.

Tras la sorprendente respuesta del público, la UNESCO continuó con la realización de este tipo de estrategias de divulgación. Así, en 1954 organizó una exposición titulada *El ser humano mide el Universo*. En esta ocasión, la exhibición estuvo dedicada a los instrumentos con los que la humanidad mide las distancias: desde lo infinitamente pequeño hasta lo infinitamente grande. Dividida en 10 secciones, la exposición transmitía los diferentes modelos que la humanidad había tomado como modelo para establecer sus sistemas de medición: la escala humana (el metro), la microbiana (el micrón), los virus y las grandes moléculas (el milicrón), la escala atómica (el ángstrom), la escala geográfica (el kilómetro), el sistema solar (la unidad astronómica), la escala interestelar (el año luz) y la intergaláctica (el pársec).

### La era espacial

Si bien la era espacial comenzó con el lanzamiento del primer satélite artificial (Sputnik I, 1957), *El Correo de la UNESCO* ya venía documentando, desde 1951, los avances de la ciencia y la astronomía en la exploración del espacio exterior. Así, por ejemplo, en un artículo publicado en abril de 1951, documentó la captación de la primera emisión radiofónica de la gran nebulosa de Andrómeda.

*Hasta hace poco tiempo —afirmaba el artículo— la astronomía era una ciencia "visual": la simple vista y el telescopio servían para sus observaciones. Hoy, una moderna rama de la Ciencia, la radioastronomía, nos abre otra ventana sobre el mundo y nos permite utilizar nuevos instrumentos para el estudio de los espacios interplanetarios. (El Correo de la UNESCO, abril de 1951)*



Figura 2. "Los proyectiles cósmicos y la investigación", artículo publicado en *El Correo de la UNESCO* (abril de 1951). © UNESCO.

Posteriormente, en noviembre del mismo año, *El Correo de la UNESCO* publica dos artículos, el primero de los cuales llevaba como encabezado: "La ciencia alcanza la imaginación de Julio Verne. La astronáutica prepara el viaje a la luna". En él, los avances de la astronáutica sirven como punto de encuentro para reflexionar sobre cómo estos logros se fundan en los grandes hitos de la astronomía y, también, en las ciencias humanas y las grandes expresiones



Figura 3. Sistema de Información Científica y Tecnológica de las Naciones Unidas (UNISIST). © UNESCO.

culturales que encuentran su raíz en la relación del ser humano con el cosmos: desde los mitos de origen distribuidos a lo largo y ancho del planeta hasta los hallazgos de Galileo y Newton, así como los postulados filosóficos de Kant o Laplace sobre aquella "nube de gas primordial que con el tiempo se contrajo, despidiendo al hacerlo la materia de la que se formaron los planetas".

En 1960, un año antes de que el ser humano finalmente realizara su primer viaje al espacio, *El Correo de la UNESCO* publicó un texto de V. G. Fesenkov, entonces Presidente del Comité de Meteoritos de la Academia de Ciencias de la ex Unión Soviética, titulado "Observatorio volante a través del espacio", en el cual se enumeraba la serie de condiciones atmosféricas que determinan los alcances en aquel entonces de la observación del cielo desde la Tierra, por ejemplo, la difusión de la luz solar, la luminosidad de la alta ionósfera o la imposibilidad de la penetración de los rayos cósmicos primarios a través del campo magnético de la Tierra.

La importancia, pues, de la cobertura y el análisis que dedicó *El Correo de la UNESCO* al tema de los viajes espaciales radica en el hecho de que, a través de ella, se reforzó la idea central que la UNESCO había manifestado desde su fundación: que la ciencia y la tecnología debían estar al servicio del mejoramiento de las condiciones de vida de la humanidad y, con ello, resultaba fundamental promover una cultura de paz a través de la cooperación para la investigación (en este caso enfocada en la astronomía) y la difusión de las implicaciones sociales de su conocimiento científico.



### Ciencia e Información en la UNESCO

Actualmente, la UNESCO se rige por el principio del Libre Acceso (*Open Access*) en cuanto a la información científica, pues sostiene que esta información, resultado de los proyectos científicos, es también el recurso más importante para la innovación. Esta dimensión, que se enmarca en el sector de la Comunicación y la Información,<sup>8</sup> tiene su primer antecedente en el Sistema de Información Científica y Tecnológica de las Naciones Unidas (UNISIST), el cual fue ideado a partir de una iniciativa conjunta entre el Consejo Internacional para la Ciencia y la UNESCO, a partir del establecimiento, en 1967, de un Comité que estudiaría la posibilidad de crear un sistema de este tipo.

*El estudio UNISIST se refiere a la manera de enriquecer este recurso mediante una mayor cooperación internacional para mejorar su accesibilidad y empleo con objeto de que, como recurso internacional, contribuya de la mejor manera posible al desarrollo científico, educativo, social, cultural y económico de todos los países. (UNESCO, 1971)*

Posteriormente, y tras la celebración en 1972 y 1979 de dos conferencias intergubernamentales sobre el tema, la UNESCO incluyó el Sistema como parte de su Programa General de Información, creado ya en 1976. A este respecto, es preciso recordar que, desde 1954, la UNESCO auspició, por solicitud de México, la creación de un Centro de Documentación Científica y Técnica para América Latina, en el que se albergaron y pusieron a disposición las colecciones de revistas científicas y los resúmenes de las investigaciones que se estaban llevando a cabo en la región. Años después, el acervo de este centro fue entregado al Instituto Politécnico Nacional para dar origen a la Biblioteca Central del Centro de Investigación y de Estudios Avanzados del Instituto Politécnico Nacional (CINVESTAV).<sup>9</sup>

### Dos programas, dos años internacionales

Desde 1973, la UNESCO y la Unión Internacional de Ciencias Geológicas (UICG) pusieron en marcha el Programa Internacional de Ciencias Geológicas (PICG, hoy conocido como Programa Internacional de Ciencias de la Tierra, PICT). Durante más de 40 años, el PICT ha funcionado como un catalizador de la cooperación internacional que estimula la transferencia de conocimientos entre las diversas regiones del mundo, promoviendo el diálogo interdis-

ciplinario y el establecimiento de redes. A lo largo de su historia, el PICT ha sustentado más de 400 proyectos con énfasis en la solución de necesidades sociales relacionadas con la geociencia. El programa ha dado prioridad al estudio de los sistemas terrestres, que incorporan temas de alta relevancia social, como la relación entre las comunidades humanas y la naturaleza (tanto biótica como abiótica), así como problemas de salud, cambio climático y extracción de recursos minerales e hídricos. El Programa ha desarrollado una muy relevante cooperación con instituciones y organismos relacionados con la investigación astronómica y el espacio. Asimismo, el PICT



Figura 4. Suplemento para niños de *El Correo de la UNESCO* (abril de 1973). © UNESCO.

8. El mandato de la UNESCO abarca actualmente cinco grandes sectores: Educación, Ciencias Naturales, Ciencias Sociales, Cultura y Comunicación e Información.

9. El 19 de enero del 2015, la Oficina de la UNESCO en México y el CINVESTAV firmaron un Convenio de Trabajo para realizar diversos proyectos de investigación científica, tales como el origen de la producción de alimentos en América o el desarrollo de la tipología de las milpas en Yucatán, entre otros.

promueve la educación en Geociencia y la creación de Geoparques. De acuerdo con sus objetivos: “Los Geoparques Mundiales de la UNESCO cuentan la historia de 4,600 millones de años del planeta Tierra y de los acontecimientos geológicos que le dieron forma, y el registro de todas las formas de vida, incluyendo la evolución humana sobre el planeta. No sólo muestran evidencia de los cambios climáticos en el pasado, sino que también informan a las comunidades locales de los desafíos actuales y ayudan a verificar riesgos y a enfrentar consecuencias tales como terremotos, tsunamis y erupciones volcánicas” (UNESCO, 2016a).<sup>10</sup> Sin duda se trata de un programa que puede coadyuvar a nuestros esfuerzos sobre los cielos oscuros (UNESCO, 2016b).<sup>11</sup>

Posteriormente, en 2002, la UNESCO puso en marcha el Programa de Educación del Espacio, a partir de los resultados y las recomendaciones de dos grandes conferencias mundiales: la Conferencia Mundial de la Ciencia, organizada por la UNESCO y el Consejo Internacional de la Ciencia (ICSU, por sus siglas en

inglés), celebrada en Budapest en 1999; y la Tercera Conferencia de Naciones Unidas sobre los Usos Pacíficos del Espacio Exterior (UNISPACE-III), organizada por el Comité de Naciones Unidas para el Uso Pacífico del Espacio Exterior y la Oficina de Naciones Unidas para Asuntos del Espacio Exterior, celebrada en Viena, también en 1999. En la Conferencia Mundial de la Ciencia se recomendó la mejora de la educación científica a través de la inclusión en la currícula de nuevos temas y metodologías de enseñanza, en UNISPACE-III se señaló la importancia de que las nuevas generaciones contaran con oportunidades para aprender más sobre la importancia de la ciencia y la tecnología en el desarrollo humano, a través de las ciencias del espacio. Así, y dado que en ambos casos se identificó a nuestra institución como la agencia de las Naciones Unidas más idónea para implementar dichas recomendaciones, la UNESCO creó un programa que vincula a las ciencias del espacio exterior (es decir, la astronomía, la aeronáutica, la ingeniería y la robótica) con la educación, introduciendo nuevos conocimientos, valores y perspectivas en la enseñanza escolar de la Tierra y del universo. Al mismo tiempo, los conocimientos del espacio exterior ofrecen una nueva y más novedosa perspectiva sobre los procesos de la ciencia y el desarrollo tecnológico. En última instancia, el programa persigue como objetivo ampliar la toma de conciencia sobre las implicaciones sociales que trae consigo la investigación espacial (y, dentro de ella, la astronomía), así como su impacto en el desarrollo sostenible y el bienestar de la humanidad.

De forma paralela, una de las estrategias a través de las cuales la UNESCO ha promovido la difusión y transmisión de conocimientos científicos, así como la concientización de la comunidad internacional sobre las implicaciones sociales y culturales de la ciencia, ha sido la celebración de los años internacionales. Así, y en el caso específico de la astronomía, se pueden destacar dos grandes ejemplos: el del Año Internacional de la Astronomía, en 2009, y el Año Internacional de la Luz y las Tecnologías basadas en la Luz, en 2015, conmemoración en el cual se enmarcó, justamente, la Reunión Internacional “El derecho a los cielos oscuros” de la Ciudad de México, cuyas conclusiones tiene ahora el lector en sus manos.

Con respecto al Año Internacional de la Astronomía, conviene destacar que en el 2009 se cumplía el 400 aniversario de la primera obser-



Figura 5. Gabriel Rodríguez, José Franco y Nuria Sanz durante la Reunión Internacional "El derecho a los cielos oscuros". © UNESCO/Nuria Sanz.

10. Véase: <[www.unesco.org/new/es/office-in-montevideo/ciencias-naturales/earth-sciences/geoparques](http://www.unesco.org/new/es/office-in-montevideo/ciencias-naturales/earth-sciences/geoparques)>.

11. Véase: <[www.unesco.org/new/en/natural-sciences/environment/earth-sciences/unesco-global-geoparks/list-of-unesco-global-geoparks](http://www.unesco.org/new/en/natural-sciences/environment/earth-sciences/unesco-global-geoparks/list-of-unesco-global-geoparks)>.





Figura 6. Diálogo y mesas de discusión durante la Reunión Internacional "El derecho a los cielos oscuros". © UNESCO/Nuria Sanz.

vación astronómica de Galileo a través de un telescopio. Así, durante el 2009 la UNESCO y la Unión Astronómica Internacional (UAI) lideraron todo un año de actividades con el fin de identificar y difundir las contribuciones de la astronomía a la sociedad y la cultura, con un énfasis en la educación, la formación de públicos y el involucramiento de los jóvenes. De acuerdo con Catherine Cesarsky, Presidenta Ejecutiva del Año Internacional, “además de celebrar las maravillas de la astronomía, los proyectos del Año Internacional 2009 tocaron las vidas de millones de personas en todo el mundo; para muchos, este fue su primer contacto con el tema” (UNESCO, 2009, p. 2). Los recuentos finales son relevantes: 40 organizaciones involucradas, 148 Comités Nacionales, 28 proyectos globales y más de 800 millones de personas que acudieron y participaron en alguna de las más de 140 actividades e iniciativas implementadas alrededor del mundo.

Uno de los grandes resultados del Año Internacional de la Astronomía fue la realización y publicación del estudio temático *Patrimonio de la Astronomía y Arqueoastronomía en el marco de la Convención del Patrimonio*, elaborado por la UAI y el Consejo Internacional de Monumentos y Sitios (ICOMOS y UAI, 2010).<sup>12</sup> El principal objetivo de este estudio fue identificar el Valor Universal Excepcional de los Sitios del Patrimonio Mundial vinculados con la astronomía, así como de otros sitios que no cuentan con un proceso de candidatura en la Lista, pero cuyo estudio resulta

igualmente significativo. El estudio presenta 44 casos de diferentes épocas y regiones, a partir de los cuales se han podido establecer las bases para desarrollar categorías de análisis comparativas. El estudio, además, contribuyó a la consolidación de una iniciativa que la UNESCO venía elaborando desde el 2003: la Iniciativa Temática “Astronomía y Patrimonio Mundial”. Esta iniciativa había comenzado como un proyecto piloto para “establecer un vínculo entre ciencia y cultura, a través del reconocimiento de los sitios y monumentos ligados a observaciones astronómicas”,<sup>13</sup> no sólo en términos científicos sino también de las culturas tradicionales. El informe se presentó en ocasión de la 36 Sesión del Comité de Patrimonio Mundial, celebrada en 2012 en San Petersburgo.<sup>14</sup>

En esa misma línea de acción, la Oficina de la UNESCO en México organizó en 2014 la Reunión Internacional “El papel de la arqueoastronomía en el mundo maya: el caso de la Isla de Cozumel”, cuyos resultados pueden consultarse en la publicación homónima, disponible en línea (<http://unesdoc.unesco.org/imagenes/0024/002447/244722S.pdf>).

Finalmente, con el Año Internacional de la Luz y de las Tecnologías basadas en la Luz, la UNESCO y la comunidad científica internacional conmemoraron varios hitos históricos de la ciencia de la luz, entre ellos: la presentación, en 1815, de la teoría de Fresnel sobre las

12. Disponible en: <[www2.astronomicalheritage.net/index.php/thematic-study-content](http://www2.astronomicalheritage.net/index.php/thematic-study-content)>.

13. Véase: <[whc.unesco.org/en/astronomy](http://whc.unesco.org/en/astronomy)>.

14. Para más información sobre la Iniciativa Temática “Astronomía y Patrimonio Mundial”, véase: <[www2.astronomicalheritage.net](http://www2.astronomicalheritage.net)>.

ondas lumínicas, la descripción de Maxwell sobre la teoría electromagnética (1865), la teoría de la relatividad de Einstein (1915) y el descubrimiento de la radiación de microondas de Penzias y Wilson, en 1965, así como el desarrollo de la fibra óptica a cargo de Charles Kao (también en 1965). Así, y a lo largo del 2015, se realizaron más de 5 mil eventos y actividades en los cinco continentes. Tan sólo con respecto a la astronomía, se llevaron a cabo cerca de 7 mil observaciones nocturnas del cielo y más de 40 materiales educativos sobre la luz y el cosmos, así como 675 exposiciones sobre el espacio en 30 países y en 12 lenguas distintas. Es, pues, con la noción del papel que tiene la luz en las actividades humanas y en la existencia misma de la vida, así como con la relación entre las tecnologías asociadas a la luz con las necesidades de bienestar y desarrollo humanos, que la Oficina de la UNESCO en México planteó, junto con el Consejo Nacional de Ciencia y Tecnología (CONACYT), la Coordinación de la Investigación Científica de la Universidad Nacional Autónoma de México y el Foro Consultivo Científico y Tecnológico, la importancia de realizar, justamente durante el Año de la Luz, la Reunión Internacional “El derecho a los cielos oscuros”, gracias a la cual hemos intercambiado experiencias e información y se ha generado una reflexión conjunta, como la que ilustran estas páginas, sobre la contaminación lumínica en México y en el mundo, además de definir las líneas de acción para continuar impulsando la investigación astronómica y el desarrollo de las comunidades astronómicas en la región. Por todo lo anterior, y en un marco más general de la cooperación científica internacional se analizaron sus implicaciones sociales, culturales y económicas, las relaciones de la astronomía con otros aspectos del desarrollo sostenible, tales como la búsqueda y el uso de energías asequibles y no contaminantes (Objetivo de Desarrollo Sostenible [ODS] número 9 de la Agenda 2030 de las Naciones Unidas), el diseño y la instrumentación de estrategias para el establecimiento de ciudades y comunidades sostenibles (ODS número 11), así como la protección y conservación de la vida y los ecosistemas terrestres (ODS número 15).<sup>15</sup>

## II. Una mirada desde América a las leyendas de la creación del cielo

Desde el inicio de nuestro propósito de organizar una reflexión multidisciplinar sobre el derecho a los cielos oscuros, defendimos la articulación de dos anhelos, por un lado, el de los científicos, y

por otro, el de las comunidades indígenas, cuya cosmogonía, ritos y prácticas culturales contemporáneas encuentran en el cielo un destino y un sentido a su quehacer sagrado y productivo. Y nos hemos dado a la tarea de investigar fuentes y estudios sobre la intrínseca relación entre cielo, cosmogonía, ritual y mito en la América indígena, que pueden ayudarnos a significar la conexión medular de cultura y pensamiento astronómico.

*La concepción mesoamericana concibe la estructura del cosmos tripartita: inframundo, tierra y región celeste, tres estadios que confluían en un centro vinculado a los cuatro puntos cardinales, una especie de ombligo del universo; un centro que daba vida a la máquina universal.*

*Durante tres milenios, mexicas, olmecas, nahuas y mixtecos, entre otros, coincidieron en representar del mismo modo la estructura cósmica, un origen del universo, en inicio, sin dioses (Florescano, 2016).*

Ya los mayas en el *Popol Wuh* describen la anterioridad del cielo con respecto a la tierra, al hombre y al maíz: “Ésta es pues la primera palabra, la primera expresión: cuando todavía no existía una persona ni animal, pájaro, pez, cangrejo, árbol, piedra, cueva, barranco, pajón, bosque, sólo el Cielo existía” (Anónimo, 2008).

Al mismo tiempo, como lo tradujo Miguel León-Portilla del *Libro de los Coloquios*, los astrónomos son los hacedores de relación humana-astral, lo cual no puede entenderse simplemente dentro de estrechos esquemas dualistas. Esta consideración nos parece esencial si se quiere analizar la concepción y la relación que establecieron los pueblos mesoamericanos con el cielo, así como su posterior desarrollo astronómico, cuya precisión aún sigue sorprendiendo a los especialistas.

*Los que ven, los que se dedican a observar el curso y el proceder ordenado del cielo, cómo se divide la noche. Los que están mirando [leyendo], los que cuentan [o refieren lo que leen]. Los que vuelven ruidosamente las hojas de los códices. Los que tienen en su poder la tinta negra y roja [la sabiduría] y lo pintado.*

*Ellos nos llevan, nos guían, nos dicen el camino. Quienes ordenan cómo cae un año, cómo siguen su camino la cuenta de los destinos y los*

15. La Agenda 2030 para el Desarrollo Sostenible puede consultarse en: <[www.un.org/es/comun/docs/?symbol=A/RES/70/1](http://www.un.org/es/comun/docs/?symbol=A/RES/70/1)>.

*días y cada una de las veintenas [los meses]. De esto se ocupan. A ellos les toca hablar de los dioses. (León-Portilla, 1986, s/p)*

En Mesoamérica, y en general en todas las antiguas culturas americanas, la observación astronómica es inextricable de la política y de la organización social, así como de otros desarrollos del conocimiento, específicamente las matemáticas, la escritura y la agricultura. “Lo que hay que destacar”, dice Alfredo López Austin (1994), “es que las sociedades que llamamos tradicionales tienen en su conducta y pensamiento una congruencia muy superior a la nuestra, proyectada en buena parte en su concepción de las leyes sociales y naturales, *indisolublemente unidas*”.<sup>16</sup> Así, por ejemplo, “las estelas [mayas] registran, sobre todo, eventos importantes en las vidas de los gobernantes y otros sucesos políticos vinculados con las dinastías. Por lo tanto, ‘el tema principal de la escritura mesoamericana fue la presentación de información política en una estructura calendárica’” (Marcus, en Broda, 2000).

En otro texto, Lucrecia Maupomé (1996, s/p) rescata una idea de Séjourné: “El pensamiento nahua [y por extensión, el mesoamericano] está cifrado por los calendarios”.<sup>17</sup> Tal expresión es rastreable en el origen mismo de Mesoamérica, en la cultura olmeca, donde el calendario era tan importante como una constitución. Desde entonces, el cielo era el pentagrama de la melodía política y productiva de las sociedades prehispánicas americanas.

Más allá de Mesoamérica, hacia el norte, los indios skidi organizaron los patrones de su existencia a partir de los movimientos estelares. Sus conceptos de organización y movimiento sideral definieron para ellos lo que debería ser masculino, lo que debería ser femenino y cómo ambos principios se combinan para producir a los seres humanos, a las plantas y los animales (Von del Chamberlain, 2009). Así, por ejemplo, las comunidades skidi consideran a la estrella Polaris como ejemplo de liderazgo político: tal y como el astro polar se mantiene en su sitio, siempre disponible, como si estuviera al tanto del resto de las estrellas, una función de faro, de vigía; así también el jefe de una comunidad debe mantenerse al pendiente de las necesidades de su pueblo (Von del Chamberlain, 2009). Por su parte, los navajos identifican a las estrellas como símbolos para vivir en equilibrio con las fuerzas de la naturaleza. Para

esta comunidad, *Náhookos bika’ii* (la Osa Mayor, principio masculino) y *Náhookos ba’iadi* (Casiopea, principio femenino) giran en torno a Polaris, así también el hombre y la mujer deben permanecer en torno al hogar, cerca del fuego, como una familia. Otro ejemplo de ética sideral lo brindan los tseltales, quienes encuentran en el camino que realiza el Sol una representación del bien. Cuando los tseltales hablan de hacer el bien, se refieren a ir hacia donde sale el Sol. El bien, *te lekilal*, permanece, nos trasciende y se enmarca en el cosmos. El bien nos llega a diario desde donde sale el Sol y con su recorrido se genera una realidad axial en la que se integra el bien del orden cósmico cotidianamente (Paoli, 2013).

### **La arquitectura que da forma a la concepción del cosmos. Arriba y hacia abajo por la misma escalera**

A partir de la orientación astronómica de sus sitios sagrados, las culturas prehispánicas dieron expresión a la unidad de medida de tiempo y de espacio. Las pirámides mismas son observatorios astronómicos en la medida en que éstas se construyeron a partir de una representación del cielo que no tiene forma de bóveda, sino que responde a una estructura piramidal. Así, el Sol sube escalonadamente hacia el cenit y luego desciende al inframundo.

“Mitología matematizada” es la manera en que León-Portilla define cómo la observación del cielo produjo otra expresión cultural característica de Mesoamérica, en la que se puede admirar la naturaleza integral de su pensamiento simbólico-práctico: “gracias a la extraordinaria habilidad escultórica de los olmecas, se levantaron algunas de las pirámides más antiguas de Mesoamérica, las cuales eran una representación simbólica del *kósmos*” (León-Portilla, 1986, s/p).

De todas las culturas mesoamericanas, los mayas son quizá quienes produjeron la mayor expresión astronómica de Mesoamérica. Gracias a sus conocimientos matemáticos, dieron seguimiento al curso de los astros, registraron solsticios y equinoccios, predijeron eclipses. Ahí está, como un testimonio, el Códice Dresde:

*Desde finales del siglo XIX se conoce muy bien cuál era la sofisticación del conocimiento de los cielos por parte del mundo maya. Desde el inicio de las investigaciones, el calendario y la práctica matemática no podían ser considerados de segunda categoría científica, pero sí provenientes de*

16. Las cursivas son nuestras.

17. Disponible en: <bibliotecadigital.ilce.edu.mx/Colecciones/index.php?c>.

*formas de hacer ciencia no-occidental. Desde las primeras lecturas del Código de Dresde se evidencian las visibilidades cíclicas de Venus y las relaciones entre los ciclos lunares y los eclipses. (Sanz, 2016, p. 16)*

El Códice Dresde está emparentado con otro códice mesoamericano, el Borgia, en el que se hallan numerosas representaciones gráficas del cielo con color dominante gris oscuro, círculos y puntos negros, o bien con pequeños detalles en forma de herradura y estrellas, representadas convencionalmente como “ojos de la noche”. A veces la imagen contiene también el dibujo de cuchillos de pedernal. Se sabe que es el cielo nocturno por la presencia de la Luna (Mikluska, 2015). “No cabe duda de que las pirámides escalonadas de los antiguos mexicanos, en cuyas cúspides había adoratorios, eran también representaciones de los asientos de las deidades en las alturas celestes” (Preuss, en Neurath, 2015).

Por ello, no sorprende que, así como en su cúspide hubo adoratorios, alrededor de las pirámides, se hayan encontrado numerosas cuevas de importancia ritual y astronómica: por ejemplo en Xochicalco o en la misma Teotihuacán. Bocas subterráneas a través de las cuales el Sol finalmente descendía al inframundo. Como recuerdan Moragas Segura y Sarabia González (s/a), debajo de la Pirámide del Sol se halla una cueva

*en la cual se realizaban ritos religiosos relacionados con el agua, la fertilidad o ceremonias de investidura y oráculos, [la cueva] parece ser el elemento que sirvió de atracción religiosa de la población en un punto concreto del Valle antes de la construcción de las pirámides. Para [Doris] Heyden la existencia de esta cueva se puede relacionar con el concepto de Chicomostoc o “lugar de origen”.*



Figura 6. Izquierda: La Tabla de Venus del Códice Dresde fue usada por los sacerdotes para conocer los augurios relacionados con este planeta. Centro: La página 27 del Códice corresponde a las ceremonias de los *uayeb*, o cinco días aciagos, los cuales marcaban el final del año y el primer día del año nuevo. Derecha: En las páginas 43 a 45 de este códice se muestra una tabla de 780 días, con un monstruo que desciende del cielo. Se le llama Tabla de Marte por coincidir con el periodo sinódico de dicho planeta, de 779.936 días. © UNESCO/Nuria Sanz.



En su aportación al volumen *El papel de la arqueoastronomía en el mundo maya: el caso de la Isla de Cozumel*, Jesús Galindo Trejo (2016, p. 21) comienza afirmando que:

*La observación sistemática de la bóveda celeste dio al habitante mesoamericano la posibilidad no sólo de generar su propio sistema calendárico, sino también la de crear una manera peculiar de orientar sus principales estructuras arquitectónicas. [...] Se trata de una especie de relojes cósmicos que todavía funcionan, aunque sus creadores ya no están.*

Quizá el ejemplo más popular del funcionamiento de esos “relojes cósmicos” es la Pirámide del Castillo en Chichén Itzá, que adquiere notoriedad cada equinoccio por el “descenso de Kukulcán”, fenómeno que incluso ha sido estudiado por la NASA, según lo refiere Montero García (2016, p. 86).

Otro caso ejemplar es, sin duda, el de Teotihuacán, la Ciudad de los Dioses, con su majestuosa arquitectura dispuesta según la perspectiva cosmogónica-religiosa, principalmente en las pirámides del Sol y de la Luna. Es ahí, en Teotihuacán, donde toma lugar el mito del Quinto Sol:

*Los pueblos que llegaron a asentarse en el valle de México después de 750 d. C. vieron esparcidos aquí y allá restos de esculturas y cerámica; adivinaron que debajo de los montículos de tierra existían edificios y calzadas; pero no sabían quién los había construido. Entonces los atribuyeron a los dioses. El mismo nombre de la ciudad así lo refiere: “lugar donde nacen los dioses”. El topónimo surge cuando esos pueblos deciden que fue en Teotihuacán donde se convocó a los dioses para crear el Quinto Sol y, por ende, al hombre. (Matos Moctezuma, 2012, pp. 11-12)*

Los incas también desarrollaron un sofisticado sistema de estructuras monumentales para registrar los movimientos del Sol a lo largo del horizonte circundante andino. En su caso, se preocuparon por ubicar en un sitio la creación del Sol, pues ello les permitió emparentarse con el astro, tal y como los mexicas lo hicieron con Teotihuacán. Para los incas, este sitio estaba en el lago Titicaca, la Isla del Sol, donde también nacieron la Luna y las estrellas y donde además se formó el primer ser humano, Manco Cápac. Así lo re-

fiere Cristóbal de Molina (1613) en su relación de 1573, de la cual respetamos la grafía del original:

*dicen que era de noche y que allí hizo el Sol y la Luna y estrellas, y que mando al Sol y Luna y estrellas fuesen a la isla de Titicaca, que esta allí cerca, y que desde allí subiesen al cielo. Y al tiempo que se queria subir el Sol en figura de un hombre muy resplandeciente, llamo a los Incas y a Manco Capac como a mayor dellos, y le dijo: “Tu y tus descendientes habeis de ser senores y habeis de sujetar muchas naciones; tenedme por padre y por tales hijos mios os jacteis [...]”.*

Recuerda David S. P. Dearborn (2000) que “existe evidencia histórica que sugiere que la Isla del Sol fue un sitio de adoración al Sol y el punto atribuido de su nacimiento desde mucho antes del arribo del imperio Inca. Esta asociación con el astro se puede extender por lo menos a los indios Colla, quienes ocuparon el área mucho antes de la incursión Inca”.

Además, como asientos de la Tierra, como sitios de refugio, como entradas al inframundo, las cuevas están emparentadas con el cielo. Confunden, sin duda, los términos castellanos *inframundo* o *subterráneo*, pero hay que recordar, como lo hace Katarzyna Mikulska (2015, p. 114), que:

*la palabra nahua ilhuicatl, “cielo”, se usa en referencia no sólo al espacio celeste, que desde el punto de vista occidental está encima de la tierra, sino a varios lugares que son al mismo tiempo destinos de los muertos. [...] Este lugar puede ser la “casa del sol” —tonatiuh ichan ilhuicatl—, el cielo [...] a donde iban los guerreros muertos en combate, las mujeres muertas en el primer parto y los niños ofrecidos a Tlalloc [sic]. También puede ser el “cielo Tlallocan”.*

Lo que estas imágenes manifiestan, escribe Ana Díaz (2015), es que “el arriba y el abajo comparten la misma naturaleza, pero la importancia de sus cualidades está en la transformación que se genera mediante la acción ritual: la palabra y la ofrenda, que preceden y dirigen la transformación”.

No por nada, para los huaves de San Mateo del Mar (Oaxaca), a cada difunto en la tierra le corresponde una estrella en el cielo. También



para ellos el Sol atraviesa el inframundo (“las entrañas de la tierra”) y vuelve a salir por el oriente, donde tiene su casa: hacia donde miran los que rezan y hacia donde se orientan las tumbas de los muertos (Lupo, 1991).

### De las palabras, de los mitos y las cuentas

De acuerdo con datos de Ulrich Köhler (2001), los tzotziles chiapanecos de San Pablo Chalchihuitán reconocen hasta 20 fases de la Luna y que su existencia no sólo se encarna en el uso de frases y palabras específicas para nombrarlas, sino también en gestos y posiciones. Por su parte, los achíes mayas de Guatemala indican el tiempo de sequía remedando con la mano un cuenco horizontal que hace referencia a la Luna llena. Para referirse al tiempo de lluvias, el mismo cuenco de la mano se gira para verter el líquido de la Luna. Actualmente, en la Amazonia peruana, los indios amuesha dividen la noche en seis subperiodos y cuentan con un término definido para identificar cada uno: *tsapuen* (de las 18 a las 20 h); *rantaren* (de las 20 a las 23 h), cuya raíz proviene de *ranto*, que quiere decir “estrella”, con lo cual se reconoce el momento en que éstas son más visibles; *po’cto’tsentsap* (de las 23 a las 24 h); *narenen* (de las 24 a las 2 h); *puetarenmoch* (de las 2 a las 4 h), y *shocshocaren* (de las 4 a las 6 h) (Santos Granero, 1992).

Sin lugar a dudas, esta expresión contemporánea de los indios amuesha recuerda la tradición cristiana de la división de la noche en vigiliat, transmitida en latín por San Isidoro en el siglo VII y luego vertidas a las lenguas romances por Alfonso de Palencia en el siglo XV: tarde (cuando el Sol se pone), crepúsculo (cuando comienzan las tinieblas), concubio (cuando los hombres se duermen), noche intempesta (cuando los animales ya reposan), continio (cuando todo se encuentra en imperturbable silencio), gallicinio (cuando los gallos comienzan a cantar), dilúculo (cuando se anuncia la llegada del alba) y antelucano (cuando el alba comienza a esparcir las tinieblas).

Ahora bien, en el caso de las culturas precolombinas, el mensaje cifrado en sus sitios arqueológicos responde a un ciclo cosmogónico que se repite en sus mitos, con ligeras variaciones. De los olmecas a los mexicas, las imágenes visuales, los ritos y ceremonias y los mitos pintados en los códices propagaron el mismo relato acerca de la

creación del cosmos y el principio de los reinos (Florescano, 2012). El cielo marcaba el origen y el destino.

Es el caso del Quinto Sol de los mexicas, como ya se ha dicho, pero es también el caso del Popol Vuh de los mayas o del Códice de Viena de los mixtecos. Como lo señala Florescano (2012), la estructura del mito es idéntica a la de los Cinco Soles: creación del cosmos, manifestación de los dioses, ordenamiento del mundo, nacimiento de los seres humanos e historia de sus reinos. Además de identitaria, la secuencia mítica contribuye a preservar la memoria colectiva, ancestral. Y son el cielo y su observación de donde se desprende este mecanismo. Como recordaba el mitólogo Joseph Campbell (2013): “Hoy sabemos que provenimos del espacio, ya que fue en ese espacio primordial donde se formó nuestra galaxia, a la que pertenece nuestro Sol, que nos da vida. Y este planeta, de cuya materia estamos hechos, es un satélite que gira alrededor de ese sol”. Para Campbell, el Universo es “nuestro gran ancestro”. Mirar al cielo, por lo tanto, es observar el punto más distante de nuestro pasado. Ahí está nuestro origen.

### El cielo está vivo, y llora

Para las culturas precolombinas, el cielo estaba vivo. Así lo demuestra, por ejemplo, la información que sobre los incas dejó el cronista Polo de Ondegardo (1571). De acuerdo con su relación, entre las constelaciones de los incas se encontraban varios animales y aves, incluyendo llamas, felinos y serpientes:

*Y, generalmente, [de] todos los animales y aves que hay en la tierra, creyeron [los incas] que hubiese un su semejante en el cielo, a cuyo cargo estaba su procreación y aumento. Y, así, tenían cuenta con diversas estrellas, como las que llamaban Chacana y Topalorca y Marrana y Mirco y Miquiquiray, y otras así. (González Pujana, 1994)*

Actualmente, los indios amuesha, a quienes ya nos hemos referido, consideran que la posición de las estrellas en determinadas épocas del año está ligada a los hábitos migratorios de las aves, a la floración y fructificación de los árboles o a las diversas etapas del ciclo biológico de los animales salvajes (Santos Granero, 1992).

En el Pacífico americano, de acuerdo con la mitología polinesia hawaiana, el viaje del Sol de un extremo al otro del cielo es un sím-



Figura 7. Vista del cielo estrellado en el Estado de Coahuila. © César Cantú.



bolo que contiene, en sí mismo, a todas las generaciones humanas habidas y por haber:

*Ku, hombre o esposo (kane), e Hina, mujer o esposa (wahine), son invocados como los grandes dioses ancestrales del cielo y la Tierra. Juntos, controlan a la fertilidad y la procreación humana. Ku significa “crecer erguido” e Hina significa “inclinarse hacia abajo”. El Sol, al amanecer, es referido como Ku, y al ponerse es nombrado Hina. Por lo tanto, la mañana le pertenece a Ku, mientras que el atardecer le pertenece a Hina. Las alabanzas para Ku se dirigen hacia el Este, las de Hina hacia el Oeste. Juntos contienen a toda la Tierra y el cielo, de Este a Oeste, en un símbolo que contiene a todas las generaciones del ser humano, tanto de los que vendrán como de los que ya han nacido. (Beckwit, 1940)*

A final de cuentas, si la Tierra es el asiento de la vida, el cielo es el techo que cobija y nutre sus manifestaciones. Quizá por ello los huicholes conciben el tejado de zacate de sus templos como un equivalente al cielo, el cual debe renovarse periódicamente mediante la acción ritual. Quizá por ello, los navajos representaron al cielo en la bóveda de sus cuevas sagradas. Quizá por ello las casas en las que habitaron los skidi eran utilizadas como observatorios desde los cuales rastrearon los movimientos del cielo. Quizá por ello los huaves de San Mateo de Mar (Oaxaca) corroboran la sacralidad del cielo al comparar a las estrellas con las velas de una iglesia. Quizá también por ello los mayas modernos de Cobá (Quintana Roo) cortan los postes que usarán para erigir sus casas en la época de plenilunio, para asegurarse así de que se conserven bien y se mantengan firmes. Porque, como lo recuerda López Austin (1994) para los pueblos indígenas actuales, los árboles, las lombrices, los animales domésticos y los mismos seres humanos contienen más o menos agua, de acuerdo con las fases lunares. Si la Luna brilla menos que el Sol es porque se trata de un recipiente que se vacía, que “llora”, que “deja escapar su líquido que es luz, que es llanto, que es lluvia”.

La América indígena contemporánea necesita cielos nocturnos visibles para seguir creyendo en lo que le significa.

### III. Soberanía nacional vs. multilateralismo astronómico exitoso

¿Cómo discutir el concepto de *soberanía celeste*? En pocos años las ventanas privilegiadas al estudio del universo van a reducirse a un número no superior a cinco países en el orbe, pero la generación de conocimiento sólo puede ser el resultado de proyectos multipaís, aunque el cielo se observe desde un territorio nacional. Y lo que es más importante, los resultados son esenciales para todos.

Esta forma de generación de conocimiento nace compartida y se disfruta colectivamente. Los megatelescopios que anuncian paisajes astronómicos cada vez más sofisticados van a concentrarse en territorio chileno en la próxima década. Chile va a emplazar 70 % de las infraestructuras mundiales en 2025, y esto ha significado un reto en cuanto a la traslación de su industria, de su innovación y de su política pública al servicio de la astronomía. Es ahora cuando la exploración debe conducirnos a una forma de diplomacia científica y cultural, capaz de formular sistemas y mecanismos de cooperación internacional y de inventar una nueva fórmula de multilateralismo eficaz en el siglo XXI. Se trata de una empresa pública internacional en un territorio nacional, lo cual implica inventar formas de innovación multilaterales y formas de protección colaborativa de largo plazo. En otras palabras, el cielo nos obliga a otra forma de concierto mundial para proteger el paisaje más común para todas las culturas sobre la tierra.

Sin duda este escenario de cooperación puede encontrar algunas referencias previas en la tan discutida Convención de las Naciones Unidas sobre el Derecho del Mar y que ahora va a reanudarse en el seno de la Organización a través de New UN Treaty for the Conservation and Sustainable Use of Marine Biological Resources in Areas Beyond National Jurisdiction under the United Nations Convention on the Law of the Sea.

#### Patrimonio Común de la Humanidad

El concepto *patrimonio común* de la humanidad surge a mediados siglo XX, aunque algunos autores han intentado rastrear su origen en la obra de Francisco de Victoria y en la obra de algunos americanistas, como Andrés Bello.

Desde el punto de vista jurídico se ha relacionado este concepto con los de *res communis* y *res nullius*, los cuales provienen del derecho romano y su usan, el primero, para definir bienes comunes y, el segundo, para recibir cosas sin dueño. En el primer caso quedaban incluidos los bienes que no le pertenecían a nadie, de uso común, eran bienes de todos pero no apropiables, lo que impedía el desarrollo de derechos reales sobre ellos e implicaba el principio de libertad de uso común para todos. En el segundo caso, las cosas sin dueño pasan a formar parte de la propiedad de las personas y, a partir de ahí, sirve como fundamento para la concepción clásica del derecho internacional sobre apropiación de territorios que han sido descubiertos, ocupados o apropiados.

Otro concepto importante que tener en cuenta es el de *interés común de la humanidad*, que para algunos expertos constituye el fundamento para la articulación del concepto de *patrimonio común de la humanidad* y forma parte de tratados internacionales más recientes, de acuerdo con una tendencia que postula la necesidad de introducir en el ordenamiento jurídico internacional un principio que descansa sobre la consideración de la humanidad como titular de derechos sobre determinados ámbitos o espacios físicos, recursos que representan el interés común de la humanidad.

La idea del interés común lleva a la comprensión de que con independencia de los intereses propios de cada nación hay una concurrencia de fines compartidos que tiene que ver con aspectos que se derivan de un interés común. Y es sin duda esta acepción la que está más cerca de nuestros propósitos. A lo largo de toda la historia de las relaciones internacionales se puede identificar cómo en determinados momentos se ha llegado a la constitución jurídica de lo que significan los intereses o bienes comunes o algunos otros conceptos que reconocen la existencia de bienes de pertenencia común a todos los seres humanos.

El concepto de *patrimonio común de la humanidad* surge en el derecho internacional en el ámbito del derecho del mar. Pero tenía que ver con los espacios situados más allá de las jurisdicciones de los Estados. La primera vez que se utiliza el concepto es en un discurso del Presidente de los Estados Unidos, Lyndon B. Johnson, en 1966, con el objeto de proteger el mar de distintas formas de competencia. Poco a poco, su utilización va avanzando en todo el derecho internacional



en relación con los bienes comunes, donde debe prevalecer sobre la competitividad un concepto de *res communis*. Y algunos de los principios que regulan ese concepto son el uso pacífico, la libertad de acceso, exploración e investigación científicas, el reparto equitativo de los mismos en beneficio de toda la humanidad. Pero toda esta reflexión parte de la existencia de un espacio determinado donde no se considera la jurisdicción de ningún estado en particular. El patrimonio de todos habría de construirse fuera de la soberanía de las naciones. Caso diametralmente contrario al que ahora nos ocupa.

Ahora se trata, sin embargo, a propósito del cielo, de fomentar la cooperación científica con fines pacíficos, difundiendo los resultados de los programas y colaborando para reforzar la capacidad de investigación, pero desde las ventanas al universo instaladas en un territorio nacional soberano y con un propósito común: beneficiar a toda la comunidad internacional.

Sin duda los cielos oscuros abren otras ventanas a la reflexión multilateral.

La lectura de estos mitos sobre el cielo define mejor nuestras formas de humanidad. El ejercicio de la astronomía puede ser demostrativo de que el beneficio es para todos y cuya práctica puede convertir esa forma ancestral de respeto en una forma de ciudadanía y de responsabilidad social.

En los aspectos aquí considerados la ciencia tiene obligación de comunicar y de ayudar a traducir los avances científicos en términos de desarrollo local. Quizá en un futuro no muy lejano podamos inventar alianzas cuyo propósito sea generar reservas internacionales de cielos estrellados. Como una forma de “astronomía para el desarrollo”. Sin duda, el conocimiento astronómico es una ventana a otras ciencias y a otras culturas, y goza de una suerte de efecto intercambiador.

Las colosales inversiones financieras que demandan las renovadas infraestructuras de observación astronómica requieren además ser explicadas a la opinión pública con todo rigor y explicitando el beneficio social que permite justificar los costos, también astronómicos, de estas empresas científicas y tecnológicas, especialmente ahora que acabamos de estrenar una Agenda Mundial para el Desarrollo

que necesita cumplir con 17 objetivos, pero que especialmente debe cumplir con la eliminación de la pobreza en el mundo, como reto primero y absoluto.

Todos los participantes son conscientes de que la puesta en práctica de las legislaciones y normativas tiene por sí misma un alcance limitado y que el practicar con el ejemplo depende de una rigurosa articulación de propósitos con una ciudadanía bien informada, responsable y exigente, que colabore con los cargos públicos responsables de las infraestructuras urbanas, planificación territorial, vivienda, y con todos aquellos que ocupan una responsabilidad en la política pública urbana, sin olvidar las alianzas urgentes con los sectores productivos y empresariales público-privados.

Los convocados a esta reunión se reiteraron convencidos del papel de la investigación arqueológica y reflexionaron sobre las recomendaciones formuladas por el Instituto Nacional de Antropología e Historia de México al respecto de los lugares ligados a la arqueoastronomía, a modo de continuidad con lo ya avanzado por la reunión organizada por el Oficina de la UNESCO en México y el Gobierno de Quintana Roo/Cozumel (UNESCO, 2016c).

Los cielos “arqueológicos” son fundamentales para entender los sitios ligados a la arqueoastronomía de una forma comprehensiva, y promover un grupo de estudio y planeación interdisciplinaria. Arquitectura, traza urbana prehispánica y bóveda celeste son realidades que deben entenderse de forma integrada. Del mismo modo reconocen el papel esencial que desarrollan los planetarios, como museo-centro de interpretación de sitio, y la necesidad de que cuenten con la mejor documentación científica y con el asesoramiento cercano y fundamental de astrónomos profesionales y de pedagogos. Poder ver el cielo arqueológico a través de la observación de los astros hoy es el mejor espectáculo, sin luces ni sonido.

Formas de interpretar (ciencia) o de interrogar el sentido de la naturaleza celeste (antropología) han ido explicitando la gran contribución social de la ciencia astronómica. A pesar de las regularidades, el cielo nunca es un blanco fijo. Las variaciones devienen en sorpresas que a su vez se convierten en respuestas. Todos debemos ser vigías del universo. Los científicos y el cielo nos necesitan a todos.



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Chapter 2

# Astronomy

Capítulo 2

# Astronomía







# The Evolution of Astronomy: from Photons to Petabytes

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## Abstract

Since the middle of the twentieth century, astronomers from around the world have sought out the unquestionably best places in the world to build great observatories from which to explore the universe through optical telescopes, seeking answers to fundamental questions of astronomy, of physics and of humanity. While many of the basic questions remain the same today, the way science is done at these modern mountaintop laboratories has rapidly evolved over the past twenty years with the arrival of digital detectors that can be mosaicked into larger and larger focal planes. This evolution has taken astronomers from the analysis of kilobytes of data to the challenge of sifting through petabytes of data and data products. We explore this evolution through the ‘case study’ of the discovery of Dark Energy, looking not only at the impacts of changes in technologies, but also at the changes in how astronomers and their collaborations approach their search for answers. That said, although our methods may be changing, the future of ground-based astronomical observations depends on the essential availability of the dark skies over the mountaintop sites, these ‘windows to the universe’ through which we explore the cosmos.

## Resumen

Desde mediados del siglo XX, astrónomos de todo el mundo han tratado de localizar los que incuestionablemente son los mejores lugares para construir grandes observatorios desde los cuales explorar el universo a través de telescopios ópticos, para buscar respuestas a las preguntas fundamentales de la astronomía, de la física y de la humanidad. Aunque muchas de las preguntas básicas siguen siendo las mismas hoy, la forma en que se hace ciencia en estos modernos laboratorios en la cima de las montañas ha evolucionado rápidamente durante los últimos 20 años, con la llegada de los detectores digitales que pueden hacer mosaicos de planos focales cada vez más grandes. Esta evolución ha llevado a los astrónomos del análisis de kilobytes de datos al desafío de examinar cuidadosamente petabytes y productos de datos. Exploramos esta evolución mediante el “caso práctico” del descubrimiento de la energía oscura, considerando no sólo los efectos de los cambios en las tecnologías, sino también los cambios en la forma en que los astrónomos y sus colaboradores abordan su búsqueda de respuestas. Dicho esto, aunque nuestros métodos pueden que estén cambiando, el futuro de las observaciones astronómicas terrestres depende fundamentalmente de la disponibilidad de cielos oscuros sobre los sitios en las cimas de las montañas, estas “ventanas al universo” a través de las cuales exploramos el cosmos.

## Introduction

High in the peaks of the Andes in northern Chile, as well as other special mountains around the world, astronomers from all over the globe work nightly, looking for answers to some of the most fundamental questions of humanity. Answers to questions such as:

- Where do we come from? How did the universe begin?
- Where do the elements from which we are made come from?
- Are there other planets, and is there life on any of them?
- Where are we going?
- What is the destiny of our universe?

We look for the answers in the skies, the dark and pristine night-time skies over these special mountaintop laboratories. These are privileged places, where we find the best skies in the world and where astronomers have worked and collaborated for more than fifty years.

### Identifying the Best Sites on Earth

Many factors go into the identification of the best sites for astronomical observatories. The most important, of course, are related to the skies. The natural conditions of the night-time skies are critical. An essential natural condition is the number of clear nights, given that at least at optical wavelengths clouds block the access to the light from the stars and galaxies astronomers seek to study. The best sites in the world offer more than 250 and, sometimes over 300, usable nights for astronomical observations. These locations provide for effective investments, given that the cost per night of operating the telescopes at an observatory may range from US\$10,000 to \$100,000. Cloudy nights with no productive observations are therefore rather expensive prospects!

Another key element of the best astronomical sites is minimal atmospheric turbulence over the mountaintops, characterised as 'seeing' by astronomers. This turbulence distorts the light passing through the atmosphere above the telescopes, which leads to blurry images, just as it does when one looks at distant objects along a hot highway. This turbulence creates the 'twinkling' of the stars

we see in most places. Good astronomical sites are characterised by having very little turbulence overhead, which leads to sharp images of stars, also known as 'good seeing'. The best sites are found where the winds flow over the mountains relatively undisturbed at all altitudes. This condition is most often found where the winds approach the site from the ocean, such as on the western coasts of the United States and Chile, or island sites such as Hawaii or the Canary Islands.

The other key requirement for excellent astronomical sites is the darkness of the skies. As astronomers push the frontiers of our understanding of the universe, they most often are studying fainter and fainter targets, objects that are either more distant or simply intrinsically less luminous than those previously studied. In order to detect and study these faint sources, the background glow of the sky must be minimal. While this is a natural characteristic of good sites, it is one that can be easily modified or destroyed by man-made lighting, such as that from nearby cities. Indeed, most of the sites along the western coast of the United States that fulfil the previously mentioned natural characteristics of good astronomical sites have been severely compromised by light pollution from Los Angeles and other large cities in California.

Beyond these natural conditions, there are additional factors that enter into the evaluation of astronomical sites that have less to do with the actual astronomical observation and more to do with the ability to operate the observatory. These include the available infrastructure, such as reliable roads, electricity and lines of communications. Perhaps the most important of these factors is the commitment and support of the government and local communities. Without long-term and solid commitments, investing the millions of dollars necessary for the installation and operation of an observatory carries great risks. Over the decade timescales that these observatories operate, support for protection of the sites is critical for the continued success and possible growth of the facilities at any given site.

### Classic Astronomy at High-Mountain Observatories

As astronomy progressed into a more and more quantitative science in the early 1900s, astronomers worldwide began to seek out the



Figure 1. Dark skies over Cerro Tololo Inter-American Observatory as the Moon rises to the east. © NOAO/AURA/NSF.



Figure 2. The mountaintop sites of AURA Observatory in northern Chile, with Cerro Tololo in the foreground and Cerro Pachon in the background. © NOAO/AURA/NSF.

most extraordinary sites on the planet for the installation of new generations of large telescopes. These sites were most often located on distant mountaintops, hundreds if not thousands of miles away from the home institutions. ‘Classical observations’ of the mid-to-late 1900s developed into a demanding endeavour, involving travelling thousands of miles to the mountaintop facilities, where one would spend several nights observing in the cold domes, concentrating on guiding the telescope for long hours in order to collect data on distant objects. The value of clear skies grew even more important given the investment that the trip to the telescope entailed and the potential disappointment of being met with cloudy skies, resulting in few or no observational results.

The data from these observations were carefully recorded for later analysis, first on photographic plates and later on a rapidly changing variety of digital media, from 9-track tapes to CD and DVD ROMs and later, portable hard disks. After the long trip home, the astronomer(s) processed and analysed the data, often dedicating months of work in order to extract detailed information from the data that had been collected during each night of observation at the observatory. While advances in detectors provided the opportunity for much more precise measurements, the fundamental characteristics of this classical approach of astronomical observation and analysis continued to be common throughout the 1990s and into the 2000s.



Figure 3. Hubble Space Telescope image of supernova 1994D in galaxy NGC 4526. © NASA/ESA, The Hubble Key Project Team and The High-Z Supernova Search Team, licensed under CC BY 3.0.

### A Case Study in the Evolution of Astronomy: Supernovae and Dark Energy

In the 1990s, advances in digital detectors, most importantly charge-coupled devices (CCDs), opened the opportunity for new methods to be applied to probe some of the fundamental questions explored by astronomers. These detectors allowed for surveys of the sky with greater uniformity, sensitivity and speed, while also opening the possibility of rapid observations of objects whose characteristics changed significantly over short periods, from hours to months, permitting the effective exploration of the universe in the time-domain. The study of supernovae and their possible use as precision distance indicators is one of the fields that best exemplifies the rapid evolution of astronomy over the past two decades.

In 1989, a team of astronomers from Cerro Calan/University of Chile and Cerro Tololo Inter-American Observatory (CTIO) undertook a supernova survey that set out to use the newly available CCD detectors to obtain high-precision photometry of supernovae. Given that these events are relatively rare, the 'Calan-Tololo' survey (Hamuy et al., 1993) used photographic plates on the wide-field CTIO/University of Michigan Curtis Schmidt telescope to observe large areas of sky in order to discover young supernovae. Follow-up observations were then performed with a CCD camera on the CTIO 0.9 m telescope, allowing for precise measurements of the brightness of these supernovae as they faded. The 32 Type Ia supernovae discovered during this survey provided the foundation for the development of the Phillips relationship (Phillips, 1993), which demonstrated that although these supernovae were not a

completely homogenous class of objects, their maximum observed brightness could be calibrated and thus, due to their immense intrinsic luminosities, they could be used to determine quite accurate distances at cosmological scales.

With this tool in hand, two teams, one led by Brian Schmidt and the other by Saul Perlmutter, set out to measure nothing less than the destiny of the universe, a determination of whether or not the predicted deceleration of the expansion of the universe would eventually lead to it collapsing back upon itself. Driven by the requirements to detect and follow faint, distant supernovae quickly and reliably, the two teams transitioned to using wide-field CCD detectors on the CTIO Blanco 4 m telescope in the search for supernovae, along with CCD imagers on telescopes around the world for the follow-up observations. The volume of digital data increased by an order of magnitude, and the data from the Blanco telescope had to be processed and analysed in close to real time in order to achieve the goals of these two supernova surveys. In the end, the abilities to collect and analyse these data and rapidly follow up with observations of the supernovae led to the completely unexpected discovery of the accelerating universe (Riess et al., 1998; Schmidt et al., 1998; Perlmutter et al., 1999), a result that was later recognized with the Nobel Prize in Physics in 2011. The mystery of what is causing this acceleration, often called ‘Dark Energy’, has been one of the key drivers in the continued evolution of astronomy towards larger and larger digital surveys, and correspondingly larger data sets.

### New Facilities and New Methods for Science

While the classic method of astronomical observations, involving astronomers travelling great distances to remote mountaintop facilities, still represents the majority of ground-based astronomy, the evolution to large surveys and massive datasets is changing the way much of astronomical investigation is carried out. At the beginning of this decade, the Sloan Digital Sky Survey (York et al., 2000) led the way by providing one of the first massive, publicly available datasets feeding statistical studies and truly data-driven discoveries.

Indeed, these wide-field digital surveys are being driven by the need for large, uniform, well-calibrated and well-documented datasets to fuel some of the most fundamental investigations in physics and



**Figure 4.** The original team members of the Calan-Tololo Survey. Left to right: Mark Phillips, Nicholas Suntzeff, José Maza, Mario Hamuy. © Nicholas Suntzeff licensed under CC BY-SA 4.0.

astronomy today, including research into Dark Energy and Dark Matter. The ‘classical’ approach simply cannot provide the statistical samples of stars, supernovae and galaxies necessary to investigate these questions. New instruments, new telescopes and new methods are required.

One example of this class of instruments is the Dark Energy Camera (Flaugher et al., 2015), a 570-megapixel camera installed on the CTIO Blanco 4 m telescope in 2012. With this instrument, an international team of scientists from the astronomy, physics and computer science communities has undertaken the Dark Energy Survey (DES) (Abbott et al., 2005). The DES will map roughly a quarter of the southern sky and use four parallel analyses of the dataset to constrain the characteristics of Dark Energy. With a production of roughly half a terabyte of data each night of this 500 night survey, the resulting database of images and measurements will reach several tens of petabytes by the time the survey is finished in 2018.

Construction has already begun on the next major step in this evolution of astronomical investigation, the Large Synoptic Survey Telescope (LSST) project. The LSST is designed to conduct a deep and wide survey of the universe, scanning the entire visible southern sky every few nights, and repeating these scans continuously for ten years. The images from its 3.2 gigapixel camera will be processed and analysed within 60 seconds to identify objects that have changed or moved, from nearby asteroids that might impact the Earth to distant supernovae and galaxies that will help astronomers continue to probe the mystery of Dark Energy. This survey will produce over 15 terabytes per night, collected in an archive that will grow to over 200 petabytes of information over the project’s



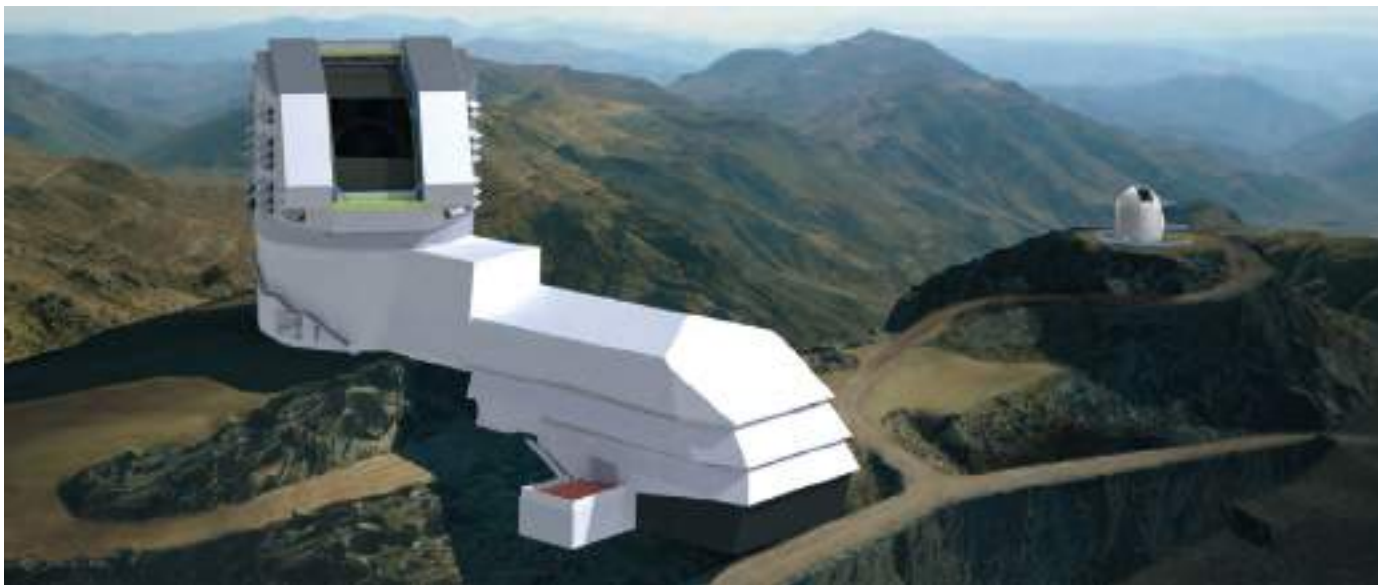


**Figure 5.** Artist rendition of the LSST and its calibration telescope on Cerro Pachon, with Cerro Tololo in the background. © LSST, licensed under CC BY-SA 4.0.

lifetime, representing the largest single astronomical resource ever produced.

Perhaps even more impressive than the advanced technologies involved in the LSST and similar new astronomical facilities is the impact they are having on the sociology of the science being carried out. While Dark Energy is apparently pushing the universe apart at an ever-increasing rate, the study of this mystery and the evolution it has brought about in the methods being used have brought together scientists from astronomy, physics, computer science, mathematics and other fields. These collaborations are critical in order to manage the transition from investigations of individual objects and small samples in previous decades to statistical analyses of massive datasets in the decades to come.

## Conclusion

During the past two decades, astronomy has truly evolved from the study of photons collected by photographic plates to data-driven

investigation, sifting through petabytes of information for clues about how the universe works. New generations of digital detectors are being mosaicked together to create larger and larger wide-field cameras that can map vast areas of the sky with both speed and sensitivity, allowing astronomers to create digital representations of the universe that can be mined with the tools and techniques of data science.

While the techniques of modern astronomy have changed dramatically, the fundamental requirement of capturing the photons from those distant stars and galaxies remains the same. This only reinforces the importance of the few extraordinary sites around the world at which the astronomical observations can be carried out efficiently, under the optimal conditions of clear, stable and extremely dark skies. These sites are truly our ‘windows to the universe’, through which we explore the cosmos, and in doing so, learn more about ourselves.

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# Modern Astronomy in the Islamic World

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## Abstract

This article is a brief account of the history of how modern astronomy was introduced into the Islamic world and its general situation in the recent years. With a population of over 1.5 billion and a projected increase in population of 73% by 2050 (2.8 billion or 30% of the 9.3 billion in the year 2050), the Islamic world will play a major role in environmental changes. However, the Islamic world makes a disproportionately small contribution in the world production of science and technology, and for this reason, it is more likely that it fails to have a constructive impact on environmental changes. This paper suggests that by wisely managing present resources, the Islamic world can minimise their lag in astronomy and effectively participate in the international campaign of preserving dark skies. The economic prosperity of the Arab world, together with its rich past history in science (especially in astronomy), the recent increase in the number of amateur astronomy clubs and astronomical media in the Middle East, and the unique geographical conditions of the region can help the Islamic world carry out operative projects to advance in astronomy. Islamic States can easily follow the IAU's Strategic Plan 2010–2020, entitled *Astronomy for the Developing World*, and the instructions of IAU Office of Astronomy for Development (OAD) to develop necessary infrastructure and initiate an astronomical renaissance in the Muslim world.

## Resumen

Este artículo es un breve recuento de la crónica de cómo la astronomía moderna fue introducida en el mundo islámico y de su situación general en los últimos años. Con una población de más de 1,500 millones y un aumento previsto en la población del 73% para el 2050 (2,800 millones o un 30% de los 9,300 millones en el año 2050), el mundo islámico desempeñará un gran papel en los cambios medioambientales. Sin embargo, el mundo islámico hace una contribución desproporcionadamente pequeña a la producción mundial de ciencia y tecnología, y por ese motivo, es más probable que no tenga un impacto constructivo sobre los cambios medioambientales. Este artículo plantea que mediante una inteligente gestión de sus recursos actuales, el mundo islámico puede minimizar su atraso en astronomía y participar eficazmente en la campaña internacional para preservar los cielos oscuros. La prosperidad económica del mundo árabe, junto con su rico pasado en la ciencia (sobre todo en astronomía), el reciente aumento en el número de clubs de aficionados a la astronomía y medios relacionados con la astronomía en Oriente Medio, así como las singulares condiciones geográficas de la región, pueden ayudar al mundo islámico a llevar a cabo proyectos operativos para progresar en astronomía. El mundo árabe puede seguir fácilmente el Plan Estratégico 2010–2020 de la Unión Astronómica Internacional (UAI) —denominado “Astronomía para el mundo en desarrollo”— y las instrucciones de la Oficina de Astronomía para el Desarrollo (OAD) de la UAI para desarrollar las infraestructuras necesarias y dar inicio a un renacimiento astronómico en el mundo musulmán.

As it is clearly stated in the briefing document of the international conference *The Right to Dark Skies*, held in Mexico in January 2016, ‘the sky is the only common natural landscape for all of the inhabitants of Earth’. The disappearance of dark skies is thus not a local problem, but a global one that demands a universal response and determination for environmental protection. For this to be effective, there must be greater awareness on the issue, both among policy makers and the general public.

In this paper, I will look at the ‘awareness’ of this problem throughout the Islamic world.<sup>1</sup> I will try to illustrate the status of modern science, specifically astronomy, in major Islamic states, and discuss their background and contribution to modern astronomy. With a population of over 1.5 billion and a projected increase of 73% by 2050 (2.8 billion or 30% of the 9.3 billion in the year 2050), the Islamic world can play a major role in environmental changes, both positively and negatively.

1. The Muslim world or Islamic world, in general, refers to those who follow the teaching of Islam. In a political sense, we mainly refer to countries or states in which Muslims constitutes the majority of population. In this sense, the majority of Muslim nations are located in North Africa, the Middle East and South-East Asia. About 15% of Muslims are Arab, more than 60% live in South-East Asia, and the rest are in the Middle East and North Africa. Muslims who live as minorities in India, China, Russia and so on are about one-fifth of the Muslim world.

To understand the status of modern astronomy in the Islamic world, I would like to give a very brief account of the history of astronomy in Islam. Islam appeared in AD 610 in the western Arabian Peninsula and, within just a few decades, it expanded to a vast empire extending from North Africa to India. It was through this expansion that Muslims became familiar with the Greek, Hellenistic, Persian and Indian traditions in science, including the theory and practice of astronomy.

From the end of the eighth century, Muslims started to systematically translate all available scientific and philosophical texts from various languages into Arabic and, within a short time they adopted Greek science, as well as Ptolemaic astronomy. The first astronomical observations and calculations in Islamic culture go back to the first half of the ninth century. By the end of the fifteenth century, Muslim astronomers were able to improve planetary parameters by means of new observations, establish the largest pre-modern observatories, produce systematic texts in plane and spherical trigonometry and introduce trigonometry as an independent subject of study, as well as developing new observational and computational techniques. Furthermore, they suggested new models to reform the Ptolemaic system in a way that planets perform uniform circular motions around the central Earth. Four of these models were later directly used by Copernicus to create uniform circular motion of planets around the new centre of the universe, the Sun.

The decline of intellectual creativity in Islam almost corresponded with the culmination of the Renaissance in Europe. The last major observatory in Islamic territories was demolished in Istanbul the same days that Tycho Brahe observed the comet of 1577, and by demonstrating the celestial nature of comets, provided the first undeniable evidence to reject at least some basic assumptions of the Aristotelian cosmology.

While the Scientific Revolution was in development, almost the entire Islamic world was unaware of and, in most cases, uninterested in the philosophical, epistemological, scientific, observational, experimental and instrumental developments which were taking place in Europe from the 1500s to even the early 1900s.

The two Islamic Empires of the medieval period, the Ottoman and Persian Empires, had a large percentage of Muslims from North Africa to the eastern borders of China and both reached their peak in power and prosperity at the time when the Scientific Revolution took place in Europe.

Despite receiving intellectual products and instruments of modern European science, albeit with a delay, these Empires were unable to integrate them effectively into their education systems. Examples of the introduction of modern astronomy into the Ottoman and Persian Empires can help us to better understand the process: the Copernican model was first introduced into the Ottoman Empire in 1732 and modern astronomy was first integrated into the Ottoman higher education system in the 1830s. In Persia, the first telescope was introduced in the late seventeenth century, however we have no records or astronomical observations from it. A simplified version of Copernican astronomy was translated into Persian in the 1780s, but it was not widely circulated. Modern astronomy was then included in the newly established Persian higher education system in the 1850s.

What is important to highlight here, however, is the fact that these higher education institutions both in the Ottoman and Persian Empires were a kind of polytechnic institution model established to train students in practical sciences, such as engineering, military skills, mining, agriculture and medicine. In other words, they were not Humboldtian universities and they never evolved to Humboldtian institutes. These universities did not develop out of the traditional Islamic educational institutions, otherwise known as madrasas, nor did they evolve from societies pursuing modern science, as was the case in Europe during and after the Scientific Revolution. These higher education institutions were established to replicate the European education system since the Islamic societies had not contributed to the modern world's developments in science, philosophy or technology for more than 300 years since the 1500s and were not familiar with scientific and educational developments in Europe.

After this long absence, the Islamic societies tried to import modern science within a short period of time, without going through adaptation or appropriation phases. Therefore, they failed at first



to acknowledge modern science as a process. Importing scientific facts and tools without recognizing the essence and foundation of modern science transformed the newly established universities into mere teaching institutions. As a result, from the mid-nineteenth century there have been two education systems throughout the Islamic world, with minimal or zero structural connections. First are the traditional schools that have a background going back more than 1,000 years, but are completely lacking and inactive in natural science education, are unaware of the modern science and criticize it. The second system is the newly ‘imported’ system, which is mainly aimed to promote practical knowledge.

Although the above relates to higher education institutions in the Ottoman and Persian Empires, the story is pretty much the same in Islamic states from east to west. Examples include Cairo University, which was established in the first decade of the twentieth century to promote practical knowledge, and the University of Indonesia, which was built in the 1850s by the colonial government of the Dutch East Indies as a medical school.

Then, the question is how important was (and is) astronomy in these education systems? How did the educated elites and policy makers evaluate the role of astronomy in national scientific and technological progress? Since, from the beginning of the introduction of modern science to Islamic societies, the imported European educational system was transformed into profesional vocational institutes, it lost its holistic nature. As a result, astronomy (like many other disciplines) was generally taught as one of the general science courses, mostly as spherical astronomy and introductory description of astronomical objects.

Modern astronomy gained more support from the government when it was useful in public and state affairs. For example, the first modern observatory in the Ottoman Empire, which was established in 1868 in Istanbul, was an institution for weather forecasting and timekeeping. Had there not been this practical need, there would have been no use for modern astronomy. For instance, in 1858 forty Persian students were sent to Paris to study modern science and one of them was assigned to pursue astronomy. For six years, he studied with the prominent astronomer Urbain Le Verrier, and is very likely

one the first Middle Eastern professional observational astronomers. Upon his return home, however, he was appointed head of the national telegraph office due to the lack of astronomical facilities.

In colonized Islamic territories, the story was slightly different. In some, Europeans created observatories or carried out observations, which was helpful in training local astronomers. In Egypt, the first modern observatory was founded in 1840; however, the only activity recorded is the observation of the solar eclipse in 1860. Nevertheless, the next observatory that was established during the British dominance in Egypt was, until 1945, the largest observatory in North Africa and the Middle East. It contained a 30 inch reflector (donated by British astronomer, John Reynolds) and other photographic and spectrometric equipment.

The observatory was directed by British astronomers, and numerous projects in galactic, cometary and stellar studies were carried out. The observatory was considered an extension of the Greenwich Observatory. After 1957, due to Egypt making closer ties with the Soviets, the observatory was equipped with instruments devoted to satellite tracking, magnetic observations and radio astronomy. A similar observatory, but active for a shorter time, was established in Algeria by the French colonizers.

From the 1920s, a second generation of higher education institutions appeared throughout Islamic territory as a result of population increase and economic growth, and the formation of

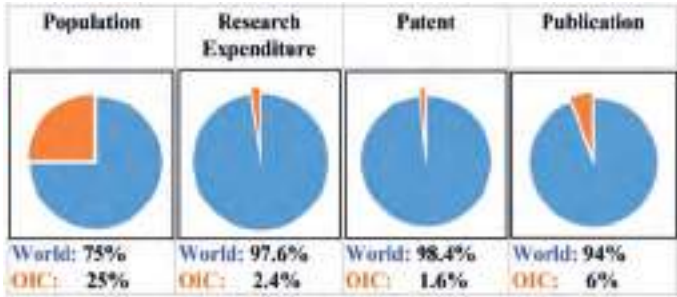


Figure 1. The OIC in comparison to the world in terms of population, research expenditure, patents and publications. © Tofigh Heidarzadeh, adapted from Guessoum and Osama (2015).

new states after the First World War. However, this quantitative expansion occurred in parallel with the existing educational mentality, in which minimum attention was paid to promoting research in pure sciences and to integrating arts and sciences with research and industry. In fact, in a majority of cases, technology in these states was completely dependent on foreign countries and even national research in science could not yield mutual interaction with the technological progress.

Recent statistics show that there are more than 1,600 universities and higher education institutions in Islamic states.<sup>2</sup> However, the productivity factors of these institutions, in terms of research, publications, inventions and impact on technology do not match with their quantitative expansion and with global standards. In 2012, the Organization of Islamic Cooperation (OIC), whose member countries make up 25% of the world population, contributed only 1.6% of the world's patents, 6% of academic publications and 2.4% of the global research expenditure. The same statistics show that papers from twenty OIC countries, which are the most productive in science and technology, are cited less frequently than those from countries of comparable GDP (Guessoum and Osama, 2015).

However, the number of peer reviewed astronomical publications in Islamic countries has been even less. An analysis of the United States National Science Foundation's statistics shows that from 1997 to 2011, the contribution of 37 Islamic states was only 0.88% of the world's astronomical publications, while Mexico alone contributed 1.06% during the same period. In other words, from 1997 to 2011 Mexico published 226 more papers than the 37 Islamic countries combined (National Science Board, 2014).

The number of astronomers can be another criterion to evaluate the situation of astronomy in Islamic states. Due to the lack of any astronomical databases in these countries, I used the individual member directory of the International Astronomical Union (IAU) as an indicator. Whilst there are about 2 IAU members per million capita from South Africa and 9 members per million from Israel, the numbers for Saudi Arabia is 0.10, for Indonesia 0.05, for Pakistan 0.01, for Turkey 0.68 and for Egypt (which holds the largest observatory in the region) 0.44.



Figure 2. Artist's conception of the Iran National Observatory (INO).  
© INO.

Finally, to have a better idea about astronomical infrastructure in Islamic states, we can survey their observational facilities.<sup>3</sup> In about 45 countries in which Islam is the majority religion of the people, only 5 countries have observatories with a telescope equal or more than 40 cm in diameter. (We exclude the 2 m telescope of Shamakhi Observatory in Azerbaijan that was created in 1958 during the Soviet era). The combined Light Gathering Power of all telescopes in Islamic states is equal to a 3 m telescope. This figure, hopefully, will improve in the next 5 years by the establishment of Iran National Observatory (INO), which will hold a 3.4 m telescope. Its primary mirror, polished in Finland, was delivered to Iranian authorities in December 2015.

With this new telescope, the light gathering power of Islamic states would increase to the size of a 4.5 m telescope. In comparison, the Southern African Large Telescope (SALT), which is the largest single optical telescope in the Southern Hemisphere and among the largest in the world, has a primary mirror array of 11 m in diameter. SALT was funded by South Africa, the United States, Germany, Poland, India, the United Kingdom and New Zealand, and the observatory has been operational since September 2011.

2. World Universities and Colleges, [http://www.canadian-universities.net/World\\_Universities/](http://www.canadian-universities.net/World_Universities/)

3. World Public Library, List of Observatories [http://www.worldlibrary.org/articles/List\\_of\\_observatories](http://www.worldlibrary.org/articles/List_of_observatories)

Among numerous factors causing this wide gap in scientific and technological progress between developed and developing countries, especially Islamic states, one factor is more conspicuous. There is a clear correlation between research and development expenditure and scientific progress. While developed countries spend something between 1.5% to 4% of their GDP on research and development, this ratio is far lower in Islamic countries (Masood, 2002). In recent years, although some Islamic countries with comparably lower GDP, like Turkey, Egypt and Iran have tried to raise their budgets in R&D, they are still spending less compared to countries with similar GDPs. In the wealthiest Islamic states, however, the ratio between GDP and R&D expenditure is disappointing (National Science Board, 2014).

Based on all these facts, what possible approaches may increase the momentum of these states towards scientific and technological progress, specifically in the field of astronomy? As was mentioned at the beginning of this paper, with a population of over 1.5 billion and a projected increase of 73% by 2050 of 2.8 billion or 30% of the 9.3 billion in the year 2050 (Pew Research Center, 2015), the Islamic world has and will have a major role in all global issues. Undoubtedly, promoting and measuring scientific literacy in Islamic states can be an immediate and most essential step.

The promotion of this science literacy can be started from self-awareness about Islamic history in science and its status quo in the matter. Unfortunately, exaggerations in the evaluation of the impact of Medieval Islamic science on the development of modern science have misled public understanding of the nature of both classical and modern sciences in the Islamic world. Promotion of astronomy and enriching astronomical literacy in these societies can play a profound role in achieving effective scientific knowledge for the twenty-first century.

Fortunately, there are a good number of opportunities to be employed in this regard. The economic prosperity of the Arab world, hand in hand with the rich past history of Muslims in science (especially in astronomy), the recent increase in the number of amateur astronomy clubs and astronomical media, and the unique geographical conditions of the majority of Islamic countries can help them to fulfil operative projects in astronomy, following IAU's Strategic Plan 2010 – 2020,

entitled *Astronomy for the Developing World*, and instructions of IAU Office of Astronomy for Development (OAD).

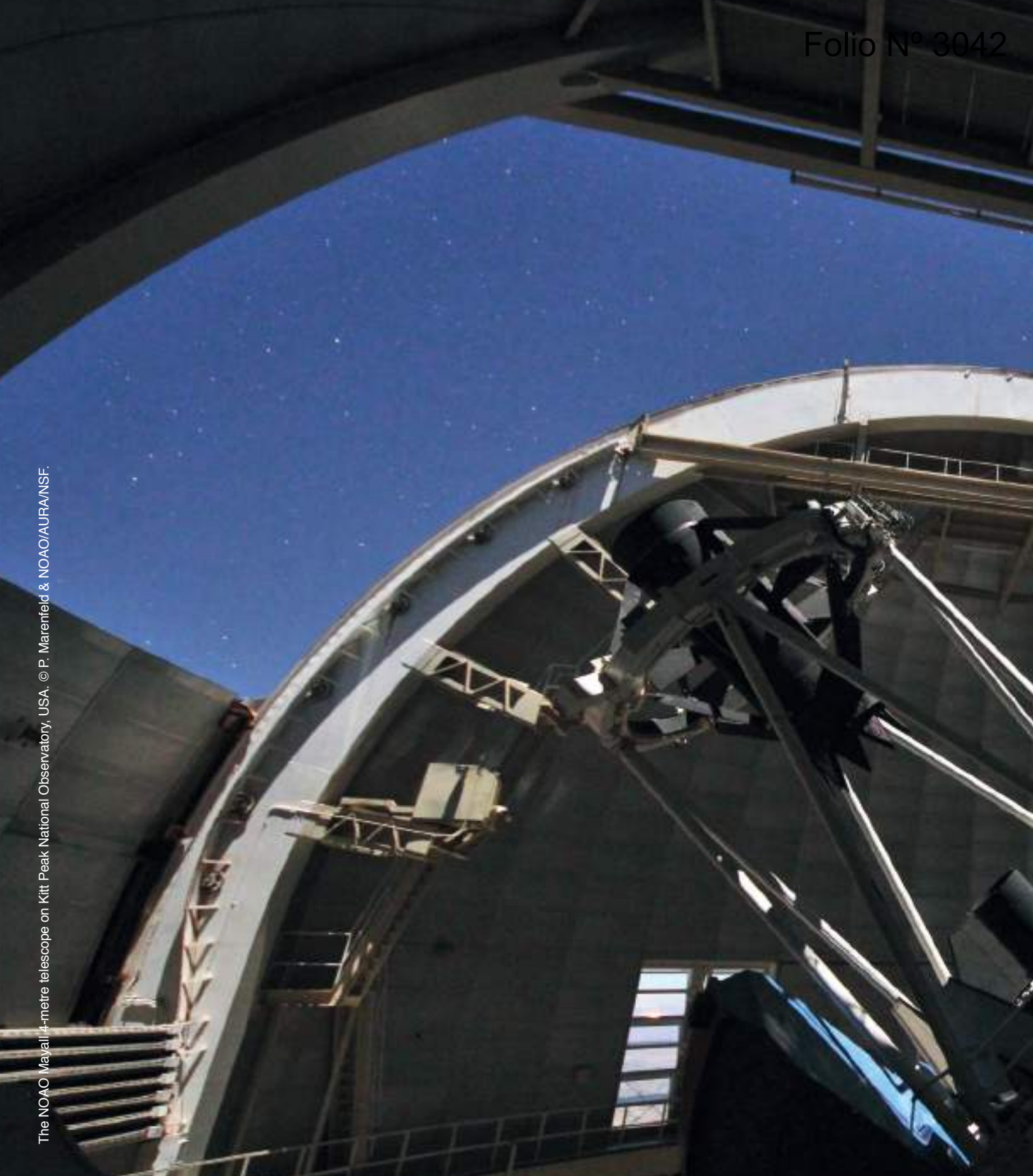
A local office for the Middle Eastern and Islamic countries can be extremely helpful in:

1. Using modern communication tools to connect people interested in astronomy and provide educational material for them. Rapid and reliable translation into local languages is vital.
2. Connecting schools and educational institutions to online observational networks and finding means to solve language barriers.
3. Helping to include modern astronomical knowledge in educational textbooks of all levels.
4. Promoting observational and hands-on astronomy by holding workshops, field trips and star parties<sup>4</sup>.
5. Helping to provide public programming for dissemination by the media in order to increase public knowledge about the connection between astronomy and development.
6. Encouraging policy makers to establish a regional big telescope funded by a consortium of regional and international partners.
7. Commemorating Islamic scientists' contribution and educating the public on the international nature of scientific knowledge, and using science as a strong peace-making vehicle.

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4. Star Party: any gathering of amateur astronomers.





Chapter 3

# Telescopes

Capítulo 3

# Telescopios







# Large Telescopes in Chile

**Miguel Roth**

*Giant Magellan Telescope, Chile*

## Abstract

From the middle of the twentieth century, Chile became an attractive destination for astronomical studies, due to its already then recognized clear skies and its full coverage of the Southern Hemisphere. Thanks to the visionary impetus of Federico Rutland, Director of the National Astronomical Observatory, in and around 1950 modern astronomy and astrophysics in Chile started to take off explosively, a growth that has continued to increase and today is looking at concentrating, by the mid 2020s, roughly 70% of all ground based observational capabilities. There are four main reasons for this. Aside from the aforementioned clear skies and favourable location, the Atacama Desert has two characteristics that are as important as the lack of clouds — extreme dryness and an outstanding unvarying atmosphere. This leads to an image quality that is second to none, also known as ‘seeing’ among astronomers. The low level of light pollution is the fourth factor.

There are currently many big telescopes larger than 4 m in diameter functioning in Chile, as well as the latest addition in the race for large telescopes, the 8 m type. These are found in Paranal, with 4 telescopes of 8.4 m in diameter (VLT), in Las Campanas, with 2 telescopes of 6.5 m (Magellans) and Cerro Pachón, with one 8.2 m (Gemini South). In the radio wave domain, the Atacama Large MM Array (ALMA) at Chajnantor is the largest radio telescope in the world.

This article will describe in moderate depth the immediate future of extremely large telescopes in Chile, addressing the fascinating projects of the Large Synoptic Survey Telescope (LSST), the Giant Magellan Telescope (GMT) and the European Extremely Large Telescope (E-ELT). The importance of preserving pristine conditions will also be discussed briefly.

## Resumen

Desde mediados del siglo XX, Chile se convirtió en un destino atractivo para los estudios astronómicos, debido a sus cielos claros, algo reconocido ya desde entonces, y a su amplia cobertura del hemisferio austral. Gracias al ímpetu visionario de Federico Rutland, Director del Observatorio Astronómico Nacional, hacia 1950 la astronomía y la astrofísica modernas en Chile empezaron a tomar impulso vertiginosamente, un crecimiento que ha seguido aumentando y hoy contempla una concentración para mediados de la década del 2020 de aproximadamente 70% de todas las capacidades de observación terrestre. Existen cuatro motivos principales para ello. Aparte de los ya mencionados cielos claros y su conveniente ubicación, el Desierto de Atacama tiene dos características tan importantes como la falta de nubes, a saber, sequedad extrema y una excepcional atmósfera inalterable. Esto lleva a una insuperable calidad de imagen, conocida también como “calidad de imagen” entre los astrónomos. El bajo nivel de contaminación lumínica es el cuarto factor.

Actualmente hay muchos grandes telescopios mayores de 4 m de diámetro funcionando en Chile, así como la última incorporación en la carrera por los grandes telescopios, el de 8 m. Éstos se encuentran en Paranal, con cuatro telescopios de 8.2 m de diámetro (VLT); en Las Campanas, con dos telescopios de 6.5 m (Magallanes), y en Cerro Pachón, con uno de 8.2 m (Géminis Sur). En el ámbito de las ondas de radio, el Atacama Large MM Array (ALMA), en Chajnantor, es el radiotelescopio más grande del mundo.

Este artículo describirá en razonable profundidad el futuro inmediato de los telescopios extremadamente grandes de Chile, abordando los fascinantes proyectos del Gran Telescopio para Rastreo Sinóptico (LSST), el Telescopio Gigante de Magallanes (GMT) y el Telescopio Europeo Extremadamente Grande (E-ELT, por sus siglas en inglés, todos los anteriores). La importancia de conservarlos en condiciones prístinas será también analizada brevemente.

In 2025, Chile will probably house about 70% or more of the world's capability to observe the sky from the ground with professional telescopes. While other countries will continue developing their observational capabilities, no other place on Earth, with the possible exception of Mauna Kea on the Big Island of Hawaii, will concentrate the largest telescopes that humans feel capable of building and operating to the fullest extent and possibilities of their designs.

### The Next Step

Humanity has made tremendous discoveries over the centuries. In astronomy, a 'discovery' is defined as a new finding that changes our view of the universe. Examples are abundant: when Galileo pointed his telescope towards Jupiter and he discovered the moons, objects revolving around something that was not 'us'; when radio-astronomy discovered the signal associated with the centre of the Milky Way and background radiation originating from the big bang, and so on.

The factor that is common to discoveries in astronomy is the **increased** capability to observe the universe by a factor of 10, as well as the opening of a new 'observing tool', like different frequencies to analyse electromagnetic radiation or a fully new technique to gather information.

In this respect, the recent announcement of the detection of gravitational waves by LIGO is one of the most striking discoveries of our times since it opens a new window to the universe that wasn't available before. Over centuries, humanity has observed the skies by means of the light (electromagnetic radiation in a general term, including X-rays, visible, infrared and radio wavelengths). The detection and analysis of light is explained by Maxwell's equations: electric and magnetic fields travelling at the speed of light as a result of atomic or molecular transitions and other phenomena associated with the discrete nature of matter, where energy is emitted in the form of electromagnetic waves. Gravitational waves are predicted by Einstein's General Relativity equations and originate in the interaction of mass. Shaking hands, hugging or a car crash will generate gravitational waves but the energy carried by them and the effect is smaller by many orders of magnitude than the energy involved in electromagnetic radiation. This is the main reason why it took a century to detect them.



Figure 1. End of the twentieth century large telescopes in Chile. From top to bottom: the Magellan 6.5 m telescopes; © Krzysztof Ulaczyk, licensed under CC BY-SA 3.0. Gemini south; © Denys, licensed under CC BY-SA 3.0.

Optical and infrared astronomy has achieved this 'factor of 10' improvement roughly every 30 to 35 years since Galileo, over approximately 400 years. The previous generation of Large Telescope (Figure 1) ended with the twentieth century. This suggests that by 2020 to 2030, humanity should take the next step. Figure 2 shows the evolution of the size of telescopes over time.

The future optical and infrared projects to settle in Chile are:

- The LSST (Large Synoptic Survey Telescope),
- The GMT (Giant Magellan Telescope) and the
- E-ELT (European Extremely Large Telescope).

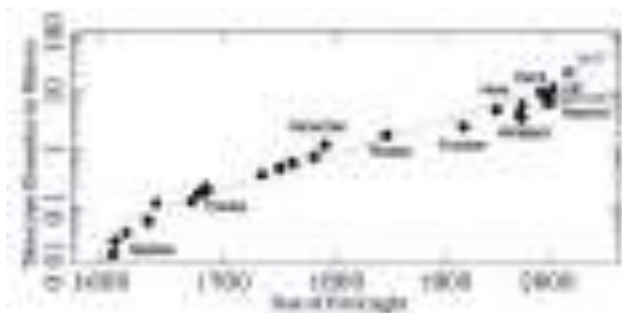


Figure 2. Evolution of telescope size in time. © Patrick McCarthy.

Needless to say, in the radio domain at longer wavelengths, Chile houses the largest radio telescope on Earth; ALMA, the Atacama Large Millimetre Array and various other large projects are either under consideration or in the commissioning phase (CCAT, the Cerro Chajnantor Atacama Telescope, the ACT, Atacama Cosmology Telescope, TAO, the Tokio Atacama Observatory and so on).

### Reasons for Making Chile the Centre of Ground-based Astronomy

...or what do we require from an outstanding site? The Humboldt current, the cold current that originates in Antarctica and runs along the coast of South America, combined with latitude, produces different effects: from extreme rains and cold deserts in the south, to the driest desert on Earth, the Atacama Desert. The different observatories are located in areas of very low cloud coverage, with some 300 nights per year that are useful for astronomical observations. The dryness of these places is an essential component, but not the only one.

The dominating winds travel for thousands of kilometres, over the Pacific Ocean, reaching the western coasts of North and South America in a smooth turbulence-free flow. This very stable atmosphere, when it reaches the first significant elevations, is responsible for the outstanding image quality recorded at the different observatories. This is the same reason why big observatories developed in California during the first half of the twentieth century and why the Big Island in Hawaii and the Canary Islands, also displays exceptional conditions.

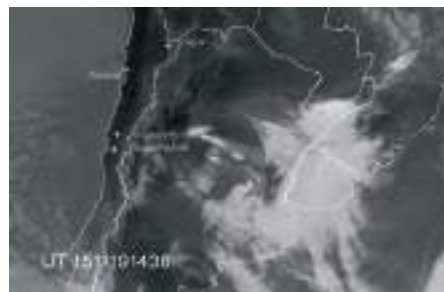


Figure 3. Random sunset image of South America, showing the very clear skies over northern Chile. Dominating winds come from the west. © NOAA.

Other aspects that make for an outstanding site include: dark skies, the ability to carry out business (in a general sense) in a stable environment and infrastructure.

In the same manner as a stable atmosphere allows the light of a point source to be concentrated in the smallest possible area (resolution), a dark sky allows for the largest contrast. The degradation of both effects, 'seeing' and contrast, are equivalent to reducing the size of the telescope. In other words, a large telescope on a poor site is equivalent to a smaller telescope on an excellent site.

A large project involves investing huge sums of money, and benefits from clear regulations for commercial transactions, a modern labour code and other items involved in a stable environment. Modern communication systems, roads, airports and ports are important as well. Last but not least, a big project also benefits from the availability of highly trained professionals and a qualified workforce in a safety conscientious environment.

All the above-mentioned aspects are fully met in Chile and very specifically so in the north.

### Optical and Infrared Telescopes for the Twenty-first Century

#### The LSST (Large Synoptic Survey Telescope)

This relatively 'small' telescope, compared to the 30 to 40 m class telescopes, has an 8.4 m primary mirror. It will be located on Cerro

Pachón, a 2,800 m high peak, east of La Serena, at the same location as the Gemini South telescope.

Its unique design has the tertiary mirror ground on the same glass as the primary one. This will accomplish an enormous field of view (10 square degrees, about 40 times the size of the full moon), which will be imaged by the camera with 3,200 megapixels and will take a 'picture' of the full sky accessible to its location every 3 nights over the period of 10 years. Upon completion, the LSST will have gathered, by adding together 10 years of images, the most complete catalogue of this part of the universe. Two of the biggest challenges for the LSST are: handling, organizing and archiving the enormous amount of data, from moving targets to supernovae and reporting them in a timely manner, as well as providing the community with the tools to mine the data, searching and finding what the astronomer is looking for. This will be the epitome of data mining.

The primary mirror, together with the tertiary incorporated in the same glass structure, was manufactured at the Richard F. Caris Mirror Lab of the University of Arizona. The mirror manufacturing facility will be further discussed in the context of the Giant Magellan Telescope.

The images from the LSST will be obtained by using a state of the art camera. For many years, the photographic plate was the natural way of obtaining large images, but they have been completely replaced by mosaics of solid-state detectors with enormous advantages in terms of sensitivity, linearity, dynamic range and fast access to data.

The LSST is under construction on Cerro Pachon, close to Cerro Tololo, in Chile's Fourth Region and expects to have 'first light' in 2020.

### The GMT (Giant Magellan Telescope)

When completed in 2021, the 25 m telescope will be the largest optical and infrared telescope in the world until two other projects, the E-ELT (see next page) and the TMT (to be constructed in Hawaii) become operational. It will be located at a privileged site on the top of Cerro Las Campanas, within the property of Carnegie's Las Campanas Observatory in the Third and Fourth Region in the Atacama Desert at an elevation of 2,500 m.

The primary optic of this telescope is formed by 7 very large 8.4 m mirrors on one single mechanical structure. It is interesting to note that each mirror is of the same size as the LSST mirror! Aside

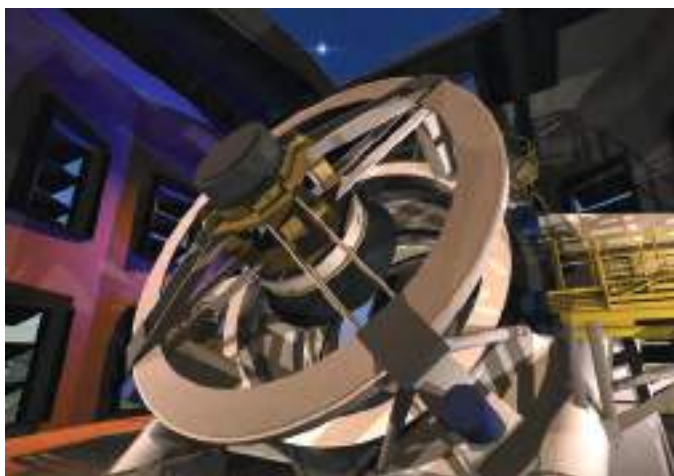


Figure 4. Left: Artist conception of the LSST, viewed from the telescope platform. Right: The primary-tertiary mirror combination, polished to specifications and ready to be stored. © LSST, licensed under CC BY-SA 4.0.





Figure 5. Two artist conceptions of the GMT telescope, showing the seven mirrors in a single structure and the enclosure. Notice several objects placed in the images for scale comparison. The laser beams emerging from the telescope in the right-hand picture are part of a complex system called Adaptive Optics (AO), used to compensate for the effects of the atmosphere's turbulence. © Giant Magellan Telescope – GMTO Corporation.

from the mechanical difficulties of supporting 140 metric tons of glass, these mirrors have an asymmetric curve polished to their surface. With the central mirror being symmetric, the six outside mirrors need to make a perfect parabolic curve. As mentioned before, these mirrors are manufactured at the University of Arizona by means of a process first implemented following an idea by the British-born American astronomer, Roger Angel, that has produced a large number of the most modern mirrors, from 1.5 m all the way to 8.4 m, including the 6.5 m of both Magellan Telescopes and the primary 8.4 m mirror for the Large Binocular Telescope, located in Arizona, and, as mentioned, the mirror for the LSST.

The process involves a very large furnace with the ability to rotate. Hexagonal cylinders made of refractory material are distributed inside this furnace. Pieces of borosilicate glass are placed on top of the hexagons, and the furnace is closed and the heaters turned on. When the borosilicate glass (Pyrex) reaches about 1,200 °C and starts to melt, the furnace starts to rotate at 5 RPM. The combination of the way the refractories are distributed, the amount of glass and the rotation speed will make the glass occupy the spaces between the refractories and leave a thin sheet of glass of roughly 5 cm with the correct approximate shape to be adjusted and polished to the stringent required specifications.

The concept of the Giant Magellan Telescope is depicted above. It will be placed in a 60 m tall enclosure, the equivalent of a 22 story building that will be required to rotate smoothly following the telescope position.

Once completed, the GMT, equipped with Adaptive Optics, a technique used by several ground based telescopes, will exploit its optical limit and will have a resolution ten times better than the Hubble Space Telescope.

### The European Extremely Large Telescope (E-ELT)

This telescope of approximately 39 m in diameter is being developed by the European Southern Observatory, a consortium of 16 European countries that operates 2 observatories in Chile. The E-ELT will be located on Cerro Armazones, south of Antofagasta, Chile, another outstanding site only a few kilometres from Cerro Paranal, the site of the VLT.

As for the GMT, it is impossible to cast and polish a single mirror of this size. Unlike the LSST and the GMT, the E-ELT will use a different technique in order to 'produce' its primary: it will use 798 hexagonal segments, each with an equivalent diameter of 1.5 m. This technique has already been used in the construction of the VLT and the Keck telescopes. Both techniques face big challenges.

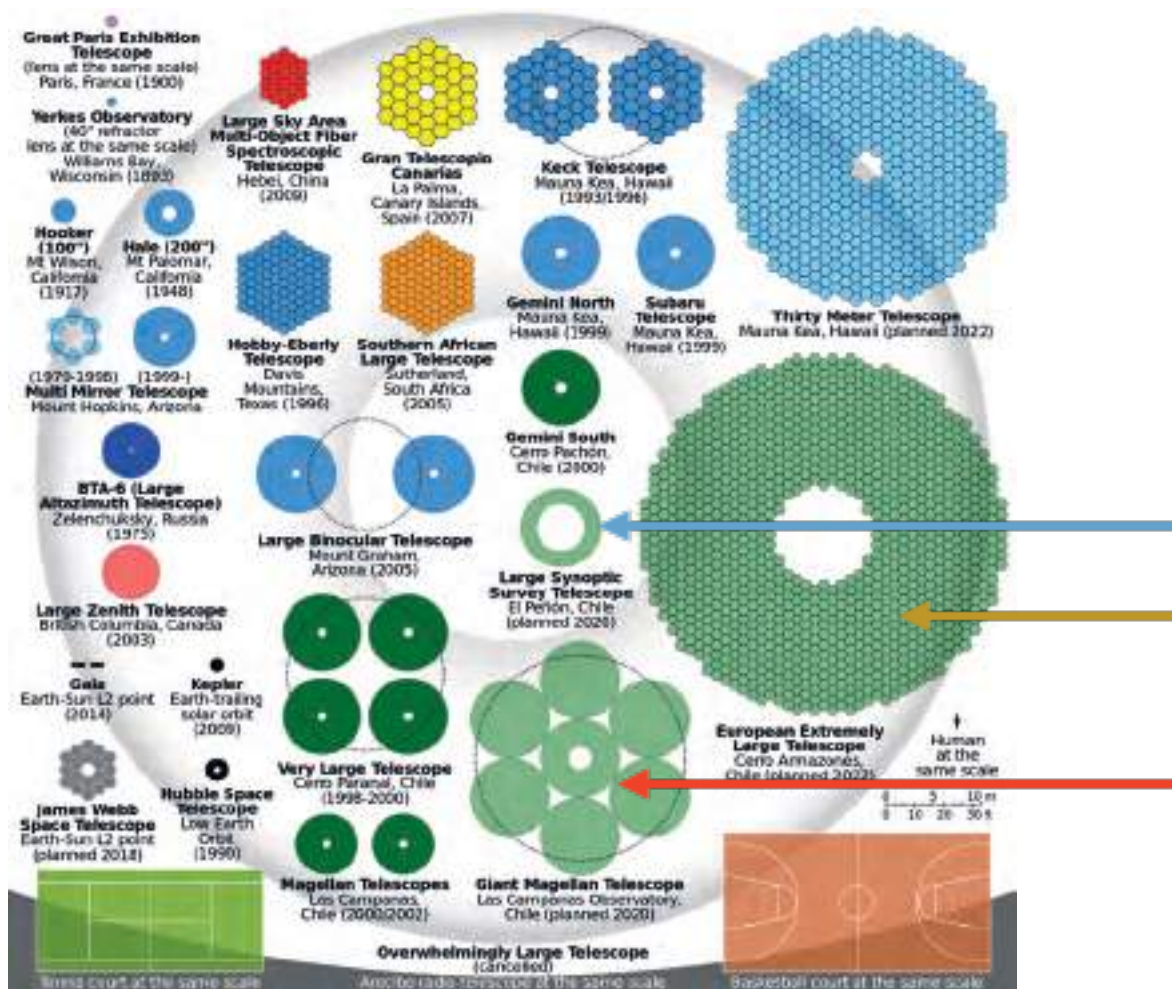


Figure 6. Comparison of the diameters of the primary mirrors of the three telescopes described here. A blue arrow, the LSST, in yellow, the EELT and in red, the Giant Magellan Telescope. © Cmglee, licensed under CC BY-SA 3.0.

While the 7 GMT mirrors have to be perfectly aligned in order to form a 25 m mirror, the segments of the E-ELT have to align perfectly too, so as to produce a single giant mirror.

As with all modern large telescopes, the E-ELT will have an ‘alt-azimuth’ mount. This enables telescopes to provide an area that is gravitationally invariant, where very large instruments can be placed. In other words, the instruments that can be very big and weigh several tens of tons do not ‘travel’ with the telescope,

but remain in the same place while the light from the telescope is tunnelled to the instrument. This is seriously beneficial for the instrument teams, simplifying the design and avoiding flexures that can make the design almost impossibly expensive. Adaptive Optics will be an obvious feature also at the E-ELT.

### Science with large telescopes

Projects of this size inevitably have to present a scientific justification. As mentioned above, the LSST will have one mission. It will obtain



Figure 7. Artist conception of the E-ELT. The blue boxes, to the right of the telescope correspond to just one of the instruments. Also shown is an example of 5 out of almost 800 segments. © ESO, licensed under CC BY 4.0.

a full image of the accessible sky, in three wavelengths, every three to four days over a period of ten years. These images will be made compatible and combined, providing the deepest and most complete image of the universe, paying special attention to objects that vary in their intensity or position (from killer asteroids to the most distant supernovae and possibly the sources of gravitational waves.) Without going into individual problems that the LSST will tackle, this is the Science Case.

Unlike the LSST, the other telescopes will perform ‘pointed’ as opposed to ‘synoptic’ observations. While the LSST will have only one instrument, its amazing camera, the GMT and the E-ELT will provide images and, more importantly, spectra, in optical and infrared wavelengths. These giant telescopes will look for planets of nearby stars, with the stated objective of finding Earth-like ones and to study in detail their atmosphere for possible indications of biological activity; stellar populations in the Milky Way and other galaxies and the origin of black holes, with special attention to the one in the centre of our galaxy. The interaction of galaxies and the first light in the universe, and the most distant galaxies will be studied. Cosmology and the origin of Dark Matter and Dark Energy are problems to be addressed also.

Considering that these projects will increase the possibilities of observation from the ground by several orders of magnitude, it is likely that new problems (for which we, for the time being, ignore the questions) will open new horizons.

### The Right of People to Dark Skies

The title of this meeting, *The Right to Dark Skies*, addresses one of the serious problems that might affect these giant telescopes: light pollution.

As mentioned previously, telescopes need dark skies in order to fully exploit their capabilities. Contaminated skies inhibit the capabilities of large telescopes making them equivalent to smaller telescopes since the contrast is diminished and the background is filled with artificial spectral features. Historically, large telescopes have been rendered close to useless because of this. Other articles will address this subject in more detail.

Let us fight this with determination: we want our children to be able to look at the marvels of the universe and our scientists to study them with the most powerful tools ever built.





# Sierra Negra: the Site of the Large Millimetre Telescope Alfonso Serrano

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## Abstract

Sierra Negra, also known as Tliltepetl, located in the Pico de Orizaba natural park in the Mexican state of Puebla, was chosen in 1997 as the site for the Large Millimetre Telescope Alfonso Serrano or Gran Telescopio Milimétrico Alfonso Serrano in Spanish (LMT/GTM). The LMT is the world's largest single dish telescope for studying the cosmos in the wavelength range of 0.8–4.0 mm. The INAOE and the University of Massachusetts Amherst have collaborated for twenty years to construct and operate the world-class LMT. The summit of Sierra Negra was selected for the positioning of the LMT as a result of the low water vapour content of its atmosphere, which is due to its altitude of almost 4,600 m. With a latitude of 19 °N, Sierra Negra has good access to the Southern hemisphere skies. The site started developing infrastructure shortly after being chosen and the LMT itself was constructed between 1999 and 2006. Its first light on the millimetre-wave range was announced on 1 June 2011, a few weeks before the passing of Alfonso Serrano, its initial and long-time promoter. Since 2013, the telescope has been used in scientific operations, with an aperture of 32 m, and is due to reach full 50 m operations by the end of 2016. The telescope is part of the Event Horizon Telescope initiative, a global project that aims to capture images of the black hole at the Galactic Centre in 2017.

The development of basic infrastructure at Sierra Negra, specifically the access road, electricity and the internet, prompted the installation of other facilities benefiting from the thin atmosphere of this high altitude site. In July 2007, Sierra Negra was chosen for the installation of the High Altitude Water Cherenkov Observatory (HAWC), a wide field of view gamma-ray detector to survey two thirds of the sky in the 0.1–100 TeV region of the electromagnetic spectrum. The HAWC was installed 1 km north and 500 m below the LMT, at an altitude of 4,100 m, and consists of an array of 300 individual water Cherenkov detectors. The full installation of the array was achieved on time for HAWC to be inaugurated in March 2015.

Sierra Negra is an exceptional site providing tolerable conditions, such as relatively mild weather at more than 4,000 m and a very low electromagnetic interference noise. The conditions for optical astronomy have been partially studied, with optical seeing data obtained from 1999 to 2002 showing a median of 0.78" and weather data aiding to characterise the site in terms of the fraction of clear skies. Despite its location in a relatively populated region of Mexico, the sky at Sierra Negra is dark to the eye, a likely effect of its altitude. The sky's actual brightness, however, remains to be quantified. Future instruments needed for dark skies, which could be considered for Sierra Negra, are optical and atmospheric Cherenkov telescopes.

## Resumen

Sierra Negra, también conocida como Tliltépetl, ubicada en el Parque Nacional Pico de Orizaba, en el Estado de Puebla, fue elegida en 1997 como sitio para el Gran Telescopio Milimétrico Alfonso Serrano (GTM). El GTM la antena individual más grande del mundo para estudiar el cosmos en el rango de longitud de onda de 0.8–4.0 mm. El Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE) y la Universidad de Massachusetts Amherst han colaborado durante 20 años para construir y operar el GTM de primera categoría. La cima de Sierra Negra fue escogida para el posicionamiento del GTM debido al bajo contenido de vapor de agua de su atmósfera, lo cual se debe



a su altitud de casi 4,600 m. Con una latitud de 19° N, Sierra Negra tiene buen acceso a los cielos del hemisferio austral. El sitio comenzó a desarrollar infraestructuras poco después de ser elegido y el GTM fue construido entre 1999 y 2006. Su primera luz en el rango de ondas milimétricas fue anunciada el 1 de junio del 2011, unas semanas antes del fallecimiento de Alfonso Serrano, su impulsor inicial durante mucho tiempo. Desde el 2013, el telescopio se ha utilizado en operaciones científicas con una apertura de 32 m y se espera que alcance operaciones de 50 m para finales del 2016. El telescopio forma parte de la iniciativa Telescopio de Horizonte de Eventos, un proyecto global que pretende capturar imágenes del agujero negro en el centro de la galaxia en 2017.

El desarrollo de infraestructuras básicas en Sierra Negra, específicamente el camino de acceso, electricidad e internet, motivó la construcción de otras instalaciones que se benefician de la delgada atmósfera de este sitio a gran altitud. En julio del 2007, Sierra Negra fue elegida para la instalación del Observatorio HAWC (por sus siglas en inglés), un detector de rayos gamma de amplio campo de visión que puede rastrear dos tercios del cielo en la región de 0.1–100 TeV del espectro electromagnético. El HAWC fue instalado a 1 km al norte y 500 m por debajo del GTM, a una altitud de 4,100 m, y está compuesto por un conjunto de 300 detectores individuales de luz de Cherenkov en agua. La instalación completa del conjunto se logró a tiempo para que el HAWC fuese inaugurado en marzo del 2015.

Sierra Negra es un sitio excepcional que proporciona condiciones tolerables, como un clima relativamente suave a más de 4,000 m. Asimismo, hay en el sitio un ruido muy bajo de interferencias electromagnéticas. Las condiciones para la astronomía óptica han sido parcialmente estudiadas, con datos en el óptico obtenidos de 1999 al 2002 que muestran una media de 0.78" y datos meteorológicos que ayudan a caracterizar el sitio en función de la fracción de cielos claros. A pesar de su ubicación en una región relativamente poblada de México, el cielo en Sierra Negra es oscuro a la vista, un probable efecto de su altitud. Sin embargo, el resplandor real del cielo sigue estando por cuantificarse. Futuros instrumentos necesarios para cielos oscuros, que podrían considerarse para Sierra Negra, son telescopios ópticos Cherenkov atmosféricos.

### **Mexico's Potential for Astronomy**

Mexico is a mountainous country with many sites that have high potential for astronomy, for example, the Baja California Peninsula, which extends for over 1000 km along the Pacific coast, reaching 3000 m at its highest point. The laminar flow of air coming from the ocean and reaching the first mountain range, almost unperturbed, provides ideal conditions for optical astronomical observations. San Pedro Mártir, where Mexico's National Astronomical Observatory (OAN-SPM) is located, benefits from these excellent conditions and low levels of light pollution. I will review the OAN-SPM site further in this article.

The evolution of observational techniques in astronomy beyond the visible portion of the electromagnetic spectrum resulted in unprecedented demands for finding potential sites for new facilities. A relevant example in Mexico are radio experiments that require

minimal electromagnetic interference. These conditions, recently measured on Guadalupe Island, may allow the unique exploration of the early universe.

Moving towards the south, the Central Mexican Plateau has peaks higher than 4000 m. These peaks could be potentially exploited by scientific facilities that benefit from high altitude conditions. The water vapour content of some of these peaks was monitored in the early 1990s during the search for the site of the Large Millimetre Telescope Alfonso Serrano (LMT). In February 1997, the tallest of these sites, Sierra Negra, was selected and development began shortly afterwards. Today, Sierra Negra hosts half a dozen experiments, including the LMT and the High Altitude Water Cherenkov (HAWC) Gamma Ray Observatory, and is becoming a world-class site in scientific research.

Sierra Negra

Sierra Negra, *Tliltepetl* in Nahuatl, meaning ‘the black mountain’, is an extinct volcano next to Pico de Orizaba, the highest peak in Mexico, with just 7 km separating the two summits. The Nahuatl name of Pico de Orizaba is *Citlaltepetl*, ‘the mountain of the stars’. The two mountains constitute the Pico de Orizaba National Park (Parque Nacional Pico de Orizaba in Spanish), which covers a total area of 196 km². The park limits at northern latitudes lie between 18°57’00” and 19°09’40” and at western longitudes between 97°12’11” and 97°22’04”. With an altitude of 4,582 m, Sierra Negra is the fifth highest mountain in Mexico, just a few metres shorter than Nevado de Toluca. While Sierra Negra is an old volcano without signs of volcanic activity, the crater of Pico de Orizaba is about 4,000 years old and has a record of minor eruptions and exhalations that started in 1533 and continues to the present day (Rossotti, 2001).

Through a Presidential Decree issued in November 2004, the Mexican National Institute of Astrophysics, Optics and Electronics (INAOE in Spanish) gained ownership of 10.2 Ha at the top of the

mountain, above 4,500 m. In addition, the INAOE has a permit from the Mexican Secretariat of Environment and Natural Resources (SEMARNAT in Spanish) to use about 4 Ha for the HAWC Gamma Ray Observatory, which lies 1 km north of the LMT, at 4,100 m. A few experiments share the Sierra Negra site and its infrastructure with the LMT, the HAWC being the most prestigious.

The Large Millimetre Telescope Alfonso Serrano

The Large Millimetre Telescope Alfonso Serrano (or Gran Telescopio Milimétrico Alfonso Serrano, GTM, in Spanish) is an antenna with a 50 m diameter dedicated to research in astronomy through observations in the 0.8–4.0 mm band (Carrasco et al., 2006). The LMT is the product of binational collaboration between the INAOE and the University of Massachusetts Amherst (UMASS) to build and operate the largest single dish millimetre-wave telescope in the world for observations in the 0.8–4.0 mm band. The LMT, the most ambitious science project undertaken by Mexico, was formally approved in 1994. The project’s important milestones are shown in Table 1. We can identify the construction (1999–2006),

| DATE              | MILESTONE                                                                                                                  |
|-------------------|----------------------------------------------------------------------------------------------------------------------------|
| 31 AUGUST 1992    | LMT PROJECT PRESENTED TO CONACYT.                                                                                          |
| 20 SEPTEMBER 1993 | CONACYT NOTIFIED UMASS ABOUT THE LMT’S APPROVAL CONTINGENT ON ITS GO-AHEAD IN THE USA.                                     |
| 14 FEBRUARY 1994  | UMASS COMMUNICATED THE POSITIVE RESPONSE REGARDING THE US CONTRIBUTION TO THE LMT.                                         |
| 31 OCTOBER 1994   | CONACYT AND THE INAOE SIGNED AGREEMENT TO FINANCE THE LMT’S DESIGN, CONSTRUCTION AND INSTAL-LATION.                        |
| 17 NOVEMBER 1994  | SIGNATURE OF THE INAOE – UMASS MEMORANDUM OF UNDERSTANDING.                                                                |
| FEBRUARY 1996     | DEFINITION OF LMT SPECIFICATIONS.                                                                                          |
| FEBRUARY 1997     | SIERRA NEGRA SELECTED AS THE LMT SITE.                                                                                     |
| DECEMBER 1997     | THE INAOE CONTRACTS MAN TECHNOLOGIE TO DESIGN THE LMT.                                                                     |
| 1999 – 2006       | THE LMT IS BUILT.                                                                                                          |
| 22 NOVEMBER 2006  | THE LMT IS INAUGURATED BY PRESIDENT FOX. M87 IS OBSERVED AT 14 GHZ.                                                        |
| 1 JUNE 2011       | THE FIRST LIGHT IN THE NOMINAL 1-3 MM BAND IS ANNOUNCED.                                                                   |
| 12 JULY 2011      | ALFONSO SERRANO PASSES AWAY.                                                                                               |
| MAY 2013          | THE LMT STARTS OPERATIONS WITH 32 M APERTURE, ENOUGH TO BECOME THE LARGEST SINGLE DISH MILLI-METRE TELESCOPE IN THE WORLD. |
| 2013 – 2015       | THE LMT COMPLETION PLAN IS SUPPORTED BY CONACYT.                                                                           |
| 2016              | TARGET FOR FULL 50 M OPERATIONS.                                                                                           |

Table 1. The LMT project’s important milestones.



Figure 1. Sierra Negra or *Tliltepetl*, the black mountain, in front of the white snowy *Citlaltepetl*, the mountain of the stars. © James Lowenthal.

the inauguration (November 2006), the first light in the millimetre band (June 2011) and early science operations (2013–2016). The LMT is still a productive telescope with relevant participation in the Event Horizon Telescope,<sup>1</sup> a Very Long Baseline Interferometer (VLBI) initiative to image the black hole residing at the Galactic Centre in 2017. With the Mexican National Council of Science and Technology (CONACYT in Spanish) supporting the LMT Completion Plan, the telescope is currently on track for entering full 50 metre observations by the end of 2016.

The search for the site of the LMT was conducted in the mountains of Mexico, that are higher than 3000 m in altitude, including a location in the OAN-SPM. The most relevant parameter was the column density of water vapour in the atmosphere for which the main competing factors were the intrinsic drier conditions of the north of

Mexico and the thinner atmosphere at high altitude. Monitoring of the Nevado de Toluca showed altitude to be dominant, leading to the eventual selection of the highest site monitored: Sierra Negra. With geographical coordinates of 18°59'N and 97°19'W, the LMT site has the additional advantage of good visibility of the southern skies.

### The HAWC Very High-Energy, Ray Observatory

Since 1912, it has been recognized that very energetic particles from outer space, termed cosmic rays, continuously penetrate the terrestrial atmosphere (Friedlander, 1989). In 1938, Pierre Auger discovered that these energetic cosmic particles produce an avalanche of secondary particles in the atmosphere, a phenomena described as 'Extensive Air Showers' (EAS) or atmospheric particle cascades. This finding led to the construction of arrays of particle detectors, or Extensive Air Shower Arrays, for the study of high-

1. <http://www.eventhorizontelescope.org/>

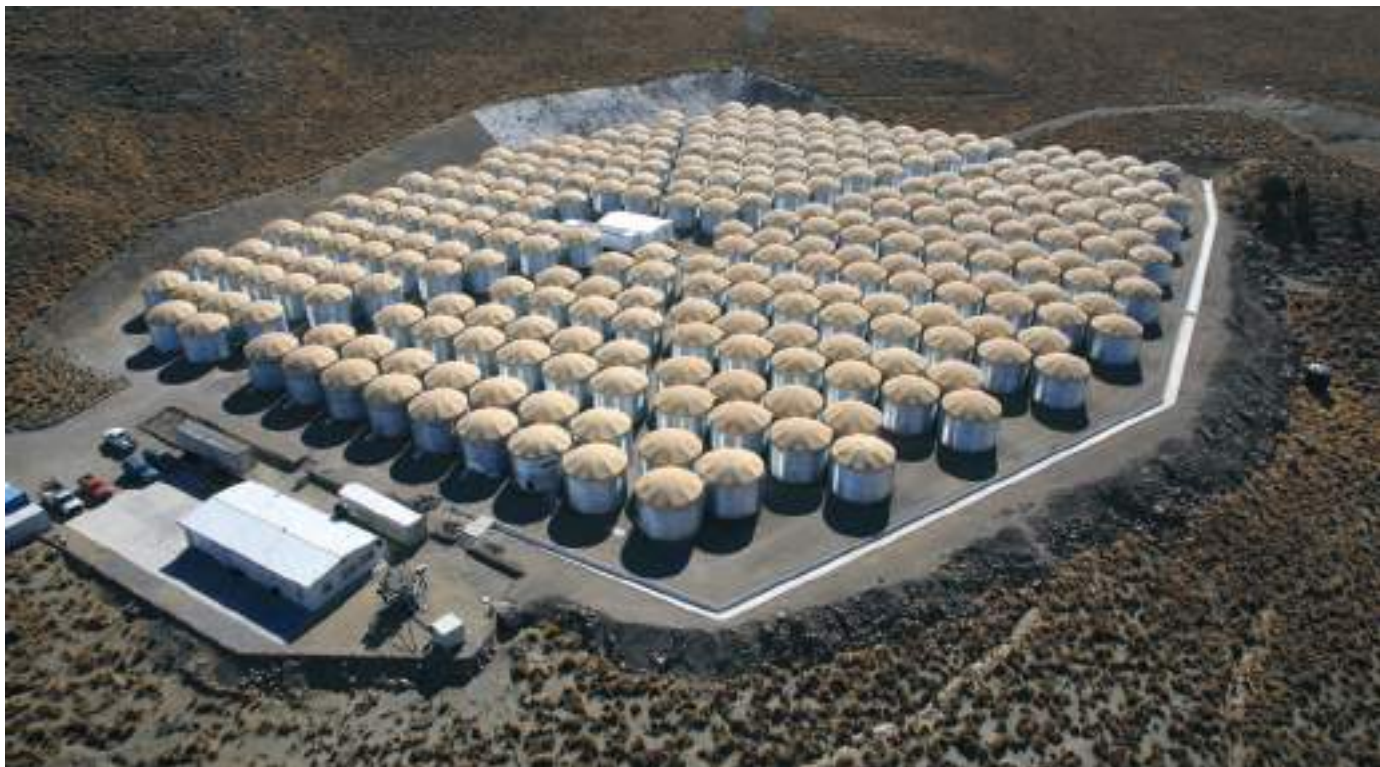


**Figure 2.** Drone view of the HAWC Gamma Ray Observatory on its inauguration, 20 March 2015. The array is approximately 150 m on each side, with a single detector 7.2 m in diameter. © INAOE.

energy cosmic rays (Friedlander, 1989). Between 1999 and 2008, the high altitude Milagro EAS, located in New Mexico at an altitude of 2650 m, proved the feasibility of effectively distinguishing between cosmic ray and gamma ray induced cascades, opening the possibility of performing studies on astrophysical sources. The detection by Milagro of TeV gamma ray emission from sources like the Crab Nebula, Mkn 421 and the Galactic Plane was the basis for proposing an improved designed detector to be located at a higher altitude: the High Altitude Water Cherenkov Observatory (Hoffman and Sinnis, 2008).

The HAWC proposal came to Mexico in January 2006 when the Milagro collaboration started to actively look for sites above 4,000 m in Mexico, China and Bolivia. A Mexican interest group comprised of individuals from several institutions formed and, as a result, a site

feasibility study was carried out for the installation of the HAWC at Sierra Negra. In July 2007, the site of Sierra Negra was selected for the High Altitude Water Cherenkov Gamma Ray Observatory. Clearance of environmental permits took a couple of years and in July 2009, an extension of the LMT road was opened to access the current HAWC site. A flattened platform of 22,500 m<sup>3</sup> was prepared in 2011 for the installation of the array between 2012 and 2014. The array consists of 300 water Cherenkov detectors, each 7.2 m in diameter and 5 m high, filled with 180,000 l of water and instrumented with 4 photomultiplier tubes to record the Cherenkov light produced by the passage of energetic particles in the water. One advantage of the HAWC's modular design is the possibility of early tests and engineering, and scaled operational phases. After sixteen months of early science operations with one-third of the array functional and the remaining two-thirds still in installation, the HAWC



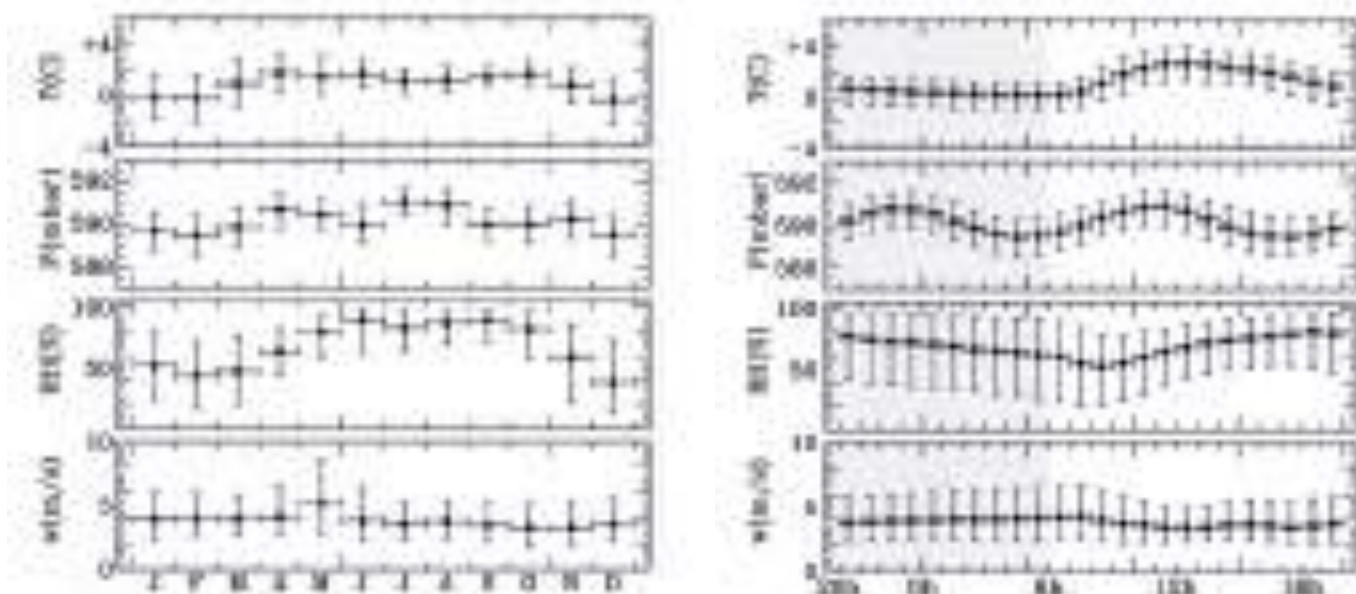


Figure 3. Temperature, atmospheric pressure, relative humidity and wind velocity at Sierra Negra for the different months (left) and hours (right).  
© Alberto Carramiñana with data from Carrasco et al. (2009).

was inaugurated on 20 March 2015, the day of the equinox. The HAWC is currently operating continuously, with a duty cycle above 95%, making daily detections of the Crab Nebula that exceed the expectations stated in the original proposal presented to the National Science Foundation (NSF), the US Department of Energy (DOE) and CONACYT (Westerhoff, 2014).

The HAWC is unaffected by observational conditions, light pollution or weather, with the exception of extreme weather, like electric storms or heavy precipitation. In the next two years, a peripheral outrigger array will be installed around the HAWC. It will be made of more than 300 smaller detectors containing 2500 l of water each and separated by 10 to 15 m. The expanded HAWC array will cover a total area of 100,000 m<sup>2</sup> centred on the current dense array, significantly increasing the response of the detector for gamma ray energies above 10 TeV (Sandoval, 2015).

### Other Experiments at Sierra Negra

There are some smaller experiments taking place in the area at the top of the mountain which were installed through agreements signed with the INAOE:

- The Solar Neutron Telescope is the result of collaboration between the UNAM Geophysics Institute, Mexico and Nagoya University, Japan. It was installed between 2003 and 2004 in a hut just 70 m south-west of the LMT, starting operations shortly thereafter. More recently, in 2010, the SciBar instrument of Nagoya University was located in Sierra Negra, next to the Solar Neutron Telescope, and rebaptized as SciCRT (Scintillation bar Cosmic Ray Telescope). This instrument, originally a neutrino detector at the Fermi National Accelerator Laboratory, consists of 14,366 scintillator bars connected to multi-anode photomultiplier tubes and has been performing as a solar neutron detector and a high resolution cosmic ray detector at Sierra Negra since mid-2013 (Sasai et al., 2014).
- LAGO: originally the Large Aperture GRB Observatory, now part of the renamed Latin American Giant Observatory, LAGO is a network of EAS detectors in Latin America (The LAGO Collaboration, 2016). The LAGO station at Sierra Negra is designed as an array of four water Cherenkov detectors, one of them of the same dimensions as those at the HAWC, while the other three are of the same diameter, but just 1 m tall. It has



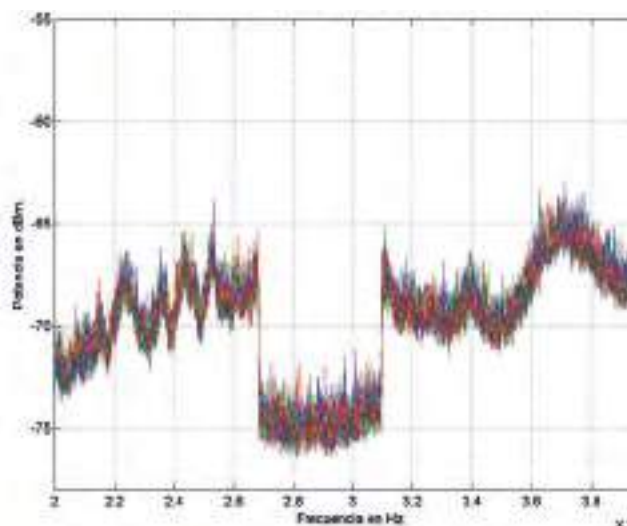


Figure 4. Measurements of electromagnetic noise for frequencies between 20 and 40 GHz. The data is dominated by instrumental noise, with no detection of interference. © Celso Gutierrez.

not began scientific operations, but has been very useful as a test bed for student training.

- OMEGA, for the Mexican Observatory of Gammas, is an atmospheric Cherenkov telescope formerly part of the HEGRA array<sup>2</sup> that is currently being installed at the HAWC site. These telescopes require dark and clear skies to operate and are sensitive to light pollution.
- Minor experiments include a station for monitoring greenhouse gases from the Climate Institute; a geo-positional reference marker from the Mexican National Institute of Statistics and Geography (INEGI in Spanish) for geodesic studies; a seismograph from the Benemérita Universidad Autónoma de Puebla, currently non-functional; radiometers and weather stations in the top zone and the HAWC site run by the INAOE.
- The 10.4 Ha area at the top of Sierra Negra has also been considered for the potential installation of optical telescopes, with a flattened area at the north-east end of the area.

### The Conditions at the Sierra Negra Site

Sierra Negra has had a particular history of monitoring, due to its origin as the site of the Large Millimetre Telescope Alfonso

Serrano. Among the studies carried out, we can list the following, to be detailed further:

- The atmospheric content of water vapour was first measured in 1995 and 1996 for the LMT site selection (Torres et al., 1997); monitoring this water vapour has since continued.
- Meteorological data has been taken at the top of the mountain continuously since 2000 and has been used for the further characterization of the site's properties, (Carrasco et al., 2005; Carrasco et al., 2009).
- The site was categorized in terms of its image quality in the visible spectrum, through optical measurements between 2000 and 2002 (Carrasco et al., 2003).
- The site was monitored for electromagnetic noise in radio for frequencies up to 40 GHz (Martínez, 2013).

### Opacity at Millimetre Wavelengths

Measurements of the atmospheric opacity at a frequency of 210 GHz were carried out between August 1995 and November 1996 for the site selection process. The opacity measurements were correlated with contemporaneous precipitable water (PPW) vapour measurements in order to obtain extrapolated opacity estimates dating back to 1990. Sierra Negra was found to show opacities below 0.4 for more than 90% of the time and incursions of opacities below 0.1 in winter (Torres et al., 1997). Radiometer measurements have continued since then as the site's opacity is monitored continuously as part of LMT operations, confirming these results and the availability of sub-millimetre conditions at Sierra Negra.

### Meteorological Data

One relevant aspect of Sierra Negra is the benign weather when considering the altitude of the site. Statistics on weather data taken over more than seven years, between 2000 and 2008, were presented by Carrasco et al. (2009). The weather station was located some 120 m north-east of the LMT, at an altitude of 4,530 m. Median values of atmospheric variables were temperature  $T=1.1\text{ }^{\circ}\text{C}$ ; atmospheric pressure  $P=590.1\text{ mbar}$ ; relative humidity  $RH=68.9\%$ ; and wind velocity  $w=3.8\text{ m/s}$ . We noted that temperature medians do not vary significantly between day ( $2.12\text{ }^{\circ}\text{C}$ ) and night ( $0.35\text{ }^{\circ}\text{C}$ ) or wet ( $1.39\text{ }^{\circ}\text{C}$ ) and dry ( $0.34\text{ }^{\circ}\text{C}$ ) seasons, while relative humidity does vary noticeably between the wet (84.9%) and dry (50.9%)

2. The HEGRA atmospheric Cherenkov telescope system. <http://www.mpi-hd.mpg.de/hfm/CT/CT.html>

| TOWN OR CITY  | ALTITUDE (M) | POPULATION (2000) | DISTANCE (KM) | DIRECTION (° E FROM N) | LOG R |
|---------------|--------------|-------------------|---------------|------------------------|-------|
| TEXMALAQUILLA | 3100         | 1,109             | 5.39          | 148.6                  | 1.78  |
| CIUDAD SERDÁN | 2540         | 34,303            | 13.93         | 270.5                  | 1.34  |
| ATZITZINTLA   | 2680         | 2,926             | 9.85          | 188.0                  | 0.97  |
| ORIZABA       | 1284         | 53,889            | 27.33         | 122.0                  | 0.16  |
| CÓRDOBA       | 924          | 132,091           | 41.55         | 103.6                  | -0.31 |
| COSCOMATEPEC  | 1588         | 21,385            | 30.91         | 72.5                   | -0.50 |
| TEHUACÁN      | 1676         | 172,510           | 58.51         | 188.2                  | -0.89 |
| PUEBLA        | 2162         | 1,157,625         | 93.17         | 273.7                  | -1.02 |
| XALAPA        | 1427         | 384,021           | 73.43         | 36.4                   | -1.08 |
| TECAMACHALCO  | 2055         | 24,108            | 45.29         | 256.2                  | -1.22 |
| MÉXICO        | 2233         | 17,500,000        | 197.63        | 283.8                  | -1.37 |
| VERACRUZ      | 14           | 381,190           | 126.04        | 79.6                   | -2.12 |

**Table 2:** Estimate of the light pollution effect of population centres on Sierra Negra, measured by the ratio between the increase of light and the natural level of sky brightness. Reproduced from Carrasco et al. (2002).

seasons (Carrasco et al., 2009). The data also contained information regarding solar radiation incidents and was used to quantify the fraction of clear skies, showing this to vary significantly between the wet and dry seasons, May to October and November to April respectively.

A setup of two identical weather stations installed at the LMT and the HAWC was implemented in 2012. Simultaneous data are currently being acquired at the two different altitudes, with the goals of correlating the weather variables and studying the structure of the atmosphere.

**Optical Seeing**

Optical seeing is a measure of the apparent size of a star, which is dominated by the widening effect of turbulent air in the atmosphere. As a result, while the Sun, located at one parsec (3.17 light years), would have an apparent diameter of 0.01” only considering geometry, atmospheric turbulence distorts stellar images to sizes comparable to 1”.

Astronomical seeing was measured at Sierra Negra between 2000 and 2002 using a Differential Image Motion Monitor, in order to

evaluate the possibility of installing a large optical telescope at Sierra Negra. The median of the seeing data acquired then was 0.78”, with a first quartile of 0.61”, showing Sierra Negra to be a competitive site in terms of the quality of astronomical images, although still not at the level of San Pedro Mártir, where the number of clear nights is also better (Carrasco et al., 2003).

**Electromagnetic Interference**

Electromagnetic interference of radio frequencies was measured at the LMT site between 2007 and 2008, as reported in Gustavo Martínez’s PhD thesis (2013). Low frequency data showed signals from radio-FM, TVs, mobile telephones, radio-localization and radio-navigation systems, as expected. Aside from these signals recorded at frequencies below 3 GHz, no interference above the instrumental noise of the detector system, between -70 and -80 dBm, was perceived.

Electromagnetic interference is an obvious concern for the LMT, in particular for frequencies above 75 GHz. However, its instrumentation is prone to interference at lower frequencies. Heterodyne instruments of the LMT, like the Redshift Search Receiver or SEQUOIA, convert the signals received to lower



Figure 5. The Large Millimetre Telescope Alfonso Serrano observing the sky at Sierra Negra, while the Milky Way transits. © James Lowenthal (Smith College).

frequencies through mixing them with local oscillators. These intermediate frequencies, often between 2 and 5 GHz, are more vulnerable to interference by systems like cellular phones or wireless links. Through an explicit protection clause in the signed agreements, the INAOE has implemented a policy with all Sierra Negra users of non-interference with the LMT. In particular, all data generated at the site is transmitted through the on-site optical fibre, avoiding the use of microwave links.

The LMT is explicitly included in the Mexican National Table of Frequency Allocations<sup>3</sup> through the radio astronomy service and note MEX-283. This note considers a 100 km radius protection zone for the LMT, difficult to implement in practice. Currently, services above 75 GHz in Mexico are virtually non-existent and the National Park does provide some protection to the site against electromagnetic noise. It is noted that the International Astronomical Union, in its XXIX General Assembly, issued its resolution B4 regarding the potential use of those frequencies in radars for cars.

### Sky Brightness

Sky brightness has not been properly studied at Sierra Negra, in part because there has not been a project with the resources to establish an optical telescope on site. The site is located near important population centres and their effect on the sky at the site was estimated in 2002 (Carrasco et al., 2009). The quantification was made using Walker's law, which quantifies the effect of urban centres to their population,  $\log(r) = \log(X) - 4.7 \log(R)$ , where  $r$  is the ratio of the observed sky glow and its natural value;  $X$  is the total luminous flux of outdoor lightning in the source, taken as 150 lumen per inhabitant; and  $R$  is the distance to the urban centre in km. The table shown in Carrasco et al. (2002) is updated below. The values of  $\log(r)$ , shown in Table 2, can only be indicative as they need to be updated and there is no consideration of the high altitude of the Sierra Negra site, which is bound to result in a lower level of light pollution as less urban light is scattered down.

On-site measurements were made back in 2005, using a 14-inch telescope. These data are not sufficient to properly define sky brightness at Sierra Negra, where night images from the site show

a starry sky that can be exploited for observations in the optical window or with air Cherenkov telescopes.

### Summary

Mexico has an invaluable number of astronomical sites. These exceptional properties, such as the high altitude Sierra Negra volcano, host facilities benefiting from its thin atmosphere, the Large Millimetre Telescope Alfonso Serrano and the High Altitude Water Cherenkov Gamma Ray Observatory. Due to the nature of its facilities, Sierra Negra has been characterized in terms of the water vapour content of its atmosphere, its weather and radio frequency interference noise. The optical seeing of Sierra Negra has been measured, showing the site to be competitive for astronomy in the visible spectrum. Located inside a national park, Sierra Negra has local conditions that allow it to keep its dark skies.

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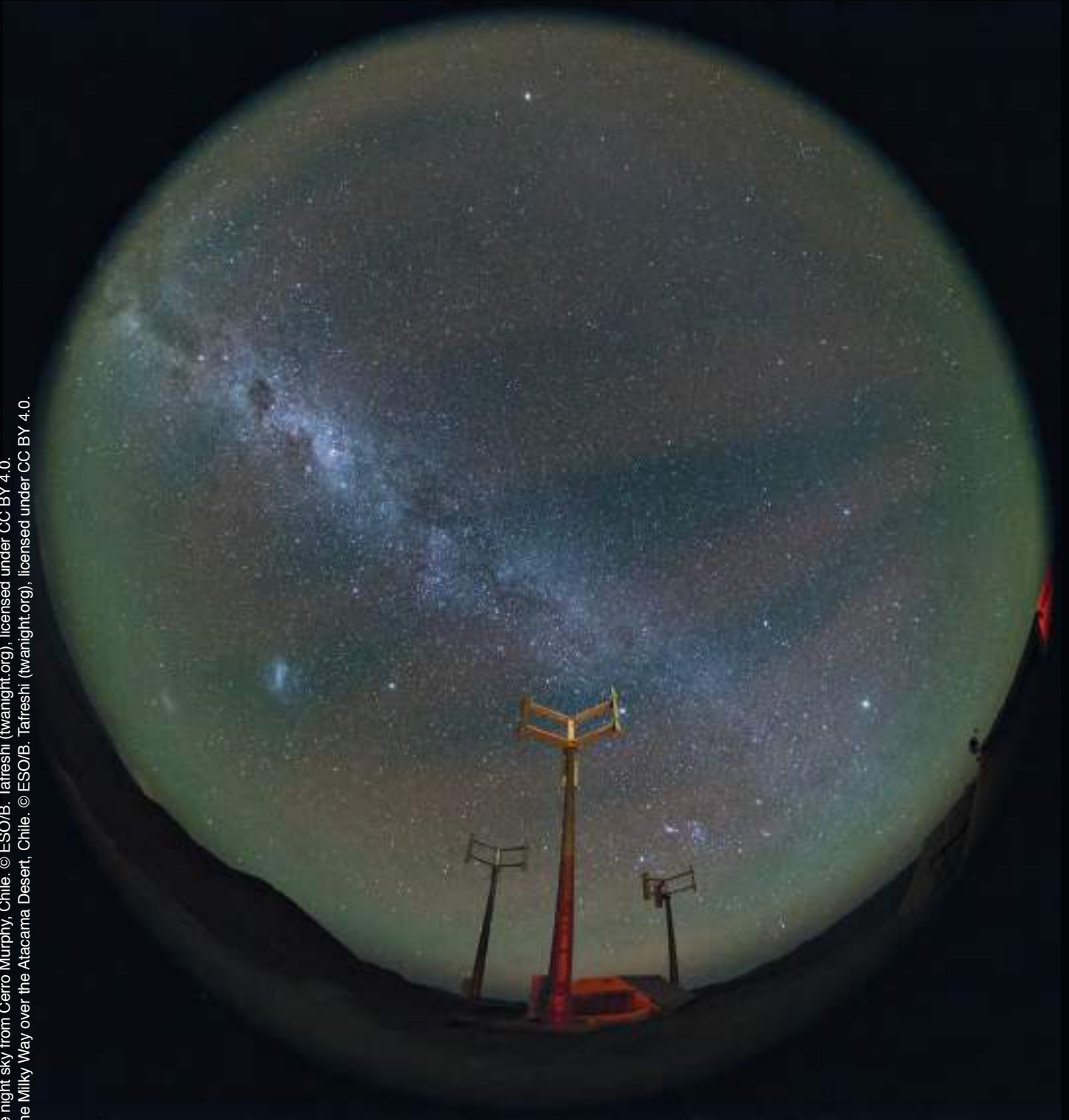
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Left: The night sky from Cerro Murphy, Chile. © ESO/B. Tafreshi (twanight.org), licensed under CC BY 4.0.  
Right: The Milky Way over the Atacama Desert, Chile. © ESO/B. Tafreshi (twanight.org), licensed under CC BY 4.0.



Chapter 4

# The Protection of Dark Skies: Regional Perspectives

Capítulo 4

# La protección de los cielos oscuros: perspectivas regionales











# Protecting the Dark Skies of Chile: Initiatives, Education and Coordination

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## Abstract

During the next decade, Chile will consolidate its place as the ‘World Capital of Astronomy’. By 2025, more than 70% of the world’s infrastructure for conducting professional astronomical observations will be installed in the Atacama Desert in the north of the country. The amazing scientific discoveries these telescopes produce have a direct impact on our understanding of the cosmos, and protecting this ‘window to the universe’ is fundamental in order to ensure humanity’s right to contemplate the night sky and decipher our origins.

As a country, Chile faces the challenge of fighting light pollution and protecting its dark skies in a context of sprawling urban growth and an ever-expanding mining industry that shares the same territory with astronomical observatories. The Chilean Astronomical Society (Sociedad Chilena de Astronomía, SOCHIAS) plays an active role in protecting dark skies through a series of initiatives involving educational programmes, aiding in the development and enforcement of public policy and regulation, and seeking the declaration of Chile’s best astronomical sites as protected heritage areas, both at the national and international levels.

Whilst describing our experiences, I highlight the importance of approaching the problem of light pollution from all sides, involving all the relevant actors (communities, national and local governments, lighting industry, environmentalists, astronomers and others). I also discuss how communication and timely coordination with potential problematic actors (like industries, cities and some government agencies) can be an effective tool to transform potential enemies into allies in the fight for the protection of the night sky.

## Resumen

Durante la próxima década, Chile afianzará su lugar como “Capital Mundial de la Astronomía”. Para el 2025, más del 70% de la infraestructura mundial para realizar observaciones astronómicas profesionales estará instalada en el Desierto de Atacama, al norte del país. Los asombrosos descubrimientos científicos que generan estos telescopios tienen un impacto directo en nuestro entendimiento del cosmos, y proteger esta “ventana al universo” es fundamental para garantizar el derecho de la humanidad a contemplar el cielo nocturno y descifrar nuestros orígenes.

Como país, Chile enfrenta el desafío de luchar contra la contaminación lumínica y proteger sus cielos oscuros en un contexto de crecimiento urbano descontrolado y con una industria minera en continua expansión que comparte el mismo territorio que los observatorios astronómicos. La Sociedad Chilena de Astronomía (SOCHIAS) desempeña un activo papel a la hora de proteger los cielos oscuros a través de una serie de iniciativas que implican programas educativos, ayudando en el desarrollo y aplicación de políticas públicas y regulaciones, y solicitando la declaración de los mejores sitios astronómicos de Chile como áreas de patrimonio protegidas, tanto a nivel nacional como internacional.

Al tiempo que describo nuestras experiencias, subrayo la importancia de abordar el problema de la contaminación lumínica desde todos los ángulos, implicando a todos los actores relevantes (comunidades, gobiernos nacionales y locales, industria de la iluminación, ecologistas,

astrónomos y otros). Analizo también cómo la comunicación y la coordinación oportuna con potenciales actores problemáticos (como industrias, ciudades y algunas agencias gubernamentales) puede ser una eficaz herramienta para transformar a potenciales enemigos en aliados en la lucha por la protección del cielo nocturno.

### **Chile: World Capital of Astronomy**

During the first half of the twentieth century, the largest telescopes in the world, like the 100-inch Hooker Telescope at Mount Wilson and the Palomar 200-inch Hale Telescope, were mostly concentrated in southern California, in the continental United States. In the 1950s and 1960s, American and European astronomers started scouting potential sites in the Atacama Desert in northern Chile. This was part of an effort to find places offering superb observation conditions and also ensuring low levels of light pollution in the future. The urban sprawl of cities like Los Angeles and San Diego was quickly diminishing the capabilities of the most powerful telescopes in the world, and the low population density of the Atacama Desert and its remoteness seemed to offer decades, even centuries, of dark skies ahead.

With the construction of the Cerro Tololo Inter-American Observatory (CTIO) in 1963 by the United States National Optical Astronomical Observatory (NOAO), the establishment of the La Silla Observatory in 1965, operated by the European Southern Observatories (ESO), and the start of operations at the Las Campanas Observatory in 1969, built by the Carnegie Institution for Science, the Atacama Desert started its journey towards becoming the most important hub of astronomical observing facilities in the world.

Today, the Atacama hosts about 30% of the total optical telescope collecting area in the world, including flagship projects like the four 8.2 metre ESO Very Large Telescopes (VLT), the two 6.5 metre Magellan Telescopes at Las Campanas and the 8.1 metre Gemini South Telescope. Chile's share of the world's optical astronomical infrastructure will increase to about 70% with the completion of projects currently in construction, such as the Large Synoptic Survey Telescope (LSST), the 25 m Giant Magellan Telescope (GMT) and the 39 m European Extremely Large Telescope (E-ELT).

Furthermore, considering telescopes that observe at radio wavelengths, where light pollution can be present in the form of radio interference

from communications and other sources, Chile already hosts most of the world's radio telescope collecting area, primarily thanks to the Atacama Large Millimetre/sub-millimetre Array (ALMA). This is the largest and most powerful radio telescope in the world, consisting of a sixty-six 12 m antenna interferometer.

All this investment in astronomical infrastructure has undoubtedly transformed the Atacama Desert into the 'World Capital of Astronomy' and has brought enormous benefits to the country on several fronts. Chile and its government see the development of astronomy as an opportunity for national development. The scientific cooperation between international observatories and Chilean universities has translated into enormous advances in the quality, quantity and impact of astronomy, astrophysics and astronomical instrumentation research that is conducted in Chile. Today, Chilean universities are at the forefront of astronomical research and compete side by side with universities in Europe and North America.

The international observatories in the Atacama have also sparked the attraction and training of highly qualified professionals in several fields of engineering, physical and mathematical sciences and computer science. The transfer of knowledge, expertise and technology between astronomical observatories, universities and the private sector offers enormous opportunities for the development of advanced technology engineering companies in Chile, an aspect of strategic importance for future economic growth and international competitiveness. Furthermore, other areas like STEM education, the growing industry of astrotourism and the protection of the country's natural and cultural heritage have all benefited in one way or another from the development of astronomy in the country.

### **Light Pollution in Chile**

Until the early 1990s, light pollution around important astronomical observatories in Chile was minimal. Most sites, even those close to large cities, like Cerro Tololo near La Serena, showed measured

sky brightness consistent with natural (virgin) levels. During the 1990s, Chile saw enormous economic and population growth, with a sustained annual GDP increase ranging from 5–10% and a 15% growth in population. This development continued over the next two decades and a significant fraction of it has happened in and around the Atacama Desert, the country's main mining region.

Figure 1 presents maps of the Atacama's sky brightness levels at the zenith computed using night time satellite imagery and atmospheric light propagation models. It is clear that the areas affected by light pollution have increased substantially over the years. Already in the mid-1990s, sites close to cities like Cerro Tololo and Cerro Pachón showed small but significantly measured enhancements in sky brightness above the natural levels. Today, the levels of light pollution at Tololo and Pachón are increasing alarmingly and remote sites that previously showed virgin dark skies, such as Las Campanas and La Silla, now sit at the edge of regions significantly affected by light pollution.

The problem of light pollution is now evident to the naked eye in remote sites such as Las Campanas. Figure 2 shows a long exposure

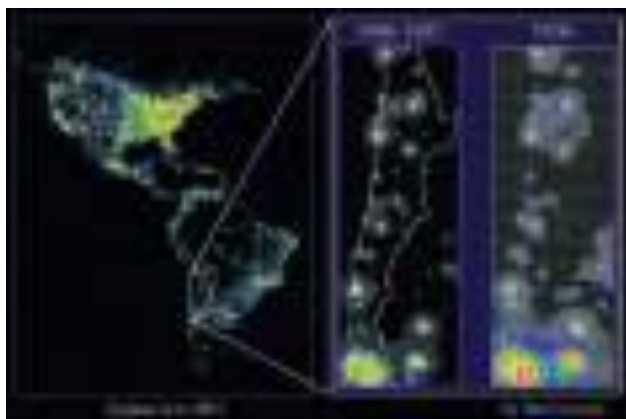


**Figure 1.** Evolution of light pollution in northern Chile 1996-2006. Red squares mark the positions of the main optical astronomical observatories in Chile. From south to north: Pachón and Tololo, La Silla, Las Campanas, Paranal and Armazones. © Guillermo Blanc adapted maps by P. Cinzano, F. Falchi, University of Padova; C. D. Elvidge, NOAA National Geophysical Data Center, Boulder; and David J. Lorenz, University of Wisconsin-Madison.

all sky image of the night sky at this site. The twin 6.5 metre Magellan telescopes are seen at the bottom. On the horizon, one can clearly identify the glowing sky above cities such as La Serena, Coquimbo, Vallenar and Copiapó. One can also see significant sources of light pollution from nearby mining operations, and the lights illuminating crossroads and toll plazas on a nearby stretch of the Panamerican Highway.

A few decades ago, these levels of light pollution at such remote sites were unimaginable. Astronomers, in pursuit of good image quality and low sky brightness, usually conduct their observations by pointing their telescopes at high elevations above the horizon. Astronomical observations, therefore, tend to avoid the areas most dramatically affected by light pollution. If the sustained increase in sky brightness is not controlled appropriately, the sky brightness of the entire night sky can be seriously affected, even towards the zenith, forever degrading the 'windows to the universe' that the dark skies above the Atacama Desert provide us.

Beyond the direct detrimental effects of light pollution on the quality of astronomical observations, several other negative effects are now recognized to be associated with excessive, unnecessary levels of illumination. These include, among other things, distortions in people's sleep patterns and associated health problems, disruption of migration patterns and the hunting and reproductive behaviour of certain animal species and negative environmental and economic impacts associated with the unnecessary overproduction of electric power that is wasted on illuminating the sky. Moreover, in the particular case of Chile, light pollution threatens to take away all the evident benefits to our society that the development of astronomy is currently providing and will provide in the future.

### Light Pollution Regulation in Chile

Astronomers in Chile had already begun expressing serious concerns about the problem of light pollution and its dramatic evolution in the 1990s. Their concerns were well received by the Chilean government and prompted the first regulation on light emissions in the country's history. The 1998 Supreme Decree N° 686 of the Ministry of Economy regulated the characteristics of exterior light fixtures in the three northern regions of the country (Antofagasta,



**Figure 2:** Present day levels of light pollution at Las Campanas Observatory. The cities of La Serena, Vallenar and Copiapó, as well as lightning on the Panamerican Highway and some nearby mining operations are clearly visible on the horizon. © Yuri Beletsky, Las Campanas Observatory.

Atacama and Coquimbo), where most of the observatories are located. Before the 1998 decree, the only protection astronomical observatories received was the designation of ‘Scientific Interest Zones for Mining Purposes’ outlined in the Chilean Mining Code, which defines relatively small buffer zones where no mining activities can be performed without the expressed authorization by the President of the Republic.

Decree N° 686 was followed by the creation of the Office for Protection of Sky Quality in Northern Chile (OPCC in Spanish) in May 2000. The OPCC currently operates under an agreement between the Chilean government, a consortium of international observatories installed in the country and more recently the Chilean Astronomical Society (SOCHIAS in Spanish). This office, under

the leadership of Director Pedro Sanhueza, has been the most important actor in the fight against light pollution in Chile during the last two decades. A 10-year effort led by the OPCC and others translated into widespread compliance with the light emissions regulation established in Decree N° 686. This enormously mitigated the growth of light pollution during the 2000s, which, given the growth of cities in the region, could have been much worse during that decade.

In the early 2010s, the advent of new illumination technologies, mainly the widespread availability of energy efficient Light Emitting Diodes (LEDs), with a strong emission component at blue wavelengths<sup>1</sup> and the popularisation of bright large area LED screens for use in advertisement, made the Decree N° 686 insufficient in terms of providing adequate protection of dark skies in the north of Chile. This prompted the development of new regulation, now coming from the Ministry of Environment.

The new Supreme Decree N° 43 of the Ministry of Environment officially replaced the original Decree N° 686 in 2014, imposing much stricter regulations concerning the characteristics of lighting fixtures and illuminated signs used in outdoor lighting, advertisement, industrial illumination (including mining) and sports events. Of particular importance is the requirement for all outdoor lighting fixtures to have ‘full cut off’ (that is, zero emissions above the horizontal), strict limits on the fraction of the total emissions that can be output at blue frequencies and the establishment of maximum levels of illumination at floor level. While this new decree has the potential to be a powerful tool for controlling light pollution in the Atacama Desert, its implementation has suffered delays. Ensuring a significant level of compliance will require major efforts in education and coordination between the different actors involved in the problem of light pollution. It is here where SOCHIAS, in partnership with the OPCC, is playing a central role in promoting the protection of dark skies.

### **The Work of SOCHIAS and the OPCC**

SOCHIAS is a scientific society that brings together most of the professional astronomers working in Chile. It was created in the year 2000 and it currently has more than 160 members, including

1. Blue light produces more light pollution than red light as it scatters more easily in the atmosphere.

researchers, professors and students at Chilean universities, as well as astronomers and engineers working at different astronomical observatories in the country. Since 2015, SOCHIAS has established a close partnership with the OPCC, the international observatories and the Chilean government, with the goal of fighting light pollution and protecting Chile's dark skies.

From the perspective of SOCHIAS, we see the problem of light pollution as one involving many diverse actors, who play different roles. These include, on one side, the astronomers, the environmentalists and the regulatory government agencies like the Ministry of Environment that have a vested interest in the fight against light pollution. On the other side, local communities, city governments, private industries and other national and regional government agencies related to energy and transportation, can all see different incentives to either produce more light pollution or reduce its levels. For example, a local city government might want to increase the level of lighting in its streets in an effort to reduce night-time crime in the area, or it might want to reduce its electric bill by adopting better illumination practices that reduce the amount of wasted energy spent on illuminating the sky. If the problem of light pollution is to be addressed effectively, we must involve all the different actors, understand their needs and priorities, and find common ground and synergies that reasonably protect their interests while also protecting our dark skies.

In this context, SOCHIAS is involved in several initiatives aimed at protecting the dark skies of northern Chile, which target different actors in the problem of light pollution. These initiatives fall under two main categories: education initiatives and coordination initiatives. Both are essential tools in our fight to protect the unique resource that our country has in its night sky.

### Education Initiatives

Education starts from raising awareness about the existence of the problem of light pollution and the importance of the protection of dark skies. In terms of strategy, it is fundamental to understand that light pollution is a 'problem' that, at least in a country like Chile, is seldom acknowledged as such. Most people are either not aware of the existence of light pollution in the first place, or consider it to be

a minor issue that should be given low priority when it comes down to enacting and enforcing environmental protections. Therefore, the starting point for our work on light pollution education is the general public, and the most effective tool to reach this public is the press. In SOCHIAS, we try to maintain a constant presence of news related to the protection of dark skies in the national press. During 2015, we were mentioned approximately twelve times in the national newspapers, television and radio shows. We also encourage all the members of our society to mention the subject of light pollution whenever they are interviewed about their scientific discoveries. This requires maintaining good relations with scientific journalists at the main news outlets in the country and also being fully available whenever an opportunity to raise the subject in the media arises.

Beyond the general public, a fundamental part of our strategy is to target specific interest groups such as companies that fabricate, import and distribute hardware for public and industrial lightning. For this, in close collaboration with the OPCC, we organized two workshops during 2015 that directly targeted the lighting industry. In these workshops, one of which included a presentation by the Chilean Minister of the Environment, Pablo Badenier, and other government authorities, we exposed the subject of light pollution and the technical requirements that the law mandates for illumination products to be certified for installation in protected regions.

We are seeing a very positive response from these companies and have taken away an important lesson from this experience. Companies in the illumination business have an obvious interest in selling more of their products and therefore have traditionally been seen as adversaries of groups trying to decrease the levels of light pollution. As a result of the new relationship that has been established through these workshops, we are happy to see some companies embracing the fight against light pollution and viewing it as an opportunity to better market their products as environmentally friendly and up to standard with the strict requirements of the law. They also see the need for massive replacement of old non-compliant luminaires as a potential business opportunity. This is a textbook case of how communication, education and an interest in understanding the



necessities of all parties involved in a problem can turn potential adversaries into allies.

Similar experiences are regularly seen with companies in the mining sector, who because of worker safety concerns have a strong incentive for maintaining high levels of illumination in their facilities. The experience of the OPCC shows how receptive these companies are when, by means of meetings and other instances of communication, they realise that by minimal investments they can maintain the same levels of safety while dramatically reducing their impact on light pollution. In the case of the mining sector, there is a strong incentive to reduce light pollution in order to offset other environmental impacts associated with mining and to maintain a good image of social responsibility and sustainability.

Maybe the most important actors in the protection of our dark skies are local city or county governments. Ultimately, these are the decision makers responsible for approving and executing most of the outdoor illumination projects in a particular region. Given the administrative structure of Chile, 'municipalities' are the fundamental government unit that we must have on our side in the fight against light pollution. To ensure this, SOCHIAS and the OPCC have started a full scale training programme that we are carrying out in all municipalities of the three regions of the country currently under the protection of the new light emission regulation (the Decree N° 43 mentioned previously).

While municipalities have a lot of influence on the way illumination is organized and implemented in their jurisdictions, they very often lack the economic resources to update their illumination systems, and they depend a lot on the national and regional governments to provide the necessary funding for such projects. Also, municipalities are often not well informed about the requirements in terms of design and certification that lighting fixtures must fulfil, and this can translate into erroneous purchases and installations of non-compliant and pollutant illumination systems.

In order to alleviate these problems, during 2015 SOCHIAS and the OPCC secured a grant from the ESO-Chile Comité Mixto Fund, which is allowing us to allowing us to finance the above

mentioned training programme for municipal staff across the Antofagasta, Atacama and Coquimbo regions. The first of these training programmes took place in June of 2016 in the cities of Coquimbo and La Serena. This programme includes a general course on 'Sustainable Illumination Practices' given by an expert on illumination design, in addition to two other sessions. The first is aimed at understanding the negative impacts of light pollution and the second is aimed at understanding the technical requirements that Chilean law mandates in terms of characteristics and certifications for new luminaires.

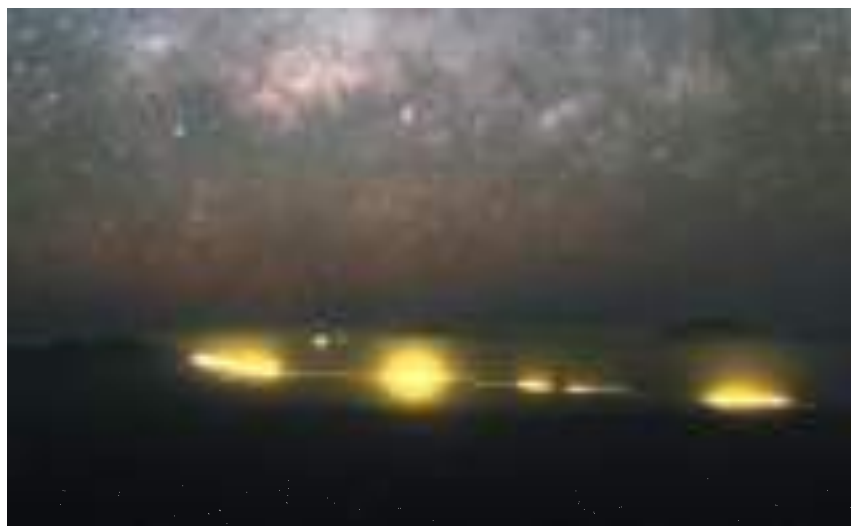
A fundamental goal of these instances is to also include regional authorities and local representatives of the national government, as well as members of the local communities (for example, interested parties like astrotourism business owners). In this way, we can start creating a network of support for the municipalities that can help them push forward the necessary projects to improve their outdoor illumination systems.

Finally, at SOCHIAS we have the responsibility of involving our members in the fight against light pollution. Surprisingly, most professional astronomers in the world are not actively involved in the protection of dark skies. Since the ability to observe the universe from places like the Atacama Desert is a fundamental part of their job, one would expect a much higher level of involvement in dark skies protection than what is currently seen. The low involvement of professional astronomers is caused in part by the enormously competitive and absorbing nature of academic work and research, but we have come to realise that there is another important factor: lack of information and opportunities for involvement. Almost all astronomers are aware of the problem of light pollution but do not know what they can do about it on an individual level.

Therefore, as a society we are trying to actively involve the Chilean astronomical community in our dark sky protection initiatives. Since 2015, we have reserved a space in the SOCHIAS Annual Meeting (the most important and highly attended scientific conference on astronomy in Chile) to have talks and open discussion about light pollution. We educate our own astronomers on what tools and resources they have at their disposal to play a leading role in the fight



**Figure 3:** A stretch of the Panamerican Highway that crosses in front of the La Silla and Las Campanas observatories. The photo shows the highway before and after the installation of new illumination systems at intersections and toll plazas that are not compliant with the new regulatory standards for light pollution in the region. © Yuri Beletsky, Las Campanas Observatory.



against light pollution. This includes providing them with material that they can use in their classes and during outreach talks, showing them how to use the existing systems to denounce violations of the legislation that regulates light pollution in the country and offering them opportunities for involvement in the different initiatives we lead. It is fundamental for us to actively involve the members of our society in the initiatives and activities that we push forward.

### Coordination

While education is a fundamental tool in ensuring the long-term support of all the different actors involved in light pollution, it is a slow process, and there are immediate threats to the quality of our night sky that must be addressed today by means of direct involvement. To this end, SOCHIAS and the OPCC are actively participating in an effort to coordinate several ongoing initiatives that can potentially have a strong impact on the preservation of Atacama's dark skies.

The first of these is a major national programme being pushed forward by the Ministry of Energy of Chile and the Chilean Agency for Energy Efficiency (AChEE in Spanish), which aims to replace 200,000 streetlights across the country for energy efficient LED lights during the next four years. The programme is expected to translate into a nationwide 20% decrease in power consumption associated with street lightning. Alarmingly, due to oversight and lack of coordination, the first incarnation of the programme did not consider the compliance with the recently published Decree N°43 of the Ministry of Environment, which updated the light pollution control norms by limiting the amount of blue emission that new LED based outdoor lighting can produce. A swift reaction by the part of the OPCC, SOCHIAS and the astronomical observatories, together with a positive response from the Ministry of Foreign Relations and the agencies pushing forward the programme, now ensures that all the new luminaires installed in protected regions as part of this initiative will be compliant with the new standards.

Another experience that shows the need for constant oversight and coordination is an illumination project undertaken by the Chilean Ministry of Public Works on a stretch of the Panamerican Highway that crosses right in front of the La Silla and Las Campanas observatories. As part of a major upgrade to the highway and in an effort to comply with current safety standards for road illumination, all new intersections and a newly installed toll plaza were fitted with extremely bright lightning. Sadly this project was approved and executed right when the updated light pollution regulations were coming out, so it did not have to comply with the 'full cut off' restrictions nor with the maximum illumination levels contemplated in the new legislation.

Figure 3 shows two photographs taken from Las Campanas Observatory, more than 1,000 m above the level of the highway, before and after this upgrade. It is impressive to see the large amounts of light being emitted towards the sky from the highway, which, as also seen in Figure 1, is a major source of light pollution in the area. Not only is this project polluting the dark skies of one of the finest astronomical sites in the world, it also implies a major waste of resources since the new regulation requires all these luminaires

to become compliant within a five year period, much shorter than the actual lifespan of these expensive systems.

A greater level of oversight and coordination could have prevented this problem. Thankfully, concerns raised by the OPCC after the project was executed have been positively received by the Ministry of Public Works. Today, there are plans for transforming this stretch of highway into a pilot project for testing Amber LED technology (one of the most astronomy-friendly types of LED illumination) on Chilean roads. If all goes well, such installations could become standard around major observatories in the country.

In summary, there is a lesson to be learned from these experiences. We cannot assume that private parties and government agencies will be aware of light pollution and will consider it as an important priority during their decision making processes. Therefore, constant vigilance by interested parties like observatories, scientific societies and environmental agencies is fundamental. In our experience, even minimal levels of communication, education and coordination can be successful at making people understand the problem of light pollution and see the overall benefits of avoiding it.

### Protecting our Heritage and Final Conclusions

The final and perhaps most important initiative that we are currently involved in, concerning the protection of our night sky, is an effort to recognize the Outstanding Universal Value that these marvellous sites in the Atacama Desert have for all of humanity. These unique places, where the best astronomical observatories in the world reside, are our 'windows to the universe'. They are the places from which humanity learns about the cosmos, unveils its origins and comes to understand its place in the world. The Chilean government, in close collaboration with SOCHIAS and the OPCC, are seeking the protection and recognition of the cultural and natural value of these sites at both national and international levels.

For this purpose, as members of a specially appointed working group created by the Chilean Ministry of Foreign Relations, we are working on preparing an application to seek the recognition by the Chilean government of the main observatory sites in the Atacama

Desert as Protected Areas. The goal is for this protection at the national level to be followed up by an application for nomination to the UNESCO World Heritage List. Such recognitions would provide enormous leverage to institutions like SOHCIAS and the OPCC to push forward the protection of these sites against light pollution, but there is a more fundamental impact that we expect from such designations. The Protected Area and UNESCO World Heritage site status will help us find a place for the night sky in the minds of millions of Chileans. We hope that the citizens of our country will start considering the beautiful clear and dark sky of the Atacama Desert as a fundamental part of their heritage. Something they should be proud of and something that their country as a nation must preserve for all humanity to enjoy for centuries to come.

It is this concept of preserving a unique and beautiful natural laboratory, which provides us with a window to the universe and to ourselves that guides our efforts. Chile as a nation has the responsibility to protect what nature has endowed us with and it is exciting to see how governments, industries, scientists and the public are starting to share this realisation. There is still a lot of work to be done, but we are on the right path to ensure that future generations will have access to the same dark sky that we have inherited from our ancestors.





# La protección de los cielos chilenos del norte, a través de reglamentos y del patrimonio

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## Resumen

Gracias a los cielos nocturnos limpios, estables y oscuros, y además a la calidad de la infraestructura, a la calificación de la mano de obra y al compromiso nacional hacia la protección de dichos cielos, ha podido desarrollarse en Chile una parte significativa de los proyectos astronómicos de vanguardia a nivel mundial. Dan cuenta de ello los observatorios de Cerro Tololo y Pachón, por parte de AURA; el observatorio de Las Campanas, de CARSO, y los observatorios de La Silla y Cerro Paranal, por parte de ESO, así como el inicio de la construcción de nuevos proyectos astronómicos de gran envergadura, como es el caso del proyecto del Gran Telescopio para Rastreo Sinóptico (LSST), el proyecto Gran Telescopio de Magallanes (GMT) y el Telescopio Europeo Extremadamente Grande (E-ELT, por sus siglas en inglés, los anteriores).

El compromiso del país con la protección del cielo nocturno de esta zona ha quedado reflejado en la promulgación de los decretos supremos de carácter ambiental: el D. S. N° 686/1998 MINECON, la llamada primera Norma Lumínica, que entró en vigencia el año 1999, y el D. S. N° 043/2012 MMA, que entró en vigencia el año 2013. Ambas normativas abarcan las regiones del norte del país: Antofagasta, Atacama y Coquimbo, y limitan la emisión de luz directa hacia el hemisferio superior en las fuentes de luz de exteriores. La segunda norma es más estricta, ya que pretende responder ante la amenaza de la irrupción de la tecnología de estado sólido (LED), reflejada principalmente en la masificación de los carteles publicitarios de alto brillo y gran formato (pantallas iluminadas) y en el uso masivo de fuentes de luz fría, con fuerte componente azul, que atentan contra el cielo nocturno de manera más agresiva que las fuentes llamadas cálidas. También limita de manera más estricta la emisión de luz al hemisferio superior, al pasar de 0.8, 1.8 e incluso 5% de Flujo Hemisférico Superior (dependiendo de la aplicación) a sólo 0.49 cd/1.000lm a 90°, lo que se corresponde con el criterio de cierre total (*full cut off*).

Complementariamente con esta puesta al día de la normativa de protección del cielo nocturno, el Gobierno de Chile, la comunidad científica y los observatorios astronómicos se encuentran abocados a ampliar las opciones de protección, explorando actualmente la de las llamadas Ventanas al Universo, un programa conjunto entre la UNESCO y la Unión Astronómica Internacional (UAI) que tiene como fin declarar Patrimonio de la Humanidad a los más relevantes sitios de observación astronómica del mundo, incluyendo los del norte de Chile.

## Abstract

Thanks to its clear, stable and dark night skies, the quality of local infrastructure, a highly qualified workforce and a bold national commitment to protect the night sky, Chile has become one of the most significant centres for major astronomical observation projects in the world. The region is home to the following observatories: Cerro Tololo and Pachón (operated by AURA), Las Campanas (operated by CARSO) and La Silla and Cerro Paranal (operated by ESO). Moreover, there are several large-scale observatories under construction, including the Large Synoptic Survey Telescope (LSST), the Giant Magellan Telescope (GMT) and the European Extremely Large Telescope (E-ELT).

The country's commitment to protecting the quality of the night sky in this region can be seen by the enactment of environmental decrees; D. S. No. 686/1998 MINECON, which was originally called the Light Standard and took effect in 1999, and D. S. No. 043/2012 MMA, which took effect in 2013. These decrees serve to protect the skies of Antofagasta, Atacama and Coquimbo by limiting direct light emissions into the upper hemisphere from outdoor light sources. The second of the two decrees is stricter as it seeks to respond to the threat of the emergence of solid state technology (LED), used mostly in outdoor billboards, and the mass use of cold light sources with strong blue components, both of which impair the visibility of the night sky more aggressively than warmer light sources. This decree also strictly limits light emissions into the upper hemisphere from 0.8, 1.8 and even 5% of the upper hemispheric flux to only 0.49 cd/1.000l m at 90°, which meets the full cut off criterion.

In addition to these regulatory efforts to protect the night sky, the Government of Chile, the scientific community and astronomical observatories are currently examining protection options, including the Windows to the Universe initiative, a joint programme between UNESCO and the International Astronomical Union (IAU), whose aim is to increase representation of the most relevant sites of astronomical observation, including those in northern Chile, on the World Heritage List.

### Resumen del D. S. N° 034/2012 MMA, Nueva Norma Lumínica

#### Reseña de la normativa anterior

El D. S. N° 034/2012 del Ministerio del Medio Ambiente (MMA) de Chile reemplaza a la Norma de Emisión para la Regulación de la Contaminación Lumínica, el D. S. N° 686/1998 del Ministerio de Economía, Fomento y Turismo (MINECON). Este anterior decreto fijaba restricciones de emisión de luz hacia el hemisferio superior en iluminación pública de 0.8% de FHS (Flujo Hemisférico Superior) para lámparas de hasta 15.000 lúmenes por vatio, 1.8% de FHS para aquellas sobre 15.000 lúmenes por vatio. Ambas requerían una eficiencia mínima de 80 lúmenes por vatio. Para proyectores de área e iluminación ornamental bajo 9.000 lúmenes, el máximo FHS autorizado era de 5%. Sobre ese valor había que referirse a las mismas restricciones establecidas para iluminación pública. Para la publicidad había restricción horaria: 1:00 am, y para los recintos deportivos, las 2:00 am. Ambas podían continuar con su iluminación nocturna, en la medida que acreditaran cumplir con los FHS de 0.8 o 1.8% antes nombrados. Los cañones láser, de discotecas por ejemplo, no podían inclinarse sobre la horizontal.

#### Dificultades con la antigua norma

El D. S. N° 686/98 tenía el problema de no incluir las nuevas tecnologías en iluminación exterior: de estado sólido (LED), ni por ejemplo, las lámparas de inducción magnética. Tampoco limitaba convenientemente los flujos de luz en ángulos cercanos a la hori-

zontal, dado que en la época en que se promulgó no había todavía evidencia científica que demostrara el grave daño que provoca la dispersión atmosférica en esos ángulos. Dicha norma tampoco restringía de manera adecuada las emisiones espectrales más perjudiciales para la astronomía, el ambiente natural y la salud humana. El rango bajo 499 nm no estaba convenientemente restringido, el correspondiente al color azul.

#### Principales aspectos de la nueva norma

La nueva norma de emisión para la regulación de la contaminación lumínica fue promulgada el 17 de diciembre del 2012 y fija un periodo de un año para su plena entrada en vigencia.

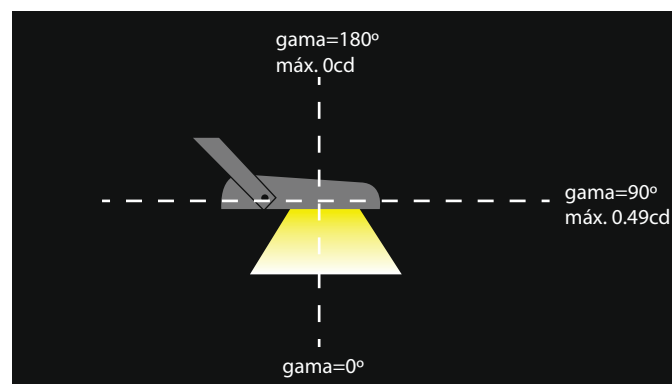


Figura 1. Forma correcta de emplazar una luminaria, en ángulo recto.  
© OPCC.

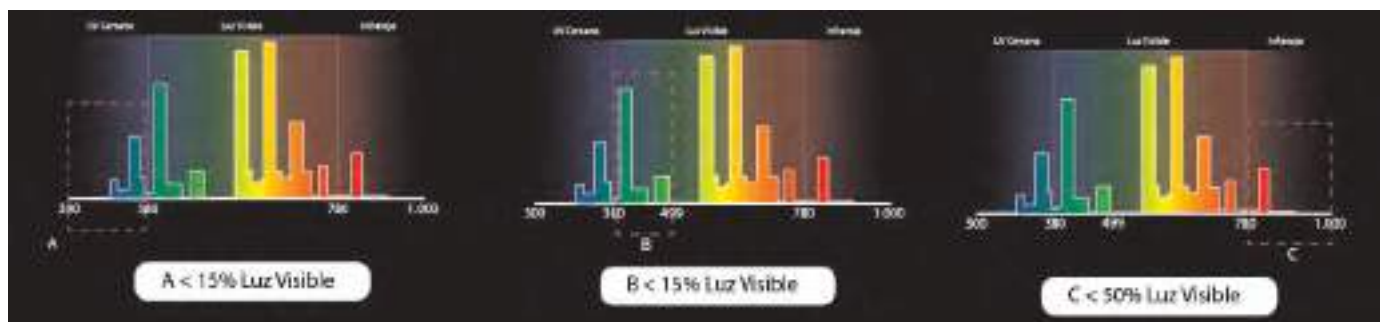


Figura 2. Límite espectral de las fuentes luminosas: restringiendo las emisiones de color azul, ultravioleta e infrarrojas. © OPCC.

Sus principales restricciones son las siguientes:

- La nueva norma establece el criterio de cierre total (*full cut off*) y lo estipula de la siguiente manera: se permite un máximo de 0,49 cd/Klumen a 90° por centro de luz. Esto, para casi todas las aplicaciones: alumbrado funcional, ambiental, industrial y ornamental.
  - Fija un máximo de 20% sobre iluminación respecto a los valores establecidos en la normativa nacional (obtenidos de la CIE) en las aplicaciones asociadas a alumbrado funcional, ambiental, ornamental e industrial.
  - Establece restricciones en tres sectores del espectro electromagnético en referencia al espectro de luz visible (entre 380 y 780 nm): no más de 15% de emisión entre 300 y 380 nm; no más de 15% para el rango comprendido entre 380 a 499 nm, y no más de 50% para el rango comprendido entre 781 y 1.000 nm. Todo esto referido respecto al rango visible. Con esto se busca limitar especialmente la emisión azul asociada a fuentes de luz blanca fría, por ser algunos LED, lámparas de inducción electromagnética y halogenuros metálicos, dada su alta dispersión.
  - Los carteles iluminados desde su interior (o retro iluminados), como pantallas de gran formato de plasma o LED, son autorizados con un máximo de 50 cd por m<sup>2</sup>. Y deben ser emplazados en la vertical o en ángulos más cerrados. No se les aplica restricción espectral.
  - La iluminación de recintos deportivos y recreacionales puede ser hecha con proyectores o luminarias con un máximo de 10 cd/Klumen a 90°, más la adición de una visera que corte el posible flujo lumínico superior. No se le aplica restricción de tipo espectral.
  - Los láser y los llamados cañones de luz pueden ser usados, apuntando hasta un máximo de 70° gama.
  - Los balizamientos a gran altura, como aquellos instalados en las torres de alta tensión, antenas o aerogeneradores, entre otros, deben ser iluminados con lámparas de color rojo, y para ello la norma fija las coordenadas cromáticas respetivas.
  - La fiscalización está a cargo de la recientemente creada Superintendencia de Medio Ambiente (SMA), institución que puede aplicar fuertes sanciones pecuniarias.
  - La acreditación de laboratorios de fotometría y radiometría y la emisión de los respectivos informes técnicos que acreditan el cumplimiento normativo queda radicada en la Superintendencia de Electricidad y Combustibles (SEC), entidad que hasta ahora se encargaba también de la fiscalización.
- Ya se encuentran aprobados los protocolos que permiten acreditar los laboratorios de fotometría y radiometría para la emisión de informes de cumplimiento normativo. Esto ha permitido la acreditación del Laboratorio de Fotometría de la Pontificia Universidad Católica de Valparaíso y del Laboratorio Faraday S. A., primera empresa privada que realiza este tipo de ensayos en Chile.

## El programa de Patrimonio Mundial y Astronomía

La propuesta consiste en la eventual nominación seriada de los observatorios astronómicos internacionales ubicados en el norte de Chile, junto con los de las Islas Canarias, España y de Hawái, Estados Unidos, a la Lista del Patrimonio Mundial de la UNESCO.

La idea inicial de postular los sitios astronómicos surge de la 1ª Conferencia Starlight (Marin & Jafari, 2007) celebrada en la Isla de La Palma, Canarias, España, el año 2007, en cuya divulgación a nivel de Latinoamérica participa activamente la Oficina de Protección de la Calidad de Cielo del Norte de Chile (OPCC).

En octubre de 2008, la UNESCO firma el memorándum de entendimiento con la Unión Astronómica Internacional (UAI), como resultado de lo cual esta última se compromete a participar plenamente en el proceso de promoción de la iniciativa temática “Astronomía y Patrimonio Mundial” de la UNESCO, creada en el 2003.

Durante el año 2009, Año Internacional de la Astronomía, y en el contexto de la iniciativa “Astronomía y Patrimonio Mundial”,<sup>1</sup> el Grupo de Trabajo de la UAI genera el estudio temático “Astronomía y Patrimonio Mundial”. El documento presenta una visión global sobre el patrimonio astronómico y determina lo que constituye la “importancia universal excepcional para la humanidad” en relación con la astronomía y, también, identifica los problemas generales que pudieran surgir en la evaluación de los bienes culturales relacionados con la astronomía. El informe genera una serie de casos de estudio, entre los que destacan los denominados “Ventanas al Universo” (véase el capítulo 16), que integran observatorios de Chile, Canarias y Hawái. La selección de casos no implica que sean lugares candidatos a inscribirse en la lista, sino que se trata de ejemplos que eventualmente pueden ser propuestos por los Estados Parte al Comité del Patrimonio Mundial para su inclusión.

En el 2010, el Comité del Patrimonio Mundial en su 34ª reunión (Decisión 34 COM 5F.1, Brasilia, 2010) pidió al Centro del Patrimonio Mundial difundir entre los Estados Partes el estudio temático sobre el Patrimonio Astronómico mencionado, de conformidad con la Decisión 32 COM 10A (Quebec, 2008) y en el marco de la Estrategia de Implementación Integrada de la Iniciativa “Astronomía y Patrimonio Mundial”.

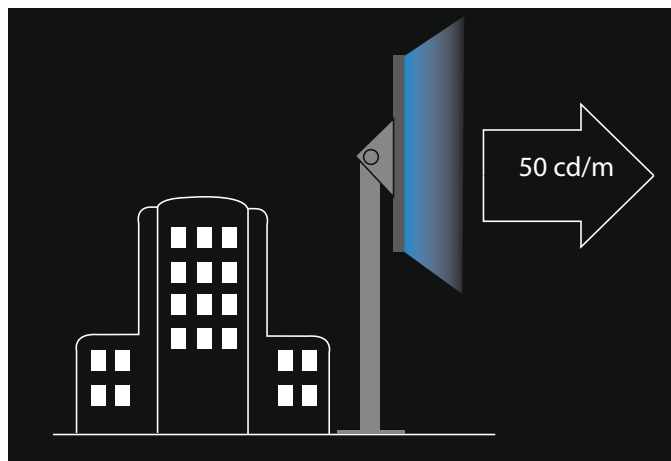


Figura 3. Un máximo de 50 cd/m<sup>2</sup> de emisión para los carteles luminosos. © OPCC.

El seminario realizado en Mt. Cook, Nueva Zelanda, el mes de junio del 2012, a continuación de la III Conferencia Starlight, se celebró precisamente para analizar a fondo estos casos particulares de estudio, denominados “Extended Case Studies” (Windows to the Universe), y para determinar con mayor precisión sus valores excepcionales y criterios de aplicación para su eventual nominación, siguiendo las directrices de las *Directrices Prácticas para la aplicación de la Convención del Patrimonio Mundial* (UNESCO / Centro del Patrimonio Mundial, 2008). Una vez analizados los casos con mayor detenimiento, el seminario finalizó con una resolución en la que se definió su presentación (y eventual aprobación) en la Asamblea General de la UAI, y su inclusión definitiva en el portal Astronomía y Patrimonio Mundial<sup>2</sup> (AWH, por sus siglas en inglés).

En agosto del año 2015, la UNESCO y la UAI organizaron la reunión “Progressing the UNESCO-IAU Initiative”, que tuvo lugar en Honolulu, Hawái, en donde se discutieron los avances de la iniciativa del Centro del Patrimonio Mundial, “Astronomía y Patrimonio”. También se realizó una sesión sobre la protección de los cielos oscuros, considerando el marco que brinda la Convención respectiva.

El hito más reciente en esta materia es la realización de la Reunión Internacional “Derecho a los Cielos Oscuros”, realizada en la Ciudad de México entre el 20 y el 22 de enero del 2016, organizada por

1. Fuente: [http://www.starlight2007.net/index.php?option=com\\_content&view=article&id=202&Itemid=86&lang=es](http://www.starlight2007.net/index.php?option=com_content&view=article&id=202&Itemid=86&lang=es)

2. Fuente: <http://www2.astronomicalheritage.net/index.php/thematic-study>

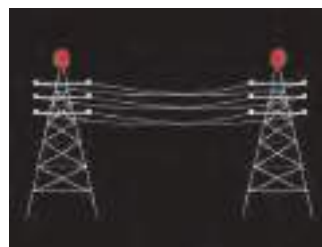
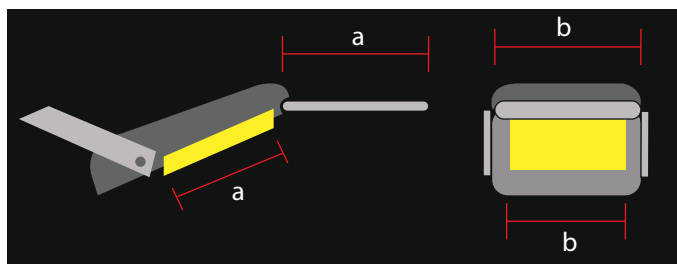


Figura 4 (Izquierda). Se autoriza un máximo de 10 candelas por kilo lumen a 90° y la adición de una visera. © OPCC.

Figura 5 (Derecha). Uso de luz roja en balizamientos. © OPCC.

la Universidad Nacional Autónoma de México (UNAM), el Consejo Nacional de Ciencia y Tecnología (CONACYT) y la Oficina de la UNESCO en México. En esta ocasión se reunió un amplio grupo de expertos y se presentaron antecedentes para la posible postulación de sitios de México a la Lista de Patrimonio Mundial y para responder a los Objetivos para el Desarrollo Sostenible de la Agenda 2030 de la Organización de las Naciones Unidas, en especial a los objetivos 7, “Energía asequible y no contaminante”; 11 “Ciudades y comunidades sostenibles”, y 15, “Vidas de ecosistemas terrestres”.

### Hoja de Ruta para la postulación a la Lista del Patrimonio Mundial

Existiendo la opción de que cada país pueda postular individualmente sus sitios, ha primado a nivel de expertos la idea de realizar una postulación conjunta o seriada. Para que los casos puedan incorporarse como una nominación seriada, hace falta que los Estados Partes los promuevan conjuntamente, siendo un requisito ineludible que los casos estén bien definidos y conceptuados.

En términos generales, se deben realizar dos pasos importantes: a) cada Estado Parte debe incluir estos bienes o propiedades en su Lista Indicativa; b) hacer la propuesta de nominación seriada desde uno de los estados con la aceptación de los demás, que en este caso bien podría ser Chile, liderando el proceso.

Siguiendo las recomendaciones y procedimientos del Comité del Patrimonio Mundial, la propuesta debe basarse en la elaboración y presentación de un *dossier* exhaustivo, más allá de la descripción de los casos de estudio referidos anteriormente. Dicho *dossier* será evaluado por los organismos asesores, como el Consejo Internacional de Monumentos y Sitios (ICOMOS, por sus siglas en inglés). Este *dossier* es mucho más amplio que el Estudio Temático mencionado y con

requerimientos muy específicos. Se recomienda recurrir a expertos que además tengan experiencia en propuestas de este tipo. Por experiencia, es posible afirmar que los puntos 5 y 6 llevarían como mínimo un tiempo de seis a siete meses para ser completados.

Una vez realizada esta evaluación, el/los Estados/s Parte/s someten la propuesta para su aprobación ante el Comité del Patrimonio Mundial que se celebra cada año.

Evidentemente las propuestas se deben hacer a nivel de los gobiernos y generalmente son coordinadas por los ministerios responsables y se gestionan ante las Delegaciones Permanentes de los gobiernos de la UNESCO en París. El gobierno de Chile ha estado ejerciendo un liderazgo en este proceso, en coordinación con otros países, desde la Dirección de Energía, Ciencia y Tecnología e Innovación (DECYTI).

Ahora bien, tanto la DECYTI, como el MMA y la OPCC se encuentran coordinados con otras entidades públicas relacionadas con esta materia. Por una parte, se encuentra el Honorable Consejo de Monumentos Nacionales (HCMN), entidad responsable en Chile de la Lista del Patrimonio Mundial, que ha incluido hasta el momento sólo sitios de valor cultural, paisajístico y ambiental. También tiene un rol relevante en este proceso la Dirección de Bibliotecas, Archivos y Museos de Chile (DIBAM).

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# Una política pública sobre astronomía y protección de los cielos oscuros: la experiencia de Chile

**Gabriel Rodríguez García-Huidobro**

*Ministerio de Relaciones Exteriores de Chile, Chile*

## Resumen

La presencia de la astronomía en Chile ha aumentado crecientemente en los últimos 50 años. Actualmente, 50% de la capacidad de observación óptica y radioastronómica del planeta se ubica en el norte de nuestro país. Considerando los grandes proyectos astronómicos recientemente inaugurados (ALMA), o los que se van a construir en los próximos 5 o 10 años (LSST, GMT, TAO, CCAT), Chile hospedará 75% de la capacidad de observación astronómica mundial a partir del 2022. En la última década, el país ha adquirido conciencia de esta situación excepcional y de sus consecuencias, en términos de oportunidades y responsabilidades.

Para los astrónomos resulta bastante obvio que la atmósfera seca y limpia, en combinación con sitios en altura, áreas de escasa población, cielos oscuros, y todo ello durante prácticamente todo el año, constituye un *mix* de condiciones ideales para observar el universo. Si agregamos a ello la ubicación en el hemisferio sur, donde la observación tanto de nuestra galaxia como del resto del universo es mejor y más fácil, las regiones en el norte de Chile son un lugar privilegiado para observaciones ópticas y radioastronómicas.

En ese sentido, Chile tiene un “recurso natural” —cielos limpios— no muy diferente de los recursos cupríferos, si lo miramos desde un punto de vista económico. Cielos limpios y oscuros son un recurso natural que podemos arrendar, obteniendo una retribución financiera, o “explotar”, extrayendo un valor agregado de ello. Durante la década de los sesenta, al comienzo de las actividades astronómicas en Chile, nuestro país facilitó la instalación de proyectos científicos en el Norte Chico y en el Desierto de Atacama. En ese sentido, y sin ser plenamente consciente de ello en un comienzo, el gobierno ha desarrollado una política para atraer proyectos de astronomía al país. Chile tiene la responsabilidad de preservar para la humanidad esos lugares excepcionales y estamos decididos a transformarnos en líderes en el desafío de proteger los “cielos oscuros”. Para ello, el gobierno ha definido una política basada en cuatro pilares, combinando los intereses nacionales con los del resto del mundo, para responder la pregunta: *¿cómo podemos crear relaciones virtuosas entre astronomía y desarrollo del país?*

El siguiente artículo explora esta cuestión con más detalle, usando ejemplos específicos de Chile.

## Abstract

The presence of astronomy in Chile has grown over the last fifty years, so much so that currently nearly 50% of the world's optical and radioastronomical observation capacity is located in the northern part of the country. By 2022, Chile will be host to 75% of the world's astronomical observation capacity thanks to the recent inauguration of large-scale astronomy projects (ALMA) and those to be built in the next five to ten years (LSST, GMT, TAO, CCAT). In the last decade, the country has become aware of this exceptional situation and its implications in terms of opportunities and responsibilities.

Astronomers have long recognized that a dry and clear atmosphere, combined with high altitude sites, sparsely populated areas, dark skies and all of this practically year-round, constitute an ideal *mix* of conditions to observe the universe. When this is coupled with Chile's vantage point in the Southern Hemisphere, where observation of both our galaxy and the universe is better and easier, it becomes clear that regions in northern Chile are privileged for optical and radioastronomical observation.

In this regard, Chile's clear skies are a natural resource with considerable economic potential, just like the copper wealth. Clear, dark skies are a natural resource that can be rented to interested parties for financial gain or can be 'exploited', thus extracting added value. In the 1960s, when astronomical activities in Chile began, the country facilitated the establishment of several scientific projects in the region of Norte Chico and the Atacama Desert. In this regard, and perhaps without initially fully understanding the implications, the government has developed a policy of attracting astronomy projects to the country. Chile is responsible for preserving these exceptional sites for humanity and is committed to being a leader in efforts to protect the dark skies. To this end, the government has established a policy based on four pillars, which combines national and international interests to respond to the question, *how can we create fruitful relationships between astronomy and national development?*

The following article will explore this question in more detail using specific examples from Chile.

### **Chile, plataforma astronómica mundial**

En los últimos 50 años, de una forma poco perceptible para el ciudadano común, Chile ha pasado de ser un país donde la astronomía prácticamente no existía, a ser una plataforma astronómica de nivel mundial, albergando más del 40% de la capacidad de observación óptica y radioastronómica mundial.

Al día de hoy, Chile alberga en su territorio casi la totalidad de los mayores telescopios de los países europeos y probablemente el

50% de la capacidad de observación de países como Estados Unidos, Canadá y, crecientemente, Japón. Confirma esta tendencia la inauguración, el año 2013, del complejo radioastronómico Atacama Large Millimeter Array (ALMA), operado por un consorcio de universidades de América del Norte, Japón y gobiernos de Europa, en las cercanías de San Pedro de Atacama, a más de 5,000 m de altura.

A nivel de capital humano, Chile pasó de tener una comunidad de astrónomos que se podía contar con los dedos de la mano, a poco



**Figura 1.** Observatorio Radioastronómico Atacama Large Millimeter Array (ALMA), Consorcio europeo-norteamericano y japonés. Meseta de Chajnantor, San Pedro de Atacama, Chile. © Massimo Tarenghi.

más de un centenar de doctores en astronomía y otro tanto estudiando para serlo. De una sola universidad que entregaba hace una década títulos de posgrado en astronomía, hoy tres universidades tienen programas de doctorado en esta disciplina.

Por lo anterior, Chile es hoy un polo científico en el cual se llevan a cabo, con importante participación de astrónomos chilenos, investigaciones, entre otros temas, sobre el origen y formación del universo, la identificación de “exoplanetas” donde podrían encontrarse vestigios de vida, las leyes de comportamiento del universo y su composición. En este último ámbito se ubican las investigaciones que llevaron a la confirmación de la hipótesis de la existencia de la materia y la energía oscuras, que dan cuenta de un altísimo porcentaje de lo que constituye el universo que habitamos. La investigación sobre la expansión acelerada del universo que ha permitido confirmar estas hipótesis fue distinguida con el Premio Nobel de Física 2011. En ésta tuvieron una decisiva participación investigadores chilenos trabajando desde instalaciones de observación astronómica en Chile, lo que confirma el creciente desarrollo de la investigación y su alto nivel.

### **Astronomía: un laboratorio natural de excelencia**

La pregunta, sin embargo, que se esconde detrás de este explosivo desarrollo es ¿por qué en Chile?

La respuesta yace detrás de un concepto que ha sido acuñado recientemente y que es el de los *laboratorios naturales*. Entendemos por laboratorios naturales la conjunción de condiciones espaciales, climáticas, geográficas y de biodiversidad que generan oportunidades para el desarrollo de la ciencia en ciertos nichos. Afirmamos que Chile tiene laboratorios naturales privilegiados, lo cual, combinado con una comunidad científica pequeña, pero de alto nivel de excelencia, hace que nuestro país tenga una oportunidad a la mano para dar ese salto al desarrollo, en la medida que se inserte decididamente en las redes mundiales de I+D e identifique cuáles son los nichos claves.

Entre los laboratorios naturales más destacados en Chile, en torno a los cuales se ha desarrollado una comunidad científica nacional muy conectada a los centros mundiales, podemos mencionar los océanos (dadas las condiciones excepcionales que genera la corriente de Humboldt), las zonas áridas, la antártica, los volcanes y la geotermia, la actividad sísmica, las concentraciones de biodiversidad mediterránea y subantártica. Hay un laboratorio natural, sin embargo, que tiene características muy especiales: los cielos limpios y secos del norte de Chile entre los paralelos 21° y 32°. Estas condiciones permiten la realización de observaciones astronómicas únicas en el hemisferio sur. Es por esta razón que los grandes observatorios internacionales, sean estos nacionales o de





Figura 2. Efecto de la luminosidad urbana sobre el cielo del Desierto de Atacama, Chile. © Massimo Tarengi.

instituciones universitarias o de investigación, han resuelto construir sus centros de observación en nuestro país. En ese sentido, la calidad del capital humano avanzado en Chile, unido a estos laboratorios naturales aptos para la astronomía, son un polo de atracción para lo que hoy se da en llamar proyectos de *big science*.

Para los astrónomos es bastante obvio que una atmósfera limpia y seca, combinada con sitios de gran altitud, baja población y cielos oscuros durante prácticamente todas las noches del año, conforma un conjunto ideal de condiciones para observar el universo. A esto

podemos sumar que el hemisferio sur es donde el centro de nuestra galaxia y el resto del universo tienen mejores y más fáciles condiciones de observación. Todo esto hace que las regiones del norte de Chile sean un lugar privilegiado para la observación óptica y radioastronómica.

En ese sentido, si lo miramos desde un punto de vista económico, Chile tiene un “recurso natural” (los cielos oscuros) que no es diferente de otros recursos naturales, como podría ser el cobre. Los cielos limpios y oscuros son un recurso natural que podríamos rentar





Figura 3. Observatorio Paranal, Telescopio VLT y rayo láser para ajuste de observación, European Southern Observatory (ESO). Atacama, Chile. © Massimo Tarenghi.

y así conseguir una retribución financiera, o bien trabajar el desafío de extraer un valor añadido de ello.

Durante la década de los sesenta, se iniciaron en Chile las actividades astronómicas internacionales. Nuestro país ha facilitado la instalación de proyectos científicos en el “Norte Chico” (350 km al norte de Santiago) y en el Desierto de Atacama. En ese sentido, y a pesar de que inicialmente no se tenía plena conciencia de lo que ello implicaba, el gobierno fue desarrollando una “política” para atraer proyectos de astronomía a nuestro país y para proteger los cielos limpios y oscuros de este Laboratorio Natural Astronómico.

Los cielos oscuros y limpios, sin embargo, no estarán allí para siempre. Nuestro país, como conjunto, Gobierno, privados y ciudadanos tienen el deber de cuidar las condiciones que nos hacen ser un laboratorio natural casi único en este campo. Una de las mayores amenazas es la *contaminación lumínica*, entendida ésta como la luminosidad reflejada en la atmósfera, producto de las actividades humanas, sean estas ciudades y carreteras, o la explotación de yacimientos mineros e industriales (que además generan material particulado ambiental).

Una responsabilidad que tiene nuestro país, por tanto, es arbitrar las medidas para que las tecnologías de iluminación que se utilicen

cumplan sus objetivos, pero sin dañar este patrimonio natural que tenemos. El MMA, con el apoyo de la OPCC ([www.opcc.cl](http://www.opcc.cl)), ha elaborado recientemente una normativa sobre tecnologías de iluminación y su certificación que justamente busca cumplir las condiciones descritas. El desafío a futuro es lograr que dicha normativa entre en operación y su aplicación sea supervisada adecuadamente. Pero junto a la coerción de la ley, debe generarse una educación del ciudadano y de las empresas para respetar estas normativas. Nuestras municipalidades y autoridades locales deben elegir adecuadamente los sistemas de iluminación que garantizan la seguridad y el esparcimiento ciudadano, pero que al mismo tiempo deben cumplir el objetivo de no derramar excesos de luminosidad sobre el espacio nocturno y menos aún en frecuencias que impiden la adecuada observación. Igual responsabilidad tienen las empresas productivas, en especial las mineras.

Al hacer esto, no sólo se está cuidando un patrimonio científico, sino también un patrimonio cultural que pertenece a todos los ciudadanos, como es el derecho a observar el firmamento con la menor interferencia posible. Al mismo tiempo, el cuidado de estas condiciones asegurará el desarrollo de nuestros cielos como un atractivo turístico internacional de primera calidad.

### Los acuerdos internacionales

Toda esta actividad astronómica que podemos celebrar hoy es producto de diversos acuerdos realizados en el pasado que han permitido a nuestro país ser receptor de estas inversiones de alta tecnología y *big science*. El punto clave es que de acuerdo con la ley chilena toda instalación astronómica que se instala en el país debe entregar un 10% de su tiempo de observación a astrónomos chilenos o extranjeros residentes, vinculados a una institución académica chilena. Ésta es una oportunidad de enormes dimensiones para impulsar la ciencia astronómica en Chile. La disposición de ese 10% no es automática. Para utilizar tiempo, los astrónomos deben proponer proyectos que son evaluados por sus pares a nivel internacional, y si son de excelencia, se les asigna tiempo.

El mecanismo existente de acuerdos distingue entre instituciones académicas y países. En el primer caso, y de acuerdo con la ley 15.172 del 7 de marzo de 1963, se entregó a la Universidad de Chile



Figura 4. Observatorio El Tololo, operado por la Association for Universities for Research in Astronomy (AURA). La Serena, Chile. © Massimo Tarengi.

(en ese tiempo la única institución que poseía un Departamento de Astronomía) la potestad de ser la contraparte para negociar los acuerdos para instalarse en Chile. Éstos se refieren al tiempo de observación reservado, al acceso a las instalaciones y toda condición que permita apoyar el desarrollo de la astronomía local. El caso de los países de Europa es distinto. Las actividades de los centros astronómicos se coordinan a través de la European Southern Observatory (ESO) y, en ese caso, el Gobierno de Chile firmó un acuerdo con carácter de tratado con dichos países, aprobado por los respectivos parlamentos. Ése es el acuerdo para el establecimiento de un observatorio astronómico en Chile, publicado el 4 de abril de 1964.

Tanto en el caso de instituciones académicas instaladas en Chile como en el caso de la ESO, el Gobierno, a través de Cancillería, otorga a estas contrapartes el carácter de representantes diplomáticos con todos los privilegios y exenciones que ello implica.

De esta forma Chile, a través de Cancillería como contraparte oficial del Gobierno, entrega las facilidades para apoyar la labor de estas instituciones científicas y al mismo tiempo envía una clara señal para atraer nuevos proyectos internacionales a instalarse en Chile en el futuro. De allí que el Ministerio de Relaciones Exteriores ha ido tomando un rol no sólo de administrador de la relación, sino de



Figura 5. Observatorio Paranal, European Southern Observatory (ESO). Atacama, Chile. © Massimo Tarengi.

proactividad en la atracción de este tipo de laboratorios y observatorios para instalarse en nuestro país.

### Los cuatro pilares de la política astronómica

Desde el año 2008, en que se asignó a la Dirección de Energía, Ciencia y Tecnología e Innovación de Cancillería la tarea de llevar el tema de la astronomía, se ha trabajado en el diseño e implementación de una “política astronómica”. Ésta tiene cuatro componentes o pilares.

#### La ciencia astronómica

Este componente es el más visible a la fecha, y se ha venido desarrollando en forma exponencialmente acelerada desde hace más de cincuenta años. Hoy día contamos en Chile con centros de dimensión mundial en astronomía entre los cuales destacan:

- El Observatorio Las Campanas de la Carnegie Astronomy, ubicado a 500 kms. al norte de Santiago.
- Los Observatorios La Silla (norte de La Serena) y Paranal (sur

de Antofagasta) de la European Southern Observatory (ESO)

- Los Telescopios ASTE y NANTEN 2 del Observatorio Nacional de Japón (NAOJ), ubicado en la planicie de Chajnantor, cerca de San Pedro de Atacama
- El complejo radioastronómico ALMA, también ubicado cerca de San Pedro y operado por un consorcio que incluye a USA / Canadá, ESO y Japón

Tal como se afirma más arriba, en cada uno de estos telescopios y Observatorios, los astrónomos nacionales tienen acceso al 10% del tiempo de observación. Además, algunos de estos proyectos, incluyeron en las negociaciones de su instalación, “fondos para el desarrollo” de la astronomía, la astroingeniería e instrumentación y la educación y extensión en Chile aportados por los consorcios internacionales. Es el caso de los fondos Gemini, ESO y ALMA, que suman una cifra cercana a los dos millones de dólares al año y que son administrados conjuntamente entre las contrapartes extranjeras y Chile, a través de RR.EE. y CONICYT.

Como es natural, en este componente científico, la Comisión Nacional de Ciencia y Tecnología, CONICYT, cumple un rol fundamental como contraparte de estos proyectos. Parte del rol de CONICYT se desarrolla a través del Proyecto Parque Astronómico de Atacama, recientemente puesto en marcha y que busca recibir, en las cumbres del Cerro Chajnantor en San Pedro, a nuevos proyectos que busquen instalarse en nuestro país, ofreciendo facilidades de seguridad, logística y comunicaciones.

A lo anterior, se suma el apoyo permanente del Gobierno a estos grandes proyectos astronómicos, por la vía de asegurarles las mejores condiciones de operación vía la protección de la oscuridad de los cielos y la no interferencia con faenas mineras y geotérmicas, a través de la concesión de zonas de protección astronómicas, así como las facilidades para disponer de acceso a la energía y las comunicaciones viales y telemáticas, y la exención de impuestos para importar equipos y tecnologías para instalarse en Chile.

Este primer componente de la política astronómica ha permitido el desarrollo de una comunidad astronómica de excelencia y vínculos de cooperación entre los centros de investigación de Chile y centros de prestigio en todo el mundo. El resultado es la publicación de un creciente número de *papers* con participación de astrónomos nacionales en revistas científicas de primer nivel.

Así como hoy día en Chile está instalado más del 40% de los grandes telescopios del mundo, el panorama futuro en términos de instalación de megatelescopios en nuestro país muestra que hacia el año 2022, Chile podrá llegar a albergar el 70% de las capacidades de observación ópticas y radioastronómicas.

### El desarrollo de la astroingeniería

Si hasta hace pocos años, el pilar científico era el principal, desde el año 2008, y a través de una política explícita se ha ido abriendo espacio al desarrollo de la astroingeniería y las tecnologías vinculadas a la astronomía.

Esta infraestructura científica disponible para los investigadores chilenos, constituye una tremenda oportunidad para el desarrollo

científico y tecnológico local. La Astronomía es una ciencia básica, y como tal sus proyectos de investigación son generalmente motivados por curiosidad científica. Cuando se empujan las fronteras del conocimiento y la tecnología suelen aparecer descubrimientos e invenciones de las formas más inesperadas.

Si pensamos que los observatorios que se instalan en Chile, no sólo están utilizando tecnologías avanzadas en óptica, mecánica, mecatrónica, robótica e informática, sino que están diseñando instrumentos que usan tecnologías que están aún en fase de prototipo, podemos imaginarnos que éste es un campo de enorme potencialidad para hacer avanzar la I+D en Chile, partiendo de la astronomía, pero expandiéndose a otros campos. Dado lo sofisticado de las observaciones y los equipamientos que se requieren para ella, en la historia se han producido notables avances a partir de su desarrollo y de la industria asociada (ej.: internet, óptica adaptativa, mecánica cuántica, los sensores CMOS de las cámaras digitales, etc.). Y no sólo la tecnología en sí, sino todo el capital humano asociado a ella, no sólo en su desarrollo, sino también en su operación. En ese sentido podemos hablar de que la presencia de estos Observatorios en Chile constituye una “escuela de ingeniería” de dimensiones colosales.

La creciente inversión en instalación de telescopios en el norte de nuestro país, puede convertirse en una oportunidad para la industria chilena, pues la Astronomía supone infraestructura y tecnología sofisticada. En los últimos cinco años, por ejemplo, el 25% de los contratos de construcción y mantención de la European Southern Observatory (ESO) han sido adjudicados a empresas chilenas. Es en la dimensión tecnológica que se requiere avanzar.

La política astronómica en este segundo campo es un área que cae en el ámbito de la Tecnología y la Innovación, que es responsabilidad del Ministerio de Economía y de la Corporación de Fomento (CORFO). En esa línea y desde hace un par de años, se creó en el Ministerio de Economía un agente coordinador (Industry Liaison Officer, siguiendo la terminología de ESO) que conecta las oportunidades que ofrecen la instalación y operación de nuevos telescopios con la industria nacional y los centros de investigación en ingeniería, electrónica y matemática de las Universidades.

Como parte de esta actividad, se han realizado tres talleres de Astroingeniería, promovidos desde Cancillería en 2012, y liderados por el Ministerio de Economía en 2013 y 2015. Igualmente, se encargó un primer estudio prospectivo de las oportunidades tecnológicas que puede traer la astronomía a Chile, estudio que ya cuenta con una segunda fase en desarrollo.

El objetivo final es no sólo dotar a las instalaciones astronómicas de profesiones y *expertise* chilena, sino especialmente utilizar este sector como un detonante de desarrollos innovadores en otros ámbitos del aparato productivo nacional.

### Educación, ciencia y cultura

La actividad astronómica presente en Chile es también una oportunidad para desarrollar las vocaciones científicas entre los jóvenes, no sólo en el ámbito astronómico. Albergar este tipo de instalaciones en nuestro país es una oportunidad para impulsar la vocación por la investigación científica y así proponerse un crecimiento significativo de la comunidad científica nacional, condición *sine qua non* para que el país pueda dar un salto al desarrollo. Chile tiene investigadores de excelencia, pero su número no permite aún tener masa crítica para participar en muchos proyectos de *big science*.

En ese sentido se han promovido y apoyado a través de Municipalidades y Universidades la instalación de telescopios amateur y la realización de actividades de extensión. Éstas están permitiendo un acceso masivo a la experiencia astronómica, orientada no sólo a jóvenes, sino también a adultos, y con presencia en las regiones “no astronómicas”. Un importante resultado ya se ha alcanzado, por la existencia de centros de observación en regiones, apoyados por las Municipalidades, gobiernos regionales y también iniciativas privadas turísticas.

La astronomía es también un inspirador de cultura y un espacio para que la experiencia científica se expanda a una experiencia más amplia sobre el origen de nuestro universo, su futuro, su estructura y el lugar del ser humano en él. La riqueza filosófica, artística y cultural de este espacio tiene una potencialidad enorme, que estamos muy lejos aún de medir.



Figura 6. Fotografía de larga exposición de la Vía Láctea. Desierto de Atacama, Chile. © Massimo Tarengi.

### Imagen país y turismo

Éste es un ámbito nuevo en que se ha comenzado a trabajar con la Fundación Imagen de Chile y la Subsecretaría de Turismo. La Astronomía, en cada uno de sus tres pilares anteriores, debe incorporarse en forma decidida a la imagen de un Chile que busca dar el salto al desarrollo. Esta componente astronómica, unida a los otros laboratorios naturales mencionados que el país posee, potencia la dimensión de avance a una sociedad del conocimiento que es finalmente lo que caracteriza a un país desarrollado en el siglo XXI.

Al mismo tiempo, el enriquecimiento de esa imagen de Chile, está contribuyendo significativamente a que Chile sea un polo de atracción de turismo.

El astroturismo tiene la ventaja de poder mostrar un país que tiene raíces profundas en la historia de miles de años, y que al mismo tiempo se proyecta hacia el futuro. Su potencial está también en lo que son los nuevos nichos turísticos, como los intereses especiales, donde las instalaciones astronómicas científicas juegan un rol preponderante. Si junto a éstas hay un relato y un circuito que las conecte con las tradiciones originarias, se genera una oferta turística de gran profundidad y alcance. En esta dimensión países como México tienen mucho trabajo adelantado y mucho que aportar, por



la riqueza de sus tradiciones ancestrales y la profundidad de los estudios arqueológicos y de arqueoastronomía que han realizado. Actualmente se trabaja en un proyecto de cooperación Chile-México para potenciar esta colaboración.

Éste es un ámbito que se conecta muy directamente con la protección de los cielos mencionado más arriba y la preocupación por la contaminación lumínica.

### **El futuro: Chile plataforma astronómica mundial**

La formulación y puesta en marcha de la política astronómica descrita más arriba ha sido central para facilitar e incentivar la instalación de nuevos grandes proyectos astronómicos en Chile que entrarán en operación entre 2015 y 2021. Entre éstos podemos destacar:

- El Telescopio Tokyo Atacama Observatory (TAO) de la Universidad de Tokyo, Japón, que se instalará en la cima del Cerro Chajnantor ([www.ioa.s.u-tokyo.ac.jp](http://www.ioa.s.u-tokyo.ac.jp)).
- El telescopio Large Synoptic Survey Telescope (LSST) de la National Science Foundation de Estados Unidos de América, cuya construcción se inició en Cerro Pachón en 2015 ([www.lsst.org](http://www.lsst.org)).
- El Giant Magellan Telescope (GMT), liderado por un consorcio de universidades de Estados Unidos e instituciones de Australia y Corea, que se instalará en el Observatorio Las Campanas ([www.gmto.org](http://www.gmto.org)).
- El Telescopio European Extremely Large Telescope (E-ELT) en Cerro Armazones, cerca de Paranal, en la zona de Antofagasta ([www.eso.org](http://www.eso.org)).

Estos nuevos proyectos nos acercan a un horizonte en que Chile albergará cerca del 70% de las capacidades terrestres de observación ópticas y radioastronómicas del planeta hacia el año 2022.

A la lista anterior, podría sumarse la instalación en Chile del proyecto Thirty Meter Telescope (TMT), liderado por el California Institute of Technology (Caltech) y un conjunto de Universidades y Fundaciones de Estados Unidos, además de Japón, China e India. Si la instalación de tal proyecto se concreta en Chile, nuestro país llegaría a albergar cerca del 90% de las capacidades mundiales de observación.

En cada uno de estos proyectos el Gobierno, a través de sus diversas agencias (Comisión Nacional de Investigación Científica y Tecnológica de Chile, Ministerio de Bienes Nacionales, Ministerio de Economía, Corporación de Fomento de la Producción, Intendencias regionales, etc.), bajo la coordinación de Cancillería, desde la Dirección de Energía, Ciencia y Tecnología e Innovación (DECYTI), ha participado en las negociaciones que han permitido asegurar su instalación en Chile.

Hoy se están explorando posibilidades de cooperación y eventualmente instalación de Centros de Observación astronómica en Chile con países como China, Rusia e India. Con China se está por iniciar a fines de 2016, un Centro Chile-China para la investigación Astronómica.

Las oportunidades que se abren son por lo tanto de enormes dimensiones y hacen de Chile una Plataforma Astronómica Mundial. Es por eso que el Gobierno ha dado su pleno respaldo a la comunidad astronómica chilena para que nuestro país sea sede de la Asamblea General de la Unión Astronómica Internacional (UAI) a realizarse el año 2024.

### **Protegiendo los “cielos oscuros”: declaratoria de patrimonio de la humanidad**

El gobierno está trabajando en diversas áreas para implementar la política astronómica descrita más arriba:

- El Ministerio de Relaciones Exteriores es el punto de contacto de los consorcios astronómicos internacionales que buscan un lugar en Chile.
- Los Observatorios Internacionales reciben “estatus diplomático”.
- Facilitación en el acceso a terrenos y concesiones a largo plazo para las instalaciones científicas.
- Declaración de “áreas científicas protegidas” y de las zonas de regulación para aislar los observatorios de las actividades industriales (especialmente minería geotérmica), incluyendo las interferencias electromagnéticas.
- Reglas claras y normas de iluminación pública y control en la aplicación de éstas.
- Regulaciones ambientales sobre la polución particulada.

Debido a que estamos convencidos de que los laboratorios naturales que tenemos no son realidades permanentes, la protección de cielos limpios y oscuros en el caso de la astronomía, es uno de los principales objetivos de esta política. Las medidas enumeradas más arriba son muy necesarias, pero no son suficientes.

Lo que se busca es que los observatorios astronómicos —que tienen un valor histórico como tal— puedan convertirse en Monumentos Nacionales en cada país y luego ser declarados Patrimonio Mundial. De este modo se podría contar con más y mejores alternativas para proteger los cielos y asegurar la continuidad de los proyectos de observación astronómica hacia el futuro. Lo que se busca es proteger estos lugares únicos para la observación, apoyados en los mecanismos de la UNESCO, basándose en el valor universal que estos tienen para la humanidad.

Este trabajo requiere de mucha colaboración entre los países que tienen condiciones de “laboratorios naturales” para la astronomía, como es el caso de Estados Unidos, México, Argentina, Chile, España y Sudáfrica. Lo que se requiere es intercambiar las experiencias que cada país obtendrá en este primer proceso de declaratoria de Monumento Nacional. Cada país avanzará en su declaratoria y obtendrá elementos que permitirían, en algún momento aunar criterios para postular con una o varias propuestas de declaratoria de Patrimonio Mundial (declaración serial).

Este proceso, para el caso de sitios astronómicos es un camino nuevo, por lo que la colaboración entre los países interesados y UNESCO es clave para definir en conjunto cuáles serían los criterios de dicha declaratoria. Demostrar que un sitio que se busca inscribir tiene un valor universal y de importancia para las próximas generaciones es una reflexión que requerirá de mucho estudio y creatividad.

Es un trabajo en que deberemos ser capaces de innovar con nuevas lecturas del concepto de Patrimonio Mundial.

Basados en la definición y objetivos de nuestra política astronómica y la oportunidad que UNESCO otorga, Chile ha tomado la decisión de avanzar en el proceso de declaratoria de Patrimonio Mundial para los sitios astronómicos que se encuentran en territorio nacional. Éste es un largo camino, pero al mismo tiempo, todo el proceso es una oportunidad para involucrar a la sociedad en esta búsqueda. La participación es un proceso bidireccional. Por un lado, es una responsabilidad del gobierno para desarrollar conciencia entre los ciudadanos sobre el valor que tenemos en nuestro país. Por otro lado, es una responsabilidad de los observatorios, de involucrarse en las realidades y las comunidades locales y para mostrar el valor social de lo que están haciendo. Educación y difusión son fundamentales para esto.

## Conclusiones

La política astronómica de Chile, con sus cuatro pilares, es un ejemplo de cómo un gobierno puede apoyar la investigación astronómica internacional a través de la protección de los laboratorios naturales que tenemos, y al mismo tiempo identificar cómo la astronomía puede ser un factor clave en la consecución de los objetivos de desarrollo que tengan un claro y eficaz impacto social sobre los ciudadanos.

Más allá de todas las consideraciones y objetivos descritos, no debemos perder de vista que a fin de cuentas lo que se busca con una política de protección de los cielos oscuros es que los hombres y las mujeres del planeta podamos ejercer el derecho a observar el firmamento a simple vista. Éste es un derecho que con el tiempo y la modernización se ha ido perdiendo y que tenemos el deber de recuperar.



# Controlling Light Pollution in the Area Close to the AURA Observatory – Communication, Development, Education and Outreach

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## Abstract

A review is presented of the history of the efforts that have been made to control light pollution in Chile, in the area close to the AURA Observatory, which includes Cerro Tololo and Cerro Pachón. Steps have included (i) communication with government at national, regional and local level, (ii) development of environmental and astrotourism initiatives and (iii) education and outreach programmes in the surrounding communities.

The Milky Way could be seen easily from the central square of La Serena in 1969. By 1993, the view of most of the stars in the night sky had disappeared in the glow of artificial light. We attempted to speak to local authorities about this and the need for sodium lighting that is directed towards the ground, not the sky, but the initial reaction could be summarised by ‘listen gringo, if you want your fancy lights, go buy them yourself’. It was immediately clear that we had to educate and communicate. However, before being able to make progress in these areas, we needed first to understand what the local community wanted and why. In the mid 1990s, we set up the ‘RedLaSer’ schools network in the La Serena area, starting with a group of seven local schools. The teachers in non-science areas (for example, art, languages and dance) were initially apprehensive about getting involved but soon joined in and brought with them creative imagination. This network grew to well over a hundred schools within the first decade. Two portable planetariums were donated by the Gemini project (the Gemini South telescope is located on Cerro Pachón). Gemini also funded a ‘Star Teachers’ exchange programme with Hawaii (where Gemini North is located).

Communication with authorities started to turn around when it was discovered that a member of the Vicuña town council, Eduardo Valenzuela, was a member of the local amateur astronomy club. Vicuña is a fairly small town in the Elqui Valley; the valley extends from the Andes down to La Serena, passing close to the edge of the AURA property. To assist commercial development based on dark-sky-friendly lighting, an agreement was worked out where AURA donated an amateur telescope, equipped with a computer (unusual and definitely state-of-the-art at the time). For its part, the municipality widened and improved an access road to Cerro Mamalluca and erected a building financed by the Chilean Arts Council. AURA completed the package with a second-hand dome. With this public observatory and some improvements to municipal lighting, we were able to prove our assertion that people from light-polluted countries would pay thousands of dollars to spend time under the starlit skies of northern Chile. The tourist industry was quick to realise the opportunity and now the Coquimbo Region of Chile is officially marketed as ‘The Star Region’. Extension of our communication with local authorities was greatly helped by the sister-city programme that was set up between the city of La Serena and the island of Hawaii.

## Resumen

Se ofrece un análisis de la crónica de los esfuerzos que se han realizado para controlar la contaminación lumínica en Chile, en el área próxima al Observatorio de AURA (siglas en inglés de la Asociación de Universidades para la Investigación en Astronomía), que comprende a

los cerros Tololo y Pachón. Las medidas han incluido: i) comunicación con el gobierno a nivel nacional, regional y local; ii) desarrollo de iniciativas medioambientales y de astroturismo, y iii) programas educativos y divulgativos en las comunidades circundantes.

La Vía Láctea podía verse fácilmente desde la plaza central de La Serena en 1969. Para 1993, la mayoría de las estrellas en el cielo nocturno habían desaparecido de la vista con el resplandor de la luz artificial. Intentamos hablar con las autoridades locales acerca de ello y de la necesidad de una iluminación con lámparas de sodio dirigida hacia el suelo, no al cielo, pero la reacción inicial puede resumirse con un “mira, gringo, si quieres tus sofisticadas luces, ve a comprarlas tú mismo”. Quedó inmediatamente claro que teníamos que instruir y comunicar. Sin embargo, antes de poder avanzar en estas áreas, primero teníamos que entender lo que la comunidad local quería y por qué lo quería. A mediados de los noventa, establecimos la red de escuelas RedLaSer en el área de La Serena. Comenzamos con un grupo de siete escuelas locales. Los maestros de áreas no científicas (por ejemplo, arte, lenguas y danza) vacilaron en un primer momento sobre su participación, pero pronto se unieron y aportaron su creatividad. Esta red creció hasta llegar a más de 100 escuelas en su primera década. Dos planetarios portátiles fueron donados por el proyecto Géminis (el telescopio Géminis Sur está ubicado en Cerro Pachón). Géminis financió también un programa de intercambio, Maestros de las Estrellas, con Hawái (donde se ubica Géminis Norte).

La comunicación con las autoridades comenzó a dar un vuelco cuando se descubrió que un miembro del gobierno municipal de Vicuña, Eduardo Valenzuela, era miembro del club local de aficionados a la astronomía. Vicuña es una ciudad relativamente pequeña del Valle de Elqui; el valle se extiende desde los Andes hasta La Serena, próximo al límite de la propiedad de AURA. Para ayudar a un desarrollo comercial basado en una iluminación respetuosa, se elaboró un acuerdo mediante el cual AURA donó un telescopio *amateur*, equipado con una computadora (algo inusual e indudablemente de vanguardia en aquel entonces). Por su parte, el municipio ensanchó y mejoró una carretera de acceso a Cerro Mamalluca y levantó un edificio financiado por el Consejo Nacional de la Cultura y las Artes de Chile. AURA completó el paquete con una cúpula de segunda mano. Con este observatorio público y algunas mejoras en iluminación municipal, fuimos capaces de demostrar nuestra afirmación de que personas procedentes de países con contaminación lumínica pagarían miles de dólares por pasar tiempo bajo los cielos estrellados del norte de Chile. La industria turística no tardó en darse cuenta de la oportunidad y ahora la Región de Coquimbo en Chile se vende oficialmente como “la Región de las Estrellas”. La ampliación de nuestra comunicación con las autoridades locales se vio enormemente facilitada por el programa de ciudades hermanas que fue establecido entre la ciudad de La Serena y la isla de Hawái.

## Introduction

When invited to participate in the International Meeting: *The Right to Dark Skies*, organized by the UNESCO Office in Mexico from 20 to 22 January 2016, in Mexico City, Mexico, I was asked to concentrate on three areas that are now the chapter headings of this article. This article covers a personal view of the history of efforts in these three areas over the last couple of decades or so, directed at controlling light pollution of the skies over the AURA Observatory in northern Chile. AURA-O includes the sites of optical telescopes such as LSST, Gemini South, SOAR, the Blanco 4 m, as well as many more, smaller instruments.<sup>1</sup>

## Communication – Some Examples

This work in Chile was started by working with the International Dark-Sky Association (IDA). One of its two founding members was David Crawford, then an astronomer at the Kitt Peak National Observatory in Tucson, Arizona. David and the IDA were particularly helpful in these early years, and I served on its Board of Directors during the period 2000–2009. The IDA remains a major source of expert advice for us all.

### Communication with Chilean Authorities – Local Level

As the new Director of the Cerro Tololo Inter-American Observatory (CTIO) I contacted various local authorities in the

1. <http://www2.astronomicalheritage.net/index.php/show-entity?identity=59&idsubentity=005>



area around the AURA Observatory on my return to Chile in November 1993, immediately after having lived and worked in Hawaii as Director of the Joint Astronomy Centre for a period of nine years (Smith, 2001). The larger towns around CTIO showed very little interest in controlling their light pollution, partly because of the initial, large, capital cost of changing existing lighting and partly because of the emphasis on beach tourism, which was booming since substantially increased lighting had been installed along the local coastline. In La Serena, there was more interest in the sister-city proposal with the island of Hawaii<sup>2</sup> – which was set up a year later, in November 1994. This sister-city connection proved to be of particular value in maintaining communication with authorities in La Serena in the early years of the Gemini operation, given the location of the two Gemini telescopes, one on the Island of Hawaii, the other near La Serena.

As the first Director of the AURA Observatory in Chile (AURA-O – which includes Gemini South, SOAR and CTIO), I followed David Crawford's early advice from the IDA to 'make friends, not enemies' – and also sought to demonstrate the financial advantage to potential hosts of better lighting. Reaching out further inland from La Serena in the general direction of the AURA telescopes, the support received from the town of Vicuña was vital for making this possible, as was recently recognized (in my article in Spanish, Smith, 2014) in the latest volume of a series aimed at covering the cultural history of the town and the Elqui River Valley (edited by Hector Hernán Herrera, a former Mayor of Vicuña). Local people, particularly Eduardo Valenzuela and Sergio Pizarro, played key roles in obtaining municipal and community support in and around Vicuña for the construction of a community observatory on Cerro Mamalluca.<sup>3</sup> As mentioned in my abstract, this enabled AURA-O to help the municipality demonstrate the social and economic advantages for the people of Vicuña. By the year 2003, over 14,000 foreign visitors were coming each year to the Mamalluca Observatory. The town's mayors soon began to appreciate the year-round employment and the increased variety of job opportunities generated by this new 'astrotourism'<sup>4</sup> industry.

Moving out of Vicuña, we found particularly welcome local support from Cecilia Prats, the then Regional Director for SERNATUR,

Chile's National Tourism Agency. She was the first to show government support for marketing the region's dark sky as a year-round, (that is to say, non-seasonal) tourist attraction that would provide at least some more stable employment beyond the summer beach season. She was initially criticized for allowing herself to be distracted and for not focusing solely on maximizing beach tourism.

Another key player was the then Mayor of the mining town of Andacollo, Marcelina Cortés, whose crucial early support resulted in the Collowara Public Observatory, the second of the numerous public tourist observatories now present in the region.

### Communication with Chilean Authorities – National Level

It was also clearly necessary to look for help at national level in Santiago. As the AURA representative in Chile receives some diplomatic recognition by the Chilean government, and thanks to the constant support of the Regional Intendente, Renán Fuentealba, I was able to secure an interview with Edgardo Boeninger, Minister, Secretary General of the government of President Aylwin (1990–1994). Mr Boeninger informed me that the Chilean Government was about to form a National Environmental Commission (CONAMA). He advised classifying Light Pollution as a *secondary* source of environmental pollution. He explained that, given the legislative and technical work involved in setting up CONAMA and its rules for controlling obvious, primary sources of pollution, only a few of these could be covered in the initial legislation.

Getting light pollution included at that primary level would, at best, take many years. However, the lawmakers were looking for a reasonably well-prepared example of secondary pollution that could be included immediately in the draft legislation for setting up CONAMA. Going down this path would greatly speed up the process for obtaining national-level legislative support.

AURA-O took Mr Boeninger's advice. Four years later, in 1998, the President of Chile, Eduardo Frei Ruiz Tagle, signed into law Supreme Decree No. 686/98, the first version of the 'norma lumínica' (lighting regulation), which came into effect in 1999. A year later, in 2000, an Office for the Protection of the Skies of Northern Chile (OPCC) was

2. <http://www.hawaiicounty.gov/my-la-serena/>

3. <http://www.astronomictourism.com/mamalluca-observatory.html>

4. <http://www.ctio.noao.edu/noao/content/light-pollution>



**Figure 1.** Quarter-hour exposures from the Cerro Tololo summit taken on 27 December 2008. a) View towards the celestial South Pole over the dome of the 4 m telescope. b) View towards the La Serena/Coquimbo conurbation, showing the light pollution. The same camera settings were used for each of these two images. © Malcolm Smith.

set up by a consortium of different organizations, i.e., CONAMA, AURA, CARSO (the Carnegie Southern Observatory) and ESO (the European Southern Observatory). AURA-O was particularly fortunate to have Adriana Hoffmann as the Executive Director of CONAMA from March 2000 to November 2001. As a schoolgirl, she had asked the Cerro Tololo Observatory if she could go into the grounds and make some observations and drawings of desert plants for a school project, and she was very well treated by the AURA people at that time. When I drove her up through the grounds of AURA-O towards Tololo, as if on cue we were escorted for about half a kilometre by a small flock of rare, colourful, burrowing parrots, birds that are in danger of extinction. I was able to explain to her in some detail how we were working with local naturalists in providing protection for the nests (the tunnels for which I was able to point out as we drove past, on our journey towards Cerro Tololo). We were delighted, of course, to hear her enthusiasm for having CONAMA be part of the new OPCC consortium.

Pedro Sanhueza, at that time the Regional Director of COREMA (a subunit of CONAMA), was hired soon afterwards to become the Director of the OPCC based in La Serena, the town that presented the greatest apparent threat to the long-term future of a major international observatory in Chile (Figure 1a, Figure 1b). Pedro's experience in handling wider environmental issues is

proving increasingly valuable as we gradually create more working relations with biologists in protecting Chile's natural, night-time environment. The astronomical message has begun to extend in Chile to the protection of the nocturnal, biological environment. Nocturnal outreach work is already underway in the Fray Jorge Biosphere Reserve, about 100 km south of La Serena, which was designated a UNESCO Man and the Biosphere Reserve in 1977 and was extended in 2012.<sup>5</sup>

Some lighting improvements have also been made at the nearest RAMSAR site (Wetlands of International Importance), at Laguna Conchalí (about 250 km south, by road from La Serena).

The OPCC maintains a webpage in Spanish.<sup>6</sup> Pedro Sanhueza gave more details on this topic at the International Meeting: *The Right to Dark Skies*, particularly related to the sometimes difficult work leading up to the new lighting regulations, Supreme Decree No. 043 2012.

Most Chilean universities were slow to join the early stages of this effort, but now, particularly through the Chilean Astronomical Society, SOCHIAS, Chileans are themselves taking over much of the support effort with Chilean authorities at local and national level. Guillermo Blanc presented more detailed examples at the

5. <http://www.unesco.org/new/en/natural-sciences/environment/ecological-sciences/biosphere-reserves/latin-america-and-the-caribbean/chile/fray-jorge/>

6. <http://www.opcc.cl>

International Meeting: *The Right to Dark Skies*. With the arrival of larger and larger telescopes, Chile's presidents have visited the AURA Observatory. On each occasion, they have publicly shown their support for the Observatory and, most recently, for controlling light pollution. As far back as November 1967, Eduardo Frei Montalva participated in the inauguration of the 1.5 m telescope, at that time the largest on Cerro Tololo. This was just a few months after he and US President Johnson had announced the intention to build what then would become the largest optical telescope in the southern hemisphere (the Blanco 4 m telescope). President Lagos (2000–2006) and former President Patricio Aylwin (1990–1994) attended the opening ceremony of Gemini South on Cerro Pachón in January 2002. As one indicator of the progress of Chilean astronomy and the huge international investment in Chile by other countries, the primary mirror of the European Extremely Large Telescope (E-ELT) is now being manufactured for installation in the north of Chile, that is to say, about half a century after operation of the 1.5 m telescope began on Cerro Tololo. The E-ELT will eventually have 798 hexagonal segments of 1.45 m in diameter making it the largest optical telescope in the world. In April 2015, President Michelle Bachelet attended the ceremony for laying the foundation stone of the wide-field, LSST.<sup>7</sup>

### Wider International Communication

The International Meeting: *The Right to Dark Skies* – and similar such events – provide the most obvious examples of international communication beyond Chile. Any list of key sources of such communication should also include the International Dark-Sky Association in Tucson, Arizona,<sup>8</sup> and the Starlight Reserve initiative.<sup>9</sup> For many years, these two organizations have provided key, internationally applicable guidelines and successful examples for us all.

The Astronomy and World Heritage workshop held in New Zealand in 2007 was particularly helpful in bringing astronomers who were learning how best to prepare Extended Case Studies, into more direct contact with the relevant experts, such as Michel Cotte from ICOMOS.<sup>10</sup> Throughout this period, Clive Ruggles has led

the IAU side of what has resulted in the Portal to the Heritage of Astronomy.<sup>11</sup>

In recent years, we have of course been able to work ever more closely with UNESCO, as different governments have started showing willingness to work with Chile on proposals for World Heritage sites related to astronomy. The IAU's recently formed Inter-Commission B7–C4 Working Group *Windows to the Universe: High-Mountain Observatories and other Astronomical Sites of the Late 20<sup>th</sup> and Early 21<sup>st</sup> Centuries*<sup>12</sup> is currently chaired by Chris Smith, the current AURA representative in Chile and AURA–O Director.

### Development, Astrotourism, Further Environmental Initiatives and Medical Interest

In 2002, building on the success of the Mamalluca Observatory in Vicuña, the Municipality of Andacollo, led by its tenacious mayor, Marcelina Cortés and the National Tourism Service (SERNATUR), made a joint proposal for funding another public observatory.

In late June, 2004, President Lagos, himself a well-informed, amateur astronomer, opened the second tourist observatory, Collowara, just outside Andacollo. The Minister for Economic Affairs praised the advance in astrotourism as a development that was highly positive for the local economy. Mayor Marcelina Cortes, although very ill, lived just long enough to be able to attend the opening ceremony, as she had long wanted to do.

The founders of the Collowara Observatory had asked for advice regarding its potential location. Some colleagues and I from the AURA Observatory advised changing their early plans for an initial possible site, which was located by a main road into the town, out to a location further from town, on the peak of Cerro Churqui, (7 km from the town centre, still readily accessible to tourists, but where traffic and light pollution would both be significantly less). This overall planning approach (which requires balancing ease of accessibility for the tourists against reasonably dark skies) had earlier been suggested by me to (and followed by) the founders

7. <http://www.lsst.org/sites/default/files/first-stone/Bachelet.pdf>

8. <http://www.darksky.org>

9. <http://www.starlight2007.net/theinitiative.htm>

10. [http://www.starlight2007.net/index.php?option=com\\_content&view=article&id=383%3AAstronomy-and-world-heritage-workshop&catid=61%3Aconferences-a-workshops&Itemid=79&lang=en](http://www.starlight2007.net/index.php?option=com_content&view=article&id=383%3AAstronomy-and-world-heritage-workshop&catid=61%3Aconferences-a-workshops&Itemid=79&lang=en)

11. <http://www2.astronomicalheritage.net>

12. [http://www.iau.org/science/scientific\\_bodies/working\\_groups/270/](http://www.iau.org/science/scientific_bodies/working_groups/270/)

of the Mamalluca Observatory. Nowadays, Hacienda los Andes, another of the public, tourist observatories close to AURA-O, has itself chosen a truly dark-sky location far from even the lighting of the Rio Hurtado village below Cerro Pachón. The Hacienda includes on-site overnight tourist accommodation as part of its dark-sky package. It is currently working with the Municipality of Río Hurtado to correct a few sources of non-compliant lighting in the village, which helps everyone.

Astronomers and biologists are gradually realizing the importance of working together (Smith, 2009). A key reference is the comprehensive book by Rich and Longcore (2006). In the next section, I have included a link<sup>13</sup> to a video of a recent local outreach initiative (in Spanish) with biologists, with some support from AURA.

A further major ally, particularly relevant for guidance of future human development of lighting practice in cities, are medical researchers exploring the effects of lighting on human beings. For example, the New York Academy of Sciences held a well attended conference in June 2009 entitled *Circadian Disruption and Cancer – Making the Connection*. Blue light affects the production of melatonin in humans. The American Medical Association issued a 25-page report on the topic in 2012 (Blask et al., 2012).<sup>14</sup>

Quoting from part of the conclusion:

*More direct health effects of nighttime lighting may be attributable to disruption of the sleepwake cycle and suppression of melatonin release. Even low intensity night-time light has the capacity of suppressing melatonin release. In various laboratory models of cancer, melatonin serves as a circulating anticancer signal and suppresses tumour growth. Limited epidemiological studies support the hypothesis that night-time lighting and/or repetitive disruption of circadian rhythms increases cancer risk*

There remains significant work to be carried out before work in this important area becomes well-known in Chile.

## Education and Outreach

In August 1999, CTIO effectively initiated the RedLaser schools network in La Serena, by inviting some local school children to view some sunspots through an (appropriately filtered) amateur telescope that was set up on the grounds of the Cerro Tololo Inter-American Observatory offices. Shortly afterwards, there were seven schools involved in the project, and whose teachers showed great ingenuity in astronomy outreach. An example was a dance teacher whose class started participating in RedLaser events. Within 3 years, the network had grown to over 100 schools and 6,500 pupils. Gemini provided a strong stimulus, including highly-motivating teacher exchanges with the Island of Hawaii, La Serena's sister-city.

By this time, March 2002, CTIO was ready to hold our first international conference on light pollution in Chile (Schwarz, 2003). Among the attendees was Pierantonio Cinzano, who made three presentations in the opening session, reaching out with images from the then recently-published First World Atlas of Artificial Night Sky Brightness (Cinzano et al., 2001), based on data taken from earth orbit. At that time, assuming average eye functionality, about one fifth of the world population, more than two thirds of the US population and more than one half of the EU population had already lost naked-eye visibility of the Milky Way. Modern estimates (Falchi et al., personal communication, December, 2015) show that large increases in these percentages have since occurred. An update on the International Astronomical Union's worldwide efforts towards controlling light pollution was also presented at that conference (Smith, 2003).

The International Dark Sky Places Programme was started by the IDA in 2001<sup>15</sup> and has proved highly popular with places around the world who have made special efforts to control light pollution. Astrotourism is just one of the beneficiaries. Last year, at the Bishop Museum in Honolulu, just before the IAU General Assembly, the IDA announced the designation of AURA-O as the World's first Dark-Sky Sanctuary.<sup>16</sup> It is encouraging to note the strong participation in recent years of the Chilean Astronomical Society (SOCHIAS) as reported at the International Meeting: *The Right to Dark Skies* by Guillermo Blanc. It is Chileans who will decide what to do to protect the skies over Chile and how to do it. At a local

13. <https://www.youtube.com/watch?v=o0ZZtr-RfEw>

14. <http://www.atmob.org/library/resources/AMA%20Health%20Effects%20Light%20at%20Night.pdf>

15. <http://darksky.org/idsps/>

16. <http://darksky.org/idsps/sanctuaries/>

level, AURA has begun sharing outreach work in our common area with CEAZA (the Centre for Advanced Studies in Arid Zones).

The recently published book on *Urban Lighting, Light Pollution and Society* (Meier et al., 2015) now gives important insight into how the desire for bright lights in cities has grown around the world since the late nineteenth century. For example, the chapter by Martin Morgan-Taylor includes a list of the effects of light pollution that may warrant regulation and then a discussion of each one. The list includes the effects on safety, human health, carbon emissions/ economic waste, ecology and the night sky.

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Mexico

México



# La Ley del Cielo

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## Resumen

El Observatorio Astronómico Nacional (OAN) se encuentra en la Sierra de San Pedro Mártir, Baja California. Este lugar ha sido considerado desde hace décadas como un sitio privilegiado para la investigación astronómica por sus condiciones geográficas y climáticas, además de una relativa lejanía de las grandes poblaciones de la región. Naturalmente, con el paso del tiempo, las poblaciones vecinas fueron creciendo, lo que puso en riesgo el recurso natural de cielo de San Pedro Mártir. Por ello, investigadores del Observatorio Astronómico Nacional buscaron un acercamiento con autoridades municipales y estatales de Baja California.

El primer resultado obtenido fue la aprobación, en el año 2006, del Reglamento Municipal para la Prevención de la Contaminación Lumínica en el municipio de Ensenada, conocido popularmente como “La Ley del Cielo”. Tomando inspiración de legislaciones similares en otros observatorios, el reglamento regula el alumbrado público para que no emita luz por arriba del horizonte que pudiera afectar la calidad del cielo oscuro. En el año 2010, el tema de la contaminación lumínica fue incluido en la Ley Estatal de Protección al Ambiente, con la meta de que el resto de los municipios del Estado de Baja California tengan reglamentos similares al de Ensenada, siendo la ciudad de Mexicali la siguiente en aprobar un reglamento municipal.

Sin embargo, aun con los reglamentos en operación, el Observatorio enfrenta nuevas problemáticas debido a la proliferación del uso de LED en el alumbrado exterior y en pantallas publicitarias, y al potencial de minería a cielo abierto en la región. Es por ello que en los últimos años se ha trabajado para actualizar la reglamentación municipal y estatal, además de iniciar labores a nivel federal para declarar regiones cercanas a observatorios, sitios arqueológicos cuya historia está relacionada con la astronomía y reservas naturales como zonas de máxima protección de la contaminación lumínica.

## Abstract

The National Astronomical Observatory (NAO) is located on the Sierra de San Pedro Mártir, Baja California, Mexico. For decades now, this site has been considered a privileged space for astronomical research thanks to its geographic and climatic conditions, as well as its relative remoteness from the region's large town and cities. Naturally, over the course of time, the once small neighbouring communities have grown, posing a risk to the natural resource of the dark skies in San Pedro Mártir. Thus, researchers working at the NAO sought a rapprochement with the municipal and State authorities of Baja California.

This approach has resulted in the approval of the 2006 Ensenada Municipal Regulation to Control Light Pollution, popularly known as the ‘Law of the Sky.’ Taking inspiration from similar legislation in other observatories, this regulation serves to prevent public lighting emissions at an angle above the horizon where it can have a harmful effect on the quality of the night sky. In 2010, the question of light pollution was addressed in the State Environmental Protection Act, with the aim of encouraging other municipalities in the State of Baja California to adopt laws similar to the one in place in Ensenada. The city of Mexicali was the next to adopt such regulations.

Even with these rules in place, the NAO is now dealing with new problems due to the increased use of LED in outdoor lighting and billboards, as well as the development of open-pit mining in the region. This is why, in the last few years, stakeholders have worked to upgrade municipal and state regulations, in addition to starting work at a federal level to declare regions surrounding observatories, archaeological sites whose history is related to astronomy and nature reserves as areas of maximum protection from light pollution.



Figura 1. Telescopio de 2.1 m, con la Vía Láctea de verano al fondo. © Ilse Plauchu Frayn.



Figura 2. Telescopio de 1.5 metros, con la Vía Láctea de fondo. © Ilse Plauchu Frayn.

El Observatorio Astronómico Nacional

La historia del Observatorio Astronómico Nacional (OAN) está ligada al crecimiento de la contaminación lumínica en México. El OAN nace en el Palacio Nacional de la Ciudad de México en 1867. Poco tiempo después, en la administración de Porfirio Díaz, se dio la orden de establecer un observatorio en el Castillo de Chapultepec, el cual fue terminado en el año de 1877 y puesto en marcha de manera oficial el 5 de mayo de 1878. Al ir creciendo la ciudad, la ubicación en Chapultepec dejó de ser óptima y se buscó un lugar en las orillas. Por ello, sólo 30 años después de haber llegado a Chapultepec, el OAN encontró un nuevo hogar en Tacubaya.

La Ciudad de México continuó su crecimiento, por lo que en 1951 la población de Tonantzintla, Puebla, recibió al OAN, aunque de manera temporal. Las ciudades de Puebla y Cholula, contiguas a Tonantzintla, se desarrollaron y con ellas la mancha luminosa que producían. Ante esta situación, investigadores del Instituto de Astronomía de la UNAM se dieron a la tarea de buscar el mejor lugar disponible en el país. En la Sierra de San Pedro Mártir, Baja California, encontraron un sitio con un cielo oscuro espectacular y condiciones climáticas estables. En 1971, inicia operaciones en este lugar el Observatorio Astronómico Nacional de San Pedro Mártir (OAN-SPM).

Las condiciones de la Sierra de San Pedro Mártir la colocan entre los cuatro mejores lugares del mundo para la observación astronómica óptica e infrarroja. Los otros tres lugares son la isla de Hawái, las Islas Canarias, frente a la costa de África, y las montañas de Chile.

A lo largo de la existencia del OAN-SPM, se han realizado diferentes estudios sobre el brillo del cielo del sitio. Uno de los más

| FILTRO | VALOR<br>(MAGNITUDES) |
|--------|-----------------------|
| U      | 22.04 ± 0.07          |
| B      | 22.56 ± 0.05          |
| V      | 22.08 ± 0.04          |
| R      | 21.17 ± 0.03          |
| I      | 19.93 ± 0.03          |

Table 1. Los datos fueron obtenidos la noche del 18 de febrero de 2013.



recientes y completos es el realizado para el proyecto Cherenkov Telescope Array (Tovmassian, 2016). Los resultados se presentan en la página anterior.

### Antecedentes de reglamentos y legislaciones

Las condiciones tan especiales que requieren los observatorios astronómicos, tales como un clima sin cambios bruscos y la gran altura de las montañas, pueden considerarse prácticamente estables. No así la existencia de un cielo oscuro libre de contaminación lumínica, el cual puede ser estropeado por la luz que escapa de las ciudades cercanas. Para contener lo más posible esta amenaza, los grandes observatorios han tenido acercamiento con sus gobiernos para implementar medidas legislativas que regulen el alumbrado público exterior. En Arizona, hogar del Kitt Peak National Observatory, podemos encontrar regulaciones en sus condados desde 1972 (Condado Pima, Tucson).

Las Islas Canarias hicieron lo propio en 1992 y Chile en 1999. Las medidas comunes consisten en no emitir luz por arriba del horizonte, usar luz ámbar en la medida de lo posible y restringir horarios en la iluminación ornamental.

### La Ley del Cielo

Siguiendo el ejemplo de los observatorios ya mencionados, los investigadores del OAN en Baja California buscaron implementar también reglamentos que protegieran los magníficos cielos de San Pedro Mártir. Ello dio como resultado lo que popularmente se conoció como la “Ley del Cielo”.

Por su ubicación geográfica en la Península de Baja California, el OAN se encuentra entre los municipios de Ensenada y Mexicali, por lo que fueron los primeros con quienes se tuvo acercamiento.



Figura 3. Ubicación del OAN-SPM. El círculo rojo tiene 100 km de radio y el amarillo 200. © Google Earth con datos del mapa de Google, INEGI, SIO, NOAA, U.S. Navy, NGA y GEBCO, modificado por Fernando Avila Castro con datos de P. Cinzano *et al.*, 2000.

## Ensenada

El Municipio de Ensenada tiene varias distinciones a nivel nacional, entre ellas ser el de mayor extensión territorial y tener a la mayor densidad de científicos per cápita, esto último por la presencia de la Facultad de Ciencias de la Universidad Autónoma de Baja California (UABC), el Centro de Investigación Científica y de Educación Superior de Ensenada (CICESE) y una sede de la Universidad Nacional Autónoma de México (UNAM; Nanociencias y Nanomateriales y Astronomía). La mayoría de la población en este municipio se encuentra en la zona urbana del puerto de Ensenada; le siguen las delegaciones de San Quintín, San Vicente y Colonet, en la zona sur del territorio.

Los investigadores Dr. David Hiriart, Dr. Manuel Alvarez, Dr. Mauricio Reyes y la Asistente Ejecutiva de jefatura del OAN, Lic. María Eugenia García, se reunieron en varias ocasiones con autoridades del XVIII Ayuntamiento de Ensenada (2003-2006), promoviendo medidas que protegieran las actividades del Observatorio. Sus visitas tuvieron éxito y el 10 de agosto de 2006, se aprobó en sesión de cabildo del XVIII Ayuntamiento de Ensenada el Reglamento para la Prevención de la Contaminación Lumínica del Municipio de Ensenada (XVIII Ayuntamiento de Ensenada, 2006). El reglamento tiene como finalidad proteger el recurso natural de cielo oscuro de San Pedro Mártir, pero al mismo tiempo auxiliar y apoyar al municipio en cumplir la necesidad de un alumbrado público de calidad y eficiente energéticamente.

Algo que distingue a este reglamento es la conformación de un Comité Técnico Asesor (CTA) que supervisará y mejorará lo estipulado en él. El CTA está integrado por el Secretario de Administración Urbana del Ayuntamiento, o quien él designe; el Regidor Coordinador de la Comisión de Desarrollo Urbano y Ecología del Ayuntamiento; el Director del Instituto Municipal de Investigación y Planeación de Ensenada (IMIP), y un representante nombrado por el Instituto de Astronomía de la UNAM. Además, se integra por un representante de la comunidad astronómica, de los centros de investigación y tecnología, de los organismos colegiados de ingeniería, de los organismos colegiados de arquitectura y de los medios de comunicación establecidos.

Los tres primeros integrantes del primer bloque son funcionarios de gobierno, que tienen facultades sobre la planeación y desarrollo del municipio. Es decir, son los responsables directos de los permisos de construcción, el crecimiento de la zona urbana y la administración y compra del equipo de alumbrado público.

El resto de los integrantes son miembros de la sociedad y tienen los conocimientos y experiencia para opinar y ofrecer recomendaciones específicas a los proyectos. Hay que resaltar la presencia de los medios de comunicación como una medida para transparentar las actividades del CTA y el gobierno en turno. El CTA debe de tener reuniones ordinarias al menos una vez cada trimestre, pero de ser necesario pueden realizarse reuniones extraordinarias tantas veces como sea necesario.

Aunque el reglamento fue aprobado en el año 2006, no fue sino hasta el 2008, en la siguiente administración (XIX Ayuntamiento), cuando se tomó la protesta de los primeros miembros del CTA. Estos miembros fueron: Arq. Cesar Cuevas Ceseña, Secretario de Administración Urbana; Arq. Catalina Talavera, Regidor Coordinador de la Comisión de Desarrollo Urbano y Ecología; Dr. Guillermo Arámburo, Director del IMIP; Dr. David Hiriart, representante el Instituto de Astronomía; Ing. José Luis Ochoa, representante de la comunidad astronómica; Dr. José Alberto Lopez, representante de los Centros de Investigación y Tecnología; Ing. Felipe David Ángeles, representante del Organismo Colegiado de Ingeniería; Arq. Víctor Hugo Sáenz, representante del Organismo Colegiado de Arquitectura, y Lic. Cesar Esparza, representante de los medios de comunicación.

Este histórico primer comité lamentablemente sólo pudo llevar a cabo dos reuniones, en las que los temas tratados tuvieron que ver con la evaluación de productos para alumbrado público de vialidades. Debido a una serie de circunstancias, principalmente el cambio en los puestos de gobierno cada tres años y la falta de continuidad que esto conlleva, no hubo más sesiones del Comité en los siguientes años.

Además, debido a que los astrónomos del OAN tenían sus propias actividades y proyectos de investigación, les resultaba complejo tener el tiempo y energía necesarios para reactivar con éxito el CTA. Por esta razón, en el año 2012 el Instituto de Astronomía de la UNAM decide crear una nueva plaza para ocupar la nueva Oficina de la Ley

del Cielo. Este nuevo puesto será el representante de la Jefatura del OAN en los temas relacionados con estas gestiones gubernamentales, además de dar asesoría sobre iluminación, realizar actividades de divulgación enfocadas en la prevención de la contaminación lumínica e implementar un programa de monitoreo del brillo del cielo.

En septiembre de 2012, inicia oficialmente actividades la Oficina de la Ley del Cielo, estando a cargo el M. C. Fernando Avila. Coincidentemente en estas fechas, el XX Ayuntamiento de Ensenada buscaba renovar el alumbrado público del municipio, el cual presentaba un gran rezago y no ofrecía una gran eficiencia energética. De un censo aproximado de 17 mil luminarias en la zona urbana, sólo funcionaba aproximadamente el 70% de ellas, siendo en su gran mayoría del tipo *semi cut off* (emisión ~5% por arriba del horizonte) y de vapor de sodio de alta presión. Una dificultad que enfrentaba el municipio era la falta de recursos económicos para llevar a cabo esta renovación, que además de tener como metas tener el 100% de cobertura, buscaba un ahorro económico por consumo de energía y dar una mejor respuesta de color para mejorar la percepción de seguridad pública.

Debido al potencial de impacto que tendría esta renovación, el OAN, a través de la Oficina de la Ley del Cielo, buscó acercamiento con la administración municipal. Lamentablemente la respuesta no fue favorable y el Ayuntamiento negó la información del proyecto al OAN bajo el argumento de que el CTA no estaba integrado. Pero no sólo el CTA fue excluido, también lo fueron la prensa y organismos comerciales de la entidad. Con el tiempo, los detalles de la renovación fueron saliendo al público a través de filtraciones del mismo gobierno y solicitudes formales de la información a través de organismos de transparencia. La renovación del alumbrado sería a través de un modelo de concesión del servicio a una empresa particular por 10 años, en un contrato poco ventajoso para el municipio. Sin embargo, para el OAN la peor noticia es que el equipo seleccionado era del tipo LED en color blanco frío, en configuración *semi cut off*. De realizarse la instalación de este equipo, las consecuencias serían catastróficas para el cielo oscuro de San Pedro Mártir. De última hora, literalmente, el contrato para otorgar la concesión no fue firmado por el Presidente Municipal, en gran medida debido a la presión de la sociedad, cámaras de comercio e industria y el Observatorio. Incluso, la Comisión Federal de Electricidad declaró

que de realizase la concesión, suspendería los apoyos económicos al municipio (Morales, 2013).

Con la entrada del XXI Ayuntamiento, la situación cambió para bien. Una de las primeras acciones de la administración municipal fue acercarse con el OAN buscando información sobre las fallas del proyecto anterior de renovación de alumbrado público. Meses después, en junio de 2014 se tomó protesta a los nuevos integrantes del CTA. Desde el primer momento, el CTA inició labores para asesorar y hacer recomendaciones para la compra de mil luminarias, mientras inician los trabajos para un proyecto de instalación de 25 mil luminarias en todo el municipio. Esta renovación de alumbrado público inició en febrero de 2016 y el equipo seleccionado es del tipo LED *full cut off*. Por cuestiones económicas, se utilizarán inicialmente luminarias con luz blanca fría, ya que la diferencia de precio para 25 mil luminarias entre este tipo y el de luminarias con luz cálida era considerable.

En contraparte, se tuvieron grandes avances en la reglamentación. El CTA publicó una serie de lineamientos para regular de una manera más estricta los medios publicitarios luminosos como espectaculares, cajas de luz y pantallas electrónicas. El auge del LED no sólo se hizo notar en las luminarias, sino que hizo mucho más accesible la tecnología para publicidad, donde invariablemente se ha caído en un abuso. Los lineamientos, además de regular intensidad y horario de operación, buscan que estas pantallas sólo se instalen, de manera que no ofrezcan riesgos de seguridad en las vialidades (que no encandilen a los conductores de vehículos, por ejemplo).



Figura 4. Recorte de prensa. Diario *La Crónica*, 12 de octubre del 2013. © Diario *La Crónica*.

El mayor avance que se ha tenido con el reglamento se dio el 9 de diciembre del 2015, cuando el Cabildo aprobó de manera unánime la definición de una zona de máxima protección en el municipio para el Observatorio (Pringle, 2015). Esta zona está dentro de un radio de 100 km, teniendo como centro el OAN. Su finalidad consiste en que sólo se use luz cálida para alumbrado público en las poblaciones que queden dentro de esta área. Para compaginarlo con el proceso de renovación de alumbrado ya iniciado, se da un periodo transitorio de cinco años para que, ante el reemplazo natural por fallas del equipo, éste se haga hacia una luz cálida, disminuyendo los efectos de la dispersión de la luz azul en la atmósfera.

### **Mexicali**

Debido a su ubicación geográfica, el siguiente municipio en adoptar la Ley del Cielo fue Mexicali, la capital del Estado. Un grupo de periodistas y entusiastas de la Sierra de San Pedro Mártir, quienes ya conocían al astrónomo Manuel Álvarez, sirvieron de enlace y apoyo para que en el año de 2011 se aprobara en el pleno de Cabildo del XX Ayuntamiento el Reglamento para la Prevención de la Contaminación Lumínica del Municipio de Mexicali (Mexicali, 2011). El contenido del Reglamento es muy similar al de Ensenada, siendo la mayor diferencia la ausencia de los medios de comunicación en el CTA.

Se estima que en todo el municipio de Mexicali existen aproximadamente 65 mil luminarias, casi todas de vapor de sodio de alta presión *semi cut off*. La mayoría de las luminarias están en la zona urbana, aunque un porcentaje considerable está en la zona del Valle, que tiene como actividad económica principal la agricultura. Mexicali presenta un reto particular en términos del control de la contaminación lumínica ya que se encuentra en los primeros lugares mundiales en contaminación por partículas suspendidas. Estas partículas suspendidas, en conjunto con la emisión de luz hacia arriba, crean un gran domo de luz que puede verse claramente desde el Observatorio aun cuando a 200 km de distancia en línea recta. Sin embargo, la delegación de San Felipe es la que más afecta al OAN por su cercanía, ya que está a sólo 60 km.

Lamentablemente, la administración del XXI Ayuntamiento no se ha mostrado sensible al problema de la contaminación lumínica. No

sólo no ha convocado al CTA como lo dicta el reglamento, sino que en un proyecto de cambio de 7,200 luminarias realizado en el año 2015, se presentaron varias irregularidades, las cuales fueron documentadas en la prensa local.

A pesar de estas dificultades, la presencia del OAN en Mexicali ha ido en aumento gracias al apoyo de la prensa y a diferentes actividades de divulgación como charlas y observaciones astronómicas públicas, las cuales han generado una respuesta favorable por la sociedad mexicalense. En especial, hay que resaltar la colaboración del Museo Sol del Niño, que no sólo ha servido como foro para charlas de astronomía y observaciones, sino que también en este lugar se encuentra instalado un sensor para medir el brillo del cielo (Sky Quality Meter, SQM).

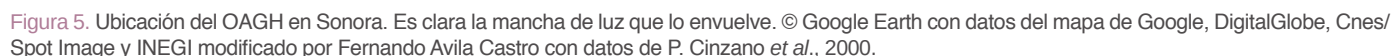
### **Tijuana**

Tijuana es la mayor zona urbana del estado y se considera como zona metropolitana junto con los municipios de Playas de Rosarito y Tecate. La situación de Tijuana es complicada, ya que en el XIX Ayuntamiento se buscó hacer una renovación del alumbrado público, la cual fue considerada un fracaso ya que el equipo que se instaló presentó fallas y la empresa responsable se deslindó, dejando al Ayuntamiento en una mala situación económica y sin dar la cobertura del servicio esperada.

Por ello, no hubo un acercamiento con este municipio sino hasta principios del año 2016. Para evitar que volviera a suceder y viendo los avances de Ensenada, funcionarios de esta administración se acercaron al CTA de ese otro municipio para solicitar apoyo en un proyecto de compra de luminarias, además de buscar aprobar un reglamento para el alumbrado público similar a los de Ensenada y Mexicali. Al momento de escribir este artículo, las reuniones para discutir el contenido del reglamento antes de su aprobación continúan.

### **Baja California**

En la estructura política mexicana, los municipios cuentan con la autonomía para atender el funcionamiento de ciertos aspectos, como los servicios públicos. Sin embargo, para hacerlo deben de seguir ciertos lineamientos estatales y federales. A nivel estatal, en Baja California se encuentra la Ley de Protección al Ambiente para el Estado de Baja



Para complementar la ley de protección al ambiente, desde el 2015 iniciaron las reuniones de trabajo con el Congreso del Estado para actualizar la Ley Estatal de Desarrollo Urbano. Es en esta legislación que se tendrán más facultades para ordenar el ámbito de alumbrado público en los nuevos desarrollos habitacionales y comerciales. De esta manera se espera tener un control preventivo en el crecimiento de la contaminación lumínica del Estado.

En enero del 2015, el Congreso del Estado publicó un exhorto a los cinco municipios para regular las pantallas electrónicas publicitarias, las cuales han proliferado los últimos años. A la fecha, el único municipio que ha atendido este exhorto ha sido Ensenada. En Ensenada, el CTA publicó un dictamen que regula horarios de operación, intensidades máximas y áreas de instalación para estas pantallas, el cual fue aprobado por Cabildo ese mismo año.

A raíz de la Reunión Internacional “Derecho a los Cielos Oscuros” organizada del 20 al 22 de enero del 2016 por la Oficina en México de la Organización de Naciones Unidas para la Educación, la Ciencia y la Cultura (UNESCO), el Consejo Nacional de Ciencia y Tecnología, la UNAM, la Academia Mexicana de Ciencias y el Foro Consultivo Científico y Tecnológico, iniciaron los traba-





**Figura 6.** Taller de luminarias, Universidad Xochicalco Ensenada, enero de 2013. © Fernando Avila Castro.

jos con la Diputada Tania Arguijo para modificar la Ley General del Equilibrio Ecológico y la Protección al Ambiente de modo que incluya el tema de la contaminación lumínica. Al momento de escribir este artículo, la iniciativa se encuentra terminada y lista para presentarse en el Congreso de la Unión.

De ser aprobada la iniciativa, servirá como referencia para actualizar normas y manuales técnicos relacionados con el alumbrado público, que permitan definir zonas de máxima protección para observatorios, parques nacionales y sitios arqueológicos relacionados con la astronomía.

### Riesgos latentes

De manera similar a la situación de Chile, el mayor riesgo que se tiene en Baja California para el OAN es el desarrollo de la industria minera. El estado es rico en hierro, oro y cobre. Existen proyectos para explotarlos en zonas al sur del OAN, lo cual tendría serias consecuencias para él. En México ya existe un antecedente con el Observatorio Astrofísico Guillermo Haro (OAGH) en la ciudad de Cananea, Sonora.

Al pie de la montaña donde se encuentra este observatorio, hay una mina de cobre a cielo abierto. El polvo levantado por la extracción del mineral

queda suspendido en la atmósfera, reflejando la luz producida por la minera y la cercana zona urbana de Cananea. Esto tiene como consecuencia que la calidad de su cielo oscuro se encuentra reducida en comparación con la de otros observatorios de la región, como Kitt Peak y Mt. Graham, en el vecino Estado de Arizona.

Sirviendo esto como aprendizaje, esperamos que las reformas federales puedan detener el desarrollo minero en Baja California en un radio mínimo de 200 km del OAN.

### Trabajo futuro

Sin duda alguna, la única acción que puede proteger los cielos oscuros a largo plazo es la educación. En este sentido, el OAN ha realizado una serie de actividades en el estado para difundir el tema de la contaminación lumínica. Además de los eventos tradicionales como la Noche de las Estrellas, se tienen programas constantes de divulgación y de apoyo a instituciones educativas, lo cual le ha dado una imagen favorable ante la sociedad. En específico, para el tema de la prevención de la contaminación lumínica, se han realizado colaboraciones con las escuelas de arquitectura y diseño del estado. La finalidad de estas actividades ha sido ir preparando y concientizando a los futuros profesionistas del Estado para que sus proyectos incorporen desde un inicio una iluminación exterior no contaminante. Un ejemplo fue el taller para los docentes de la Universidad Xochicalco de Ensenada, en el que usando materiales reciclables fabricaron cubiertas para los focos de exterior de las casas de interés social.

Con la Facultad de Arquitectura y Diseño (FAD) de la UABC, se realizó material de divulgación como carteles y calcomanías en la materia Diseño de Marca impartida por la M. A. V. Martha Alcaraz Flores.

Este material ha sido bien recibido por el público y se encuentra disponible en la página de la Ley del Cielo del Instituto de Astronomía ([leydelcielo.astrosen.unam.mx](http://leydelcielo.astrosen.unam.mx)).

Como comentario final, la mayor enseñanza que hemos tenido en la protección del cielo oscuro tiene que ver con la respuesta de la gente que visita por primera vez San Pedro Mártir o ve por un

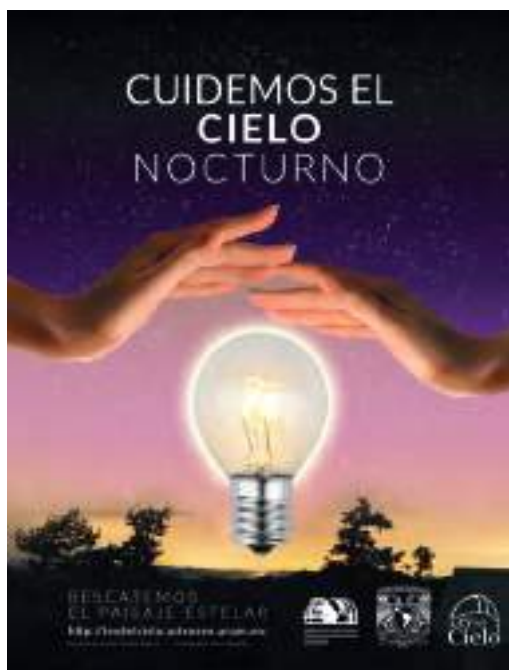


Figura 7. Carteles de divulgación.  
© Fedra Matus, 2014.

telescopio en una plaza pública y observa la gran cantidad de estrellas que estaban veladas a sus ojos. A lo largo de estas visitas y observaciones hemos visto cómo una pregunta tímida de un niño era el preludio de una interminable serie de preguntas. La manera en que una pareja joven se tomaba de las manos mientras sus miradas se perdían en lo infinito de las estrellas. Hasta llegar a la persona mayor que toda su vida había trabajado en el campo y con plena convicción declaraba que él ya sabía el porqué del color de las estrellas, concluyendo que era lo mismo que pasaba al calentar el hierro para marcar al ganado.

Cada una de estas experiencias nos han enseñado que para proteger el cielo oscuro, el derecho de poder apreciarlo, debe de ser de todos. Será a través de la educación que la población tomará conciencia de su importancia. Así, cuando las personas se apropien de esta maravilla natural y lo atesoren, la Ley del Cielo dejará de ser un reglamento forzado y podrá convertirse en un Patrimonio de la Humanidad.

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United States of America

Estados Unidos de América





# Protecting Arizona's Dark Skies

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## Abstract

The state of Arizona contains the highest concentration of research telescopes in the continental United States. Protecting the dark skies above these observatories is essential to the continued investment in major astronomical research initiatives by government agencies, academia and foundations. In this contribution, I describe how a coalition of Arizona observatories is working to protect our dark skies. Efforts date back to the creation of one of the first Outdoor Lighting Codes in the United States and continue today, including educational outreach, public policy engagement and sky brightness monitoring. I review some proven strategies, highlight some recent successes and look ahead to the imminent threat posed by widespread use of broad-spectrum LEDs.

## Resumen

El Estado de Arizona alberga la mayor concentración de telescopios de investigación de los Estados Unidos. Proteger los cielos oscuros sobre estos observatorios resulta fundamental para la continua inversión en grandes iniciativas de investigación astronómica por parte de agencias gubernamentales, el mundo académico y fundaciones. En esta contribución, describo cómo una coalición de observatorios de Arizona está trabajando para proteger nuestros cielos oscuros. Estos esfuerzos se remontan a la creación de uno de los primeros códigos de iluminación al aire libre de los Estados Unidos y continúan al día de hoy, incluyendo divulgación educativa, implicación en políticas públicas y monitoreo del resplandor del cielo. Analizo algunas estrategias probadas, subrayo algunos éxitos recientes y miro adelante hacia la inminente amenaza planteada por el uso generalizado de LED de amplio espectro.

## Introduction

Dark sky protection in Arizona began in 1958 when the city of Flagstaff adopted the world's first Outdoor Lighting Code (OLC) aimed at protecting dark skies. Specifically, it was developed to protect Lowell Observatory from advertising searchlights that swept the sky. In 1972, the city of Tucson adopted the second OLC in Arizona to protect Kitt Peak National Observatory, which lies 90 km to the west. The Tucson OLC required that lights be directed downwards. This requirement was soon implemented by Flagstaff to strengthen its own code. In subsequent years, both cities led the way in OLC updates, adopting low-pressure sodium lights and banning mercury vapour lights. Today, the codes in Flagstaff and Tucson serve as model codes for other cities and towns in Arizona. New threats (and opportunities for improved lighting) arise regularly, so dark sky advocates can never rest or become complacent and outdoor lighting codes must evolve.

## Why Protect Arizona's Dark Skies?

Arizona's dark skies are a unique natural resource. They enable significant investment in the State's economy, a benefit that is quantifiable. Less measurable but more significant is the intangible value of dark skies to the experience and enjoyment of nature. It is often said that the sky belongs to everyone, and for good reason – when we look up at a dark night sky blanketed in stars, we contemplate and perhaps appreciate humanity's place in the vast cosmos.

## Astronomy Assets in Arizona

Astronomy is a high-tech industry providing high-tech jobs. Astronomical research spawned the Arizona optics industry, a State-wide economic and innovation engine. Astronomical research attracts government, private and foundation funding to the State. Astronomy uses all of the sciences in the quest to better understand the universe and has great connective power with students and schools of all levels. It is a gateway to the STEM fields, which help build a technically advanced work force.

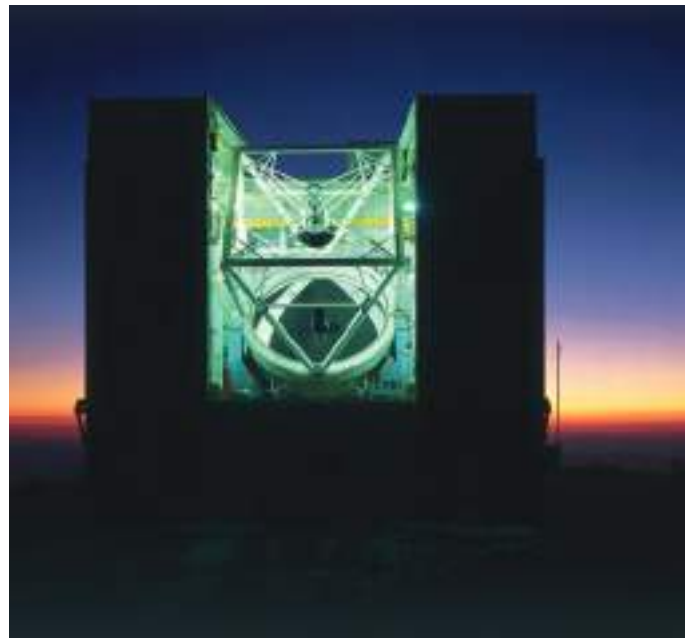
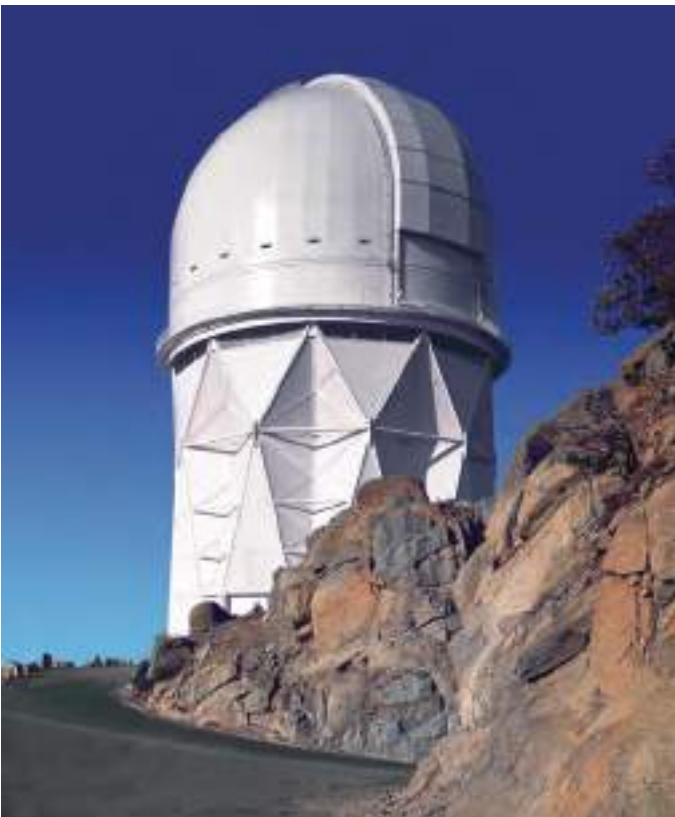


Figure 1. Some of the largest telescopes in Arizona. Clockwise from top left: the Large Binocular Telescope on Mount Graham, the Discovery Channel. Telescope near Happy Jack, the MMT on Mount Hopkins and the Mayall Telescope on Kitt Peak. Image credits, clockwise from top left: © Courtesy NASA/JPL-Caltech, © Jeremy Perez, © MMT Observatory, © NOAO/AURA/NSF.

Astronomical research has a significant and ongoing economic impact on Arizona. A 2008 study by the University of Arizona's Eller College of Management found substantial capital investment in, and economic return from, astronomical research in Arizona (*Arizona Republic*, January 17, 2008):

- US\$250 million in annual economic activity
- US\$12 million in tax revenue
- US\$1.2 billion in capital investments
- Over 3,300 jobs

Arizona has the largest optical telescope in the world (the Large Binocular Telescope on Mount Graham), one of the largest collections of research telescopes (Kitt Peak National Observatory) and the first, third, fifth and sixth largest telescopes in the continental United States.

Recent investments in astronomical research in Arizona (since 2010) total about US\$500 million and include:

- US\$200 million Large Binocular Telescope on Mount Graham (completed in 2010).
- US\$53 million Discovery Channel Telescope near Happy Jack (completed in 2012, with anticipated lifetime economic impact of approximately US\$500 million).
- US\$100 million for new research projects funded by the National Science Foundation, the Department of Energy and NASA, based at Kitt Peak National Observatory.
- US\$125 million invested since 2012 in astronomical assets near Flagstaff in support of the mission of the Department of Defense.
- US\$43 million currently being invested by the US Navy for a telescope array near Flagstaff.

Large research telescopes have active and useful lifetimes of fifty to one hundred years, so the State's economy has much to lose if Arizona fails to protect its dark skies. To respond to this threat, astronomers have banded together to work collectively on dark sky protection. The Astronomy, Planetary and Space Sciences (APSS) collective consists of members from observatories, astronomy departments

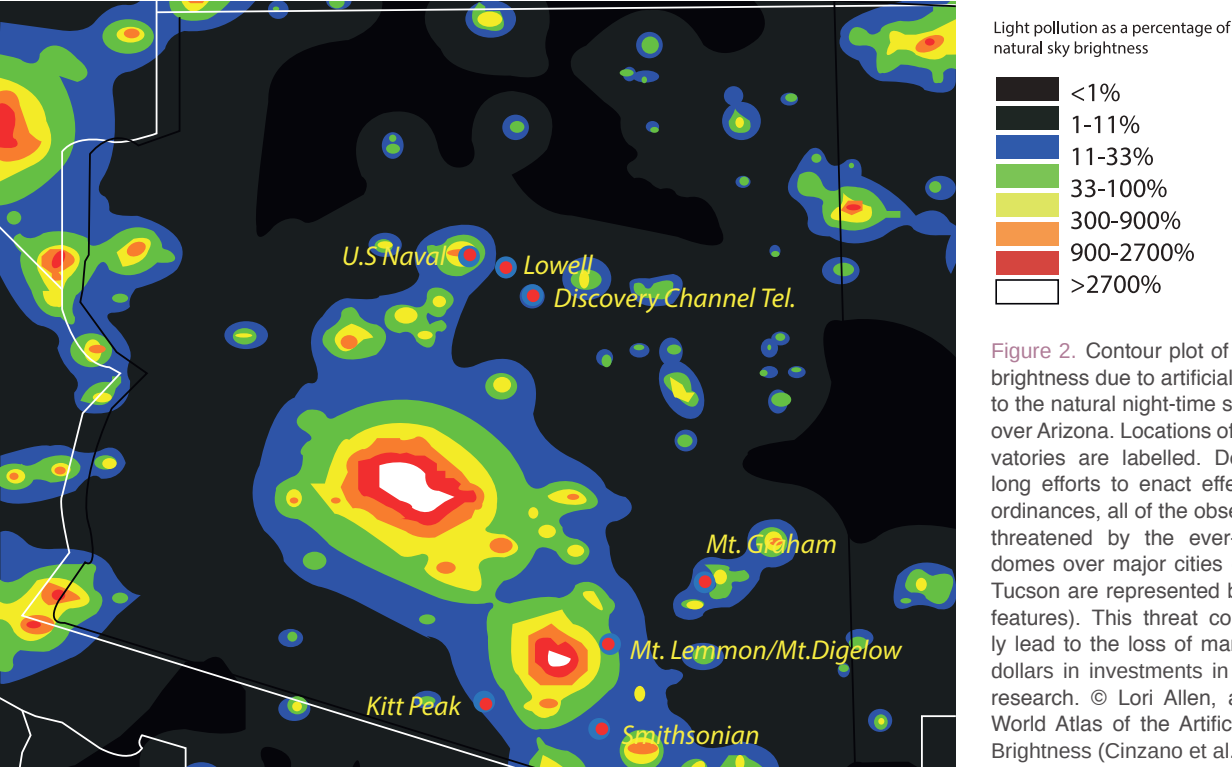
and space science institutes across the State. Our members pool resources and coordinate work with State, county and local officials to research, develop and update OLC, consult on various issues like variance applications to sign regulations and contest legislation that would compromise the skies over our observatories. Natural allies of the APSS include the International Dark-Sky Association (IDA), the Arizona Optics Industry Association (AOIA), the Arizona Tech Council, the National Park Service and environmental groups like the Sierra Club and Scenic Arizona.

### The APSS Collaboration in Action

A major threat to dark skies in Arizona arose in 2012 when the State legislature passed a bill allowing electronic (LED) billboards on any state highway. Until that time, electronic billboards were illegal in Arizona, though a number of them existed in the Phoenix metropolitan area. The bill was opposed by astronomers and other dark sky advocates but was passed anyway.

The then Governor, Jan Brewer, recognizing the importance of dark skies to astronomy and of astronomy to Arizona, vetoed the bill, forcing the billboard industry to sit down with the astronomers and negotiate a compromise. The astronomers agreed to allow electronic billboards in the Phoenix metropolitan area, the most densely populated region of the State (and where advertising dollars could reach the most people). In return, the billboard industry agreed to a 75 mile protected radius around the existing observatories. Billboard industry representatives also agreed to a brightness limit of 300 nits (much higher than is needed) and an 11 p.m. curfew. Enforcement of both the brightness limit and the curfew is challenging, and it is not yet clear how to achieve this. In the political climate of the day, that was the best agreement that the astronomers could obtain. It is important to realize that before this legislation, electronic billboards were illegal throughout the whole of Arizona, so effectively all of the compromise was made by the dark sky advocates.

In 2016, a new bill was proposed in the Arizona State house that would extend the allowable region for electronic billboards to an approximately twenty thousand square mile sector in the north-west corner of the State. The bill passed in the house but was fortunately killed in committee in the Senate, due in part to APSS testimony. It



seems likely that lawmakers' efforts to increase the allowable areas for LED billboards will continue in the future.

Imminent Threats

Not surprisingly, light-emitting diodes (LEDs) are showing up in all kinds of outdoor lighting applications. One of the biggest threats to Arizona's dark skies is the replacement of low-pressure sodium streetlights with 'white' light LEDs. These LEDs are strong emitters of blue light, peaking at a wavelength of around 450 to 460 nm. The spectral power distribution of these sources casts a light that is colder and harsher to most people, who usually prefer the warmer, redder lighting produced by incandescent bulbs and other light sources. But the real problem with these LEDs is their effect on dark skies. The blue light that dominates their spectrum is scattered more efficiently by the Earth's atmosphere than redder light, so if they are unshielded, they affect the sky brightness more adversely than other sources.

A common characterization of LEDs is their Correlated Colour Temperature (CCT), which is a measure of a light source's colour appearance and gives a general indication of the apparent 'warmth' or 'coolness' of the light emitted. Lamps with low CCT values (below 3000 K) provide 'warm' light, while lamps with high CCT values (more than 4000 K) provide light that appears 'cool'. In general, if LED lighting is required, the low CCT bulbs (2500 K or less) are far less harmful and should be preferred.

Developing Public Awareness: the Quality Lighting Teaching Kit

Poor quality lighting not only impedes astronomical research and our right to see a starry night sky, but also creates safety issues, affects human circadian sensitivities, disrupts ecosystems and wastes billions of dollars per year in energy consumption. It also leads to excess carbon emissions. How do you change the mindset of a society that is used to turning night into day? You educate the next

generation on quality lighting. The remainder of this contribution is devoted to a detailed description of the Quality Lighting Teaching Kit, developed by the Education and Public Outreach group at the National Optical Astronomy Observatory.

The United Nations' International Year of Light in 2015 (IYL2015) provided an opportunity to increase public awareness of dark skies preservation, quality lighting and energy conservation. The Education and Public Outreach (EPO) group at the US National Optical Astronomy Observatory (NOAO) received a grant through the International Astronomical Union (IAU) and the Optical Society of America (OSA) to produce official 'Quality Lighting Teaching Kits' (QLT Kits) for the IYL2015 cornerstone theme, 'Cosmic Light'. The QLT kit allows students to do creative problem solving using quality lighting.<sup>1</sup>

The concepts and practices of quality lighting are explored through problem-based learning, hands-on/minds-on activities, as well as formative assessment probes. The six activities use quality lighting to solve realistic cases on how light pollution affects wildlife, the night sky, our eyes, energy consumption, safety and light trespass into buildings. The impact of the kits is amplified by providing professional development using a tutorial video created at the NOAO, and conducting question and answer sessions via Google Plus Hangouts for programme instructors. The Quality Lighting

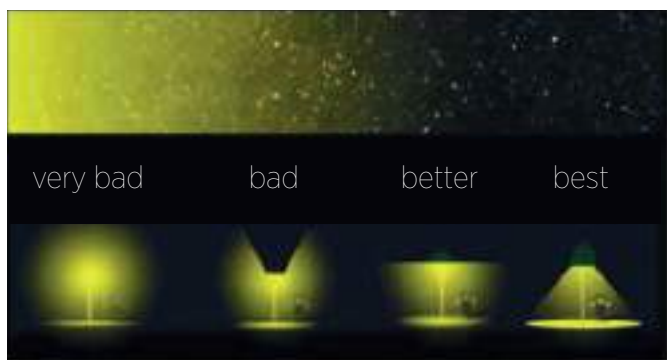


Figure 3. Outdoor Lighting Codes regulate not only the brightness, but also the directionality of light. Unshielded lights shine indiscriminately in all directions, polluting the sky and wasting energy. Shielded fixtures direct light where it is needed. © Canadian Space Agency.

Teaching Kit programme leverages the NOAO EPO group's work over the last ten years in lighting and optics education (for example, 'Hands on Optics', the International Year of Astronomy's 'Dark Skies Rangers', the IAU's 'Dark Skies Africa' and Arizona Public Services' 'Dark Skies Yuma' programmes).

The premise of the activities is that the instructor is the Mayor of a fictitious city in which the students live (inspired by the 'City of the Future' poster). The mayor has been receiving complaints from the city's citizens, which all have to do with the lights in the city (stated on the 'Issues' poster). The students have been assembled into six different task forces to determine the underlying problems expressed in each of the six complaint categories, as well as to come up with feasible solutions to solve those problems.

The students start by reading the information presented in their group's poster. The 'Now Try This!' section gives instructions for an experiment, game or activity to complete in order to gain a better understanding of the problems with which they are presented.

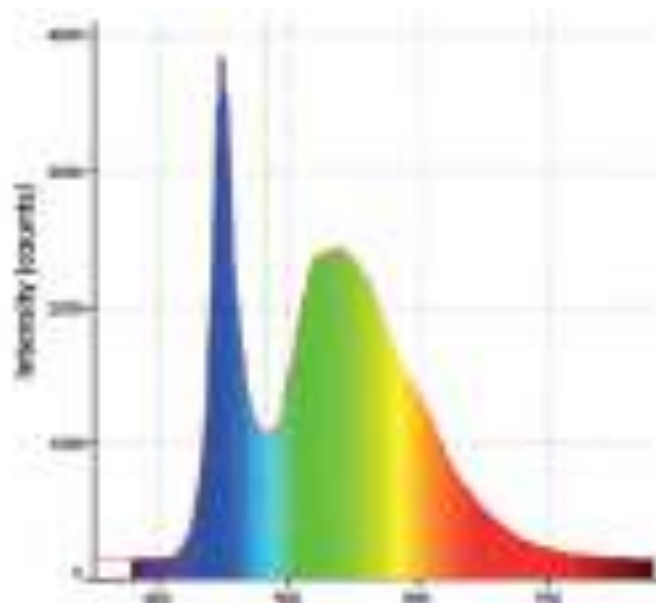


Figure 4. High Correlated Colour Temperature (CCT) white LEDs ('cool white') are extremely damaging to astronomy because of the large amount of blue light they emit. © Chris Monrad.

1. The QLT kit files can be found at [www.noao.edu/education/qltkit.php](http://www.noao.edu/education/qltkit.php)



They use the materials in their box and/or envelope to complete the activity. Using what they know along with help from the 'Problem Solving' poster, the students brainstorm solutions to their problem. The students then carefully consider the implications (both positive and negative) of their solutions as well as any exceptions where their solutions may not work. They determine if there is any other information they need to better understand the problem or have better solutions. This may involve using the links provided or key ideas from the poster to research more about their problem. The six areas of investigation are: safety, light trespass, glare, sky glow, energy and wildlife. These are summarized below.

### Safety

It is a common misconception that more light is safer; however, this is not always true. While light is needed to see and be safe at night, poorly designed or placed lights can actually be less safe! Poorly shielded or glaring lights provide areas for criminals to hide. Criminals also exploit the false sense of security people feel in overly lit areas. In this activity, students use a lux meter to measure light levels in different scenarios and compare their results to standardized lighting levels.

### Glare

As one of the three main types of light pollution, glare is caused by an exposed light bulb. An overly bright bulb can severely impair vision, especially while driving at night. Glare is worse for older adults due to the presence of cataracts and loss of pupil control. In this activity, the students will explore glare from a 'headlight' (a cap-less Mini-Maglite) at night (in a darkened room). With an unshielded light source, students will see how glare affects their ability to read an eye chart 20 feet away. Layers of inkjet transparencies are used to simulate varying degrees of cataracts. The students then explore how cataracts (both with and without a glaring light) can impair their reading ability.

### Light Trespass

The second type of light pollution is light trespass, where light goes where it is not needed, wanted or intended. The most common example of light trespass is a streetlight shining into a window at night. This can make sleeping (even with curtains or blinds) difficult. Light at night, in particular, can have negative health

effects on humans. Blue light (which is common in most LEDs) is especially bad because, at night, it inhibits the production of melatonin, which is a hormone that is only replenished when asleep in the dark. Other sources of blue light such as computer, tablet and cell phone screens before bed also inhibit melatonin production. In this activity, students have a 40:1 scale model of a street, complete with a house, a person, a streetlight with a slight drop-down Cobra lens and a globe light. The students try to recreate the problems voiced in the complaints poster and experiment with the position and angle of the light. Then they come up with solutions to keep the light task oriented and mitigate light trespass (for example, find ways to avoid shining light where it is not needed).

### Sky Glow

As a third major type of light pollution, sky glow, is caused by unshielded lights from a city shining up into the sky. This light scatters off of dust, water, smog, clouds and other things in the atmosphere creating a light dome or glow over the city. Sky glow washes out the sky, obscuring the stars from view. As a result, most people in cities have never seen a dark night sky. In this activity, students use a star projector to determine how different kinds of lights, shields and distances affect the number of stars that can be seen.

### Wildlife

The NOAO's EPO group's staff designed a game for students to explore how light pollution affects animals, specifically birds. In the game, they are Kirtland's Warblers that migrate from the Bahamas to the Great Lakes region of the United States and back again. Along the way, they fly through many major cities. Each year, up to 1 billion birds are killed by crashing into buildings in North America alone. Buildings lit at night cause many of these deaths and injuries. Birds and other animals use the Sun or stars to navigate and the lights can confuse the animals causing them to circle the building and collapse from exhaustion. A great 'Going Further' idea is to have students research and design a game centred on an animal that is threatened by light pollution where they live.

### Energy

In this activity, students are given an aerial night-time view of Houston, Texas with a grid superimposed on top. There are three different colours of lights shown in the image: white (along the

highways), yellow (oil refineries) and brown (everywhere else). The students count the number of squares of each coloured light to determine how much energy, cost and carbon footprint this city uses and wastes each night. These values accurately reflect the actual energy usage of Houston as well as the type of lights currently used. Students may determine a more energy efficient scenario by changing the types and/or wattages of the lights or by implementing timers or motion sensors to limit the amount of time the lights are on.

### Project Partners

The NOAO's partners are the International Commission on Illumination (CIE), the IDA, the International Society for Optics and Photonics (SPIE), the OSA and the International Astronomical Union Office of Astronomy for Development (OAD), with sponsorship from the IAU and the OSA. This is the first time that all six stakeholders have partnered in educating the public on the importance of quality lighting and its effects on society. The partners are now disseminating the kits to audiences worldwide.

### Kit Distribution

By the end of February 2016, there have been 24 countries to which 75 kits have been sent on behalf of the OSA, the SPIE, the IDA and the IAU's OAD group. The CIE is deciding which of their national committees are getting 10 QLT Kits. Once those have been sent out, there will be a total of 85 kits distributed. The NOAO has the last 15 kits being considered for distribution.

The 24 countries are Argentina, Armenia, Belgium, Canada, Chile, China, Colombia, Denmark, Egypt, Ethiopia, India, Ireland, Italy, Jordan, Latvia, Nigeria, Portugal, Russia, Russian Federation of Tatarstan, Singapore, Tanzania, Thailand, USA and Zambia. The

countries were chosen on the basis of need, interest, dedication and commitment of the recipient or receiving organization.

### Creating a Legacy

Our next steps for the programme include creating a video tutorial, having the kit recipients review it and holding Google Plus hangouts to answer questions about the activities and programme.

The funding from the IAU and the OSA made building the Quality Lighting Teaching Kit possible. It is the fourth kit developed by the NOAO's Education and Public Outreach group to address issues on and solutions to quality lighting and light pollution. We consider it the penultimate kit in this area. We hope the programme becomes a legacy of the IYL2015 and the IAU. To make that possible, our future steps would be to build another 100 kits, translate the kit's documents into Spanish (at least) and adjust aspects of the kit's activities to better suit the areas to which the kits will be sent. The key to accomplishing these goals is to secure the necessary funding. Based on the responses to the testing and use of the kit thus far, the kit will be wildly successful in its popularity and effectiveness and will be applicable to a wide variety of audiences and ages. It is our hope that we will be able to sustain the programme in the future.

### In Conclusion

Dark sky protection is crucial to the future of astronomical research in Arizona and to the State's economy, due to the significant monetary contribution it represents. Dark skies enrich our lives by revealing the wonder and beauty of the universe, and stimulate our interest in the natural world. We can all take steps to help protect this precious resource, through education, activism and political and civic engagement.





Italy

Italia





# The Defence of the Night in Italy

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## Abstract

Despite its centuries-old astronomical tradition and heritage, Italy is one of the most light polluted countries in the world. Thanks to the pressure of amateur and professional astronomers, since 1997 regional regulations have been progressively implemented across most of the territory. Yet, Italy still suffers from extreme light pollution, particularly in more densely populated areas. Sky brightness measurements over the last decade show that, at least, the very steep yearly increase of the past has recently been halted as a result of the reduction of upward light emissions, as prescribed by most of the regulations. However, this result is not good enough, and nor it is one that can last as the installed luminaries and total luminous flux are still increasing. Just like other forms of pollution, the aim is to significantly reduce emissions (direct upward and reflected light).

Further to imposing fully shielded luminaries, light pollution can be successfully controlled with additional measures, such as defining lower luminance and illuminance levels in standard norms, protecting scotopic and melatonin suppression bands, using light only where and when needed and limiting the per-capita light flux with progressive reduction. If these simple actions are not taken, light pollution can be expected to substantially increase in the near future, especially in the blue part of the spectrum, due to extensive use of white LED sources. If LED lights with a proper spectral signature are used, LED sources have an advantage over High Pressure Sodium (HPS): the flux can be easily adjusted. This potential is still poorly exploited as LEDs are considered per se as the ultimate energy-saving panacea. However, simply swapping light sources from HPS to LED without also implementing adaptive lighting is a waste of resources and will not reduce pollution. Adaptive lighting, controlled by sensors, allows lights to be switched off or left very dim for most of the night. The LED market is currently driven by an efficiency race that does not take into account the downsides of using blue-rich light at night. A one-to-one lumen change from HPS to 4000 K white LEDs will determine a several-fold increase in scotopic and melatonin-suppression bands. LED producers should therefore take into consideration that their products may soon have serious consequences for people's health, as has been the case for the tobacco and asbestos industries.

Even the best regulations are worthless if they are not respected so strict controls are needed. In Italy, the Veneto Region has pioneered the control of its territory involving its environmental protection agency (Agenzia Regionale per la Protezione dell'Ambiente del Veneto – ARPAV [The Regional Agency for Environmental Protection of the Veneto]) and has obtained encouraging results. Controlling millions of luminaries may seem like an impossible task, but remote sensing may help. Photographs taken by astronauts from the International Space Station (ISS) can be conveniently used to identify and locate the 'brightest' violations. The astronauts' RGB colour imagery also permits to monitor the changes in the spectrum of the installed lights. Space agencies should therefore start a more systematic monitoring of night lights, allowing scientists and administrators to monitor light pollution on a global scale. Cameras in orbit can not only show how magnificent our cities appear from the sky, but can also help preserve the more exciting view of the heavens and the starry night for billions of the Earth's peoples.

## Resumen

A pesar de su tradición y patrimonio astronómico secular, Italia es uno de los países con mayor contaminación lumínica del mundo. Gracias a la presión por parte de astrónomos aficionados y profesionales, desde 1997 se han implementado progresivamente regulaciones regionales en la mayor parte del territorio. Sin embargo, Italia sigue sufriendo una extrema contaminación lumínica, sobre todo en las áreas más densamente pobladas. Las mediciones del resplandor del cielo durante la última década muestran que, al menos, el muy pro-

nunciado aumento anual en el pasado se ha detenido recientemente como resultado de la reducción de emisiones de luz hacia arriba, tal como prescriben la mayoría de las regulaciones. Sin embargo, este resultado no es suficientemente bueno, y tampoco es uno que pueda durar conforme siguen aumentando las luminarias instaladas y el flujo luminoso total. Al igual que con otras formas de contaminación, el propósito es reducir significativamente las emisiones (luz directa hacia arriba y reflejada).

Además de imponer el uso de luminarias totalmente protegidas, la contaminación lumínica puede controlarse satisfactoriamente con medidas adicionales, como definir niveles inferiores de luminosidad e iluminancia en las normas estándar, protegiendo las bandas escotópicas y de supresión de melatonina, utilizando luces sólo donde y cuando sea necesario y limitando el flujo de luz per cápita, con una reducción progresiva. Si no se emprenden estas simples acciones, puede esperarse que la contaminación lumínica aumente considerablemente en un futuro cercano, sobre todo en la parte azul del espectro, debido al uso extendido de fuentes de luz LED blanca. Si se utilizan luces LED con una firma espectral apropiada, las fuentes LED tienen ventaja sobre el Sodio a Alta Presión (SAP): el flujo puede ajustarse fácilmente. Este potencial sigue estando mal aprovechado, puesto que los LED se consideran de por sí como la definitiva panacea en eficiencia energética. Sin embargo, cambiar simplemente fuentes de luz SAP por LED sin implementar también una iluminación adaptable supone un desperdicio de recursos y no reducirá la contaminación. La iluminación adaptable, controlada por sensores, permite que las luces se apaguen o se dejen muy tenues durante la mayor parte de la noche. El mercado de LED es actualmente una carrera por la eficiencia que no toma en cuenta los inconvenientes de utilizar luz rica en componente azul por la noche. Un cambio de lúmenes uno por uno de SAP a LED blancos de 4,000 K determinará un aumento en varios múltiplos de las bandas escotópicas y de supresión de melatonina. Los fabricantes de LED deberían por tanto tomar en consideración que sus productos pueden traer graves consecuencias para la salud de las personas, como ha sido el caso de las industrias del tabaco y el asbesto.

Incluso las mejores regulaciones resultan inútiles si no se respetan; por consiguiente, son necesarios controles estrictos. En Italia, la región del Véneto ha sido pionera en el control de su territorio, implicando a su agencia de protección medioambiental (Agenzia Regionale per la Protezione dell'Ambiente del Veneto, ARPAV [Agencia Regional para la Protección Medioambiental del Véneto]) y ha obtenido resultados alentadores. Controlar millones de luminarias puede parecer una tarea imposible, pero la detección remota puede ayudar. Es posible utilizar convenientemente fotografías tomadas por astronautas de la Estación Espacial Internacional (ISS, por sus siglas en inglés) para identificar y ubicar las violaciones “más radiantes”. Las imágenes en color RGB de los astronautas permiten también monitorear los cambios en el espectro de las luces instaladas. Las agencias espaciales deberían por tanto iniciar un monitoreo más sistemático de las luces nocturnas, permitiendo a científicos y administradores monitorear la contaminación lumínica a escala global. Las cámaras en órbita no sólo pueden mostrar lo espléndidas que parecen nuestras ciudades desde el cielo, sino que pueden también ayudar a preservar la vista más fascinante de los cielos y la noche estrellada para billones de personas de la Tierra.

The night sky is certainly part of Italian tradition and cultural heritage. In the motherland of Galileo Galilei, the beauty of the cosmos has been celebrated since Medieval times in a large variety of monuments and artistic renditions within churches and non-religious buildings (Figure 1). Astronomical culture is also quite popular in the country and just in the Veneto Region there are 15 public and 2 professional observatories (almost 1 observatory every 100 km<sup>2</sup>) and 26 protected astronomical sites. However, in recent times, our window to the

universe is getting blinded by the increasing amount of artificial light that causes skyglow and prevents the vision of faint stars, not just from cities but also from the suburbs and remote rural areas.

Whilst researching a suitable site for the Italian National Telescope, which was eventually built outside Italy, in La Palma, Canary Islands, Bertiau et al. (1973) elaborated the first map of light pollution ever made (Figure 2a). After more than a decade, using, for the first time,



Figure 1. Left panel: tower clock at the entrance of the Arsenale di Venezia (the historic Venetian shipyard), © Luca Zaggia. Right panel: a fresco of the Cappella degli Scrovegni in Padua, decorated by Giotto in the first years of the fourteenth century, © Wikimedia commons, Public Domain. The comet in the scene of the Magi Adoration might be a portrait of the Halley comet, presumably seen by Giotto during its great apparition in 1301 (Olson and Pasachoff, 1987).

satellite radiance data as an input to study the propagation of light pollution over large areas, Falchi (1998) produced a similar, but more detailed map of light pollution for the Italian peninsula (Figure 2b). Based on a comparison between the two situations, an increase of artificial night sky brightness of about a factor 7 was estimated.

As shown by these studies and confirmed by recent images taken by astronauts on board the International Space Station (ISS), Italy is today one of the most light polluted countries in the world. The per-capita national yearly energy demand for public lighting in 2010 ([www.terna.it](http://www.terna.it)) was more than 100 kWh and the power usage for private outdoor lighting was estimated to be of the same order of magnitude. A considerable fraction of this energy and associated

light flux is wasted by direct and indirect emissions and creates a progressive decay in the quality of our night sky. The Milky Way is now only fully visible from the continental territories in just a few sites in mountainous areas in the Alps or the Apennines. Still, even in these relatively dark places the sky quality at low angles above the horizon is heavily affected by light pollution from larger cities in the plains or coastal areas.

A projection of night sky brightness by the year 2015 made by Cinzano et al. (2001) based on the same growth rate, resulted in the prediction map of Figure 2c. If we consider data on energy usage for public lighting and average luminous efficacy, this prediction seems actually quite realistic as we can estimate a two-fold increase in the

total flux emitted in the night environment from 1998, when we first measured sky brightness (Falchi 1998) until the first decade of 2000.

On the contrary, our measurements (Figure 3) show that the zenith sky brightness in the sites we monitored is almost unchanged (Falchi, 2011 and Bertolo et al., 2015). This is primarily a consequence of the significant change in lighting habits, which was driven by the enactment of several light pollution regulations in different Italian regions.

Chronologically, the Veneto Region was the first to approve a light pollution regulation in 1997 and further improved it in 2009. In 2000, the Lombardy Region followed, adopting what was considered, at that time, a ‘revolutionary’ regulation: fully-shielded fixtures were prescribed for most of the new installations including all roads, car parks, bikeways and working areas. This law, effective on both private and public lighting, banned direct emissions above the horizontal plane through light fixtures and also put a cap on the lighting levels of streets and public areas.

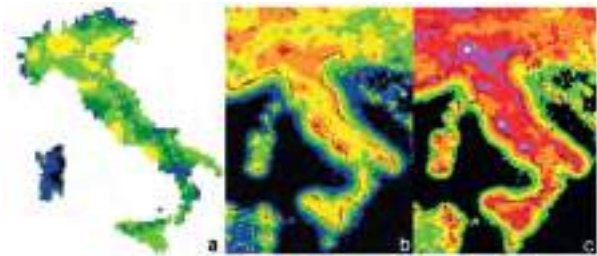
In the wake of this encouraging success, other regions adopted similar regulations, the majority of which are based on the same criteria. Since 2012, eighteen of the twenty regions, including special administrative provinces, have light pollution regulations (Figure 4).

After more than fifteen years after the introduction of the first regulation, several cities in Italy are now only lit by fully shielded fixtures as new installations or retrofits of former polluting systems. The resulting reduction in the upward direct emissions can therefore

explain the observed constant trend of artificial sky brightness in the last decades. However, if the total flux produced by our lighting systems keeps increasing, we can envisage a further jump in sky brightness in the future, once the conversion to fully shielded fixtures is completed.

This is in no way an acceptable option and, by way of comparison with other forms of pollution, we need to pursue a progressive reduction of emissions. Our societies, especially in advanced economies, make significant efforts to control pollutants. For instance, the emissions of hazardous compounds, like CO, in the atmosphere in the US have significantly decreased over the last decades thanks to regulations like the Clean Air Act ([www.epa.gov](http://www.epa.gov)). The same happened to the emissions of other pollutants in the environment like greenhouse gases, CFC's and other ozone-killers, organic (PCBs, pesticides) and inorganic contaminants (Zonta et al., 2005). Similarly, we can obtain large improvements with light emissions without massive investments, as technology is readily available at no extra cost, permitting an almost immediate payback in the form of energy savings.

What has happened in the last decade in the Region of Veneto is a great example of the potential of good practices in outdoor lighting.



Figures 2. Artificial sky brightness maps for the years 1971 (a), 1998 (b) and projection to 2025 (c). The sky brightness increases from blue to white and colour scale correspond in the three maps. © Fabio Falchi, panel (a) adapted from data in Bertiau et al. (1973).

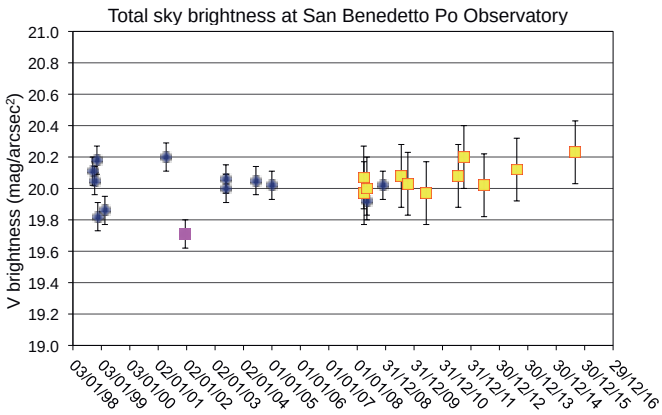


Figure 3. Sky brightness in visual band as measured by San Benedetto Po Observatory. In blue are the measurements taken with astronomical digital cameras (CCD), in yellow those taken with Sky Quality Meter (SQM, Unihedron, USA). The sky brightness increases with decreasing values of y-axis. A pristine natural sky should have a value around 22 magnitudes per squared arcsecond. The brightest measurement (in magenta) was due to snow coverage that increased the light reflected towards the sky. Updated from Falchi, (2011). © Fabio Falchi.





Figure 4. Regional dark sky regulations in Italy. © Luca Zaggia.

In this region, despite the regulations being far from fully applied, a reduction of about 16% of the energy use was recorded from 2009 to 2014 (Figure 5). This accounted for an estimated overall savings of more than EUR 13 million.

This reduction in energy usage for outdoor lighting might partially be due to the cut in national funding of municipalities after the start of the economic crisis in 2008 and may be due to the increasing cost of kWh for public lighting. However, a study made on a sample of more than 300 cities in Veneto Region (Bertolo et al., 2015) showed that, despite a 4% reduction in energy usage from 2010 to 2013, the number of luminaries per inhabitant has increased by 7%, with a corresponding 10% reduction in the power per fixture. Therefore, even if partially driven by the shortage of public funding, we can reasonably observe that something is changing in the lighting practices of local administrations, confirming that it is possible to invert the impact of outdoor lights on the environment and energy bills.

Besides economic implications (Galloway et al., 2010) and the impact on sky quality, which affect astronomical observations and

Energy use for public lights in the Veneto Region

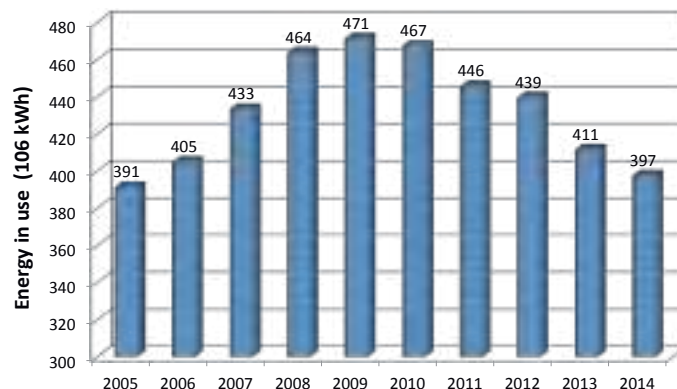


Figure 5. Energy usage for public lights in the Veneto Region from 2005 to 2014. © Luca Zaggia with data from TERNA (<http://www.terna.it/>).

eventually raise cultural issues (Marin and Jafari, 2007), artificial light also has negative consequences on human health (for instance, Haim and Portnov 2013) and on the environment (for example, Rich and Longcore, 2005). These problems have become more severe with the start of the progressive migration from yellow-rich High Pressure Sodium lamps (HPS) to blue-rich white LEDs. All being equal, a 4000 K white LED light is two or three times more polluting than HPS light sources in the blue region of the spectrum (Falchi et al., 2011; Aubé et al., 2013; Luginbuhl et al., 2014). An uncontrolled transition towards LED lighting will therefore substantially increase the flux in the more polluting part of the light spectrum, more than doubling blue light emissions in the night environment. To limit the adverse health effects of circadian rhythms disruption and decreased melatonin production by the exposure to light at night, given the dependence on wavelength of melatonin production, we recommend the adoption of strict limits to the blue component of artificial lights.

The low emissions of HPS lamps in the blue region could be chosen as a standard for the upper limit of what can be initially accepted for outdoor light. Thus, as suggested by Falchi et al., 2011, the following specification should be incorporated in lighting regulations and enforced:

*The wavelength range of the visible light spectrum under 540 nm, corresponding to high sensitivity of the melatonin suppression action spectrum, should be established as a protected range. Lamps that emit*



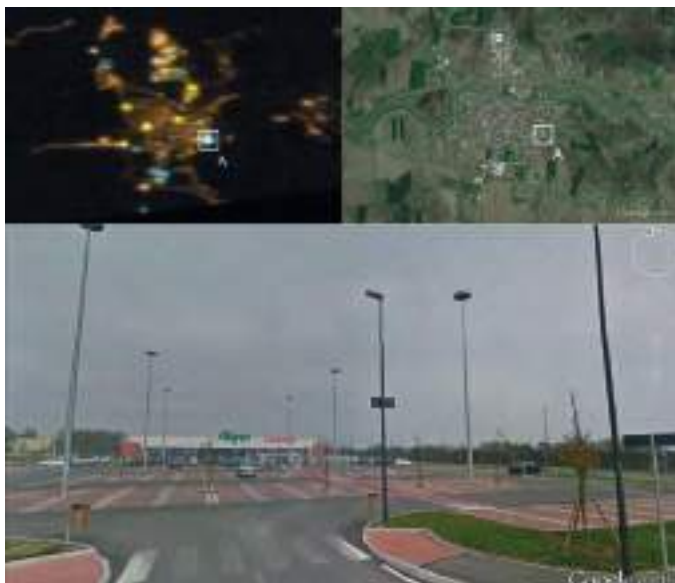


**Figure 6.** Excessive illumination in a shopping mall car park in a town in south-eastern Veneto. The area is lit by fully shielded luminaries, but with levels several times higher than required, making it appear as the brightest spot on the photograph taken by astronauts on board the International Space Station georeferenced to match geographic databases. Top left, © Image courtesy of the Earth Science and Remote Sensing Unit, ISS026-E-10976. Top right and Bottom, © Google Earth, Map Data: Google.

*an energy flux in the protected range larger than those emitted by the standard High Pressure Sodium lamp on a basis of equal photopic output should not be installed for night-time uses.*

Similar rules are already enforced in Chile (the new 2012 Norma Luminica – lighting regulation – dictates that the spectral radiance between 380 nm and 499 nm should not be more than 15% of the spectral radiance over the entire visible spectrum) and in La Palma in Canary Islands (the *Ley del Cielo* enforces Low Pressure Sodium or PC Amber LED type lights after midnight).

In Italy, the law in the Emilia-Romagna Region was recently revised imposing an upper limit of 3000 K on the Correlated Colour Temperature of the lights installed in natural protected areas, and similar recommendations would be of great help if included in other regional laws.



**Figure 7.** Terme di Caracalla, Rome. The archaeological site is illuminated with asymmetric floodlights with the direction of the main beam aimed almost vertically determining a strong skyward emission, with negative consequences on the quality of the night above the capital and its surroundings all night long. © Top, Image courtesy of the Earth Science and Remote Sensing Unit, ISS043-E-121738. Bottom, © Google Earth, Map Data: Google.

The ‘blue protection rule’ should be part of a comprehensive set of measures to be globally enforced in order to limit the consequences of light pollution, as we summarize here:

- do not allow luminaries or lighting systems with direct emissions over the horizontal plane (that is to say, upward light flux);
- do not waste the downward light flux outside the area to be lit;
- avoid over lighting;
- dim at minimum levels or switch off lights when the area is not in use;
- zero growth and then progressively decrease the total installed flux;
- strongly limit the use of short-wavelength ‘blue’ light.

Point c is quite a critical subject in Italy as in many other countries. In this context, we need to distinguish between private and road

lighting systems. In the private sector, a further distinction is made between commercial and industrial lighting. For commercial lighting in Italy, as in other countries, it is common practice to try to outshine competitors (Figure 6), while in the industrial sector much of the attention is on the amount of light rather than on its quality, based on an erroneous equivalence between light intensity and safety. This gives individuals the perception of darkness when moving from one of these over-illuminated areas to the urban road network, resulting in a continuous pressure by citizens on administrators for more light on public areas. This mechanism must be broken if we really aim for a sustainable use of light and energy.

With regards to roads, we consider it fundamental to revise the standard norms for road lighting at the national and EU level, limiting the required levels to a minimum without compromising safety, also aided by innovative technologies.

Point d is nowadays only limited by cultural issues. LEDs have in fact a great advantage over high discharge lamps: they can be easily dimmed to a fraction of their nominal output and can be switched-on instantly, making it possible to design systems based on adaptive light or light on-demand. This great potential of LEDs technology, though already available, is not yet exploited, resulting in an enormous waste of resources. Adaptive lighting, will instead allow extremely dim light levels to be maintained (compared to the usual all-night brightness of our roads) or lights to be switched-off in low traffic periods and to be instantly switched-on or increased as soon as the traffic flux demands it, making possible to reduce light pollution to a minimum for most of the night.

Point e, for example, setting caps on light flux, does not necessarily mean that our cities cannot install any new light fixture. More simply, before new installations can be made, our municipalities must reduce the flux where it is already too high, triggering positive feedback that will lead to an inversion of the current trend in the long term.

By integrating all these criteria on regulations at the regional or national levels and enforcing them in the regions currently not covered by protection measures will permit further progress in the defence of the night sky, mitigating the negative consequences so

far induced by light pollution in Italy. But on top of all these criteria, a 'rule zero' should be introduced: do we really need to illuminate everything? This issue should be analysed carefully before we keep investing public funds to light roads with the aim of increasing security and safety. Concerning crime, for example, the question is still pending an evidence-based and un-biased answer (Marchant, 2006). On the traffic side, especially outside urban perimeters, there is also contrasting evidence on the role of light on safety. One main key issue in historic centres is also monument and architectural lighting. Do we really need our historic and architectural heritage to be illuminated as if it were daytime for the whole night? Italian regional regulations have criteria for monumental lighting, which are quite effective in principle and could be used as a reference in other situations across the world. We just need to be rigorous in their enforcement, convincing authorities to limit levels or switch-off lights when the number of potential beneficiaries reduces to a minimum. One extreme, although not unique, example of deregulation in monument lighting is the archaeological site of *Terme di Caracalla* in Rome. As shown by the International Space Station images (Figure 7), this is one of the brightest spots in the Italian capital when viewed from the sky.

The archaeological site is illuminated with a large number of asymmetric floodlights placed on the ground and with the main beam aimed at the sky with a detrimental effect on the quality of the night environment and an enormous waste of energy and public money. Most of the monument lighting systems in Italy and elsewhere are quite similar to this example. This is due to an intrinsic limit of past technologies: the difficulty of illuminating historical monuments with downward-looking devices without compromising aesthetics with poles, arms and fixtures. In most cases, these limits are today overcome by the use of modern LED technology, which can in the future determine a revolution in the basic concepts of monument lighting. It still comes with one main recommendation, to only use it where and when it is really needed, ensuring the minimization of emissions outside the perimeter of targeted spots and with moderate total flux. If we think about the origins of these constructions, night-time illumination was not an option and most of them were designed and built to be illuminated from a downward looking natural light source, the Sun.

Even the best regulations on public and private outdoor lighting are worthless if they are not strictly controlled and if the effects of its enforcement are not monitored. Until recently in Italy, this task was left to the volunteers of dark sky associations, like Cielobuio. As representatives of amateur groups of astronomers and public observatories, Italian dark sky associations report to authorities on irregularities and interact with stakeholders and the general public in order to promote dark sky awareness. They participate in technical round tables and training courses for light designers and technicians and cooperate with municipalities in urban light planning. In some regulations, dark sky associations (and then the public observatories and amateur astronomers they represent) are clearly identified by law as qualified subjects in the surveillance of sky quality and reporting irregularities to local authorities. The Veneto Region regulation also defines the role of the environmental protection agency (Agenzia Regionale per la Protezione dell'Ambiente del Veneto – ARPAV) as a technical subject to refer to for light pollution issues. ARPAV is in charge of verifying violations and irregularities in private and public installations. This institution also chairs a Permanent Observatory on Light Pollution that has the role of monitoring the effects of the enforcement of the dark sky regulations and reporting to the regional government on a periodical basis. Besides ARPAV, the observatory also groups representatives of professional astronomers and engineers from the academic community, representatives of parks and dark sky associations. In addition to the main institutional tasks, the observatory also promotes initiatives (for example, dark nights, round tables) and studies light pollution. One recent piece of research has been published in the Observatory's first report. In this work, the results of a survey on a sample of more than 300 municipalities show that the small communities have the largest per capita power usage (Bertolo et al., 2015). This is an expected outcome, given the peculiarity of rural areas. However, it was also found that small rural towns have the highest power per unit luminaire (Figure 8), which is undoubtedly a sign of bad light policies. Much of the attention in the future, therefore, has to be dedicated to ensuring the professional qualifications of technical staff in small municipalities through initiatives promoted by the regional governments.

This participative management of light pollution regulations has led to the successful results described above. Dark sky associations reported

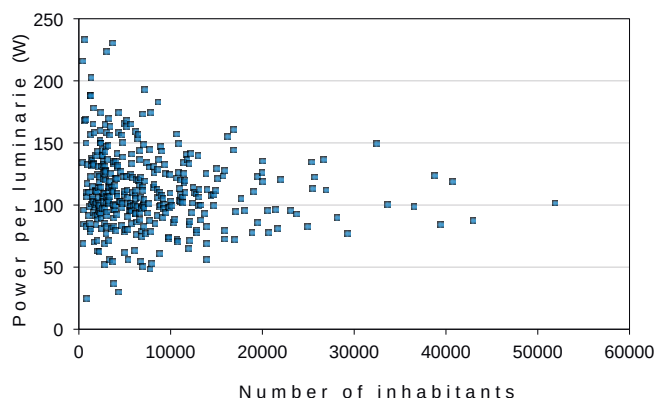


Figure 8. Distribution of the parameter power per luminaire versus number of inhabitants in the cities of the Region of Veneto. © Luca Zaggia with data from Bertolo et al. 2015.

on more than 2,500 irregularities, while ARPAV so far verified more than 3,500 installations that in most cases were amended in a short time without the need for further measures. Despite this capillary interaction between associations and institutions, the private and public installations to be controlled largely outnumber the amount of systems that can be verified in a reasonable time so other tools must be considered to support field controls. Remote sensing could significantly advance the monitoring of administrative territory. As shown in Figures 6 and 7, images taken by astronauts on board the ISS, once georeferenced have a great potential to identify the brightest violations and, in some cases, their resolution permits the identification of groups of fixtures or even single luminaires (<http://www.citiesatnight.org>). Night-time space images of our cities are also a useful tool in monitoring the transition from HPS to LEDs and its effects on the environment, as recently shown for the city of Milan by Tafreshi (2015). However, astronaut images are not taken on a systematic basis; they mainly cover larger cities or interesting subjects with different fields of view and only a minor percentage of the shots are taken from the zenith. In addition, only a few images are of the excellent quality such as those reported here. Spacecraft orbit motion, which is only partially compensated by the camera tracking system, largely affects resolution and just a minor percentage of all available data can be used for high detail studies. A more comprehensive coverage including rural areas made with a standard technique would permit a step forward in the protection of the night sky. For the management of light pollution, we would need images taken with the same technique (angle, viewfield,

exposure, spectral coverage and so on) in order to reduce the efforts for calibration (Sanchez de Miguel et al., 2012) and georeferencing. This is obviously beyond the scope of ISS missions, and a night-time earth observing programme at an adequate resolution should be funded at a regional or national level with specialized instruments. This would cover the gap between the large-scale mapping by satellites (Cinzano et al., 2001, 2007) and the extremely high-resolution, but limited spatial coverage, of airborne surveys (Kuechly et al., 2012) and would help astronomers and environmental agencies to protect astronomical sites and the night environment on a local to global scale, giving future generations a further chance to enjoy the view of the universe, at least from remote areas.

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Spain

España



# La protección del cielo en los observatorios de Canarias: valores científicos, culturales y ambientales

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## Resumen

Hace no más de unos 70 años, la gente podía mirar a las estrellas desde el patio trasero de casa. De hecho, los principales observatorios reales que se construyeron en el siglo XVIII se hicieron en el centro de las ciudades, a veces grandes, como Londres, París o Madrid. Incluso en la Ciudad de México se construyó el Observatorio Nacional, ya avanzado el siglo XIX, en una pequeña colina del Bosque de Chapultepec. Hoy, sin embargo, no es posible ver la Vía Láctea desde casi ninguna de nuestra ciudades, lo que priva a gran parte de la humanidad del espectáculo de un cielo oscuro.

Y es que el cielo oscuro debe ser patrimonio cultural de la humanidad. Nadie debería sentirse privado de contemplar el cielo a causa de la contaminación lumínica. Dicha contaminación es tan perniciosa como el ruido ambiente o el CO<sub>2</sub> y, como en estos casos, no somos sólo los humanos quienes sufrimos los efectos perniciosos del exceso de iluminación, sino que afecta también a las plantas nocturnas y a muchos animales.

Afortunadamente estamos a tiempo de corregir esta tendencia al exceso de iluminación, a la iluminación mal diseñada. A nuestro favor está que al mismo tiempo que se consigue una iluminación mejor pensada y más eficiente, se ahorra dinero, argumento que suena a música para los responsables de las ciudades, que gastan en energía un alto porcentaje del presupuesto municipal. Quizás promovido por los astrónomos profesionales, se está consiguiendo implementar legislaciones que tratan de promover el uso eficiente de la iluminación municipal.

Por su parte, la sociedad está aprendiendo que más luz no es necesariamente más seguridad. Más seguridad es una iluminación adecuada y bien diseñada. En las Islas Canarias, por ejemplo, se ha conseguido reformar la iluminación de todos los pueblos y ciudades que están en un radio de aproximadamente 100 km de los observatorios. En estos pueblos y ciudades se ha eliminado cualquier luminaria que esparciese luz hacia el cielo y han sido sustituidas por otras que dirigen la luz directamente hacia el suelo. Además, se ha cambiado a luces de bajo vapor de sodio, con lo que la contaminación que llega a los observatorios es mínima y no afecta a la espectroscopía.

La Fundación Starlight surge en este ambiente de preocupación por el correcto uso de la iluminación, pero trasciende y une tal preocupación al interés por una iluminación medida, así como a la conservación del medio biológico y natural. La Fundación Starlight se ocupa de formar expertos que a su vez llevarán el interés por los cielos oscuros, no sólo por y para la astronomía, sino también por la biología y por la mera contemplación, al mayor número de población posible. Como decía, el cielo oscuro es un bien cultural que hay que proteger.

## Abstract

No more than seventy years ago, people could gaze at the stars from their back yards. In fact, during the eighteenth century the first real observatories were built in city centres, even in large cities such as London, Paris or Madrid. Even Mexico's National Observatory,

constructed in the nineteenth century, was built in Mexico City on a small hill in Bosque de Chapultepec (Chapultepec Park). Today, however, the Milky Way cannot be seen from almost any of our cities, depriving a large part of humanity of a dark sky.

Dark skies should be considered as cultural heritage of humanity and nobody should feel deprived of the opportunity to gaze at the stars because of light pollution. This type of pollution is as harmful as ambient noise and CO<sub>2</sub> emissions. It is not only humans who suffer from the damaging effects of excess lighting, but also nocturnal plants and many animals.

Fortunately, it is not too late to correct the problem of excessive and poorly designed lighting. Luckily for us, at the same time that well-designed and efficient lighting solutions are implemented, money can be saved, and this comes as music to the ears of city authorities who spend a high percentage of municipal budgets on energy bills. Perhaps due to efforts made by professional astronomers, laws are being passed to promote the efficient use of municipal lighting.

Society itself is learning that more light is not necessarily safer and that safety is ensured with adequate and well-designed lighting. In the Canary Islands, for example, lighting has been reformed in all towns and cities within a 100 kilometre radius of an observatory, by eliminating all lighting that emits light into the sky and substituting them for designs that emit light towards the ground. Furthermore, they have opted to use sodium vapour lamps, which cause very low levels of light pollution and do not affect spectroscopy.

The Starlight Foundation was born of this environment of concern for the correct use of lighting and transforms its concern into action for the promotion of measured lighting, as well as the conservation of the biological and natural environment. The Starlight Foundation trains experts to spread interest in dark skies to as many people as possible, not only for astronomy and for its benefits, but also for biology and mere contemplation. Dark skies are a cultural resource that must be protected.

## Introducción

Imaginemos a Galileo terminando su telescopio... Con ilusión, con la idea de mirar al cielo. Sin embargo Galileo no se preocupó de pensar dónde ponía el telescopio. Sencillamente se subió a la azotea de su casa y apuntó al Sol que ya se ponía, a la Luna que estaba en otra zona del cielo, y en días sucesivos a Júpiter, a Venus, etc... Sus descubrimientos fueron fundamentales para el avance de la ciencia moderna. Galileo observó las manchas del Sol, observó fases en Venus, cráteres en la Luna y los satélites, que hoy llamamos galileanos, de Júpiter. La ciencia moderna estaba apuntando. El cielo no tenía atributos divinos como se creía, un gran cambio que causó numerosos problemas a Galileo. Pero el principal problema con que se hubiera encontrado hoy día, Galileo no lo tuvo. Me refiero al tener que irse a un lugar alejado de la ciudad para poder ver lo que vio con su primer telescopio. Yo me pregunto si Galileo hubiera construido su telescopio si, previamente, no hubiera quedado fascinado por la visión del cielo, en sus tardes/noches florentinas.

Asimov, en su relato “Anochecer”, menciona una civilización alumbrada por seis soles. Una civilización que no conocía la noche porque siempre había varios soles en el cielo desparramando luz. Esta civilización no conocía la noche, y con la noche desconocía también la existencia de un vasto universo, lleno de estrellas y galaxias. En el relato de Asimov, un extraño acontecimiento cósmico oculta subrepticamente los seis soles y la noche cae sobre esta civilización. Sólo entonces se dan cuenta de la grandeza del universo, del espectáculo de la noche plagada de estrellas.

Imaginemos el caso contrario al relato de Asimov. Imaginemos que nuestro querido planeta pierde la noche. No por cualquier acontecimiento cósmico, sino porque nosotros mismos la matamos, iluminando el cielo. De repente perderemos el universo, nuestro mundo se hará más pequeño porque no podemos ver qué hay más allá, no podremos especular con la grandeza del universo, no podríamos elucubrar sobre otros planetas, otra vida, otros mundos...

Los cielos oscuros son una necesidad para todos nosotros. También para nuestro entorno, tanto animal como vegetal. No se concibe la humanidad sin noches oscuras que inviten al sobrecogimiento de admirar el universo.

### El cielo oscuro necesario para la astronomía

La astronomía ha sido la ciencia que ayudó a los marinos a viajar por todo lo largo y ancho de este mundo. Desde el siglo XVII, se han venido perfeccionando las *cartas del cielo*, que eran efemérides elaboradas para su uso en la navegación. Estas cartas del cielo se hicieron a lo largo de los siglos XVII a XIX, en observatorios que estaban, en general, en los centros de las mayores ciudades europeas. Recuérdese el caso de los Observatorios de Greenwich, en Londres; del Observatoire de Paris; del Observatorio Nacional español, en el madrileño Parque del Retiro, o del Observatorio Nacional de México, instalado primeramente en pleno Bosque de Chapultepec. Gran parte del estudio de las estrellas y nebulosas realizado entre los siglos XVIII y XIX se lleva a cabo en estos observatorios. La iluminación de las ciudades era entonces a base de quemar combustibles tipo aceites (de ballena u otros aceites) o más adelante gas. En todo caso hasta casi finales del siglo XIX, el uso de iluminación era muy escaso, con lámparas que equivalían en el mejor de los casos a una bombilla moderna de 2.5 vatios. Esto explica que la observación astronómica pudiese hacerse sin grandes problemas desde el mismo centro de las ciudades.

A partir de la invención de la electricidad comercial, en el siglo XX se inició un proceso imparable de iluminar cada vez más las ciudades. Iluminar era signo de modernidad, y seguridad. A mitad del siglo XX la implantación de lámparas en las ciudades es una prioridad. A finales de siglo la iluminación es ya omnipresente, inutilizando los antiguos observatorios para la observación.

Así, la observación astronómica profesional, que antes se podía hacer desde las ciudades, hoy se hace normalmente desde sitios remotos, altas montañas o enclaves singulares. Además, estos enclaves se ven en muchas ocasiones amenazados por el exceso de iluminación de ciudades más o menos cercanas. Hasta el punto de que algunos observatorios profesionales pueden verse amenazados en corto tiempo si no se toman medidas.



Figura 1. Casa de Galileo en la colina de Arcetri, cerca de Florencia. © Cyberuly, CC BY-SA 3.0.

En La Palma, en el archipiélago de Canarias, España, este aspecto se tomó en serio desde el principio. Siempre se contó con el apoyo de las autoridades y gran parte de la población, como demuestra la colaboración de las autoridades de los municipios de La Palma, que con ocasión del Aniversario del Observatorio, apagaron todas las luces de los pueblos y ciudades durante una hora. Esto ocurrió el 25 de junio de 1995. Y durante esa hora se hicieron espectros del cielo antes, durante y después del apagón. En esa época todavía había luces de mercurio y de sodio de alta presión. Se pudo observar como la contaminación debida a líneas de mercurio desaparecía durante el apagón (Benn & Ellison, 1996), y la debida al sodio decrecía, quedando un resto debido al resplandor natural por la excitación de átomos de sodio por partículas de alta energía en las altas capas de la atmósfera.

Este apoyo popular, así como de la autoridades, permitió elaborar una Ley del Cielo que fue aprobada y entró en vigor en 1988. Su reglamento se creó en 1992, el mismo año que la Oficina Técnica en el Instituto de Astrofísica de Canarias (IAC). Esta ley obliga a utilizar un cierto tipo de luminarias en toda la Isla de La Palma, y en la parte de la Isla de Tenerife que puede verse desde La Palma. Aunque inicialmente hubo alguna oposición al tipo de iluminación que se propuso, ahora, después de muchos años de aplicación de la Ley del Cielo, existe consenso acerca de la bondad de dicha



ley. Muchos municipios están ahorrando dinero con la nueva iluminación.

En dicho reglamento se especifican los tipos de luminarias que pueden ser utilizadas. Con ellas se ha conseguido reducir la polución lumínica en los observatorios, y al mismo tiempo se ha conseguido una iluminación más racional y segura de las ciudades de La Palma.

### Cielos oscuros por el medioambiente

La oscuridad de la noche es necesaria para el desarrollo del mundo animal y vegetal. Son muchas las especies, sobre el 50% según algunas estimaciones, tanto animales como vegetales, que desarrollan gran parte de su actividad en la noche. Hay plantas que florecen de noche, que son polinizadas por insectos que viven de noche. Grandes poblaciones de pájaros viajan de noche en su



Figura 2. Londres y el Observatorio de Greenwich en primer plano. © Wikimedia Commons, CC BY-SA 3.0.



Figura 3. Observatoire de Paris-Meudon en Boulevard Aragó. © Victor R. Ruiz, Flickr, CC BY-SA 2.0.



migración estacional. Algunas tortugas marinas salen a la arena a desovar en la noche. Todos estos ejemplos ven perturbadas sus actividades nocturnas cuando esa noche se ilumina. La iluminación indiscriminada de la noche altera las relaciones entre predador-presa. Incluso el zooplancton se ve afectado en su migración vertical. El zooplancton baja a los fondos durante el día y sube durante la noche a la superficie donde hay más alimentos. Si se iluminan las costas o los lagos, este zooplancton deja de subir a alimentarse, por lo que descende su población. Esto redundaría en la cadena alimenticia que se ve perjudicada por la escasez de este componente primario de la cadena.

### Cielos oscuros por su mero disfrute

El disfrute de la noche ha sido un espectáculo para generaciones y generaciones de humanos. La mera contemplación del cielo es un valor puesto de manifiesto por poetas, músicos, artistas, filósofos, así como por la población general. ¿Hubiera, por ejemplo, Van Gogh imaginado sus cuadros repletos de espectaculares estrellas si apenas hubiese contemplado noches estrelladas en sus paseos nocturnos? Pintar esas estrellas requiere haberlas visto muchas veces, haberse emocionado con ellas y tenerlas en el subconsciente. ¿Hubiera cantado Debussy a la Luna, como lo hizo en su “Claro de Luna”, con semejante delicadeza, si no hubiera paseado a la luz del astro infinidad de veces? Ejemplos hay montones. La noche está presente en el arte, esa noche oscura, a veces embrujada, a veces misteriosa, a veces transfigurada como en Arnold Schönberg. ¿Perderán nuestros artistas la capacidad de inspirarse en las noches oscuras? ¿Perderemos todos la capacidad de admirar ese cielo oscuro llenos de luceros?

### La Fundación Starlight

La Fundación Starlight fue promovida por la Organización de las Naciones Unidas para la Educación, la Ciencia y la Cultura (UNESCO) y el IAC. Su misión es proteger los cielos oscuros para el disfrute de la humanidad y el bienestar de los animales y las plantas. La Fundación trata de llevar la cultura de la astronomía a la población. Al mismo tiempo se ocupa de que se usen luminarias adecuadas, y de que se promueva una iluminación inteligente, que a su vez resulta en un ahorro energético.



Figura 4. Espectros del cielo antes, durante y después del apogón tenido en La Palma, el 25 de junio de 1995. Nótese la desaparición de las líneas de mercurio, y parcialmente la de sodio NaD 5890/6. Gráfico de Benn & Ellison (1996). © Chris R. Benn.



Figura 5. Logotipo de la Fundación Starlight. © Fundación Starlight.

La Fundación tiene asimismo un carácter formativo, de embajadores de la Fundación. Estos embajadores son formados en la promoción de la astronomía, y en la necesidad de mantener los cielos oscuros. La Fundación fue un actor importante en promover la Declaración de los Cielos Oscuros.

La misión de la Fundación Starlight puede resumirse como sigue: valorizar, proteger y promover el patrimonio cultural, tangible e intangible, asociado a la visión del cielo nocturno. Un patrimonio en peligro y a menudo poco conocido o valorado.

### Conclusiones

Los cielos oscuros pertenecen a la Humanidad. El avance tecnológico ha permitido entre otras cosas iluminar las ciudades y pueblos. Pero no sólo las ciudades y pueblos. ¡Últimamente se está iluminando la noche! Esta excesiva iluminación tiene graves efectos para la vida animal y vegetal. Así mismo sus efectos para la población son quizás poco conocidos, pero no por ello menos graves. Quizás en este escrito sólo hemos mencionado los efectos perjudiciales para el mundo cultural y artístico. Sus efectos para la salud de las personas no se han descrito, pero son igualmente perniciosos.



**Figura 6.** Imágenes del Puerto de la Cruz, en Tenerife, donde se ha aplicado el reglamento para iluminación de las zonas visibles desde el Observatorio. La imagen de arriba es de antes del cambio de luminarias. La de abajo muestra la reducción conseguida. © OTPC/IAC.

Afortunadamente, todavía estamos a tiempo de mejorar la situación de al menos zonas especialmente delicadas. Éstas deben ser especialmente protegidas por su importancia para la preservación de la riqueza natural de la flora y fauna. Asimismo, merecen protección las zonas dedicadas a la observación astronómica. Y todas aquellas zonas que por su especial significado, y por haber quedado hasta ahora libres de ese afán de iluminación, deben protegerse porque son refugios para la vida animal, vegetal, y para la contemplación humana de la belleza del Universo.

### Referencias

Benn, C. R. & S. L. Ellison. 1996. *La Palma night-sky brightness*. ING, nota técnica 115.





Chapter 5

# The Protection of Dark Skies: Global Approaches and the Role of Interinstitutional Collaboration

Capítulo 5

# La protección de los cielos oscuros:

aproximaciones globales y el papel  
de la colaboración interinstitucional



# Identifying, Safeguarding and Promoting Cultural Properties Related to Astronomy. The UNESCO & UAI Thematic Initiative 'Astronomy and World Heritage'

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## **Abstract**

For over ten years now, the IAU, UNESCO and its related Advisory Bodies (ICOMOS or IUCN) have worked together in cooperation in the area of the heritage of astronomy and related fields. During this period, there have been a number of ongoing and important initiatives, memoranda, workshops and publications. This paper aims to provide a quick overview of the topic and aims to highlight the most important milestones of the numerous activities and programmes, especially with regards to the World Heritage Convention. Astronomical heritage could be considered a new matter directly related to the Global Strategy launched by the World Heritage Committee in 1994 for a 'representative, balanced and credible World Heritage List'. One of the main objectives of this strategy is 'to ensure that the List reflects the world's cultural and natural diversity of Outstanding Universal Value' and to promote new forms of heritage that have not properly been recognized to date, such as science heritage.

The many activities that this initiative produces, especially those between the IAU and ICOMOS, intend to identify possibilities and to define an appropriate methodology for credible and significant nominations to the World Heritage List in this area of study. This paper also aims to lay out the main origins of these joint works and to view the present situation, in particular reference to the World Heritage Convention and the listing of realistic nominations. It therefore aims to identify the most promising subjects in this regard, to give technical advice and to also pinpoint epistemological difficulties in the heritage of astronomy in order to avoid possible disappointments in the context of World Heritage evaluations. To give an example, the strategy specifically focuses on the very popular concepts within the astronomical community, such as 'dark skies' and 'windows to the universe'.

## **Resumen**

Durante ya más de 10 años, la Universidad Abierta Interamericana (UAI), la Organización de las Naciones Unidas para la Educación, la Ciencia y la Cultura (UNESCO) y sus Órganos Asesores (Consejo Internacional de Monumentos y Sitios, ICOMOS, o la Unión Internacional para la Conservación de la Naturaleza, UICN) han trabajado conjuntamente, colaborando en el área del patrimonio de la astronomía y ámbitos relacionados. Durante este periodo, ha habido varias iniciativas, memorandos, talleres y publicaciones regulares e importantes. Este artículo pretende proporcionar una rápida visión general del tema y pretende subrayar los hitos más importantes de las numerosas actividades y programas, sobre todo con respecto a la Convención del Patrimonio Mundial. El patrimonio astronómico podría considerarse una nueva materia directamente relacionada con la Estrategia Global, emprendida por el Comité del Patrimonio Mundial en 1994 para una "Lista del Patrimonio Mundial representativa, equilibrada y creíble". Uno de los principales objetivos de esta estrategia es "garantizar que la

Lista refleje la diversidad cultural y natural de Valor Universal Excepcional del mundo” y promover nuevas formas de patrimonio que no hayan sido debidamente reconocidas hasta la fecha, como el patrimonio científico.

Las muchas actividades que esta iniciativa genera, sobre todo aquellas entre la UAI y el ICOMOS, están destinadas a identificar las posibilidades y definir una metodología adecuada para nominaciones creíbles y significativas a la Lista del Patrimonio Mundial en esta área de estudio. Este artículo pretende también exponer los principales puntos de partida de estas labores conjuntas y considerar la situación actual, haciendo particular referencia a la Convención del Patrimonio Mundial y a la inclusión de nominaciones realistas. Pretende, por tanto, identificar los más prometedores temas en este sentido, brindar asesoría técnica y señalar también las dificultades epistemológicas en el patrimonio de la astronomía con el fin de evitar posibles decepciones en el contexto de las evaluaciones sobre el Patrimonio Mundial. Para dar un ejemplo, la estrategia se centra específicamente en conceptos muy populares dentro de la comunidad astronómica, como “cielos oscuros” y “ventanas al universo.”

### More than Ten Years of Astronomical Heritage Activities

The first significant event for the promotion of astronomical heritage on an international level occurred in March 2004 in Venice, Italy, with the first international experts meeting on scientific and astronomical heritage organized by the World Heritage Centre in collaboration with the UNESCO Venice Office and with the support of the Government of the United Kingdom (17 to 19 March 2004). It drew an initial picture of the very poor recognition of scientific heritage by UNESCO, even if Science is one of the International Organization’s five programme sectors. The meeting brought to light the fact that countries didn’t know how to identify and to evaluate the importance of such places of heritage.

In 2005, the World Heritage Committee at its 29th session (Decision 29 COM 5B, Durban, South Africa) requested the Director of the World Heritage Centre to further explore the Thematic Initiative ‘Astronomy and World Heritage’ as a means to promote, in particular, nominations which recognize and celebrate achievements in science.<sup>1</sup>

Its essential aim was ‘to establish a link between Science and Culture towards recognition of the monuments and sites connected with astronomical observations dispersed throughout all the geographical regions, not only scientific but also the testimonies of traditional community knowledge’. This very important objective opened the way to an approach that was broader than that of Modern Astronomy, making it more inclusive and allowing the involvement

of indigenous cultures and popular beliefs related to sky and archaeoastronomy. Archaeoastronomical sites therefore appeared as a specialized branch of archaeology, analysed from a scientific point of view, based on both astronomical and archaeological evidence. As mentioned above, the Initiative and the first results of the Venice meeting were taken into account by the World Heritage Committee in 2005. The Committee approved the development of the Initiative as a pilot project and a Memorandum of Understanding formalized the cooperation between UNESCO and the IAU in 2008.

At the same time, volunteers, supported by astronomers, developed an important North American NGO initiative<sup>2</sup> to ‘protect locations of exceptional night-time visages for future generations’ and to promote the ‘Dark Sky Places Programme’. The main aim was to preserve and protect the genuine night sky quality from light pollution coming from modern urbanism, industry, transportation networks and so on. The initiative focused on the global trend of more respectful relationships between humankind and its natural environment, and being able to preserve good conditions for professional astronomical observations that were under pressure by aggressive modern lightning. In 2007, the Mont Mégantic Observatory in Quebec, Canada, was the first site to be recognized as an International Dark Sky Reserve, followed rapidly by others in the USA, Canada and more slowly in other parts of the world. Today, there are around 60 Dark Sky Reserves or parks recognized by the organization that have the precise criteria to control light pollution in more or less large regulated buffer zones. The harmonization and the promotion of common rules are at the core of the meeting *The Right to Dark Skies*.

1. <http://whc.unesco.org/en/astronomy/>

2. The IDA International Dark-Sky Association, <http://darksky.org/>

These two main branches of initiatives converged for a first apogee with the International Year of Astronomy in 2009, promoted jointly by UNESCO and the IAU, with numerous important events around the world to celebrate it, both for the outreach of the scientific knowledge of astronomy and for the recognition of its heritage and cultural value. A consequence was the beginning of cooperation between the IAU and ICOMOS in order to prepare a Thematic Study on the Heritage of Astronomy from the perspective of the World Heritage Convention. The official ICOMOS Thematic Study could be considered as a World Heritage Convention document to help the States Parties prepare nominations. There were also some regional initiatives, such as the important meeting on Modern Astronomical Observatories organized in Hamburg by the Observatory (Gudrun Wolfschmidt) and ICOMOS-Germany (Michael Petzel) (Wolfschmidt, 2009). It was the world's first attempt to put forward a kind of inventory for observatories from the seventeenth to the twentieth centuries, or promoted by Western Science.

In parallel, the IAU Commission for the History and the Heritage of Astronomy (whose current President is Clive Ruggles) and ICOMOS, as an Advisory Body to the UNESCO World Heritage Committee (under Michel Cotte) launched an extensive programme to gather a representative set of authors from all around the world. As stated by the introduction to the Thematic Study:

*The central aim of this study is to extend these efforts by presenting a global survey of astronomical heritage from the standpoint of the identification and evaluation of heritage sites relating to astronomy and archaeoastronomy that might have the potential to demonstrate Outstanding Universal Value (OUV)—the term of recognition for the value properties need to manifest in order to be inscribed on the World Heritage List. (Ruggles and Cotte, 2010)*

Framed by two notable introduction and conclusion chapters, the Thematic Study contains a global, regional and/or thematic overview and some representative case studies designed in line with the World Heritage methodology. The chronological and geographical part of the overview must be highlighted, as well as the balance between great epochs and world regions. The topics covered by the authors are:

- Earlier Prehistory
- Pre-Columbian and Indigenous America
- Later Prehistoric Europe
- Later Prehistoric and Indigenous Africa, Asia (not covered elsewhere), Australasia and Oceania
- Ancient and the Medieval Far East
- India
- Mesopotamia and the Middle East
- Ancient Egypt
- The Classical World (Ancient Greece; the Hellenistic Period; Rome)
- Arab and Islamic Astronomy
- Medieval Astronomy in Europe
- Astronomy from the Renaissance to the Mid-Twentieth Century
- Contemporary Astronomy and Astrophysics (since the mid-twentieth century)
- Space Astronomy (including launch sites)
- 'Windows to the Universe' (Dark Sky sites)

The global framework for more in-depth local studies and methodological recommendations was addressed by the baseline study. The Thematic Study was presented to the 34th Session of the World Heritage Committee, held in Brasília, Brazil, from 25 July to 3 August 2010. Important examples gave a good idea about what could potentially be future World Heritage nominations. The editors of the Thematic Study claim that this was not at all the objective of the collective work, but the goal was more of a first systematic survey of the Heritage of Astronomy and Archaeoastronomy, and an attempt to define the identification and description of this kind of heritage.

Following the joint Thematic Study, in 2012 the IAU Commission in charge of Astronomical Heritage launched the Heritage of Astronomy web portal.<sup>3</sup> The initial idea was to call for Extended Case Studies, following a process inspired by the World Heritage Convention, especially that of the Tentative Lists. They also envisaged that a selection of the Extended Case Studies could support a second volume of the Thematic Study, to complete the first one and to be closer to making definitive nominations. During the same year, the World Heritage Committee at its 37<sup>th</sup> Session (held in Phnom Penh, Cambodia, from 17 to 27 June 2013)

3. <http://www2.astronomicalheritage.net/>



asked for a Global Thematic Study on the Heritage of Science and Technology, including Space Technologies.

Over the last few years, the already existing activities and initiatives have developed and have grown. In 2013, a new Memorandum of Understanding was signed by the IAU and UNESCO, which updated the initial one. The main goals concerned ‘launching projects and actions in line with the Global Strategy for a representative and balanced World Heritage List’ and to ‘contribute to the enhancement of a link between Science and Culture’.<sup>4</sup>

In August 2014, for the first time, the 40th Scientific Assembly of the Committee on Space Research (COSPAR) held in Moscow echoed the World Heritage Committee by paying specific attention to technological space heritage. During the 39th Session of the World Heritage Committee (held in Bonn, Germany, from 28 June to 8 July 2015), a joint side event on the Heritage of Astronomy and archaeoastronomy was organized by the World Heritage Centre (run by Anna Sidorenko), with the involvement of the IAU Commission and ICOMOS. Finally, the IAU XXIX General Assembly held in Honolulu, Hawaii, from 3 to 14 August 2015 set forth the organization of an independent IAU Commission for the Heritage of Astronomy with a set of Working Groups.

## Today's Results Related to World Heritage List

### The Scientific Community's Intense Activities

Recent years of cooperation and joint work carried out in multidisciplinary teams have resulted in noteworthy activity in terms of international conferences, workshops and the organization of meetings. We can point out some of the most important of these, with the aim of bringing together different types of heritage and the World Heritage Convention. The below activities stem from different initiatives and organizers:

- Hamburg (Germany), for the Heritage of Modern Western Astronomy and its Inventory;
- Kazan (Russian Federation), for a Broader View of Modern Heritage and an Introduction of Technological Space Heritage;
- Tekapo Lake (New Zealand), Concerning Dark Sky Reserves

Related to Culture and Nature, and the Concept of the ‘Window to the Universe’;

- Cairo (Egypt), for General Issues Related to the Heritage of Astronomy and for the Importance of Archaeoastronomical Heritage;
- The COSPAR General Assembly (Russian Federation), for the In-Depth Study of Heritage of Space Conquest;
- Cozumel (Mexico), for exploring the matter of archaeoastronomy in context, especially in the Maya World;
- The IAU General Assembly Focus Meeting, (Hawaii, USA, 2015), for general questions on astronomical and archaeoastronomical heritage and their relationship with the World Heritage Convention;
- and so forth.

### But What Really Happened on the World Heritage List During this Period?

As already stated, astronomical heritage is welcomed by the *Global Strategy for a Representative, Balanced and Credible World Heritage List* initiated by the World Heritage Committee.

The first question concerns sites inscribed onto the World Heritage List that express Outstanding Universal Value (OUV) mainly related to astronomy and/or closely related fields. Indeed we can see two or three sites related to astronomy on the World Heritage List, and not more! The second question is about the degree of correlation with the Initiative and the ICOMOS/IAU joint Thematic Study.

*Struve Geodetic Arc* is a serial nomination made by ten European countries: Belarus, Estonia, Finland, Latvia, Lithuania, Norway, the Republic of Moldova, the Russian Federation, Sweden and the Ukraine. It was inscribed onto the World Heritage List in 2005, under criteria (ii), (iii) and (vi). The elaboration of the nomination dossier took place at the end of 1990s and at the beginning of 2000s, which means before the general movement in favour of the Heritage of Astronomy Initiative. It could be seen as a pioneering proposal with an international serial approach that consequently went on to form one of the roots of the Initiative. On the other hand, it was a nomination that was clearly related to the end of the Cold War (the collapse of the Berlin Wall in 1989), with diplomatic aims

4. UNESCO & IAU Memorandum of Understanding, 2013

to promote joint cooperation between the Central, Northern and Eastern European countries that were divided by the two sides of the Iron Curtain. In other words, it was a very political nomination and decision by the World Heritage Committee, and not really a rational starting point for the promotion of Astronomical Heritage.

Furthermore, some scientific observations could be made about the Struve Geodetic Arc nomination. Firstly, it was not directly a Heritage of Astronomy nomination. If we wish to be strict about the term, it

is in fact a measurement of the Earth's dimension and size and not an observation of the sky. However, we can point out that astronomers have exclusively done this type of measurement throughout all epochs, in relation to the definition of the meridian and the passage of time. Friedrich Georg Wilhelm Struve himself was a famous astronomer and Director of the Pulkovo Observatory. Secondly, the Struve Arc measurement occurred at the end of a scientific movement lasting around two centuries for the exact measurement of the Earth. The movement started in France and England during the seventeenth century. The triangulation method was first implemented by Jean Picard and used for measuring and establishing the *Méridien de Paris* as early as the 1670s. The Picard method was used throughout the eighteenth and nineteenth centuries to determine different meridian lines all over the world, and to establish the exact shape and size of the Earth. Indeed, Struve Arc was the last great Earth measurement made by the Picard method of triangulation, in the middle of the nineteenth century (Cotte, 2010).

*The Jantar Mantar of Jaipur* from India was inscribed in 2010, under criteria (iii) and (iv). Its short description states:

*The Jantar Mantar, in Jaipur, is an astronomical observation site built in the early 18th century. It includes a set of some 20 main fixed instruments. They are monumental examples in masonry of known instruments but which in many cases have specific characteristics of their own. Designed for the observation of astronomical positions with the naked eye, they embody several architectural and instrumental innovations. This is the most significant, most comprehensive, and the best preserved of India's historic observatories. It is an expression of the astronomical skills and cosmological concepts of the court of a scholarly prince at the end of the Mughal period.<sup>5</sup>*

It is certainly an exceptional place for the late achievement of the naked eye observation of the sky, resulting from the very old Ptolemaic tradition throughout the lengthy Islamic astronomical period as shown by the heritage of Maragheh Observatory (Iran, thirteenth century) or by the Ulugh Beg's Observatory (Uzbekistan, fifteenth century) (Heidarzadeh, 2010). That Ulugh Beg's nomination likely resulted from news and events that came from the Initiative in different forms, but it was not directly related



Figure 1. Struve Geodetic Arc. © UNESCO, licensed under CC BY-SA 3.0 IGO.

5. <http://whc.unesco.org/en/list/1338/>

to it. Its presentation in the aforementioned Thematic Study resulted from the nomination dossier submitted by the State Party for evaluation, and not in the reverse sense.

Another nomination that was probably more directly influenced by the Initiative was the proposal by Macedonia for a possible archaeoastronomical site at Kokino. The nomination was evaluated in preparation for the 36th Session of the Committee, held in Saint Petersburg, Russian Federation, from 25 June to 5 July 2012. However, the ICOMOS evaluation advised to not inscribe the site as archaeoastronomical, and as a result, the State Party withdrew the nomination before any decision was made by the World Heritage Committee.

These are, in fact, very few examples, but we have to also take into account other World Heritage sites that have diversified attributes and broader OUV that encompass more than astronomy or have it as a central pillar of the nomination.

### Archaeoastronomical Heritage among Sites with Broader Cultural Meanings

There are numerous examples of archaeoastronomical heritage among sites with broader cultural meanings. We have to mention the three main areas where a site's archaeoastronomical value is important within the site's larger.

The first and the oldest of these areas is clearly the Ancient Egypt of the Pharaoh Dynasties with *Nubian Monuments from Abu Simbel to Philae*, inscribed on the World Heritage List in 1979, under criteria (i), (iii) and (vi), *Ancient Thebes with its Necropolis*, inscribed onto the World Heritage List in 1979, under (i), (iii) and (vi) and *Memphis and its Necropolis – the Pyramid Fields from Giza to Dahshur*, inscribed onto the World Heritage List in 1979, under criteria (i), (iii) and (vi). However, apart the first site, the sites' statements of OUV don't mention their important astronomical significance by means of tangible proof from urbanism and architecture and nor do they mention their intangible meaning of social and spiritual values (Cotte, 2016)!

We must also note the very important role of astronomical observation within pre-Columbian heritage in Mesoamerica, with numerous

sites bearing tangible attributes related to archaeoastronomy: *Tikal National Park*, Guatemala, inscribed in 1979, under criteria (i), (iii), (iv), (ix) and (x); the *Maya Site of Copan*, Honduras, inscribed in 1980, under criteria (iv) and (vi); the *Archaeological Park and Ruins of Quirigua*, Guatemala, inscribed in 1981, under criteria (i), (ii) and (iv); the *Historic Centre of Oaxaca and Archaeological Site of Monte Albán*, Mexico, inscribed in 1987, under (i), (ii), (iii) and (iv), the *Pre-Hispanic City and National Park of Palenque*, Mexico, inscribed in 1987, under criteria (i), (ii), (iii) and (iv); the *Pre-Hispanic City of Teotihuacan*, Mexico, inscribed in 1987, under criteria (i), (ii), (iii), (iv) and (vi), *Pre-Hispanic City of Chichen-Itza*, Mexico, inscribed in 1988, under criteria (i), (ii) and (iii); *El Tajín, Pre-Hispanic City*, Mexico, inscribed in 1992, under criteria (iii) and (iv); and the *Pre-Hispanic Town of Uxmal*, Mexico, inscribed in 1996, under criteria (i), (ii) and (iii). A number of these sites were inscribed during the first period of the Convention, but their descriptions generally refer to the astronomical attributes along with others such as architectural, historical and social attributes (Cotte, 2016).

The last main case is the example of megaliths in Western Europe, with the emblematic Stonehenge, Avebury and Associated Sites, England, UK, inscribed in 1986, under criteria (i), (ii) and (iii). It very clearly illustrates the problem for the recognition of archaeoastronomical value in the short front-page description of the site: 'The two sanctuaries consist of circles of menhirs arranged in a pattern whose astronomical significance is still being explored'. Indeed important progress was made in this way, and the OUV could be improved for a future statement. Other megalith sites could also bear astronomical significance such as the Heart of Neolithic Orkney, Scotland, UK, inscribed in 1999, under criteria (i), (ii), (iii) and (iv) or the Brú na Bóinne – Archaeological Ensemble of the Bend of the Boyne, Ireland, inscribed in 1993, under criteria (i), (iii) and (iv). Some others sites are on the national Tentative Lists of Portugal, Spain and France.

### Historical Periods and the Heritage of Astronomy as Associated Value

We have some symbolic examples for more recent times, such as the Ulugh-Beg's Observatory in central Asia. It is an attribute of the *Samarkand – Crossroad of Cultures* World Heritage site, in

Uzbekistan, inscribed in 2001, under criteria (i), (ii) and (iv). The short description of the site on the World Heritage webpage clearly shows the strong interweaving of astronomical meaning with other architectural and cultural values:

*The historic town of Samarkand is a crossroad and melting pot of the world's cultures. Founded in the 7th century B.C. as ancient Afrasiab, Samarkand had its most significant development in the Timurid period from the 14th to the 15th centuries. The major monuments include the Registan Mosque and madrasas, Bibi-Khanum Mosque,*

*the Shakh-Zinda compound and the Gur-Emir ensemble, as well as Ulugh-Beg's Observatory.*<sup>6</sup>

Nevertheless, the Ulugh-Beg's Observatory is not at all mentioned within the three criteria it is inscribed under, that express Samarkand's OUV.

The Historic Monuments of Dengfeng in "The Centre of Heaven and Earth", China, was inscribed onto the World Heritage List 2010, under criteria (iii) and (vi). Its OUV very clearly expresses



Figure 2. Stonehenge. © UNESCO licensed under CC BY-SA 3.0 IGO.

6. <http://whc.unesco.org/en/list/603/>



astronomical value as a framework for broader meaning. The link of astronomical features with human beliefs and socio-political organization is pivotal. It is probably the first nomination to be inscribed in the spirit of the Initiative and Thematic Study (Xu, 2010). Criterion (iii) for which it is inscribed is very significant:

*The astronomical idea of the centre of heaven and earth is strongly linked with the idea of imperial power, with the propitiousness of establishing capitals at the centre of heaven and earth, and with its natural attribute, Mount Songshan and the ceremonies and ritual associated with it. The serial property reflects the significance of the area in terms of prestige and patronage.<sup>7</sup>*

Finally, concerning Modern astronomy in Europe, we can mention some observatories among heritage sites that have broader cultural meaning. An example of this is Maritime Greenwich, England, UK, inscribed in 1997 under criteria (i), (ii), (iv) and (vi). This ensemble of buildings at Greenwich was devoted to sciences linked with the seas, with a peculiar urbanism related to its functions, and among the buildings lies the Old Royal Observatory, one of the first classical European observatories. Another example is the Pulkovo Observatory listed among a very impressive set of constructions and architectural value of the very large inscription, the Historic Centre of Saint Petersburg and Related Groups of Monuments, Russian Federation,



Figure 3. Maritime Greenwich. © Steve F-E-Cameron, licenced under CC BY-SA 3.0.

7. Ibid.

inscribed in 1990 under criteria (i), (ii), (iv) and (vi). In this World Heritage site, the observatory is recognized more for its architectural value and global historical significance in context of the Russian capital in the nineteenth century than for its scientific meaning.

Here we reach a point where epistemological difficulties arise and make it difficult to apply the World Heritage Convention to the heritage of astronomy and archaeoastronomy. The very limited number of credible nominations provided as a result of this Initiative is perhaps a sign of these issues.

### Epistemological Difficulties Related to Astronomical Heritage

#### A Very Specific Field of Heritage or Not?

What were the main theoretical issues resulting from the numerous aforementioned meetings and workshops and from the cooperation between the IAU and ICOMOS?

Firstly, we can point out the main conceptual questions raised over the last few years. For instance, what does the term ‘astronomy’ mean in a broader sense for humankind in general, and not only for the present time and for the ‘modern scientific astronomy’? Frequently, astronomers see past times of astronomy almost as a ‘prehistoric period’, with generally limited knowledge and an invasion of ‘false science’ or ‘false use’, as in the case of astrology, or having more pleasant facets such as ‘cosmological legends and myths’. As the promoters of multidisciplinary work, where the exact sciences and human sciences meet, we clearly must not accept such a reductive vision of the past and we should nullify poor and subjective evaluations of the past uses made only based on the results of astronomy. This could be seen as reducing the scope of heritage.

What are the main characteristics of the Heritage of Astronomy? We need to define it in a broader sense to involve any type of observations of the sky and any type of technical use or social use of its results. The Thematic Study clearly underlines that every civilization has a specific relationship with the sky and consequently these particular relationships have shaped cosmological representations and beliefs, and have also influenced in certain sites devoted to observations and celebrations. Furthermore, astronomy is more than just rational



knowledge, forming a well-identified corpus of data and methods. It is part of a more global cultural system that involves technical, social and philosophical issues that have complex relationships and mutual influence. Astronomy alone is not a recommended way to study heritage; it must be studied in context or it could lead to considerable misunderstandings.

Cooperation between the IAU and ICOMOS has brought about a joint methodology, well balanced between scientific issues and heritage issues for defining and studying astronomical heritage correctly. But is it in-depth enough? Probably not.

Nevertheless, the methodology based on the *Operational Guidelines for the Implementation of the World Heritage Convention* (World Heritage Committee, 2015) shows both important similarities with 'classical' architectural or urban heritage and some strong specific features. What is similar with classical heritage, for instance, is the strong relationship with tangible heritage, as an initial step of recognition by the World Heritage Convention, and with intangible heritage giving context and meaning to the tangible one. For instance, what is more specific to astronomical heritage is the crucial role of instruments such as telescopes and more largely, of moveable artefacts for technicians and sciences. The moveable artefacts indeed meet a specific difficulty in applying the World Heritage Convention, because if they are essential for the astronomer or for the engineer they are not very relevant in the scope of the Convention. They are more secondary attributes that give context to the site rather than major attributes that support its OUV!

What is also extremely important, especially for modern astronomy, is the role of innovation with the permanent need to update machines/instruments to get more accurate observations and more in-depth data of the sky. Indeed, such specific features are not peculiar to the heritage of astronomy in the context of the World Heritage Convention; we already had found similar difficulties with the heritage of industry and science in general. Innovation and change are a common value to these connected fields of human activities and knowledge, but they could hamper heritage conservation.<sup>8</sup> It is a contradiction between heritage requirements and science development.

Such heritage sites generally remain as living places and are always used at the front edge of the development of technology and science. In terms of heritage, such places have specific conservation problems, which have not really been studied until now as precise case studies, nor with credible proposals by the observatories' managers and heritage advisers.

Certainly, one of the main weaknesses of the Extended Case Study process is the inability of those promoting sites' nominations to clearly place the conservation problem in line with the reference terms of the World Heritage Convention, and beyond that, to really integrate what the concept of heritage means as 'authenticity' and 'integrity'. Such terms are generally associated to scientific results and demonstrations themselves by astronomers (original and complete data and theoretical demonstrations), but are not related to the tangible set of constructions that make up the materiality of the heritage site. The limit of inconsistency is probably reached by the complete contradiction of the wish to have some important contemporary observatories recognized as World Heritage sites and to keep free the total capacity to demolish everything on the site to replace obsolete instruments/edifices with new ones, without consideration for the heritage. Even with many meetings on and information about the World Heritage Convention, we remain close to zero on this matter. Recognizing living places of astronomy and science is undeniably a very delicate and complex matter, and we must work together so that we can propose credible solutions to the World Heritage Committee in order to be able to take real care of the heritage and also the scientific developments in the future.

### Could the Dark Sky Itself Be Listed?

The sky is obviously the astronomer's object of study, and all devices and artefacts found in an observatory are there to help the astronomer in his/her task. But the sky cannot be defined as a given site, nor does it belong to a State Party! A World Heritage Listing clearly requires a mapping of the site, the names of the site owners, the managerial body, the State Party responsible for the site and so on. The sky itself is not a property in a juridical sense or even part of a property, but it remains the object of knowledge and is at the very core of the functioning of a site. The difficulty in recognizing the sky alone is clearly this: it is impossible to define it within the terms of the

8. <http://www.icomos.org/fr/notre-action/participation-aux-conventions-internationales/convention-du-patrimoine-mondial/etudes-thematiques>

World Heritage Convention. It could, nevertheless, be stated as an environmental quality of a site by its exceptional visibility. But, it cannot be considered as a fully delimited site that has OUV by itself.

The sky must of course be considered as a major natural feature of the Earth's environment, but it seems strange that humans can attribute an OUV to the universe; in other words, to associate a human label of universality to the universe! It is clearly a paradox. In philosophical terms, it opens questions that deal directly with an anthropocentric approach of the universe. In such a case, that means that humankind bestows upon the sky a human recognition and value to its global astrophysical environment. By that, it joins antique cosmologies and medieval descriptions of the Earth as the centre of the universe, and humankind by its gods as rulers of the universe. Clearly, contemporary astrophysics shows us humans' tiny place within the universe and the idea of giving a human value to the sky, even if it is called OUV, seems to not make any sense at all.

In terms of the World Heritage Convention, this leads us to come back to the site itself and to define it as a 'windows to the universe', as astronomers sometimes call it. We therefore need to define what is a window to the universe and to study its attributes and qualities as a cluster of local attributes for a possible nomination. Clearly the 'dark sky' alone doesn't meet World Heritage Convention requirements. It could, however, be an essential attribute among others supporting the exceptionality of a given place.

In this way, dark sky quality can be considered as a local environmental attribute. Clearly, intrinsic dark sky quality is a natural attribute of a site among other natural and/or cultural attributes. Assessing its importance will involve an analysis of its objective properties (purity as minimum of physical constraint) and of its aesthetic qualities in the context of a local skyline. Dark sky quality is one local environmental attribute among a cluster of natural attributes. It contributes to form its natural environmental component. One of the best ways to use the value of the dark sky is among a set of other remarkable attributes that characterize a generally outstanding landscape both at night and during the day. Potential OUV results from the combination of a set of extraordinary attributes that contribute to the significance and beauty of the whole.

Furthermore, a very important associated issue is the preservation and management of dark sky qualities in the site's surrounding area, both for scientific efficiency and for heritage preservation. The noteworthy international movement nowadays supports the promotion and the recognition of the dark sky reserves, and it faces a very important challenge to control human light pollution on a large scale. The maintenance of dark sky quality could certainly, in itself, be a major management goal for an astronomical site and its surroundings. This has implications relating to the concept of the buffer zone of the World Heritage methodology (World Heritage Committee, 2015).

## Conclusion

Whether we wish to be frank, results from the Initiative for World Heritage listing are not very convincing at the time being and for the immediate future, apart perhaps from some well identified individual archaeoastronomical sites, such as Chankillo in Peru and Risco Caído in Gran Canaria, Spain. These sites are waiting to finish their nomination dossiers and to receive the final decision from the State Party in order to apply for World Heritage listing. For Modern astronomy, the situation seems slightly confused, firstly by the inertia for the few sites that have possible individual OUV and secondly, by the difficulty to put together really convincing international serial nominations. This is due to their complexity, resulting simultaneously from the inherent difficulties for promoting international nominations, to the theoretical difficulties of living sites that are not really well studied such as heritage sites, to difficulties inherent to specific local contexts, to a lack of real understanding of the Convention's goals in recognizing a heritage site.

Finally, astronomical heritage looks like as a very paradigmatic example of the heritage of sciences and technology, both for its promising possibilities to renew the subject of heritage in a World Heritage context and for its specific difficulties. It faces remarkable problems in being recognized due to its composite nature with its large set of different attributes going from intangible fixed ones to moveable instruments, and from the importance of data conservation to pure and applied knowledge. Frequently, the site by itself and by its architectural components are more of a physical

support and an envelope than the core of its scientific value. The site's monumental appearance is very minor for science itself. The sky itself is the object of observation but it is reduced to an environmental quality in pure heritage terms! It is clear that the World Heritage Convention (1972) doesn't recognize by itself all the facets of scientific heritage. The UNESCO Convention for the Safeguarding of Intangible Cultural Heritage (2003) and some programmes for archives or human artefacts must also be taken in consideration. But is the joint use of these tools possible? To date, we have no examples or precedence of this. Could scientific recognition by UNESCO be the first? It is not impossible to imagine.

Efforts must be pursued with tenacity and with multidisciplinary respect, both by scientists and by heritage authorities. Efforts also may take local communities into consideration when they wish to promote local sites within real and notable meanings with possible and valuable integration in serial nominations. The need of these three kind of stakeholders and a good balance between them must be maintained to open up real perspectives.

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# How to Protect Astronomical Sites and other Environmentally Sensitive Locations from Light Pollution

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## Abstract

Astronomical observatories are extremely vulnerable to increases in sky brightness coming from artificial lighting. Sky brightness increases have led to the closure of some major observatories and have limited the productivity of many others. The remaining major observatory sites are located at remote mountaintops, but these sites are becoming progressively more threatened by light pollution.

Until recently, the most energy efficient forms of lighting were sodium based, emitting most of their light at redder wavelengths. Astronomers and other environmentally sensitive areas benefited from the amber colour of the sodium lighting, which is deficient in blue light. Blue light is efficiently scattered by air molecules (Rayleigh scattering) and is well known to be harmful to a wide range of endangered species, such as turtles and birds. The natural night sky is extremely dark at blue wavelengths (when the Moon is down) and is extremely precious to astronomical research.

The energy efficiency of light emitting diodes (LEDs) has improved dramatically in the last decade. Since LEDs are a solid-state lighting device, their lifetime is much longer than high-intensity discharge lamps such as sodium and metal halide (for which the bulbs have a lifetime of approximately five years). This results in lower maintenance costs, which makes them attractive to many users, including governments. As the light from LEDs is easier to direct, most lighting tasks can now be lit more efficiently with LEDs than by other forms of lighting. White LEDs, which typically form white light from blue LED emission and a phosphor, have a spectral energy distribution that is very damaging to astronomy, since much of the light they emit is bluer than sodium lights and is much more readily scattered by the atmosphere. For casual stargazers with scotopic adaptation, the blue light from LEDs causes a major increase in perceived sky brightness and consequent inability to see faint objects.

A worldwide switch to LED lighting is inevitable. Practical steps are described here that must be taken to minimise the impact of this switch on astronomical observatory sites, on animals (such as birds and turtles) that are affected by light and on other environmentally sensitive locations. The proposed steps include very careful shielding of the lights, limitations on the amount of light, dimming of the lights later at night when there are less pedestrians, strict spectral management, including reduction or elimination of blue light from the LEDs and rigorous enforcement of lighting regulations.

## Resumen

Los observatorios astronómicos son extremadamente vulnerables a aumentos en el resplandor del cielo procedentes de iluminación artificial. Los aumentos en el resplandor del cielo han conducido al cierre de algunos importantes observatorios y han limitado la productividad de muchos otros. Los observatorios restantes están ubicados en remotas cimas de montañas, pero se están viendo cada vez más amenazados por la contaminación lumínica.



Hasta hace poco, las formas de iluminación de mayor eficiencia energética eran las basadas en sodio, que emiten la mayor parte de su luz a longitudes de onda más rojas. Los astrónomos y otras áreas medioambientalmente sensibles se beneficiaron del color ámbar de la iluminación con lámparas de sodio, la cual es deficiente en luz azul. La luz azul es eficientemente dispersada por las moléculas del aire (dispersión de Rayleigh) y se sabe a ciencia cierta que es perjudicial para una amplia variedad de especies en peligro de extinción, como tortugas y aves. El cielo nocturno natural es extremadamente oscuro a longitudes de onda azules (cuando la Luna está en la parte baja del cielo) y es algo sumamente valioso para la investigación astronómica.

La eficiencia energética de los diodos emisores de luz (LED) ha mejorado radicalmente en la última década. Puesto que los LED son un dispositivo de iluminación de estado sólido, su vida útil es mucho más larga que la de las lámparas de descarga de alta intensidad, como las de sodio y haluro metálico (cuyos focos tienen una vida útil de aproximadamente cinco años). Esta característica de los LED da lugar a gastos de mantenimiento inferiores, lo que los hace atractivos para muchos usuarios, incluyendo gobiernos. Como la luz de los LED es más fácil de dirigir, la mayoría de las tareas de iluminación pueden ahora alumbrarse con mayor eficiencia. Los LED blancos, que normalmente forman luz blanca a partir de la emisión de LED azules y un fósforo, tienen una distribución de energía espectral que resulta muy perjudicial para la astronomía, puesto que gran parte de la luz que emiten es más azul que las luces de sodio y es dispersada mucho más fácilmente por la atmósfera. Para los observadores casuales de estrellas con adaptación escotópica, la luz azul de los LED provoca un gran aumento en el resplandor del cielo percibido y la consiguiente incapacidad para ver objetos apenas visibles.

Es inevitable un cambio a nivel mundial hacia la iluminación con LED. En este escrito se describen medidas prácticas que deben adoptarse para minimizar el impacto de este cambio sobre los sitios de observatorios astronómicos, sobre los animales (como aves y tortugas) que se ven afectados por la luz y sobre otros lugares medioambientalmente sensibles. Las medidas propuestas incluyen la protección minuciosa de las luces; las limitaciones en la cantidad de luz; la atenuación de las luces en la noche, cuando hay menos transeúntes; una estricta gestión del espectro, incluyendo la reducción o eliminación de luz azul de los LED, y una rigurosa aplicación de las regulaciones sobre iluminación.

## Introduction

Since the mercury vapour lamp came into widespread usage in the 1930s, humankind's view of the dark night sky has been slowly but incessantly compromised by the increased sky brightness coming from artificial lighting. The slow increase in sky brightness — barely noticeable over a timescale of one year — but profound on a timescale of ten years — has been accepted by society as the 'price of progress.' The new world atlas of light pollution (Falchi et al., 2016) shows that much of the world's population now lives in locations where the Milky Way cannot be seen, and an entire generation of children has now grown up without ever having seen the Milky Way. Mount Wilson Observatory and Palomar Observatory in California, once humankind's most powerful observatories, have been rendered impotent by growing light pollution.

Some increase in sky brightness from reflection of light off the ground from urban lighting is inevitable. However, there is

widespread use of unshielded lights and these lights are one of the main sources of light pollution. Improperly shielded lights increase sky glow, waste energy, cause glare and produce light trespass. Strict lighting ordinances are required to eliminate or reduce the use of unshielded lighting.

In many locations, contemporary lighting is sodium based. The most common form is high-pressure sodium (HPS), which emits most of its light as pressure-broadened emission centred at 589 nm. A weaker sodium line near 569 nm adds yellow light and much weaker lines at 465, 498, 515 and 616 nm add some additional red, green and blue light. With an energy efficiency of approximately 100 lumens/Watt, HPS is more energy efficient than metal halide and most other forms of lighting, making it a popular lighting source across the planet. It is commonly used near major astronomical observatories and other environmentally sensitive locations, because most of its light is emitted close to, but redward of the photopic

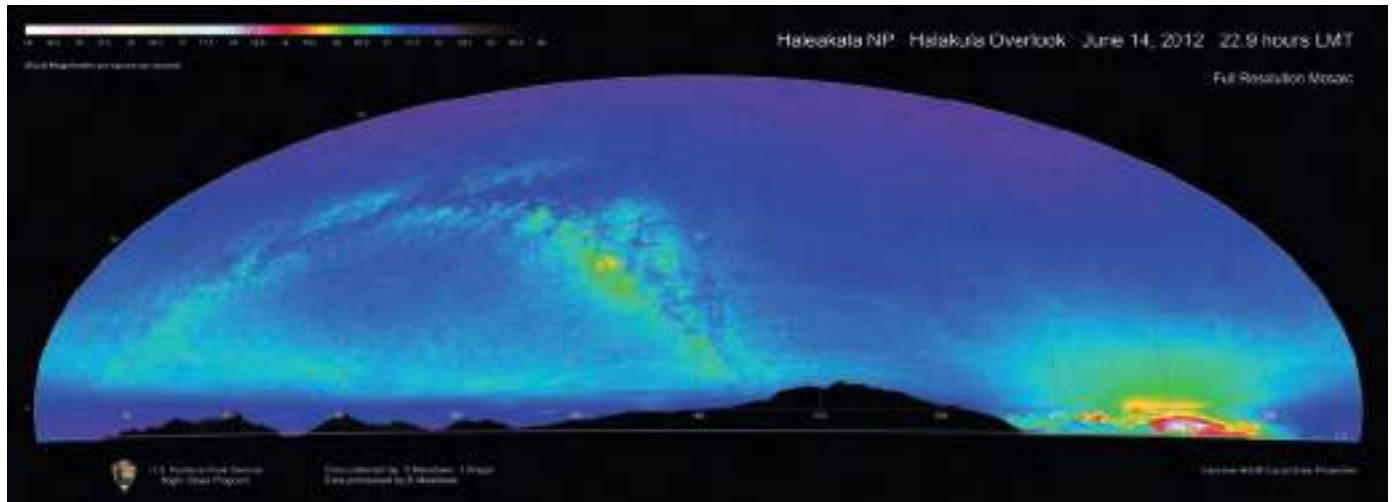


Figure 1. All sky projection of night sky brightness measured by the US National Park Service, seen from Haleakala on the island of Maui. The Milky Way is seen on the left side of this image. White, red and yellow colours represent the brightest light levels. Green represents intermediate brightness, blue represents darker sky and the darkest sky is shown as purple. The red and white region on the lower right shows light from the towns of Kahului and Wailuku on Maui; immediately above, the yellow and green colours show sky glow from Honolulu. © Dan Duriscoe.

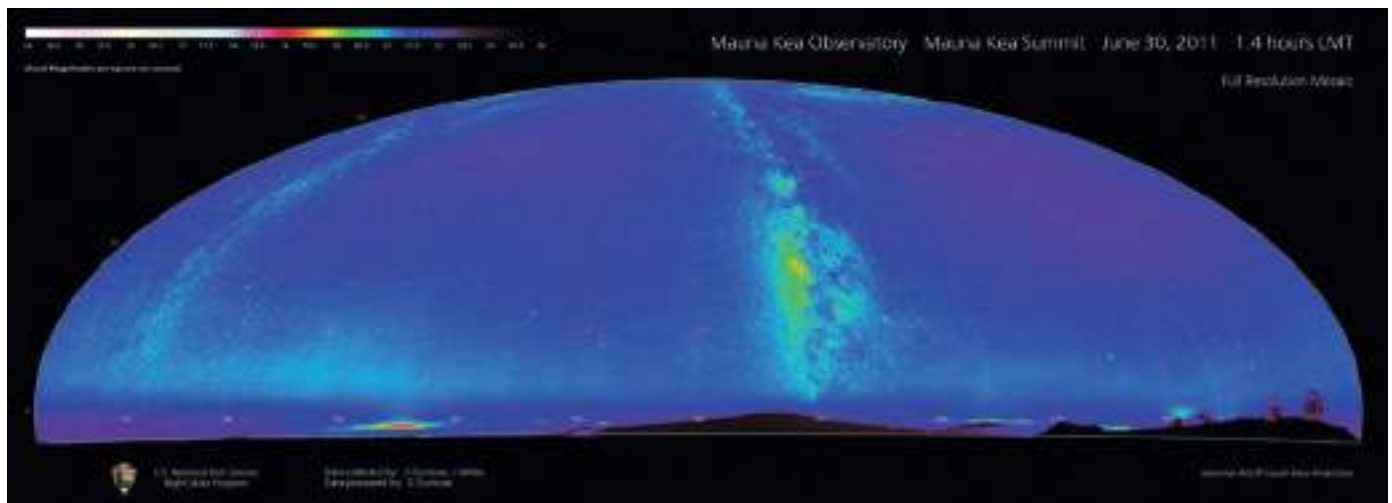


Figure 2. All sky projection of night sky brightness measured by the US National Park Service, seen from Maunakea on the island of Hawaii. The Milky Way is seen on the extreme left side of this image and near the center. Red and yellow colours represent the brightest light levels, green represents intermediate brightness, blue represents the darker sky and the darkest sky is shown as purple. The red region on the lower left shows light from the town of Hilo. The small green glow on the lower right is caused by Honolulu. © Dan Duriscoe.

peak at 555 nm, making it less vulnerable to Rayleigh scattering. Low-pressure sodium (LPS) lighting is very energy efficient, approaching 200 lumens/Watt. This high-energy efficiency is the reason for its adoption away from observatories. The light from LPS lamps is near monochromatic at 589 nm (with an amber hue), which makes it very attractive for use near observatories, since its light can be filtered out, and only affects the one wavelength that is already compromised for spectroscopy by natural sodium emission in the upper atmosphere. The near-monochromatic light from LPS lamps has made them unpopular due to the lack of colour rendition. The long cylindrical bulbs also make efficient light distribution more challenging.

Solid-state lighting is rapidly replacing other forms of lighting. Light emitting diodes (LEDs) have much longer lifetimes than high-intensity discharge lamps, which reduces maintenance costs. Nearly all white LEDs are based upon a blue LED that emits light near 450 nm in wavelength and a phosphor that converts some of the blue light to green, yellow, orange and red light, producing a light that is perceived as white. All white LEDs have substantially more blue and green light than sodium lighting.

Shorter wavelength light (blue and green colours) is more harmful to astronomy because of the strong wavelength dependence of Rayleigh scattering of light on air molecules in the atmosphere. The scattering is proportional to  $\text{wavelength}^{-4}$ , meaning that blue light at 450 nm is scattered almost three times more readily than amber light at 589 nm. The natural night sky is very dark in the blue part of the spectrum and the dark-adapted (scotopic) human eye is more sensitive to blue light. Professional astronomers and casual sky gazers are therefore extremely vulnerable to the increase in sky brightness that will come from switching to LED lighting.

Many species are affected by light at night. Take for example endangered turtles: mothers become confused by light when nesting and hatchlings are confused by artificial light sources when trying to find the ocean. Likewise, in Hawaii, the endangered Newell's shearwater seabird becomes confused by unshielded light sources, circling them until they become exhausted and fall to the ground, where they may die or become vulnerable to predators.

Fortunately, the methods that are appropriate for protecting an astronomical observatory from light pollution, including limiting the spectral energy distribution and shielding, are the same methods that are needed to protect many species that are affected by light at night.

### Methods to Protect Observatory Sites and Other Environmentally Sensitive Locations

Below, a series of steps are detailed that must be taken in order to preserve the dark sky over observatory sites and in other environmentally sensitive locations. In the coming decade, there will be a widespread change to LED lighting. This is a wonderful opportunity to replace aging, inefficient and improperly shielded light fixtures with properly shielded, more efficient lights. It is vital that the improved energy efficiency of LEDs is not simply used as an excuse to produce even more light at night.

### Light Travels Enormous Distances

Strategies to protect the dark night sky at observatory sites must encompass large areas of land. Light's travel through the atmosphere is stopped only by the curvature of the Earth. Figure 1 shows that Honolulu, with a population of approximately 1 million, produces a large increase in sky brightness in the north-west, as seen from Haleakala Observatory on Maui, 175 km away. Figure 2 shows that Honolulu's impact on the Maunakea Observatory on the Island of Hawaii is less, because it is located at a larger distance (300 km). The sky glow from Sydney, Australia (population of almost 5 million), can be seen low on the horizon from Siding Spring Observatory, 350 km away.

Protection strategies for major observatory sites must therefore use many of the methods described below for large distances around the observatory site — at least 250 km in each direction, depending on the size of the urban development.

### Shielding

One of the most important requirements for the protection of dark night skies is the full shielding of light sources. Light fixtures that do not emit any light above the horizontal plane must be used. Figure 3 shows a light source, identifying both ideal light distribution and the most harmful angles of light emission that contribute to light

pollution. All light emitted directly above the horizontal plane represents wasted energy. Light emitted at small angles above the horizontal is the most harmful, because it has a near 100% likelihood of interacting with the air and producing light pollution. Light emitted directly upwards is slightly less harmful as up to 80% of that light may escape the atmosphere (depending on air quality, altitude and colour) without interacting with the air. Light reflected directly upwards from the ground behaves similarly.

Fully shielded lights also improve road safety because they produce less glare. Some lighting engineers have argued that use of fully shielded lights requires closer pole spacing to achieve adequate lighting uniformity. This is no longer true for LED light fixtures. Exquisite control of the light emissions from LED fixtures is now possible and there are no longer any excuses for not making exclusive use of fully shielded fixtures.

Upward lighting of buildings, monuments and flags must be reduced or eliminated in the vicinity of observatory sites and in other environmentally sensitive locations. In general, this type of lighting should be avoided; when it is necessary, these types of structures should be lit from above using fully shielded light fixtures and the spectral power distribution of the light should be carefully controlled.

### Amount of Light

In North America (United States, Canada and Mexico), the amount of light used for various lighting tasks usually follows recommended values established by the Illuminating Engineering Society of North America (IESNA). Elsewhere, lighting levels usually follow recommended values from the International Commission on Illumination (CIE). The IESNA recommended lighting levels are typically lower than CIE recommended levels. There are strong cultural differences in expected lighting levels. European, South American and Asian pedestrian areas are typically more brightly lit at night than similar areas in North America. Using less light directly results in less light pollution.

### Dimming and Curfews

Typical street lighting levels are based upon the number of pedestrians who use a street and the time of night when the highest

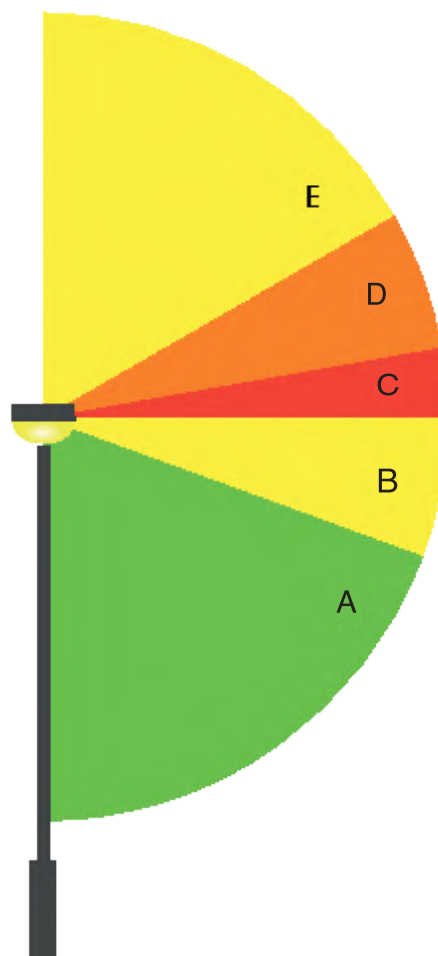


**Figure 3.** Angular distribution of light from a light fixture. The green region, marked 'A', between 0 and 70 degrees from directly down, is the ideal distribution of light from a light fixture. The yellow region, marked 'B', between 70 and 90 degrees from directly down, can cause glare and is more prone to reflection from surfaces, which can contribute to light pollution. The red region, marked 'C', between 0 and 10 degrees above the horizontal, is a major contributor to light pollution. Light emitted in this region is very likely to interact with air molecules or aerosols and produce light pollution. The orange region, marked 'D', between 10 and 30 degrees above the horizontal, is also a major contributor to light pollution. Light emitted in the yellow region marked 'E' is more likely to leave the atmosphere without causing light pollution than light emitted into the 'C' and 'D' regions. Fully shielded light fixtures emit no light into the 'C', 'D' and 'E' zones. All light emitted into the 'C', 'D' and 'E' zones is wasted energy. © Richard Wainscoat.

number of pedestrians are present (early evening). Later at night, there are significantly less pedestrians and a lower lighting level can be used. This reduces energy usage and light pollution.

The 2014 revision of the IESNA roadway lighting document (2014) describes ‘adaptive lighting’ for the first time and recognizes that if the criteria change during the night (for example, if there are less pedestrians), then the lighting level can be adjusted (dimmed). The CIE is also working on similar recommendations. Dimming of lights directly results in a corresponding reduction of the light pollution caused by reflection of the light into the sky.

Curfews have been adopted in astronomically sensitive areas. These typically require that high-output lighting, such as recreational lighting and lighting related to businesses, be turned off by a specified time, or when the business closes, until sunrise. In La Palma in the Canary Islands, high-pressure sodium lights are turned off later in the evening, leaving only the less harmful low-pressure sodium lighting on for the remainder of the night. A problem with lighting curfews is that they create a widespread misconception that telescopes are not turned on until the lights are turned off. Telescopes at major observatories are used every night from evening twilight until morning twilight, and most telescopes are operated every night of the year, including nights with a Full Moon. Near the Full Moon, astronomers adapt to the brighter sky by working at red or infrared wavelengths (where Rayleigh scattering of moonlight is less problematic), or by studying bright objects. Faint objects must be observed when the Moon is down, or between New Moon and Quarter Moon phase, when the sky is still naturally dark.

### **Efficient Use of Light and Reduction or Elimination of Light Trespass**

Outdoor lighting must be used as efficiently as possible, and this is critically important near major astronomical observatories. The lighting designer must minimize the total number of lumens needed for the lighting task. By minimizing the total amount of light used, the energy usage will also be minimized, the impact on the night sky will be reduced and light trespass onto adjacent properties will be decreased. Light trespass is poor control of outdoor lighting, such

that someone else’s light enters your property or residence, detracting from your quality of life. Light trespass occurs when inefficient lighting is used, and light escapes from the specific task for which it has been installed. Light trespass in countries such as China and Taiwan has become so severe that many people are having difficulty sleeping at night. Light trespass is commonly caused by improperly shielded lights or when lights are aimed in a horizontal direction. Instead of aiming lights in a horizontal direction, shielded luminaires with asymmetric light throw should be selected.

Requiring efficient lighting and minimizing light trespass will inevitably place strong constraints on luminaire design: highly efficient luminaires must be specified and selected — these are typically not the cheapest. It must be noted, however, that the luminaire cost is typically only a small fraction of the total cost of a lighting installation, and that the poles, trenching and electrical work is much more expensive.

### **Is Lighting Needed?**

One of the best ways to protect an astronomical site is to turn off lights. Different locations use different criteria to decide whether or not to use light at night. For example, freeways in California are only lit at intersections, but in Hawaii, most freeways are lit at night. It is clear that a decision not to light a roadway will result in less light pollution and reduce energy usage. In the United States, it is common practice to light urban roadways and intersections, but it is certainly not required. Widespread adoption of adaptive lighting (dimming) will hopefully reduce the impact of street lighting in the future.

### **Spectral Power Distribution of the Light**

If all lights are fully shielded (as recommended in Section 2.2), then all light that produces light pollution that may affect observatory sites or endangered species is reflected light. The spectral power distribution (or spectral energy distribution) of the light is of critical importance. Surfaces that reflect light may be more or less grey in colour, such as roadways or concrete, or may be green in colour, such as vegetation. Luginbuhl et al. (2014) provides a detailed discussion of the impact of spectral power distribution on sky glow.



| LAMP TYPE        | LUMENS/WATT | COLOURS | TURTLE SAFE | S/P RATIO |
|------------------|-------------|---------|-------------|-----------|
| LPS              | 200         | AMBER   | YES         | 0.2       |
| HPS              | 100         | bGYOR   |             | 0.6       |
| AMBER LED        | 50          | AMBER   | YES         | 0.3       |
| PC AMBER LED     | 100         | BGYOR   |             |           |
| FILTERED LED     | 100         | GYOR    |             | 0.8       |
| LEAKY FILTER LED | 100         | bGYOR   |             |           |
| 2400 K LED       |             | bGYOR   |             |           |
| 2700 K LED       | 102         | BGYOR   | NO          |           |
| 3000 K LED       | 103         | BGYOR   | NO          | 1.2       |
| 4000 K LED       | 110         | BGYOR   | NO          | 1.5       |
| WHITE/RED HYBRID | 100         | BGYOR   | NO          | 1.5       |

**Table 1.** A list of some of the LED types presently available compared to existing LPS and HPS light sources. The LEDs are listed in the order of increasing damage to astronomy. The colour letters correspond to Blue, Green, Yellow, Orange and Red, with ‘b’ used to represent a small amount of blue light. Some LED types listed are prototypes and not yet in widespread production.

Low-pressure sodium light is the least harmful light source for professional astronomy, for casual stargazing and for many endangered species. It emits near-monochromatic light at 589 nm wavelength that is close to the eye’s peak photopic sensitivity at 555 nm, but well redward of the eye’s peak scotopic sensitivity at 507 nm. This reduces the impact to the dark-adapted human eye and the amber colour is subject to less Rayleigh scattering than bluer colours. In many places, LPS lighting is being replaced by LEDs; there is now only one manufacturer of LPS bulbs and few companies supply LPS luminaires. Light from LPS lamps is difficult to control and more energy efficient lighting is possible with LEDs. LED lighting also provides much better colour rendition, which is leading to replacement of LPS lighting by LEDs.

High-pressure sodium lighting is less harmful to astronomy and endangered species than blue-rich lighting, but is also being replaced by LED lighting. Since LED light is easier to control, it is more energy efficient than HPS lighting and large-scale replacements of HPS lighting with LED lighting are occurring throughout the world.

Widespread use of LEDs is inevitable, so controlling their spectral power distribution is critically important. Table 1 lists some of the LEDs presently available and compares their properties to LPS and HPS lights. The best LED for astronomy at the present time is the intrinsic amber LED that produces amber light directly using an AlInGaP LED. Its light is similar to LPS, but with a broader spectral emission. Unfortunately, this type of LED is not as energy efficient as the blue InGaN LED and this makes it unattractive, particularly for locations that have high energy costs (such as the Hawaiian and Canary Islands). Phosphor converted amber LEDs are a more energy efficient option. They use a blue InGaN LED and a phosphor to convert the blue light to amber light and have an even broader spectral emission. Both the direct amber and the phosphor converted amber LED have the same colour as the amber (or yellow) traffic signal and were developed for that purpose. The phosphor converted amber LED has better colour rendition than the direct amber LED because the phosphor converted amber LED emits green, yellow, orange and red light as well as amber light, whereas the direct amber LED emits only amber light. Filtered LEDs are the next best choice for use near observatories. White LEDs that emit only a small amount of blue light can be used for

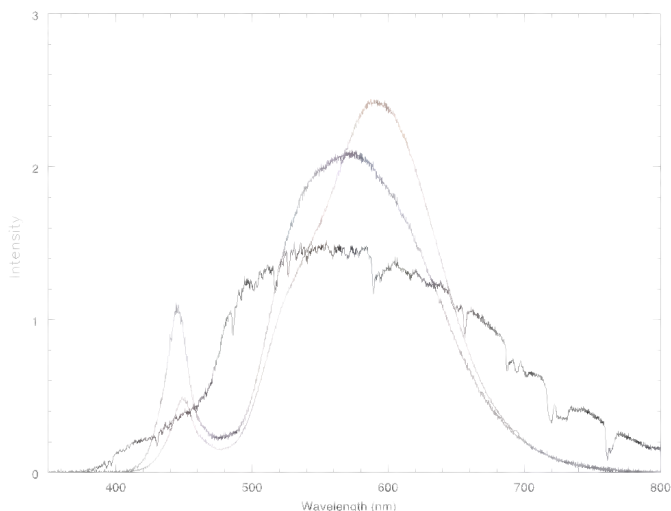


**Figure 4.** The spectrum of moonlight, compared to 3000 K and 4000 K LEDs. The black line is light from the full Moon. Moonlight is reflected sunlight. The structure in the moonlight spectrum is real and is caused by absorption of light in the Sun's atmosphere by hydrogen, calcium, magnesium, sodium and other elements, as well as absorption by Earth's atmosphere. The same instrument was used to record all three spectra. The red line is a 3000 K LED and the blue line is a 4000 K LED. Both LEDs were manufactured by Nichia. Violet corresponds to 410 nm wavelength, 450 nm is blue, 530 nm is green, 570 nm is yellow, 600 nm is orange and 630 nm is red. Human eyes are insensitive at light wavelengths below 400 nm and above 700 nm. © Richard Wainscoat.

tasks that require white light, but their usage should be strictly limited. White LEDs with larger amounts of blue light must be avoided.

The switch from sodium based lighting to LED lighting will increase reflection from the ground, because sodium lighting is deficient in green light, whereas LEDs are rich in green light which will increase reflection from plants.

The Correlated Colour Temperature (CCT) is increasingly being used to characterize white light sources. The CCT of a light source is the colour of the blackbody radiator that most closely matches the perceived colour of the light source. It is commonly used to characterize the spectral power distribution of LEDs. However, the spectral power distribution of LEDs is nothing like a blackbody,

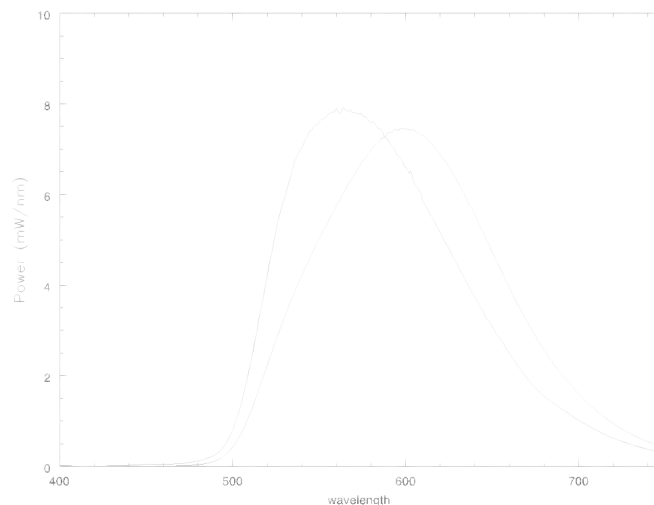


**Figure 5.** Spectral power distributions of filtered LEDs in use on the Island of Hawaii. The blue line shows a filtered cool white (5000 K) LED and the red line shows a filtered warm white (3000 K) LED. The effective CCT for the filtered cool white LED is ~3600 K and for the filtered warm white LED is ~2500 K. © Richard Wainscoat.

as shown in Figure 4. Figure 4 illustrates the spectral power distribution of a 3000 K LED, a 4000 K LED and moonlight, all measured by the same instrument. Moonlight has a similar spectral power distribution to a 4200 K blackbody. It is sunlight (5800 K blackbody modified by atomic absorptions) reflected from the brown coloured Moon surface. LED sales people have argued that moonlight has a similar CCT to 4000 K LEDs, so should not harm the environment. This argument is badly flawed. Firstly, the Moon is below the horizon on average for half of the night every lunation, and when the Moon is up and is between New and Quarter phase, it is not very bright. Secondly, the spectral power distribution of moonlight looks nothing like an LED. The 4000 K LED has a large amount of emission, near 450 nm (which is not present in moonlight), at the wavelength that regulates melatonin secretion and the circadian rhythm in most advanced forms of life. The LED is deficient in blue and blue-green light between 470 and 510 nm (because the phosphor cannot easily make blue-green light).

Filtered LEDs are in use on the Island of Hawaii, where the Maunakea Observatory is located. These represent an energy

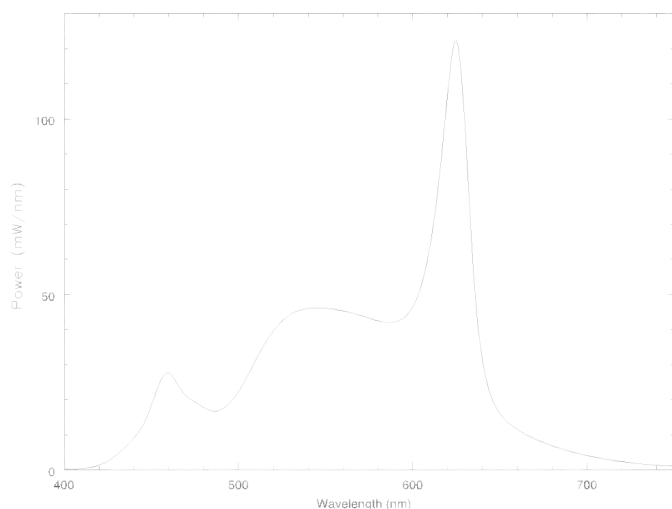


**Figure 6.** Spectral power distribution of a hybrid LED light that uses white and red LEDs. Note the strong blue emission near 460 nm and very strong red emission near 630 nm. © Richard Wainscoat.

efficient compromise. A filter is used to block the blue light from the LED, so that only the green, yellow, orange and red light pass through. Filtered 3000 K and 5000 K LEDs are in use. Spectra of these LEDs are shown in Figure 5. The filtered 3000 K LED light appears yellow in colour and the filtered 5000 K LED light has a yellow-green appearance. Hubble lighting has produced a variant of the filtered LED light using a fluorescent filter that converts blue light to green light rather than absorbing it.

One LED manufacturer, Cree, has recently introduced a hybrid 3150 K LED light that is composed of white LEDs rich in blue light with high CCT, supplemented by red LEDs with emission near 630 nm to reduce the effective CCT. This kind of light source is extremely damaging to astronomy because it combines large amounts of blue light near 450 nm (where the photopic eye is not very sensitive, but the scotopic eye is more sensitive), with large amounts of red light at 630 nm (where the human eye is also not very sensitive); it is noteworthy that astronomical telescopes are very sensitive at both 450 nm and 630 nm. The spectral power distribution of these LEDs is shown in Figure 6 and is very different from a blackbody and natural light sources. This type of lighting

should be avoided outdoors in any location where the dark night sky needs to be protected or where there are other environmental concerns, such as endangered species.

The Correlated Colour Temperature is an ineffective measure of the damage a light source will do to the dark night sky, because the spectral power distribution of LEDs departs wildly from a blackbody shape, particularly when different colours of LEDs are mixed, or when filters are used. It is clear that light sources with high CCT (4000 K and above) are very damaging. A second measure of the spectral power distribution that is becoming more widely used is the scotopic to photopic ratio (S/P). This is calculated by multiplying the spectral power distribution of a light source by the scotopic and photopic luminous efficiency functions and taking the ratio. Light sources with high S/P ratios are the most damaging to astronomical observatories and should be avoided. High-pressure sodium lamps have an S/P ratio of approximately 0.6 and low-pressure sodium lamps have an S/P ratio of approximately 0.2. For all light sources near observatory sites, the S/P ratio should be minimized. Ratios less than 1.0 should be the target. For outdoor lighting well away from observatories, the S/P ratio should be less than 1.2. The filtered LEDs in use on the Island of Hawaii have an S/P ratio of approximately 0.8.

Another method of evaluating the damage a light source will do to astronomical sites is to examine the CIE  $xy$  chromaticity of the light. Blue light should be minimized. This is achieved by requiring that a light source have its  $xy$  coordinates close to the yellow-orange-red monochromatic locus between 560 nm and 600 nm. Moving shortward of 560 nm (yellow-green) adds too much green light and risks affecting scotopic vision. Moving longward of 600 nm (orange) moves the light too far into the red where human vision becomes insensitive.

A further reason to reduce blue light emission is that blue light increases the sensation of glare, which causes visual discomfort, tends to make us instinctively look away and produces difficulty in seeing a task. Most people are now familiar with the discomfort that blue-rich car headlights produce (CCT ~5000 K), compared to conventional car headlights (CCT ~2700K). Similar discomfort is caused by other forms of blue-rich lighting at night. It is noteworthy that many

people choose brown coloured sunglasses for use in the daytime — the brown tinting preferentially absorbs blue light. In the same way, most people are more comfortable with blue-deficient lighting at night.

Ultraviolet light is very damaging to astronomy and is harmful to insects. It cannot be seen by the human eye, but is very readily scattered by air molecules. Mercury-based lights often emit some ultraviolet light. Light sources that emit ultraviolet light should be avoided.

Some studies have attempted to determine whether certain types of artificial light sources are safer. Travis (2011) compared visibility under 3500 K and 6000 K LED lighting and found that neither source provided a significant benefit over the other. Clanton (2014) made a study in Seattle and suggests that 4100 K LEDs provide the best visibility. However, detailed examination of the protocol in this study reveal that the tests were not properly controlled, with some test lights malfunctioning and glare from unrelated lighting likely affecting the findings. It is clear that the studies on visibility carried out to date are inadequate. To meaningfully impact national or international lighting policy, additional detailed and controlled studies are needed.

## Measurement

Continued monitoring of the sky brightness near major observatory sites and in environmentally sensitive locations is very important. Natural hourly and night-to-night variations in sky brightness, along with variations related to solar activity, make interpretation of zenith sky brightness measurements at observatory sites very difficult. Instead, it is important to monitor sky brightness lower in the sky in the direction of the major light pollution sources in order to monitor changes in light emission. Duriscoe (2016) provides detailed information about the quality of the dark night sky as derived from all-sky photometric measurements taken from the ground.

Aerial surveying is being performed on the Island of Hawaii to evaluate changes in light pollution produced by switching from LPS streetlights to filtered LED. Surveys are being performed both before and after the change.

Imaging from the International Space Station (ISS) is difficult to obtain, but invaluable, since it has high spatial resolution. The digital cameras on board the ISS are now very sensitive and produce detailed colour images that show the location and types of light sources.

The new Suomi NPP satellite with its Day/Night Band of its Visible Infrared Imaging Radiometer Suite produced the photometric data used by Falchi et al. (2016) to produce their new light pollution world atlas and is a valuable new tool. However, this instrument is not sensitive to wavelengths shorter than 500 nm, so it does not see blue light and it cannot monitor changes in lighting and light pollution associated with the switch to LEDs.

## Lighting Ordinances

Areas near observatories and areas that have endangered species that are affected by artificial light need strong lighting ordinances or regulations. These regulations must specify proper shielding, the amount of light that can be used, when it can be used and the spectral power distribution. Resistance to these rules is common. For example, many people care more about what a light fixture looks like in the daytime than how well it works at night. ‘Old fashioned’ light fixtures are often popular, to create a historic appearance for example, but many of these fixtures are not properly shielded. Limiting the spectral power distribution, along with strict shielding requirements, often eliminates many types of light sources and fixtures, and vendors of those lights try to lobby the governments to weaken lighting regulations.

Lighting regulations at multiple levels of government may be necessary. In the United States, lighting ordinances are typically created and enforced at the county level. State lighting regulations are often needed to supplement the county regulations. Lighting in federal facilities (such as military installations) is not subject to county or state regulation, and must also be carefully controlled.

## Population Growth

The areas around the world’s major observatory sites, including Hawaii, Chile, the Canary Islands and Arizona, are all experiencing rapid population growth. These observatory sites are all located in places with good weather and, not surprisingly, are also tourist

destinations. Lighting ordinances put in place to protect these sites must be forward looking and anticipate increased population in the future. It is critically important that the infrastructure put in place to support tourist activities — in particular resorts, hotels and airports — respect the need for protection of the dark night sky. Astrotourism is experiencing strong growth (particularly in Chile), and as light pollution continues to grow in most urbanized areas, more people will visit places where dark night sky protection has succeeded.

### Enforcement

Even when strong lighting ordinances exist, violations are common. Building inspectors, who approve lighting plans, work in the daytime, but the lights are turned on at night. After lights have been approved and inspected, they are sometimes exchanged for a type that does not conform to the law. In many cases, lights that violate lighting regulations are installed without any approval or review.

In Hawaii, the island with the best lighting is Kauai (which does not have a major observatory site). This is the result of the impact that artificial lighting has on the Newell's shearwater, an endangered bird that is strongly affected by unshielded lighting and strong enforcement via the United States Endangered Species Act.

Rigorous enforcement is not being done near major observatory sites. The most active enforcement near observatory sites at present is in the Canary Islands. Flagrant violations of lighting ordinances occur in Arizona, Chile and Hawaii.

### Summary of Recommended Changes

The change from high-intensity discharge lamps to LED lighting presents a wonderful opportunity for lighting near astronomical observatories to be improved by replacing poorly or improperly shielded light fixtures with fully shielded fixtures that emit no light above the horizontal plane and reengineering lighting levels to save energy. However, great care must be taken with the spectral power distribution of the LED light and the amount of blue light in particular must be minimized. LED lighting can be easily dimmed and lighting levels should be reduced later at night when the higher levels used early in the evening (when pedestrians are present) are no longer warranted.

Comprehensive lighting regulations must be put into place near observatories and in other environmentally sensitive locations to ensure proper shielding, to restrict the amount of blue light and to limit the amount of light to only what is needed. These regulations must be forward thinking, anticipating the rapid population growth that is occurring around major observatories. Monitoring programmes should be started immediately to track changes in lighting levels coming from the switch to LEDs and from population growth and other urban development. The dark night sky is a fragile resource that can be seriously damaged by just one ill-advised government decision, or by one poorly designed lighting installation.

Finally, it is vital that the improved energy efficiency of LEDs be used to produce real energy savings and not simply as an excuse to produce even more light at night.

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# A Global Approach to the Protection of the Sky, International Cooperation and International Science Policy: the Case Study of ESO

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## Abstract

The paper discusses international cooperation perspectives, especially in the context of the United Nations, to secure the protection of the skies, both for the benefit of global human culture, and for the science of astronomy and astrophysics. It argues that international cooperation is crucial to leverage regional, national and local efforts and provide long-term sustainability by underpinning the necessary regulatory measures.

## Resumen

En el artículo se analizan perspectivas de cooperación internacional, sobre todo en el contexto de las Naciones Unidas, para garantizar la protección de los cielos, tanto para beneficio de la cultura humana a nivel global como para el de la astronomía y la astrofísica. Se sostiene que la cooperación internacional es crucial para aprovechar los esfuerzos regionales, nacionales y locales, así como para proporcionar una sostenibilidad a largo plazo apuntalando las medidas regulatorias necesarias.

## International Cooperation – the Case of ESO

ESO is an intergovernmental organization, established by means of an international convention, signed in 1962 by five European countries. The Convention accords ESO with two specific tasks: a) to provide astronomers in its Member States with state-of-the-art observational facilities and b) to further organize collaboration in astronomy and astrophysics. As regards the former, ESO meets its obligations by operating cutting-edge observational facilities in Chile at the La Silla site (with medium-sized telescopes), at the Paranal site with the Very Large Telescope array and, in cooperation with external partners, at the Chajnantor with mm/submm telescopes. Furthermore, ESO entertains a strong technology programme with industry and national research institutes in its Member States. As far as the second task is concerned, ESO operates a large open access online data archive, organizes meetings and produces publications, has

active, and highly coveted, Student, Fellows and Visiting Scientists Programmes and finally, undertakes a strong public information and educational programme. The latter is obviously also important in the context of the current ‘dark skies’ debate.

Today, ESO has fifteen Member States, while a sixteenth country (Brazil) is in the joining phase, awaiting the conclusion of its legal ratification process. ESO’s annual budget is in the 200 million EUR range, and thanks to its status, ESO can negotiate and enter into agreements with governments and other international organizations. Thus ESO has, among others, agreements with its two host states, the Federal Republic of Germany and the Republic of Chile. While ESO has no formal science policy remit (unlike ESA, the European Space Agency), it does interact with policy makers through various channels, for example, with the European Union

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1. The European Organization for Astronomical Research in the Southern Hemisphere – or for short, the European Southern Observatory (ESO).

(partly through its participation in the EIROforum partnership). ESO is also a permanent observer at the United Nations Committee for the Peaceful Uses of Outer Space (UNCOPUOS).

All of this has enabled ESO to develop a long-term, financially and legally secured strategy thanks to which ESO is today a world-leading organization in ground-based astronomy with a strong, multi-programme, multi-wavelength portfolio, including the 39 m European Extremely Large Telescope (E-ELT), currently under construction at Cerro Armazones in Chile and set to become the largest optical/near-IR telescope ever built.

The drivers behind the establishment of ESO were threefold: cost, exploration potential and the importance of optimal observation conditions – a site with clear, dry and dark skies.

At the time of its conception, it was considered impossible for any of the involved countries to make the necessary resources available on their own for a similar national facility, hence the need for international cooperation. At the same time, the lure of the less explored southern skies with the promise of a great harvest of discoveries was clear to Europe's astronomers. This included the objects only observable from the Southern Hemisphere (notably the Magellanic Clouds) or objects that could be much better observed from such a vantage point as they would be high in night sky, in particular the Galactic Centre. And, finally, the need for a good site. The importance of a good site had been clearly demonstrated by the US astronomers, who with their mountain site observatories had established a leading position in observational astronomy in the early twentieth century. Europe's new observatory was set to follow suit. Originally, a year-long site testing was carried out in South Africa, whereas similar tests had been undertaken in Chile by American institutes with aspirations in the south. In the end, ESO realised that the observational conditions prevalent in Chile were superior to those found in South Africa. Blaauw (1991) and Madsen (2012) offer detailed descriptions of the site testing campaign in South Africa and also mention the parallel events in Chile. A description of the search for astronomical sites in Chile, mainly through Jürgen Stock, can be found in Lorenzen, (2002).

## Dark Skies

It is, however, noteworthy that in this context, the notion of 'dark skies' was not itself a prime parameter during the site tests (if obviously implied). Rather, the dryness and the stability of the atmosphere, as well as the presence (or not) of clouds were monitored. This is not at all to say that the darkness of the sky and the sky transparency were not important, but as it were, to some extent they could be taken as a given in the sites chosen for investigation. Herein lies an important message: when choosing a site for a research infrastructure, say a synchrotron, a particle accelerator or a laboratory, considerations will mostly deal with questions of economy and ease of access. But astronomy is different: The site selection for an astronomical observatory is mission critical. It follows that those few places on Earth that offer prime conditions for astronomical observations, indeed also the locations for the world's most advanced observational facilities, must also be protected from adverse environmental effects.

## ESO and the Dark Skies of Chile

From the perspective of the dark skies, however, it is interesting to note that the original agreement between ESO and Chile, the *Acuerdo* from 1963, only mentions that the granting of mining rights would require presidential approval (supplementary agreement, Article 1). It seems that back then, the issue of light pollution was much less pronounced in this part of the world, so that this simple provision was deemed sufficient.

Things had changed when in 1995, ESO and Chile in reviewing the 1963 agreement concluded an 'Interpretative, Supplementary and Amending Agreement', in which Article 8 states that "The Government and ESO shall adopt *all* necessary measures within their competence to maintain and protect the astronomical and environmental quality of the centres for observation."

To this should be added that buffer areas around the sites had been established (through ownership or concessions), so that the sites enjoyed a certain degree of protection against light pollution.

Various initiatives at the national Chilean level have provided further important underpinning for the undisturbed operation of the observational facilities, especially the 1998 Presidential



Figure 1. The United Nations Committee for the Peaceful Uses of Outer Space convenes on a yearly basis in Vienna. © Claus Madsen.

Decree (Decreto Supremo 686/1998) to protect scientific sites as well as other decrees and declarations (M. Rubio and G. Rodriguez, *The Right to Dark Skies*<sup>2</sup>, 2016). Finally, frameworks have been created for a continued dialogue between the international observatories and the Chilean authorities, notably the Ventana al Universo framework. The creation of a joint Office for the Protection of the Sky Quality (OPCC after its name in Spanish) in 2000, with the participation of the international observatories and Chilean governmental organisms, has proven to be instrumental in providing expert advice on technical and legal matters related to outdoors illumination, monitoring the environment of the observatories and coordinating with worldwide efforts.

With respect to the specific situation in Chile, ESO's position can therefore be described as follows:

- ESO has not carried out independent efforts to protect the quality of its sites, but efforts are undertaken in concert with other observatories and the Chilean authorities;
- These joint efforts are reflected in the creation of the joint Office for the Protection of the Quality of Sky (OPCC) in 2000;
- ESO supports initiatives in Chile addressing the problem from

the sociocultural side, like a possible UNESCO declaration of the astronomical sites as World Heritage as promoted by the Chilean government.

In this sense, ESO is:

- Committed to the protection of the dark skies in Chile through its association with the Chilean government and other observatories on this matter;
- Committed to raising public awareness on light pollution in Europe through its general outreach efforts;
- Aware of, but not as yet an active player in, international efforts to promote legislation for the protection of dark skies given the location of its current observatories in Chile.

### Dark Skies in a Broader Context

When discussing the need to protect the dark skies, two strands of arguments are normally pursued: a) the altruistic right for all humans to be able to see and contemplate the objects in the sky and b) the more specific needs of scientists as they observe the sky. In many ways the arguments are similar, but it should be noted that they are not congruent, at least not as regards the goals. This becomes clear in the

2. Presentations from the International Meeting: *The Right to Dark Skies*, which was organized by the UNESCO Office in Mexico and took place 20 to 22 January 2016 in Mexico City, Mexico.

case of the need for radio-quiet zones to enable observations of the cosmos in this wavelength domain. Awareness of this is important as the astronomical community develops and implements its communication strategies regarding dark skies. A discussion of public communication aspects of this topic can be found in West and Madsen (2001). Equally, it is important to distinguish between the *primary* goal (to protect the sky) and the *secondary* goal (to protect the physical observation site). Once again, the arguments are similar, but not congruent.

Of course, the astronomical community is not alone in this struggle. If communicating sensibly, it can bank on the enhanced public sensitivity to environmental issues in general. Furthermore, there are a number of activities and initiatives across the world that work towards the same goal: the International Dark Sky Association and a large number of amateur astronomical societies whose help can be enlisted. Some have already translated into real political actions. Examples include cases in Spain (the pioneering work in the Canary Islands), in Italy and in Mexico (San Pedro Mártir in Baja California).

In Spain, the *Instituto de Astrofísica de Canarias* (IAC) has promoted a special ‘Sky Protection Law’ to preserve the observatories from light pollution, disturbing radiofrequencies and even airplane exhaust contamination (J. Espinosa, *The Right to Dark Skies*<sup>3</sup>, 2016). Thanks to the work of Cielo Buio in Italy, local regulatory actions have been introduced (L. Zaggia and F. Falchi, *The Right to Dark Skies*<sup>4</sup>, 2016), as well as in Baja California, the latter as an outcome of the International Year of Astronomy in 2009.

Furthermore, selected areas, mainly in North America, have already been designated Dark Sky preserves (Parks, Reserves or Sanctuaries). An important argument, however, has been the protection of natural wildlife on-site, not necessarily access to the night sky. Finally the Starlight Initiative, supported by UNESCO, the World Tourism Organization (UNWTO) and the International Astronomical Union, should be mentioned. The Starlight Foundation can certify specific areas and locations that feature particularly dark and well-protected skies.

### Multilateral Actions

Examining the efforts to protect the observational capabilities of the night sky so far, it becomes clear that these efforts have 1) been

driven by dedicated groups of professional astronomers and/or *aficionados* and 2) the efforts have been local or national by nature. In other words, no effort has been undertaken to address the issue from a global perspective. However, two examples can be given that points towards a more global approach: 1) the International Year of Astronomy (IYA2009) and 2) the current considerations about inscribing selected astronomical sites on the World Heritage List.

During the International Year of Astronomy in 2009, in which ESO was strongly involved, activities were carried out in 148 countries. 40 international organizations were involved, 28 global projects were carried out and an estimated 815 million people were exposed to astronomy during the year (Russo and Christensen, 2010). Equally important have been the legacy activities that continue to this very day, including the establishment of an IAU Office of Astronomy for Development. Of relevance to the issue at hand, was the Dark Skies Awareness cornerstone project led by NOAO of the USA. An important part of the Dark Skies Awareness programme was the ‘Globe at Night activity’, in which citizen scientists in 70 countries performed measurements of the night sky in the course of a two-week period. It was in the nature of IYA2009 that public awareness and public engagement should take centre-stage, but this should not distract from the fact that the IYA itself was underpinned by a multilateral approach.

ESO’s engagement began with substantial support to the political process of winning approval of the IYA at the General Assembly of the United Nations in 2007. The resolution,<sup>5</sup> adopted on 19 December 2007, designated UNESCO as the lead agency and accorded key roles to the International Astronomical Union (IAU) and also to ESO – and ESO followed up on this in a number of ways during the implementation of the IYA.

There can be no doubt that the UN emblem with its both implied and explicit endorsement was key to generating support at the national, regional and local level and thus contributed decisively to the mobilisation of resources and to the ultimate great success of the IYA. It is evident that UNESCO has played a central role in this matter and that a multilateral initiative can significantly leverage national efforts. The second initiative that points towards a multilateral approach is the effort, begun in 2013 and currently ongoing, to inscribe at least some of the great observatories on the World Heritage List under the

3. Presentations from the International Meeting: *The Right to Dark Skies* which was organized by the UNESCO Office in Mexico and took place 20 to 22 January 2016 in Mexico City, Mexico.

4. Ibid.

5. Resolution A/RES/62/200, published 29 February 2008



World Heritage Convention. If so, and pending further decisions, we shall see if this leads to a national (Chilean) presentation or a transnational presentation, and whether a 'single' or a 'serial' inscription will be pursued. Without prejudice to previous sessions of the World Heritage Committee and relevant conferences, the current discussion is a continuation of the deliberations at the 1–2 October 2013 meeting at UNESCO in Paris and the subsequent site appraisal work. In any event, it is a commendable effort that ESO supports, as mentioned.

This notwithstanding, in the context of the World Heritage List, much focus has been on sites in Chile, Hawai'i and the Canary Islands. But we are aware that there are other sites (for example, in Argentina, southern Africa, Australia, Mexico, and Asia) and it should be realised that new observational sites could be developed elsewhere. Finally there are the non-optical 'sites'. It is indeed not clear that these observatories, whether existing or still to come, will be able to benefit from effort to inscribe a subset of the observatories on the World Heritage List. Finally, framing modern and continuously developing astronomical observatories exclusively in a historical context may give rise to operational issues that need urgent clarification. It is therefore worthwhile to consider, as a complementary action, how to broaden the discussion about the dark skies and the related site protection to other fora within the framework of the United Nations and beyond. This could, for example, happen by involving the United Nations Committee for the Peaceful Uses of Outer Space (UNCOPUOS) with the aim of elaborating a series of recommendations to the UN Member States, possibly even at some stage evolving into a 'Ramsar-Convention'<sup>6</sup> for astronomical sites.

It could also involve organizations and structures like OECD that has undertaken significant work regarding the question of sustainability of research infrastructures or the Group of Senior Officials, established by the G7 group that discusses international cooperation relating to especially new research infrastructures.

## Conclusions

It seems clear that protecting the dark skies will require a multifaceted effort, with a strong public awareness dimension, national regulatory initiatives and international cooperation. The value

of successful international cooperation in astronomy is clearly demonstrated, as the example of ESO shows. Equally, the value and efficacy of multilateral initiatives in this field have been demonstrated by the International Year of Astronomy, led by UNESCO and the International Astronomical Union. There is now not only justification but also sufficient expertise and experience in the community to begin to address the issue of light pollution and the protection of the skies from a global perspective.

In this sense, the effort would clearly benefit from the involvement of multilateral mechanisms such as those offered by the United Nations system. Given both the global nature of the issue and its dual challenges, the loss of access to the night sky for humanity as a whole and the severe constraints on future astronomical research, such an involvement by the United Nations is warranted.

## Acknowledgements

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6. The Convention on Wetlands of International Importance, signed in Ramsar in 1971



# International Astronomical Union and the Protection of Dark Skies

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## Abstract

Astronomers are very concerned that the increasing amount of artificial night illumination will affect future observations of very faint celestial objects. In this paper, I will discuss the involvement of the International Astronomical Union on this topic, as well as some actions that can be taken in order to raise the general public's awareness about this problem.

## Resumen

Los astrónomos están preocupados de que la creciente cantidad de iluminación nocturna artificial afecte las observaciones de cuerpos celestes tenues. En este artículo, discutiré la participación que la Unión Astronómica Internacional ha tenido en el tema, así como algunas acciones que pueden ejecutarse para sensibilizar al público general sobre este problema.

## Introduction

Modern life requires us to use artificial light for our evening and night-time activities and the disadvantage is the loss of dark skies. At present, more than half the world's population lives in cities and this number is growing. A particular problem is the illumination surrounding astronomical observatories, as it is increasingly more difficult to detect the fainter, and/or more distant cosmic objects. Fewer and fewer places on Earth are really dark and it is very difficult to see the wonders of the sky.

## Astronomical Observatories

With the installation of modern artificial illumination, the performance of observatories originally built in secluded areas in the vicinity of cities was seriously affected by the increasing amount of light and industrial pollution. The increase in light pollution and urban growth has rendered these observatories useless for present research, and it is now pointless to enlarge their facilities. Superimposed over a bright background, it is very difficult or impossible to study faint objects. Even with clear skies, it may not be possible to distinguish celestial objects because it is only possible to detect features that significantly contrast against the background skylight. Excessive brightness therefore limits the scope of astronomical observations, as it does not allow the detection and analysis of the faintest and most distant objects in the universe.

Starting in the twentieth century, astronomers in the United States set up several observatories in California and later in Arizona in their search for cloudless nights and dark skies. From the 1960s onwards, new sites for astronomical observations in the Southern Hemisphere were founded in the Andes in Chile, whilst observatories were built in Hawaii in the Northern Hemisphere. European astronomers decided to form a consortium and created the European Southern Observatory and installed their new telescopes in Chile. At the same time, several countries constructed Northern Hemisphere observatories in the Canary Islands and southern continental Spain.

Although the sites for these observatories were chosen for their dark skies, they are under the continuous threat of the increasing nocturnal illumination from the surrounding communities. The desire to explore fainter cosmic objects has spurred on the construction of even larger telescopes and instruments of much higher cost, and thus the sites with the best atmospheric conditions are anxiously sought.

Selecting a good observatory site has many requirements, including high altitude, low humidity, low cloud cover, stable atmospheric flow and low levels of smog and illumination from nearby cities. In this sense, light pollution is a great obstacle for astronomical research.

## The International Astronomical Society

Founded in 1919, the International Astronomical Society's membership is at present composed of 12,431 astronomers from 97 countries and is funded by 74 member countries.

Since its creation, its main mission has been 'to promote and safeguard the science of astronomy in all its aspects through international cooperation'.

To accomplish its mission, the IAU established 'Commissions', each one corresponding to different astronomical topics or activities. In recognition of the need of selecting and preserving observatory sites with the most extremely dark skies, the IAU has established as one of its scientific bodies a Commission to this effect. It is currently called Commission CB7 'Protection of Existing and Potential Observatory Sites' and its goals are: (a) to make tangible progress in stopping the intrusion of artificial sky glow on major astronomical research facilities, (b) to raise public awareness to prevent the loss caused by light pollution for all observatories and for the fundamental right to starlight and (c) to work with relevant national and international authorities to set up legal policies and guidelines for the protection of astronomical quality of areas suitable for observational research and/or meriting astronomical World Heritage status.

## Legislation

For several years certain organizations, especially groups of scientists, have taken on the task of securing the right to dark skies and there have therefore been a number of initiatives that seek to determine limits on light pollution. This has resulted in legislation, in several places, put in place to preserve suitable sites for astronomical research, that allows citizens to enjoy looking at the sky. Laws have been passed in areas surrounding certain observatories across the globe that protect them from excessive illumination (for example, in Arizona, in some regions of Chile, Hawaii, the Canary Islands, Baja California and so on).

Nevertheless, astronomers recognize that the most effective way to protect the dark skies is by convincing the general public of the advantages of keeping illumination at a level that can provide safety, while saving energy and expenditure and protecting the night sky.

## Public Awareness

During 2009, the International Year of Astronomy (IYA2009) was celebrated in more than 100 countries and approximately 800 million people participated. For this celebration, the IAU organized many programmes to disseminate our science to the general public. In particular, it carried out several programmes to raise awareness on our need for dark skies and started new ones, too. Among them there were *Dark Skies Awareness*, which was one of eleven Global Cornerstones; similarly, *Dark Skies are a Universal Resource* was one of its nine key programmes. Their goal was to advance the level of public knowledge about the adverse impacts of excess artificial lighting on local environments and to help more people appreciate the ongoing loss of a dark night sky for much of the world's population.

As a follow-up activity of the IYA2009, the IAU enlarged its activities by approving an *Astronomy for the Developing World Strategic Plan 2010—2020* (soon substituted for *Astronomy for Development Strategic Plan 2010—2020 with a 2012 update on implementation*) with the main goal of stimulating the development of a generation of youth leaders in science and technology (see Miley, 2012). The essence of this plan was to create a specific office with this task. In 2011, the Office of Astronomy for Development was launched at the South African Astronomical Observatory in Cape Town and is supported jointly by the IAU and the South African National Research Foundation. It has 3 main tasks, namely to promote: (i) tertiary education and research training, (ii) primary and secondary education and (iii) public outreach. At present, this office has broadened its activities by promoting the establishment of eight regional offices and language centres. In addition, it has funded more than sixty projects with these goals around the world. In 2015, the Strategic Plan was extended one year longer to coincide with the corresponding General Assembly in 2021.

At the same time, the IAU established an Office for Astronomy Outreach (OAO) in Tokyo, Japan, in collaboration with several Asian institutions to coordinate its public outreach activities worldwide. The OAO is responsible for the IAU's interaction with the general public, including building networks to support and disseminate information to the amateur astronomy and public outreach communities.

For the International Year of Light 2015, the world astronomical community expanded several projects already established and launched new ones to promote dark sky awareness. Among them are: *Galileoscope*, a high-quality, low-cost telescope kit, optimized for both optics education and celestial observation; *Light Beyond the Bulb*, an astronomy exhibition that by the end of 2015 had been presented at approximately 675 locations around the world; the *Cosmic Light EDU kit*; the *Dark Sky Meter IYL2015 Edition*, a free application on smart phones to measure the night sky brightness with the press of a button; the *Quality Lighting Teaching Kit* to highlight the use of proper optical design in achieving quality lighting that promotes both energy efficiency and energy conservation of our dark skies; as well as a wealth of *Cosmic Light* endorsed projects.

## Conclusions

The IAU recognizes the value of dark skies, certainly it considers that its responsibilities include identifying and preserving those sites

suitable for astronomical observations. Furthermore, it recognizes that excessive artificial night light is an unnecessary waste of energy and that we should preserve the cultural value of stargazing.

Within its strong programme of outreach astronomical activities that connect the general public to different aspects of the discipline, the Union includes several projects to explain the problems about excessive illumination and to engage more people in the quest to preserve dark skies.

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Messier Marathon 2016, Tierra Blanca, Guanajuato, Mexico. Every year, astronomical societies of the world look toward the dark skies to identify the 110 astronomical objects first listed by Charles Messier. © César Cantiú.



Chapter 6

# Public Outreach and Astrotourism

Capítulo 6

# Divulgación y astroturismo







# La Noche de las Estrellas en México

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## Resumen

En el presente artículo, se describen las motivaciones, objetivos y alcances de un proyecto mexicano de divulgación de la ciencia, la Noche de las Estrellas, que se realiza año con año en diferentes sedes, tanto del país como de Latinoamérica. Se trata de un evento que a lo largo de sus ediciones ha logrado reunir a más de un millón de entusiastas que comparten la fascinación por la observación del cielo estrellado.

## Abstract

In this article, we describe the motivations, objectives and scope of a Mexican project of science outreach and dissemination, Night of Stars, which takes place yearly in different venues not only in Mexico but throughout Latin America. This is an event that throughout its iterations has brought together more than a million of enthusiasts who share a fascination for observing the starry sky.

## La pasión por transmitir el conocimiento

La Noche de las Estrellas es una gran fiesta astronómica que se ha realizado en México, de forma anual y con un éxito creciente, desde el año 2009. Podríamos decir que es el evento masivo de divulgación de la ciencia más grande e importante de Iberoamérica. Fue inspirado por la Nuit des Étoiles, que se creó en Francia en 1991 y unió el trabajo y talento de astrónomos profesionales y aficionados. El artículo de Bruno Monflier, quien es el motor principal de esta iniciativa en Francia, da una magnífica síntesis del trabajo que ha realizado a lo largo de todos estos años. Las características del evento son diferentes en México y en Francia, pero se persiguen los mismos ideales: acercar el conocimiento de forma lúdica y gratuita a la mayor cantidad posible de personas. Para lograr un impacto social importante, el evento se realiza de forma simultánea en muchas sedes distribuidas a lo largo y ancho de cada país.

En el caso de México, se programan actividades todo el día y se organizan eventos culturales y musicales, así como juegos para niños, talleres y charlas con científicos. Al caer la noche, inicia la observación con telescopios. Es toda una fiesta, donde también se invita a todo aquel que tenga un telescopio a que lo sume al proyecto y lo ponga a la disposición del público. Esto ha permitido que los asistentes participen activamente y que un gran número de personas de bajos recursos, que nunca antes habían tenido la posibilidad de mirar a través de un telescopio, lo puedan hacer.

Cada año se define una temática específica (preferentemente en consonancia con la temática de los Años Internacionales definidos por la Organización de las Naciones Unidas), y del primer encuentro en el 2009 al más reciente en 2015, se ha logrado congregarse a un total de más de un millón de personas. Todos estos asistentes han sido atendidos año con año por, en promedio, cerca de 5 mil voluntarios, quienes organizan las actividades, dan asesorías, hacen talleres sobre diferentes temas y ponen a disposición del público más de 2 mil telescopios.

Las temáticas que se han definido en estos años son:

- 2009, “El cielo de nuestros antepasados”
- 2010, “Nuestro universo en movimiento”



Figura 1. Observación solar en sede Mochitlán, Guerrero, 2015.  
© Noche de las Estrellas.

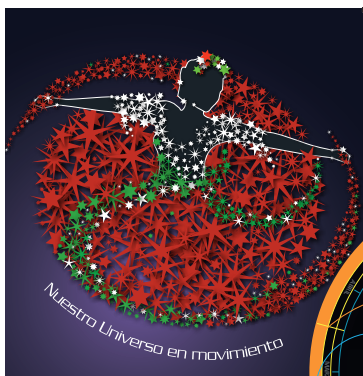


Figura 2. (Izq.) Cartel Noche de las Estrellas en 2010; (Der.) Cartel del Reto México, 2015. © Noche de las Estrellas.



- 2011, “Haz química con el universo”
- 2012, “Universo maya”
- 2013, “El universo y el agua”
- 2014, “El universo según el cristal con que se mira”
- 2015 “Préndete con la luz del universo”

En los últimos tres años, la Noche de las Estrellas de México se ha extendido a sedes ubicadas en otros países. En Latinoamérica ya se ha realizado en Puerto Rico, Guatemala, Colombia, Costa Rica, Brasil y Argentina, pero el entusiasmo se ha contagiado a más regiones y en 2014 se realizó también en el Planetario de Beijing, China.

Como una acción complementaria, para estimular que la gente use los telescopios que tiene guardados, se estableció un récord Guinness que hemos denominado Reto México. El evento consiste en reunir el mayor número de telescopios, apuntando simultáneamente a la Luna. Se ha realizado en tres ocasiones y se ha obtenido un número récord de 3,006 telescopios (sumados en varias sedes del país), gracias a la entusiasta participación de aficionados a la astronomía y del Rotary Club, quienes fungieron como jueces en el conteo.

### Los voluntarios, el alma de la Noche de las Estrellas

Desde sus inicios, la Noche de las Estrellas ha contado con la generosa participación de un gran número de voluntarios, astrónomos

aficionados y estudiantes, quienes son la gran fuerza vital, los verdaderos héroes de cada evento. Estos talentosos voluntarios laboran durante varios meses en la organización y luego llevan a cabo las actividades. Además atienden a todos los asistentes con entusiasmo, comparten sus conocimientos, llegando a sumar más de 5 mil en cada evento. Por su lado, como mencionamos antes, los miembros del Rotary Club también han colaborado de forma altruista en la Noche de las Estrellas y en el Reto México, fungiendo como jueces de calidad que certifican todos los conteos.

Asimismo, los astrónomos profesionales comparten los detalles de sus amplios conocimientos y participan en todas las actividades. Esa noche, astrónomos profesionales y aficionados colaboran mano a mano en la atención a los telescopios con la única intención de acercar la ciencia a la sociedad y mostrar la belleza de una observación del cielo.

### La organización

La organización de la Noche de las Estrellas está formada por diferentes instituciones educativas, culturales, gubernamentales y de la sociedad civil. Actualmente existen dos niveles o estructuras en la organización: un Comité Nacional, que define la temática y las fechas de celebración, y un Comité Local por cada sede, que define



Figura 3. Niño jugando con los materiales que se entregaron en la sede Ciudad Universitaria, Ciudad de México, 2015. © Noche de las Estrellas.





Figura 4. Zona de telescopios en la sede MUTEK, Ciudad de México, 2015. © Noche de las Estrellas.

la organización y programación específica de dicha sede.

El Comité Nacional está formado por representantes de la Academia Mexicana de Ciencias, la Universidad Nacional Autónoma de México, el Instituto Politécnico Nacional, el Consejo Nacional de Ciencia y Tecnología, la Embajada de Francia, el Instituto Nacional de Astrofísica, Óptica y Electrónica, la Asociación Mexicana de Planetarios, la Agencia Espacial Mexicana, las Alianzas Francésas, la Asociación Mexicana de Telescopios y Binoculares, las Sociedades Astronómicas y la compañía Celestron. Por otro lado, los Comités Locales están formados por instituciones de educación, culturales, de la sociedad civil y gubernamentales de las entidades donde se encuentran ubicadas las sedes. Esta suma de voluntades ha sido muy fructífera y su labor está ayudando a construir una cultura científica en todos los estratos de nuestra población.

Al día de hoy, la red de la Noche de las Estrellas se conforma por 60 sedes distribuidas en todas las entidades federativas de la República Mexicana y en otros países como Colombia, Brasil, Costa Rica y Argentina. Los integrantes de todos los Comités Locales se mantienen en contacto a través de la página oficial ([www.nochedelasestrellas.org.mx](http://www.nochedelasestrellas.org.mx)) y de las redes sociales Facebook ([www.facebook.com/nochedelasestrellasmx](http://www.facebook.com/nochedelasestrellasmx)) y Twitter (@NocheEstrellas).

La preparación de esta fiesta es un ciclo continuo que inicia al término del evento de cada año; primero se determina la fecha y la



Figura 5. Grupo de voluntarios en la sede MUTEK, Ciudad de México, 2015. © Noche de las Estrellas.

temática que se adoptará, para posteriormente continuar con el resto de los preparativos, entre los que se encuentran:

- La capacitación sobre la temática anual en las instalaciones del Instituto Nacional de Astrofísica, Óptica y Electrónica en Tonantzintla, Puebla, donde se imparten talleres y conferencias por expertos en la temática seleccionada.
- La creación, verificación y distribución de materiales impresos y digitales. Esto incluye comunicados con contenidos detallados sobre la temática, mapas celestes, planetarios personales, estampas para telescopios, etcétera.
- Para cada evento se diseña una imagen representativa de la temática, y a partir de ella se elaboran elementos gráficos genéricos para carteles, programas de mano, etcétera.
- Se elabora una estrategia de comunicación.
- Como último paso, se diseñan y distribuyen playeras con la imagen del evento para darle una misma identidad a la presencia de los voluntarios de todas las sedes.

Para este 2016, la Noche de las Estrellas se realizará a principios del mes de diciembre con la temática “El derecho a los cielos oscuros”. Finalmente, deseamos agradecer a todas las instituciones que participan en el evento que ha sido firmemente sostenido a lo largo de todos estos años. Muy en particular, deseamos hacer público nuestro reconocimiento a las asociaciones de astrónomos aficionados y a la gran fuerza de los miles de voluntarios que, de manera anónima y altruista, hacen posible este evento. Nuestro más respetuoso agradecimiento a todos ellos por su entrega a esta noble labor.



# La Ferme des Etoiles (La Granja de las Estrellas)

**Bruno Monflier**

*La Ferme des Étoiles, Francia*

## Resumen

El grupo Ferme des Etoiles (Granja de las Estrellas) es un colectivo de asociaciones privadas, independientes y sin fines de lucro. Creado en 1991, tiene su base en Fleurance (al sudoeste de Francia), emplea a 12 colaboradores de tiempo completo y a una veintena de tiempo parcial. Sus actividades se realizan en Francia o en el extranjero (México, Líbano, Egipto, Etiopía, España, Marruecos...), de acuerdo con las demandas que le son hechas.

La Granja de las Estrellas desarrolla actividades en cuatro grandes campos: las animaciones pedagógicas, la creación de herramienta pedagógicas, la participación en grandes proyectos y la organización de eventos de envergadura. En este artículo se exponen a detalle los proyectos, actividades y alcances del grupo.

## Abstract

The Ferme des Etoiles (Star Farm) is a group of private, independent and non-profit associations. Created in 1991, it is based in Fleurance (in southwestern France) and employs 12 full-time and 20 part-time staff. They carry out their activities in France and abroad (Mexico, Lebanon, Egypt, Ethiopia, Spain and Morocco among others), according to demand.

The Ferme des Etoiles develops activities in four main areas: pedagogical animations, the creation of pedagogical tools, participation in large projects and the organization of major events. This article discusses, in detail, the projects, activities and scope of the *Ferme des Etoiles*.

## Un paso científico y cultural

El ser humano siempre levantó la mirada hacia el cielo. Se interrogó sobre la naturaleza de los objetos y de los fenómenos que veía allí y procuró interpretarlos. Proyectó allí, primero, sus creencias, pero también sus temores y sus esperanzas; paralelamente, intentó comprenderlos y explicarlos.

De manera progresiva, el desarrollo científico ha ido revelando las interpretaciones mitológicas del cielo, pero éste aún queda cargado de misterio. Si bien los numerosos fenómenos encontraron una explicación racional, el cielo es aún una fuente inagotable de sueño y de imaginación.

¿Situación paradójica? ¡En apariencia, solamente! Primero, porque si bien la ciencia desveló numerosos misterios, también se ha percatado de otros, por lo que el universo y los fenómenos que lo conforman están, hoy, lejos de ser totalmente conocidos y explicados. En segundo lugar, porque los descubrimientos de la ciencia mostraron

un universo infinitamente grande e increíblemente variado que se revela al ser humano como una “nueva frontera” que hay que explorar y descubrir. En tercer lugar, y sobre todo, porque nos enteramos de una cosa fascinante: formamos parte del universo, nuestra historia comienza con él y estamos hechos de la misma materia. Somos, como lo dice Hubert Reeves, “hijos de las estrellas”.

Observar el cielo no es, pues, interesarse en un mundo abstracto, ajeno; es, por el contrario, descubrir nuestra propia historia y la de nuestros orígenes. Es comprender nuestro sitio y el de nuestro planeta en el universo. Es abrir el campo de la formidable aventura espacial. Es, también, darse cuenta de la fragilidad de la Tierra, de los peligros que la amenazan y de la necesidad de preservarla para legársela intacta a nuestros hijos. Lejos de ser un simple objeto de estudio, hoy el espacio —como el cielo de nuestros antepasados— nos remite a nosotros mismos, a nuestras preocupaciones diarias, a nuestras interrogaciones sobre nuestro pasado y nuestro futuro.



Figura 1. La observación del Sol en una escuela para niños. © Bruno Monflier.

Los oráculos que procuraban predecir el futuro leyendo el cielo, las misiones espaciales que intentan resolver los enigmas del universo y los satélites que observan la Tierra desde el espacio responden a la misma preocupación: conocernos mejor. Levantar la mirada, ante todo, un modo de mirar la Tierra y a sus habitantes y de buscar allí respuestas para el futuro; tal como nuestros antepasados creían ver allí signos que permitían predecir el porvenir, hoy buscamos los medios de preverlo y, más todavía, de prepararlo.

Es en este paso que se halla la imagen del ser humano mismo, impregnada de razón y de pasión, de rigor y de sueños, de ciencia e imaginación. Es este enfoque, vivo, complejo y diverso del ser humano y de la vida entornada hacia el futuro lo que constituye el hilo conductor que el grupo Ferme des Etoiles sigue y desarrolla desde hace 25 años, desde la región Mediodía-Pirineos.

En esencia, es éste un enfoque pluridisciplinario que, ante todo, supone la existencia de un lazo estrecho entre cada uno de nosotros y el cielo. Al parecer cuanto más conocemos el cielo y más conocidos son sus misterios nos es menos familiar: los cambios en el estilo de vida, la urbanización, la televisión y la contaminación luminosa nos

cortaron poco a poco el contacto directo con él y la mayor parte de nosotros ya no sabe reconocer ni nombrar las estrellas.

Recrear este lazo perdido entre el ser humano y el cielo se convirtió, así, en el objetivo prioritario del proyecto del grupo Ferme des Etoiles. Éste se construyó alrededor de tres firmes ideales:

- Emocionarse por la belleza del cielo: de la observación del cielo nocturno a simple vista al descubrimiento de los objetos del cielo profundo fotografiados por los telescopios más grandes, el cielo nos descubre una parte escondida —u olvidada— de la belleza del mundo.
- Comprender nuestro sitio en el universo: la astronomía nos enseñó que formábamos parte del universo: nuestra historia comienza con él y estamos hechos de la misma materia. Observar el cielo es, pues, descubrir nuestra propia historia y la de nuestros orígenes.
- Darse cuenta de la fragilidad de nuestro planeta, de los peligros que lo amenazan y de la imperiosa necesidad de protegerlo: es también lo que nos ayuda a comprender la astronomía.

Sobre esta base, el grupo Ferme des Etoiles definió sus misiones:

- Facilitar el acceso a la cultura científica y técnica para todos.
- Sensibilizar a los jóvenes a las disciplinas científicas.
- Establecer un lazo entre ciencia y las problemáticas ciudadanas.
- Facilitar una conciencia de los problemas de medio ambiente.

Con el fin de lograr nuestra misión, elegimos llevar a los otros al descubrimiento mediante la diversión y el placer. Procuramos ante todo suscitar la emoción a través de nuestras actividades y en nuestros diferentes espacios. Ello no nos impide seguir un paso científico riguroso.

El grupo está apadrinado por el célebre astrofísico Hubert Reeves y su actividades son seguidas por un Comité Científico compuesto de 20 personalidades del mundo de la investigación.

### Presentación

El proyecto vio la luz en 1991 con la creación de un Festival de Astronomía en Fleurance (Gers), aproximadamente a 100 km de Tolosa y 150 km de Pic du Midi. De manera progresiva, se desarrolló y se diversificó con numerosas actividades de sensibilización, de formación y también de ocio alrededor de la astronomía y de las



Figura 2. Los observadores esperando la noche en la La Ferme des Etoiles. © Bruno Monflier.

ciencias del universo. Hoy, el grupo Ferme des Etoiles reúne cuatro asociaciones. Cada una posee una misión distinta, con competencias específicas, pero cuyo fin es contribuir al mismo proyecto.

### La Ferme des Etoiles

Es el sitio emblemático del grupo y el que le da su nombre, acoge al público asegurando su alojamiento y el descanso en el mismo lugar. Situada en el corazón de los valles del Gers, que gozan de un cielo puro, esta antigua granja gascona ha sido escogida por la televisión francesa para instalar allí la locación principal de la emisión de “La Noche de las Estrellas”.

### A Ciel Ouvert

Es el corazón de la actividad del grupo. Encargada de la actividades pedagógicas, su misión consiste en iniciar y acercar al público a la astronomía y a las ciencias del universo, del cielo y de la tierra. A Ciel Ouvert participa también en la formación de profesores de ciencias. Está compuesta por un equipo de guías profesionales y apasionados que elaboran y ponen en ejecución los contenidos pedagógicos.

### Festival de Astronomía de Fleurance

Creado en 1991, fue el punto de partida de todas las iniciativas del grupo. Su misión es organizar tres grandes eventos anuales: el Maratón de las Ciencias, el Festival de Astronomía y el Festival Astro-Jeunes.

### Ciencia en Bigorre

Tiene su base en Tarbes y su misión consiste en desarrollar las actividades del grupo en los Altos Pirineos, más particularmente alrededor del Pic du Midi.

La localización de las asociaciones del grupo no es arbitraria. El departamento del Gers, en el sudoeste de Francia, es un territorio rural donde la presencia de la naturaleza se afirma con fuerza. La población practica allí diariamente un respeto a la Tierra, a su fauna y a su flora. Su cielo, privado de toda contaminación luminosa, ofrece condiciones incomparables de observación de la bóveda celeste. Tierra rural, pero igual tierra de vuelo, la región de Mediodía-Pirineos está entornada hacia el cielo. Capital europea de la aeronáutica y de la aeronáutica espacial, comprende también, entre sus riquezas, el Observatorio del Pic du Midi, el más importante



del continente europeo. ¡Era lógico, pues, que el grupo Ferme des Etoiles se instalara allí con el fin de compartir mejor al público la gran aventura del cielo y del espacio!

Las asociaciones del grupo Ferme des Etoiles son privadas, independientes y sin fines de lucro. Emplean a 12 empleados de tiempo completo, así como a una veintena de tiempo parcial.

### Los principales lugares de actividad

Los lugares de actividad del grupo se reparten como sigue:

#### Tres lugares permanentes

1. *La Ferme des Etoiles*. Antigua granja gascona, situada en el corazón de la naturaleza. Es un lugar propicio para la observación de la bóveda celeste. Sus cuatro hectáreas de naturaleza florida y preservada le permitieron obtener la categoría de “oasis natural”. Situada en la cumbre de uno de los valles del Gers, su cielo, de una gran pureza, es una verdadera delicia para los ojos y permite admirar más de 3 mil estrellas, así como nuestra soberbia Vía Láctea. El sitio acoge numerosas actividades, estancias y cursos de formación en astronomía, aeronáutica y astronáutica. También se organizan jornadas astronómicas específicas con ocasión de aniversarios y otras celebraciones.

La Ferme des Etoiles puede acoger a 20 personas en cuartos de huéspedes acondicionados con mucho cuidado (categoría 3 estrellas) y

20 personas en *astrobulles* (viviendas situadas en el corazón del parque, que ofrecen una vista nocturna sobre las estrellas).

La Ferme des Etoiles dispone de tres aulas y de actividades que permiten acoger hasta 80 personas durante el día. También cuenta con una treintena de instrumentos de observación, entre los que están: un telescopio de 620 mm de diámetro, binoculares Fujinon 25 x 150, refractores solares H alfa de 60 mm, telescopio Schmidt-Cassegrain de 200 mm, Dobson de 300 mm, Dobson de 200 mm.

Asimismo dispone de herramientas numéricas como una sala especialmente arreglada con seis simuladores de vuelo, equipados con una gran pantalla, de manecillas de mando, de asientos dinámicos y de un *software* de simulación; 10 tabletas numéricas puestas a disposición del público en el momento de las observaciones; un casco de realidad virtual Oculus Rift®, a la punta del desarrollo tecnológico; el Planetario Hubert Reeves, de los más grandes del sudoeste. Este planetario numérico de 7 m de diámetro acoge a 40 personas cómodamente instaladas en asientos abatibles. Herramienta notable y pedagógica para explorar el cielo, es también un instrumento verdadero de ensueño, gracias a la proyección de películas en 360°.

2. *Le Hameau des Etoiles*. Situado en Fleurance, es un centro de vacaciones totalmente dedicado a la astronomía. El público puede alojarse ahí, en pensión completa, en cabañas de madera, en el corazón



Figura 3. Un grupo de astroturistas mirando el cielo en la La Ferme des Etoiles. © Bruno Monflier.



Figura 4. Los astrobulles en la Ferme des Etoiles. © Bruno Monflier.



Figura 5. La cúpula de observación y el teatro en Le Hameau des Etoiles.

© Bruno Monflier.

de un campo de 30 hectáreas, adornado por un bosque, un lago y una alberca.

Le Hameau des Etoiles recibe a niños y adolescentes para estancias o clases de descubrimiento, así como familias, que tienen oportunidad de participar en días de actividades alrededor de la astronomía. Estructura única en Europa, cuenta con una Cúpula de Exploración del Universo, una sala de espectáculo equipada con la multimedia más sofisticada y cuyo tejado se abre totalmente a la bóveda celeste. El espectador puede entonces observar las estrellas en directo y por medio de un telescopio unido a pantallas individuales. El centro de animación también dispone de espacios polivalentes de estancia.

3. *El Pic du Midi*. Observatorio mítico y destacado lugar para la investigación científica desde 1880. El público es invitado a compartir la vida de los investigadores. Situado a 2,877 m de altura, el Pic du Midi ofrece una vista panorámica sobre la bóveda celeste y sobre la cadena de los Pirineos.

El alojamiento se hace en el hotel del Pic du Midi, frente a los Pirineos. Los cuartos habitualmente están reservados para los investigadores y totalmente equipados con todas las comodidades. El sitio también cuenta con un restaurante, con especialidades de las montañas pirenaicas. El grupo Ferme des Etoiles es socio exclusivo del Pic du Midi en las noches de observación. También organiza allí una parte de sus estancias. En el mismo lugar, nuestros guías conducen al público al telescopio Bernard Lyot, los coronógrafos, el espacio museográfico más alto de Europa. La cúpula Charvin, equipada con un telescopio de 400 mm, está reservada para las observaciones multitudinarias. Un telescopio de 500 mm también está disponible en la terraza.

### Cuarenta y dos lugares temporales

A través de acuerdos de colaboración, el grupo Ferme des Etoiles dispone de una red de 42 establecimientos asociados, repartidos en todo el territorio francés. Los animadores se desplazan por estos centros con todo el material de observación y pedagógico necesario para la realización de las actividades. Esta red nos permite así pro-



Figura 6. Una noche estrellada en el Pic du Midi.  
© Allen Salez.

poner a las escuelas que desean organizar clases u otras actividades soluciones que reducen los costos de transporte.

### Lugares ocasionales

Los equipos del grupo Ferme des Etoiles son móviles y pueden intervenir ocasionalmente en cualquier lugar, de acuerdo con las demandas que le son hechas. Intervienen regularmente en numerosos lugares en Francia, pero también en el extranjero, particularmente en México, Líbano, Egipto, Etiopía, España y Marruecos.

### Las actividades

Las actividades del grupo se reparten en cuatro grandes categorías:

#### Animaciones pedagógicas

Constituyen la actividad principal del grupo Ferme des Etoiles. Se imparten, cada año, a más de 12 mil personas, lo que representa 1,200 días de animación. Son concebidas y organizadas de acuerdo con los públicos a quienes se dirigen:

- *Formación para los jóvenes en y fuera del marco escolar.* Clases de descubrimiento con programas adaptados a los cuatro niveles educativos: maternal, primaria, colegios y liceos, y cinco grandes temáticas: astronomía, aeronáutica, astronáutica, medio ambiente y prehistoria. Con una duración media de cinco días, las 150 clases realizadas anualmente involucran a 3,750 alumnos.
- *Jornadas pedagógicas.* Aproximadamente 200 de ellas son organizadas para 2 mil jóvenes.
- *Colonias de verano.* Una treintena de estancias es propuesta cada año para 450 jóvenes de 8 a 17 años, aproximadamente.
- *Estancias de descubrimiento para adultos y familias.* Se dirigen a un público de personas que no tienen la intención de dedicarse a la astronomía y todavía menos de equiparse de un instrumento, sino que simplemente desean descubrir el cielo, comprender la

historia del universo y el sitio del ser humano en éste. Estas estancias tienen duración de algunas horas durante un día y una noche. Las actividades son propuestas en la Ferme des Etoiles y comprenden: cenas en común, seguidos por una noche de observación; estancias de noche con observación y diaporama; estancias de astronomía-gastronomía, en las que se mezcla el descubrimiento de la cocina local con el del cielo; periodos de prácticas de una semana reservados para las familias, con actividades para los niños y los padres. Más de 60 actividades de este tipo son organizadas cada año para cerca de 600 personas.

- *Prácticas de iniciación para adultos.* Se dirigen a personas que desean iniciarse en astronomía y enterarse de las bases, así como escoger un instrumento de observación y saber utilizarlo. Son varios los tipos de prácticas de iniciación: estancias de fin de semana (iniciación básica en la astronomía, pero también, en la aeronáutica); prácticas sobre un fin de semana para aprender a fotografiar simplemente el cielo de día y de noche; estancias de fin de semana especialmente dedicadas a los meteoritos; prácticas de iniciación de tres, cuatro días o una semana completa. Una treintena de periodos de prácticas en el año se realizan para cerca de 250 personas.
- *Prácticas de perfeccionamiento para adultos.* Estos periodos de prácticas se dirigen a verdaderos apasionados. La mayoría de las veces se trata de astrónomos aficionados, deseosos de completar su formación y de dominar nuevas técnicas. En esta categoría, el grupo Ferme des Etoiles también propone estancias diferentes y variadas con el fin de responder a las expectativas de cada uno: fines de semana “Práctica con el instrumento”, para aprender a utilizar bien su instrumento de observación; fines de semana “Tratamiento de imagen”, destinados a adquirir técnica de tratamiento de las imágenes del cielo profundo; fines de semana o semanas de iniciación a la astrofísica; fines de semana de encuentro y de intercambio con investigadores; estancias de tres, cuatro días o de una semana de perfeccionamiento; semanas dedicadas a la astrofotografía numérica. Cerca de 20 periodos de prácticas al año tiene cabida, en los cuales participan cerca de 200 apasionados.

- *Formaciones (capacitación).* El grupo Ferme des Etoiles también organiza actividades de formación para futuros guías de astronomía (en clubes, centros recreativos para niños, escuelas) y profesores, con el fin de completar o de actualizar su formación científica. Más de 60 personas cursan estas actividades cada año.
- *Noches de observación para todo público.* Organizadas en la Ferme des Etoiles, en el Hameau des Etoiles y en el Pic du Midi, constituyen la “actividad faro” que moviliza el número de personas más grande. En efecto, las 270 noches organizadas cada año acogen más de 5 mil personas.

Desde hace más de 20 años, los contenidos presentados por el grupo Ferme des Etoiles se adaptan sin interrupción a las evoluciones de las técnicas y de los saberes. Responden a los elementos de conocimiento y de competencia de los diferentes ciclos, desde los primeros aprendizajes hasta los del colegio y el liceo.

Los programas de las estancias son elaborados en estrecha colaboración con el equipo docente. Los conocimientos y las competencias son adquiridos en el marco de un paso de investigación que desarrolla la curiosidad, la creatividad, el espíritu crítico y el interés para el progreso científico y técnico.

El alumno debe ser capaz de practicar un proceso de investigación (saber observar, interrogar); manipular y experimentar, formular una hipótesis y someterla a examen, argumentar; poner a prueba varias soluciones; expresar y explotar los resultados de una búsqueda (investigación), utilizando un vocabulario científico oral y escrito; dominar los conocimientos en campos científicos diversos, y ejercer habilidades manuales y realizar ciertos gestos técnicos. La disposición de numerosos objetos técnicos (reloj de sol, equipos de meteorología, brújula...) enriquece esta aproximación.

El uso de nuevas herramientas de aprendizajes numéricos responde también al objetivo de las escuelas y de los colegios. Los trabajos de los alumnos son escritos consignados en una libreta de observaciones y de experimentos que repite el vocabulario específico. Un expediente pedagógico también se entrega al profesor.

## La creación de herramientas pedagógicas

Desde hace 25 años, la asociación ha concebido herramientas y soportes pedagógicos bajo formas diversas:

- *Módulos pedagógicos.* Los módulos pedagógicos han sido creados para las necesidades de la mediación científica. Existen, al día de hoy, 185 módulos repartidos como sigue: 50 módulos teóricos, 75 módulos prácticos y 60 módulos de visitas.
- *Soportes pedagógicos.* Acompañan los módulos prácticos y son muy diversos: mapas del cielo para construir, relojes de sol, maqueta del sistema solar.
- *Exposiciones.* El grupo concibe y realiza exposiciones ya sea por su propia cuenta o por encargo. Podemos citar a título de ejemplo: “El calendario cósmico”, un gran fresco de 15 tableros que cuenta la historia del universo condensado en 1 año. Una exposición realizada para nuestras necesidades internas; o “Descubrir los cometas”, exposición realizada para el Centro Nacional de Estudios Espaciales en ocasión de la Misión Rosetta.
- *Maletines pedagógicos.* Sirven de soporte a las actividades de animación. Contienen una serie de herramientas pedagógicas. Como ejemplo puede mencionarse el maletín sobre los cometas, destinado a acompañar la exposición mencionada, o el maletín sobre la biodiversidad (actualmente en realización).



Figura 8. Campamento de verano para jóvenes astrónomos. © Bruno Monflier.

- *Aplicaciones numéricas.* Se trata de nuevos soportes hoy ineludibles para el avance pedagógico. El grupo lanzó una aplicación de lectura de paisajes titulada “Los paisajes que dicen mucho” y otra aplicación sobre los sitios de caídas de meteoritos (actualmente en construcción).

Desde hace algunos años, el espacio virtual invade el espacio público y privado. Ya sea por la digitalización y el procesamiento de datos, la fabricación y la difusión de la información, la utilización de los motores de búsqueda en Internet, la asistencia a numerosas actividades diarias o a la creación, por supuesto, de las redes sociales, se vuelve cada vez más difícil de escapar de eso.

Por cierto, el interés y las ventajas del espacio virtual son reales: apertura al mundo, el acceso casi ilimitado a la información y al saber, racionalización y simplificación de numerosas tareas, participación... Pero los inconvenientes (¿los peligros?) son también reales: desconexión de la realidad, aislamiento, diluvio informacional, difusión de informaciones peligrosas, intromisión en la intimidad, utilización de datos personales para fines comerciales o políticos, manipulación de las mentes...

La educación no escapa, evidentemente, de este movimiento, y las iniciativas para introducir el espacio virtual en la escuela se multiplican. A la divulgación científica, nuestro oficio, este hecho también le concierne. Numerosas herramientas (software y hardware) aparecen para el gran público (tabletas y celulares) y en innovaciones (casos de realidad virtual) o soportes pedagógicos específicos (arpa láser). Si bien reconocemos la utilidad de algunos de estos dispositivos, pensamos que estas herramientas deben estar al servicio de un fin (la educación o el aprendizaje) y no constituir un fin en sí. Conviene identificar lo que cada una de las herramientas aporta y cómo pueden contribuir a una mejor comprensión y facilitar el aprendizaje, evitando el aislamiento o el ensimismamiento. Utilizar el espacio virtual como herramienta participativa de aprendizaje es nuestro objetivo. Es por eso que decidimos dar un paso que nos permite someter a examen y evaluar la pertinencia de ciertas herramientas y su interés educativo. Con este fin, seleccionamos primeramente en nuestros módulos a quienes pensamos que pueden hacer una aportación interesante sobre espacio virtual. El resultado



obtenido para los niños puede, así, ser objeto de una apreciación común entre los padres o los profesores.

### La participación en grandes proyectos

La participación en grandes proyectos constituye el tercer aspecto de la actividad del grupo Ferme des Etoiles. Entre los proyectos más importantes cabe mencionar:

- *Reserva de Cielo Estrellado del Pic du Midi*. Este proyecto, llevado a cabo por la administración del Pic du Midi y el Observatorio de Mediodía-Pirineos, tuvo como resultado la certificación de una vasta zona alrededor del Pic du Midi como Reserva Internacional de Cielo Estrellado. Estas acciones siguen en proceso para ampliar y fortalecer el proyecto.
- *Carta de calidad en la iluminación pública del país Puertas de Gascuña*. El Grupo Ferme des Etoiles realizó un estudio y escribió una carta de calidad en la iluminación pública destinada a proteger el cielo nocturno y a reducir el consumo de energía sobre este territorio.
- *Polo de excelencia rural del país Puertas de Gascuña*. El grupo activamente participó en este proyecto, cuyo tema era la creación de una plataforma de aplicación de las técnicas satelitarias en

ambiente rural. En este marco, ha sido creado un Centro Pedagógico del Desarrollo Sostenible, administrado por el grupo.

- *El proyecto INMEDIAT*. Al ser miembro de Ciencia Animación Midi-Pyrénées (SAMP), el grupo Ferme des Etoiles participa en este proyecto, cuyo objetivo es desarrollar, experimentar y promover nuevas formas de divulgación científica para la utilización del espacio virtual y de sus prácticas de innovación. Se trata de crear un entorno propicio para el desarrollo de proyectos innovadores sobre nuestros territorios. Actúa como una incubadora de proyectos al servicio de todos los actores de la cultura científica.
- *Proyecto Vigía-Cielo*. Es un proyecto de ciencia participativa vinculado al proyecto científico Fripón. Este último consiste en la instalación de una red de 100 cámaras sobre el territorio francés, cuyo objetivo es la localización de las caídas de meteoritos. Vigía-Cielo consiste en movilizar y formar equipos de personas susceptibles de ir al sitio de la caída para recobrar meteoritos o sus fragmentos.
- *Proyecto Sideral*. El grupo Ferme des Etoiles integró el proyecto nacional Sideral. Apoyado por la Asociación Francesa de Astronomía y el Francas. Su objetivo es iniciar a 20 mil jóvenes al año en la astronomía en estancias colectivas. Para alcanzar este objetivo, la formación de 300 guías cualificados es necesaria.
- *Proyecto Web TV*. El grupo desarrolló una Web TV cuyo objetivo es poner en línea las conferencias del Festival y también acercar la ciencia al ciudadano a través de videos cortos en los cuales los investigadores hablan de su oficio.
- *Proyecto Ruta de los Orígenes*. El grupo participa en un vasto proyecto de colaboración europea con Cataluña, apuntando a la creación de un camino turístico sobre el tema de los orígenes. Cuenta con socios franceses como La Ciudad del Espacio y el Museo Natural de Historia de Tolosa, y del lado catalán, con la Universidad Autónoma de Barcelona, el Centro de Prehistoria de Nogueira, así como el Consorci del Montsec.



Figura 9. Un futuro Einstein frente a una representación hermosa del sistema solar. © Bruno Monflier.

- *La Noche de las Estrellas en México*. El grupo Ferme des Etoiles ha sido contratado para una misión de asistencia técnica que apunta a la organización de noches de las estrellas, basadas en el modelo desarrollado en Francia. La primera noche mexicana de las estrellas se efectuó el 31 de enero de 2009 y reunió cerca de 300 mil personas en 22 sitios. Se prosiguió sin interrupción después y la 7ª edición se efectuó en noviembre de 2015 en 26 sitios.
- *Proyecto Suena Desierto*. El grupo es el encargado de un estudio y de realizar asistencia técnica y de acompañamiento para la definición y la puesta en ejecución de un proyecto de cultura y de turismo científico en Bernal, en el Estado de Querétaro (México).
- *Festival de Astronomía de Fleurance en Líbano*. El grupo Ferme des Etoiles ha sido seleccionado por Líbano para organizar el 1º Festival de Astronomía de Fleurance en Líbano (la elección del nombre fue a petición de los libaneses). Éste se celebró en mayo de 2015 y será reconducido en 2016.

### La organización de grandes eventos

El grupo Ferme des Etoiles organiza cada año varios acontecimientos de cultura científica alrededor de la astronomía y las ciencias del universo.

- *Festival de Astronomía de Fleurance*. Se celebra anualmente desde hace 26 años, en la ciudad de Fleurance. Es el evento más importante de cultura científica destinado al gran público en Europa. Acoge durante una semana a una centena de investigadores y de divulgadores científicos y registra cerca de 25 mil entradas. Consta de tres acontecimientos principales:
  - *El Maratón de las Ciencias*, en el cual 12 de los especialistas más notables, científicos, filósofos, escritores, se

relevan durante 12 horas de mediodía a medianoche para analizar desde ángulos diferentes y complementarios, a los grandes sujetos de la ciencia contemporánea.

- *Festival “Adultos”*. Durante todo una semana, hay numerosos eventos adaptados para todo público: conferencias, capacitaciones por nivel en forma de curso o de talleres, exposiciones, animaciones y tardes de observación para todos.
- *Festival “Astro-jeunes”*. Se trata del único evento astronómico en Europa totalmente dedicado a jóvenes de 4 a 17 años. Propone más de 60 actividades organizadas por jóvenes investigadores, los guías de la asociación A Ciel Ouvert (grupo de Ferme des Etoiles) y los científicos del Festival “Adultos”.
- *La Noche de las Estrellas*. Como el Festival de Fleurance, la Noche las Estrellas surgió en 1991. La idea era simple: invitar al conjunto de la población a encontrarse para observar el cielo, el mismo día, en el mismo momento. Se trataba de crear, así, un acontecimiento verdadero y popular susceptible de movilizar al número más grande posible de personas. Los objetivos han sido: sensibilizar al público en la ciencia, ofrecer un momento de ensueño y promover la práctica de la astronomía. El contenido es el siguiente: un solo tema al año para todos los sitios, observación a simple vista, observación con los instrumentos, utilización de un mapa del cielo, posibilidad de proponer otras actividades personalizadas (astronómicas o no). En el 2015 se realizó la 25 edición de la Noche de las Estrellas en 443 sitios en Francia, siete en otros países participantes, 2,504 guías de estrellas en los diferentes sitios, 135,000 personas en los sitios de observación.

# Cerremos las ventanas

Sí, cerremos las ventanas a través de las cuales observamos el cielo, encendamos todas las luces posibles y dejemos ciegos a los astrónomos y aficionados que se refugian en los últimos sitios privilegiados para mirar el cosmos desde el suelo terrestre. Hay que darle la espalda a este conocimiento milenario, el más antiguo de la humanidad.

Celebremos nuestra insensibilidad e interrumpamos el relato cósmico, cuyos orígenes se remontan a nuestros antepasados homínidos que habitaron aquí hace unos 2.5 millones de años. Al tener que aguardar el paso de la noche salpicada de puntos titilantes dio inicio la gran aventura de la poesía sideral. Poco importa, parece insignificante frente a las necesidades de la civilización. Nadie en sus cabales se atrevería a negarle a un poblado remoto de las ciudades alumbrar sus calles y caminos rurales. Pero tampoco ninguna persona sensata desconocería el derecho que tienen los humanos de perpetuar una tradición, quizá la más valiosa: observar el espacio exterior. Valiosa porque la astronomía no es una actividad esotérica ni cosmética, sino un factor económico a lo largo de la historia y un concepto ontológico, estético. Tiene que ver con nuestra más profunda definición de ser como individuos y como sociedad, así como con un resorte ancestral de la evolución humana: la búsqueda de belleza.

El 10 de junio de 2016 BBC News publicó un artículo según el cual el 80% de la población mundial vive en una especie de “exceso luminoso”, es decir, padece algún tipo de contaminación debido a la diversidad de fuentes de luz artificial, no solo de luminarias en calles y autopistas, sino la que se desprende de los anuncios comerciales y las casas de los trashochados, quienes, dicho sea de paso, sufren trastornos del

sueño y enfermedades relativas. Millones de personas en todo el mundo ya no pueden elegir entre salir a mirar el cielo nocturno o entretenerse con alguna clase de pantalla, apenas lo miran de día. Lo peor de todo es que una buena parte de esa luz artificial se fuga, no alumbra a nadie, y perturba la vida de muchas otras especies, ya sea en su descanso o en su actividad cotidiana cuando el sol se ha ocultado.

Así se provoca un dilema y la tentación de confundir los términos: creer que unos tienen más derecho que los otros, que se debe sacrificar “algo” en aras del progreso. Sin embargo, el mundo ha cambiado y las sociedades, gobiernos y organismos internacionales pueden entender el dilema e intentar resolverlo de la manera más diligente. Por diversas razones que se conjugan en este momento (cambio climático, necesidad de ahorrar energía, la exigencia de no destruir la cultura astrofísica) el alumbrado público en las calles de los poblados y en los caminos rurales, sobre todo en los cercanos a sitios privilegiados, debería rediseñarse. ¿Es mucho pedir que el alumbrado de los centros urbanos sea más eficiente y permita a los miles de estudiosos y aficionados que gustan de contemplar el cielo hacerlo sin tener que correr por ahí en busca de un rincón, como si fueran extraños en su propia casa?

Vale la pena recordar la frase acuñada por los amigos del Instituto de Astronomía de la UNAM en Ensenada para defender el derecho a un cielo oscuro: “Apaga un foco, enciende una estrella” o, dicho de otra manera, “rediseña un foco, enciende una estrella”. Evitemos al malvado personaje al que José Gorostiza alude en su poema *Muerte sin fin*, quien es “como una estrella mentida / por su sola luz, por una / luz sin estrella, vacía / que llega al mundo escondiendo su catástrofe infinita”.

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# Pensar en un planetario, el caso de estudio del Planetarium Torreón

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## Resumen

La preservación de los cielos oscuros como un derecho de la humanidad es una responsabilidad compartida entre científicos, políticos, sociedad civil y divulgadores de la ciencia. Estos últimos tienen una gran responsabilidad debido a su inherente capacidad de comunicar aspectos relevantes del ámbito científico y vincularlos con la comunidad.

En ese sentido, los planetarios son el escenario perfecto para que la comunidad científica presente iniciativas relevantes que busquen atenuar el efecto de la contaminación lumínica en el cielo de todo el planeta; pero también, es responsabilidad de los comunicadores de la ciencia hacer ver este problema como una oportunidad para mejorar nuestras condiciones de vida, tanto económicas como encaminadas a cuidar nuestro medio ambiente.

Los planetarios nacen a principios del siglo XX como una opción para educar sobre astronomía dentro de los museos, presentando el cielo como un espectáculo que permite explicar los movimientos de las estrellas, planetas y todo lo que nos rodea. Con el avance de la iluminación en las ciudades, estos espacios se convirtieron en un lugar donde el espectador observaba lo que desde su casa no podía; el cielo se restringió a lejanos parajes donde la luz excesiva de las ciudades no afecta la observación de las estrellas.

Los planetarios, pues, al presentar el cielo estrellado en perfectas condiciones dentro de sus domos, permiten al participante sensibilizarse del problema que muchas veces ni siquiera conocemos. Pero ahora estos espacios van mucho más allá, al ser digitales y al tratar casi cualquier tema; se han convertido en verdaderas instituciones de divulgación científica multidisciplinaria, capaces de sensibilizar a grandes públicos sobre temas de importancia global. Así, la vinculación con la sociedad reviste especial importancia y genera puentes que, sin duda, nos ayudan a trabajar en pro de recuperar los cielos oscuros, para seguir descubriendo el universo como un derecho de la humanidad.

El caso de estudio de Planetarium, en la ciudad de Torreón, México, presenta aspectos importantes por tomar en cuenta en la vinculación con la comunidad, con la diferencia importante de que fue primero el gobierno quien decidió tomar la iniciativa de mejorar la calidad de iluminación de la ciudad. Ahora, el trabajo de la institución es sensibilizar a la gente sobre la importancia de este cambio en la vida social y el entorno ecológico de la comunidad.

Así pues, las estrategias implementadas por el planetario como elemento interlocutor entre especialistas, tomadores de decisiones y el gran público generan un cambio paulatino en la sociedad en la que están inmersas dichas instituciones.

## Abstract

The preservation of dark skies as a human right is the shared duty of scientists, politicians, civil society and science disseminators, the latter of which are especially duty-bound because of their ability to communicate relevant information from the scientific field and link them to the community. In this sense, planetariums are the perfect stage for the scientific community to present relevant



initiatives that seek to mitigate the effects of light pollution in our planet's skies. It is also the responsibility of science disseminators to present this issue as an opportunity to improve standards of living both in terms of economic development and the protection of the environment.

Planetariums arose in the early twentieth century as an educational tool to inform people about astronomy in museums, presenting the marvels of the night sky and thus explaining the movement of stars, planets and other astronomical objects that surround us. As lighting has increased in cities, planetariums have become places that allow people to see what they cannot see from their homes since the view of the night sky became restricted to distant places where the excessive light of cities does not affect stargazing.

Planetariums show the starry sky in perfect conditions within their domes, allowing the observer to become aware of a problem that we often do not even know exists. More recently, planetariums have become genuine institutions of dissemination of multidisciplinary science, capable of raising awareness among large public audiences on matters of global importance. Thus, the relationship with society is particularly important and creates bridges that will undoubtedly help us in our work towards recovering the dark skies and to continue discovering the universe as a right of humanity.

The case study of the Planetarium in the city of Torreon, northern Mexico, presents important issues to consider when connecting with the general public, with the important difference that it was the local government that first took steps to improve the quality of public lighting in the city. Now, the Planetarium works towards raising awareness about the importance of this change in the community's social life and environmental surroundings.

Thus, the strategies implemented by the planetarium as an interlocutor between specialists, decision makers and the general public create gradual change in the society in which they are involved.



Figura 1. Las exhibiciones tradicionales en los planetarios son importantes para explicar conceptos básicos. © Carmen González.

El planetario tal como lo conocemos nace en 1923 gracias al diseño de la empresa Alemana Carl Zeiss, la cual por encargo del Museo de la Ciencia y la Técnica de Berlín construyó un instrumento optomecánico capaz de simular el cielo estrellado dentro de una pantalla en forma de media esfera. Hasta ese momento, los planetarios eran esferas de unos pocos metros, repletas de pequeñas perforaciones con la posición de la estrellas, con asientos para unas 10 personas. El éxito de aquel primer *planetario*, como se le conoció al instrumento, consistió en su capacidad para representar en un gran auditorio el cielo con un realismo impresionante (Artigue, 2002). En los años siguientes se construyeron planetarios en las ciudades más importantes del mundo, con lo que comenzó una historia de la comunicación de la ciencia desde el punto más puro de la historia de la humanidad, la simple contemplación del cielo.

Hoy, cuando nos referimos a un planetario, hablamos de un concepto mucho más amplio. Hemos dejado atrás la sala de simulación

del cielo para centrarnos en una institución de divulgación científica completa. Si bien no todos los planetarios son así, quiero hacer referencia a los casos exitosos donde la integración de más elementos propicia mejores prácticas y, por ende, una mayor capacidad de divulgar ciencia y atender a diversos públicos.

Aunque actualmente el concepto popular de planetario es el de una sala donde “se ven las estrellas”, quiero referirme al nuevo significado de la palabra: un centro de divulgación científica orientado a la astronomía y ciencias afines, que mediante simulaciones del cielo, exposiciones, talleres y observación por telescopios permite al público acercarse a las ciencias (Reynoso, 2016).

Como caso de estudio de vinculación y trabajo con la comunidad, para este artículo tomamos el Planetarium Torreón, uno de los dos planetarios independientes de México que nace en el año 2008 del trabajo de la asociación civil Planetario Torreón. La idea primordial de esta asociación era dotar a la ciudad de un planetario, observatorio y museo de ciencias que pudiera ayudar a elevar el nivel educativo de los habitantes de la Comarca Lagunera. Planetarium Torreón es una organización no gubernamental que cumple dos años con instalaciones abiertas al público y ha atendido a la fecha más de 170 mil personas.

Es un centro de divulgación científica que cuenta con una sala planetario de 12 m para 90 personas, con un sistema totalmente digital (Digistar 5 4k) capaz de mostrar simulaciones del cielo, pero también películas en formato inmersivo; éste es el corazón de la institución. Sin embargo, para complementar su sala y de acuerdo con este concepto más amplio de planetario, también cuenta con tres salas temáticas de astronomía, una de talleres llamada “Ciencia en tus manos” y otra con juegos interactivos de física; además de una “Sala de la Tierra”, con un simulador de cambio climático. No menos importantes que el planetario son sus dos observatorios astronómicos: uno con un telescopio de medio metro de apertura totalmente robótico, el más grande de México abierto al público, con un auditorio anexo para 70 personas; otro instalado en una torre con un telescopio refractor apocromático de 10", también el más grande en su tipo en México. Ambos observatorios aprovechan la condición de esta zona del norte del país, con hasta 300 días al año de cielo despejado, y ahora, con una iluminación

LED totalmente apantallada en toda la ciudad que ha reducido enormemente la contaminación lumínica.

Con estas instalaciones, el público tiene una experiencia completa mediante la que puede viajar por el espacio en un increíble simulador, jugar y experimentar en sus manos con conceptos básicos que le ayudan a entender el universo, así como vivir la experiencia de ver por un telescopio profesional.

Al día de hoy, los planetarios cuentan con capacidades muy superiores a las de los primeros instrumentos diseñados hace 90 años; al ser totalmente digitales, se puede proyectar en el domo casi cualquier temática en un ambiente de inmersión total. Es precisamente ahí



Figura 2. Exterior del nuevo observatorio del Planetarium. En su interior se encuentra un gran telescopio Refractor de 10". © Eduardo Hernández.



Figura 3. El telescopio refractor apocromático de 10". Se trata del más grande de su tipo en México. © Eduardo Hernández.

donde podemos encontrar el primer punto de acción relacionado con la contaminación lumínica.

Todos los simuladores de estrellas diseñados para planetarios tienen la función de representar un cielo contaminado con iluminación de la ciudades. Las empresas expertas en simuladores saben que es uno de los temas fundamentales dentro de un domo, ya que trabajan con expertos en astronomía que buscan hacer de estas simulaciones una experiencia científicamente correcta. Ésta es una buena oportunidad para hablar de la contaminación lumínica como la responsable de que no se vean las estrellas en las ciudades, ya que el público puede entenderlo a la perfección; sin embargo, por lo regular no se dimensiona el problema real y se considera que dicho problema sólo importa a aquellos que observan las estrellas. Esta falta de cercanía del problema con respecto al público es quizás el primer punto que debemos atender. Si no consideramos la contaminación lumínica como un problema que nos afecta a todos quizás no será posible llegar a soluciones de fondo y aceptadas por la mayoría.

Como institución, el planetario debería tener la corresponsabilidad de trabajar con astrónomos en generar políticas internas para presentar a su público toda la serie de problemas que ocasiona la contaminación lumínica; pero en igual proporción, también debería

comunicar los beneficios que se pueden obtener de reducir y mejorar las formas en que iluminamos nuestras ciudades, en particular nuestras casas.

Existe mucha gente preocupada por el medio ambiente que sin duda tomará medidas en su entorno para reducir este problema; sin embargo, para otros el problema será irrelevante. Con estos últimos es necesario realizar un trabajo más intenso de sensibilización acerca de los beneficios que podrían tener si efectuarán cambios sencillos en su vida cotidiana.

La sociedad cambió rápidamente la forma en la que ilumina sus casas en virtud de los costos asociados a la energía eléctrica. La transición de los focos incandescentes a las lámparas fluorescentes (ahorradoras) se dio cuando estas últimas tuvieron precios suficientemente bajos como para permitir que su adquisición redujera el consumo eléctrico en casa. Lo lamentable es que estas lámparas continuaron enviando mucha luz innecesaria a la atmósfera; sólo cambiaron las longitudes de onda en la contaminación lumínica. Afortunadamente, estamos en el momento en que la iluminación LED está llegando a los costos apropiados para llevar a cabo esa migración, es un momento propicio para informarle a la gente cuáles son las formas correctas de iluminar, reduciendo



Figura 4. La interactividad del público con experimentos de ciencia hace más fácil explicar conceptos complejos en un planetario. © Carmen González.



Figura 5. Actividades de divulgación y sensibilización sobre la contaminación lumínica dentro del observatorio. © Carmen González

su consumo de energía y ayudando a atenuar los problemas de la contaminación lumínica.

Si a este tema agregamos el ingrediente de la seguridad, explicando por qué la correcta iluminación hace más seguros nuestros hogares, calles y parques, la gran mayoría de la población tomaría nota de estas medidas que benefician directamente su calidad de vida. Para la mayoría de las personas (según un muestreo aleatorio de 500 muestras de salida; Planetarium Torreón, 2015), conceptos como *encandilamiento*, *dispersión de la luz*, *longitud de onda*, entre otros, son totalmente ajenos a su vida cotidiana y prácticamente inexistentes en términos de contaminación lumínica. Éste es un campo donde podemos buscar aliados como grupos de ambientalistas, departamentos de ecología de los tres niveles de gobierno y otros más que estén conscientes y dispuestos a buscar mejores condiciones de vida en sus comunidades.

El caso de estudio del Planetarium Torreón tiene un aspecto muy importante en cuanto a contaminación lumínica. Estas instalaciones fueron construidas en el Bosque Urbano de Torreón, un parque ecológico que se modernizó totalmente en el 2014; desafortunadamente, esa administración municipal no tomó en cuenta las solicitudes hechas por el Planetarium para una correcta iluminación en todo el parque, quedando instaladas luminarias de vapor de sodio con pantallas que lanzan la luz con ángulos de hasta 45° hacia arriba o que incluso iluminaban directamente el observatorio astronómico.

Con el cambio de gobierno en 2015, una de las medidas que tomó el Presidente Municipal fue mejorar el deteriorado alumbrado de la ciudad para renovarlo totalmente con luminarias LED que fueran totalmente apantalladas. Así, durante el 2015, la ciudad cambió de una iluminación totalmente amarilla a una blanca amarillenta que presenta mejores condiciones de seguridad y consumo de energía. Pero el cambio no quedó sólo en las calles de la ciudad; en las plazas y en el Bosque Urbano fueron sustituidas todas las luminarias por equipos totalmente apantallados y colocados sólo en áreas donde era necesario contar con visibilidad. Incluso en la plaza principal del Planetarium fueron sustituidas las lámparas omnidireccionales de focos ahorradores por luminarias LED totalmente apantalladas. También en colaboración con la con el propio planetario, se programó la ilu-

minación de sus fachadas para que permanezcan sólo dos horas encendidas después de que se oculta el Sol. Así, de la mano sociedad civil y del gobierno se ha dado un claro ejemplo de que se puede trabajar en conjunto por el bien de la comunidad. Cabe hacer mención de que, sin embargo, este cambio de luminarias fue realizado principalmente por un factor económico, es decir, por el ahorro en el consumo de energía que a un mediano plazo permitirá a la ciudad ahorrar en este rubro.

Como había comentado, el trabajo del Planetarium es sensibilizar a la población sobre por qué es importante contar con mejor iluminación en la ciudad; es ahí donde vemos otra parte del problema: cómo beneficia este cambio al ciudadano.

Si volvemos al mismo caso en el que el ciudadano es ajeno a la contaminación lumínica, una familia que ve que la erogación por parte del gobierno de una cantidad mayor de recursos para una luminaria LED y no para una convencional de vapor de sodio puede considerar que es un gasto innecesario. Es por ello, que ya sea que el gobierno ya realizó el cambio de luminarias por cuestiones económicas, o bien que pugnamos porque queremos realizar el cambio para preservar los cielos oscuros para su estudio, la clave es sensibilizar.

Aunque el cambio de luminarias en toda una ciudad representa un costo alto, la duración de estas lámparas comparadas con otras es mucho más larga. Si tomamos en cuenta su consumo eléctrico, los parámetros de reducción son semejantes, la luminaria LED gastará una menor cantidad. Al inicio, el gasto puede ser mucho mayor al beneficio, pero a mediano plazo la inversión se amortizará y comenzaremos a ver beneficios directos en un tema imprescindible, el económico.

Además del tema económico, el cambio beneficiaría al ciudadano en la seguridad, ya que habrá calles mejor iluminadas, con el tipo de luz correcto que genera mejores condiciones de conducción. De igual forma, zonas mejor iluminadas y sin destellos ayudarán a prevenir incidentes delictivos. Y podríamos hablar de muchos otros factores, pero el tema principal es ver las oportunidades de comunicación entre la ciencia y la sociedad.

La clave de la vinculación de los investigadores con los ciudadanos podrían ser los museos de ciencia y planetarios, lugares ideales para exponer temas y replantear puntos de vista de nuestra sociedad (SEP, 2011). Debo hacer mención de que es imprescindible que los investigadores estén mucho más cercanos a la fuente del problema —que somos todos—. Este acercamiento podría darse mediante la participación u organización de foros en diversas instituciones con el tema de la correcta iluminación, o escribiendo artículos de divulgación sobre la importancia de cuidar nuestros cielos. Lo anterior habría de realizarse con base en los dos elementos fundamentales: el primero, el derecho del ser humano a observar el cielo estrellado y estudiarlo también; el segundo, los beneficios que tiene la correcta iluminación para la sociedad y el planeta. Es imprescindible que ambos aspectos se traten juntos; de lo contrario, no estaríamos atacando el problema de fondo.

Podemos comenzar con lo más obvio: los centros de investigación, planetarios y museos de ciencia deberían cumplir todas las normas aplicables para cuidar nuestros cielos; de no ser así, es imposible sensibilizar a la población en un aspecto que ni siquiera los propios interesados podemos solucionar. En el caso del Planetarium Torreón, la gente que visita los observatorios, además de observar las estrellas, aprende nociones básicas de iluminación, ya que durante la plática es posible ver ejemplos de buena y mala iluminación, con lo que estamos poniendo nuestro granito de arena para reducir este problema que es de todos.

La contaminación lumínica es un problema que nos afecta a todos, no sólo a los astrónomos, y sus consecuencias van mucho más allá de no poder observar las estrellas. Con esta sencilla idea, debemos trabajar para mejorar nuestras políticas de sensibilización, para lograr una conciencia global de esta problemática; por supuesto, los planetarios son herramientas poderosas para lograrlo.

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Double rainbow over Alfa Planetarium. 24 August 2015, Nuevo León, México. © César Cantú.



Chapter 7

# Conclusions

Capítulo 7

# Conclusiones

# The Right to Dark Skies: Results and Conclusions

As a result of two days of presentations and one day of collective reflection in working groups, the experts present at the International Meeting *The Right to Dark Skies* defined the following lines of action to safeguard and protect the visibility of our night skies.

## Measurement of Light Pollution and International Monitoring

In recognition that dark skies are both an important scientific and cultural resource and in order to promote the preservation of dark skies at visible and radio wavelengths for both scientific and cultural purposes, the group of experts gathered in Mexico City recommend that a set of standardized systems of measurement for monitoring light pollution be developed. This system would provide quantitative information about the status and progression of sky brightness and radio interference as well as their impact on areas of astronomical significance; likewise, it would include a system of monitoring impacts on human health and other biological systems in general in order to ensure the ability of current and future generations to appreciate the stars together with encouraging more efficient use of energy for sustainable development.

This information could then be transmitted to governmental agencies for action at local and national levels as well as to UNESCO and other heritage management organizations. The information generated can contribute to the implementation of management and conservation plans in areas particularly suitable for observation, as well as contribute to the preservation of night sky visibility over natural and cultural protected areas.

In particular, the development of such a set of standardized systems of measurement is an urgent need for astronomical observatories and

their surrounding areas due to the recent increases in light pollution from urban and productive development around the world.

As a fundamental premise for the establishment of such standards, it is strongly recommended that the proliferation of unshielded lighting of any kind or lighting fixtures with excessive blue emission (e.g., colour temperatures higher than 3000K) be controlled. The monitoring system(s) defined should have the ability to measure colour temperature, brightness and directionality.

## Priorities for International Cooperation

One of the key guarantors for the development of a standardized set of measurement systems that could be applied globally is international cooperation. In this vein, the importance of cultural, scientific, environmental, governmental and commercial entities is fundamental.

Of the actors called upon to develop collaborations in the field of international cooperation, the following are highlighted (in no particular order of importance):

- United Nations Educational, Scientific and Cultural Organization (UNESCO), The Office for Protection of Sky Quality in Northern Chile (OPCC in Spanish) and the Technical Office for the Protection of Sky Quality (OTPC in Spanish)
- International Astronomical Union (IAU)
- Other darks skies institutions such as the International Dark-Sky Association (IDA), Starlight Foundation, CieloBuiro and Cel Fosc, among others.
- Professional observatories
- Professional astronomical societies
- Space agencies
- National parks
- Amateur astronomy societies
- Associations of specialists in the conservation and management of heritage
- National, state, and local governments
- Environmental protection organizations
- Urban planners

- Health experts
- Lighting professionals and associations
- Lighting companies
- Energy companies
- Museums
- Archives
- Academic centres specialized in the social sciences

### Plan of Action

1. It is highly recommended that an international team be set up (with the participation and perhaps leadership of the IAU and/or other agencies, in cooperation with other astronomical organizations) with the aim of establishing a common glossary and standard system of characteristics suitable for allowing the future installation of astronomical observatories. Proposed measurement system elements include, among others:

- all-sky coverage
- colour information
- spatial resolution
- satellite data (space agencies and private companies)
- archival and open database
- standard open-source software to archive, analyse, and share results

This system should include complementary sources of measurements, such as aerial surveys.

Concerning the standardization of techniques and protocols for the collection of night sky quality data, it is encouraged that the work conducted by the Loss of the Night Network (LoNNe)<sup>1</sup> be reviewed. This European funded effort, which has been ongoing since 2012, provides a network for almost 40 organizations to share their experiences with the aim of fostering cooperation between these players in order to cross-fertilize skills and capacities to create standard operating procedures.

For the harmonization of monitoring data (primarily SQM), the work of the Italian coordination for the collection of light pollution data (CORDILIT in Italian)<sup>2</sup> is highlighted and should be reviewed. The CORDILIT network, which has been

operating in Italy since 2011, is a lightweight infrastructure, aggregating data from stations deployed in various parts of the country. The core of the network was started by two civic associations, Veneto Stellato and Attivarti.org with the BuioMetria Partecipativa project, which have since been joined by other activists and scientists, including the National Research Council of Italy. All of the data is released with an open license online.

2. It is also recommended that the implementation of such systems take place as soon as possible in order to provide the information necessary to governmental and international authorities at various levels to support and encourage the development of legal and social frameworks for the protection of areas of astronomical significance in the face of ever increasing urban processes and to serve in the decision making processes of multilevel government systems.
3. It is recommended to promote awareness-raising activities about the need to preserve dark skies for their scientific, health, environmental, and cultural value. These actions could be directed to the general public, agencies of the United Nations system, governmental agencies, non-governmental organizations and civil society, without forgetting the private business sector, the education sector and academia as a whole.

Specifically, within the context of UNESCO, the group of specialists recommended that a working group be created to generate a report on the subject with the aim of including it in the annual UNESCO Science Report, incorporating the elements below:

- Society: citizenship involvement to reinforce the conscience of (national and world) citizenship. Various “citizen science” initiatives could be implemented, such as making and sharing sky measurements at home and comparing them with measurements in other parts of the world.
- Culture:
  - Creative Cities (UNESCO), as communities of defence and conservation of dark skies.
  - Sustainable development cities (heritage as well as

1. <http://www.cost-lonne.eu/>

2. <http://www.cordilit.org>



efficiency, long-term approaches), impacts on long-term sustainability of the environment and the World and inclusion of dark skies in UNESCO manuals to teach about sustainable development.

- Educational modules that generate children's knowledge of the sky. Specialists have found that an ever-growing percentage of children have never seen or appreciated the constellations. A related practice with this theme could be developed in the UNESCO Global Geoparks.<sup>3</sup>
- Educational tools able to generate an engaging and comprehensive concept of dark skies that communicates their importance to society with a clear, friendly and strong message. The preparation and distribution of educational materials to schools, along with instructions to teachers on this topic, is recommend. An example is the Quality Lighting Teaching Kit<sup>4</sup> from the National Optical Astronomy Observatory. This kit contains tools for inquiry-based learning activities that explore different aspects or effects of bad lighting.

- “Citizen Science” activities: smartphone apps can be used to measure the sky brightness at any site. The International Dark-Sky Association hosts a website where these measurements can be entered and compared to other participants' sites.

### Legislation and Technical Norms

It is recognized that the standards of lighting will be different for different types of usage in public spaces, industrial areas, sports and recreation facilities and protected zones. They will also be different in different parts of world, where technological solutions will vary based on an areas' specific needs and resources. So rather than trying to enforce a detailed set of standards indiscriminately across the board for all of these different areas and kinds of usage, it is recommended that a global norm be adopted that promotes staying within 20% of an established set of “minimum recommended safe level(s)” such as those already established by international organizations such as IDA, IESNA, CIE and the Starlight Foundation. It is recognized that these standards and norms should be exacting and uncompromising

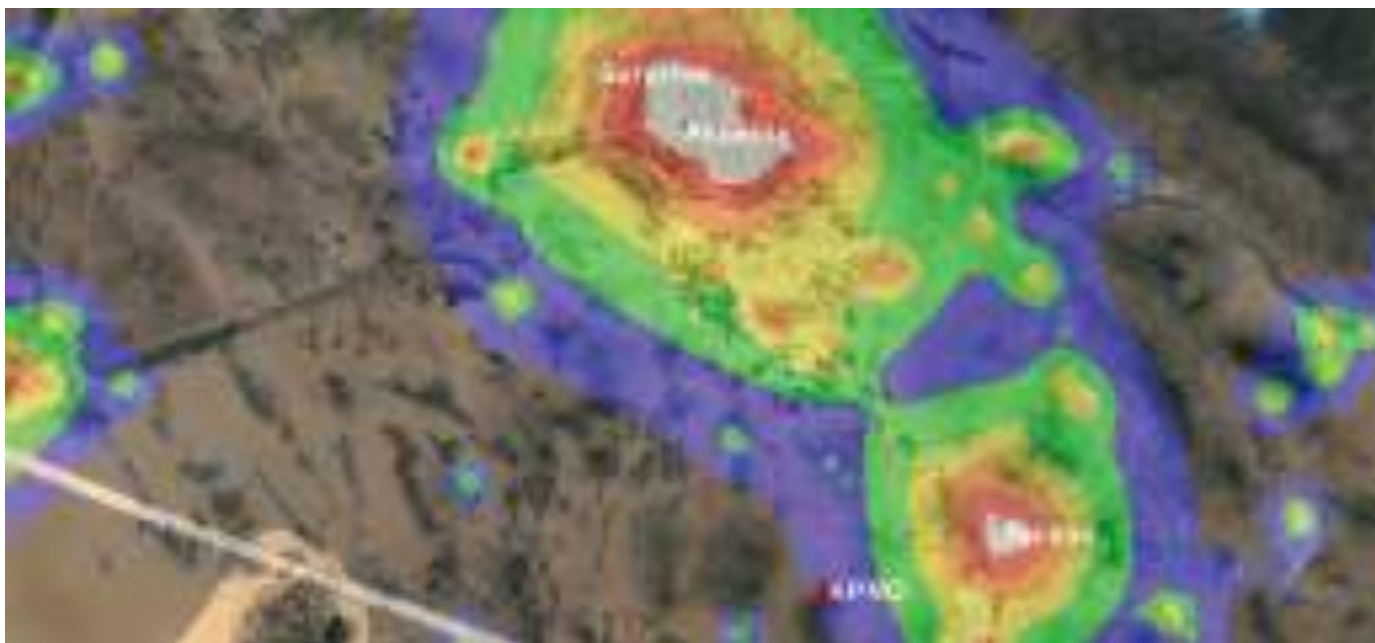


Figure 1. Light from Tucson Arizona in relation to KPNO. © Google Earth with map data from Google, INEGI, SIO, NOAA, U.S. Navy, NGA and GEBCO with annotations by Fernando Avila Castro and data from P. Cinzano et al.

3. For more information on the UNESCO Global Geoparks, see: [www.unesco.org/new/es/office-in-montevideo/ciencias-naturales/earth-sciences/geoparks](http://www.unesco.org/new/es/office-in-montevideo/ciencias-naturales/earth-sciences/geoparks)

4. See <http://www.noao.edu/education/qltkit.php>

in their goal to reduce light pollution effectively. It is emphasized that all countries should strive to achieve the very best practices and communicate in terms of international cooperation.

The specialists consider the establishment of specific legislation to mitigate light pollution to be best served at national and local levels. What follows is a list of recommended legislative solutions that could be applied locally and especially in the construction of outdoor lighting codes. This list is not exhaustive:

1. Requirement to use absolute minimum levels of lighting necessary to perform the required task and stay within 20% of minimum recommended safe levels.
2. Enforcement of a lumen per capita limit, with the aim to arrive at no more than 1000 lm per capita, as a target level. The level of light installed in developed countries in the 1970s should be used as the maximum allowable level.
3. Enforcement of uniformity of outdoor lighting (public AND private spaces). Vehicular and pedestrian traffic may be endangered by abrupt transitions between bright and dark areas. Eye pupil response (opening and closing) might suffer going from poorly lit to overly lit areas and vice versa, creating a potential security hazard to drivers and people with poor eye sight.
4. Requirement of appropriate shielding on lighting fixtures (noting possible differences in residential and industrial areas)
5. Requirement to turn off public lighting in areas where it is not needed during certain hours. E.g. parking lots, billboards, decorative fountains and sculptures and parks.
6. Requirement that Correlated Colour Temperature (CCT) be capped at 3000K and that narrow spectrum sources be used to lower possible impacts on wildlife and health (e.g. PC amber LED).
7. Delineation of exclusion zones around protected areas (with a possible extension of 200 km in diameter). Scientific models show that escaping light from big cities can travel hundreds of miles due to atmospheric dispersion. This has been observed at Kitt Peak National Observatory (KPNO) where the light from the city of Tucson 100 km away has started to affect the dark sky in KPNO. In a similar way, the cities of Mexicali,

Ensenada, Tijuana and San Diego, might be a potential problem for the National Astronomical Observatory in Baja California (OAN-SPM in Spanish). Considering that some of these cities have populations of over one million at a distance of less than 200 km, the proposed exclusion area becomes a form of contingency needed against the relentless pace of urban development (see Figure 1).

8. Installation of adaptive lighting systems, which may substantially lower (by ten times or more) the lighting levels when they are not in use; this saves both energy and money.
9. Elimination of broad spectrum LEDs and investment in developing cheaper, more efficient narrow spectrum LEDs.

Currently there not enough options available to consumers to safely and ecologically light their outdoor areas. There needs to be ecologically safer and more affordable options for better lighting made available for both industrial and residential applications. We recommend that national and local governments and electric companies take steps to incentivize safe lighting for urban and rural areas that benefit consumers.

It is recommended to look for examples of pre-existing legislation that have led to the improvement of other aspects of our environment like Clean Air Legislation and Clean Water Legislation, and explore whether or not there are parallels present for legislation that could protect the sky.

Finally, the experts highlight the importance of encouraging the development of specific adaptations to the generic regulations and including local solutions as a key factor. Engaging diverse actors in finding solutions leads to more innovation with which to find new solutions to combat light pollution.

### Compliance

It is recommended to use all available and future technologies to track the compliance with any recommendations that are set out in new agreements. For example, a global Sky Quality Meter (SQM) network could be employed in conjunction with higher resolution satellite data which incorporates colour/spectral information to these data, as SQM and satellites don't detect the difference between

different sources and satellites are blind to blue light.<sup>5</sup> These data, acquired periodically, could be used to analyse results and present them in a way that could inform this effort. It is recommended that in any documentation that is produced, good practices are called out by naming specific examples of cities, industries and governments that took the initiative.

### **Social Communication and Education**

It is necessary that the public in general, all of the inhabitants of populated areas, be aware of the need to preserve dark skies. This need cannot only be expressed through the concerns of scientists, unique to astronomers, technicians or specialists. It should be understood as an effective exercise of citizenship.

It is recommended that a series of meetings or workshops be convened to define strategies, contents, and specific tools of communication and education based on 4 types of “publics”:

1. Decision-making authorities in all of the involved disciplines;
2. The General Public;
3. Youth and Children;
4. Manufactures of goods and services related to the topic.

### **Decision-Making Authorities at Various Points of Interest**

In terms of economic actors, it is necessary to highlight the financial benefits to be gained by mitigating light pollution. In most cases, more efficient lighting means more efficient spending and lowered costs. In terms of security at night, there is a general misconception that light=safety and, consequently, that darkness=danger but there is actually no direct relationship between dark skies and being unsafe. In fact, in some cases excessive lighting can create glare which decreases visibility and can ultimately be more harmful.

It has been shown that excess lighting can actually be toxic and damaging to people’s health and that less lighting can lead to lowered CO2 emissions. Less lighting also protects animals who thrive in nocturnal environments.

It would be these main lines of action—economy, security, welfare and environment—that would need to be communicated to decision makers. This communication could be facilitated by UNESCO or other international organizations through acknowledgement, incentives or the creation of specialized scientific technical working groups, making use of communication strategies that employ a strong and organized online presence, which simultaneously serves to generate knowledge and respect for dark night skies.

### **The General Public**

It would be possible to appeal to the general public in much the same way as the decision makers. The same economic, security, welfare and environmental benefits to mitigating light pollution would be of interest to the general public. Additionally, the idea of reconnecting to the relationship that one has with the sky should be highlighted. It is fundamental to analyse the flow of information in social networks.

The education of the general public could be achieved through the cooperation of all of the pre-existing organizations involved in environmental protection. Using this network, the reach of dark skies education would be significantly impactful. It is recommended to produce and distribute informative material to engage the general public through the use of non-formal educational activities and the creation of a website for exchange and collaboration on the topic. The institutions convened in Mexico City are willing to develop an information portal on the issues and, specifically, on the recommendations presented herein.

### **Youth and Children**

In the first two groups, the collection and dissemination of relevant information was emphasized but in terms of youth and children, education is key to generating lasting conviction and commitment. It is recommended that education about the sky and about the universe be included in all formal curricula for students at primary, secondary and university levels, especially emphasizing the importance of public participation in the preservation of cultural values in addition to scientific research:

5. This means that they’ll detect a decrease in light pollution when actually an increase is taking place in the migration from High Pressure Sodium lights to white LEDs.

- The dark skies as liaison link between humans
- The dark sky as a teaching support for multidisciplinary actions
- The dark sky as heritage of humanity and of each culture

For this to be successful, the appropriate awareness raising efforts must be made with the educational authorities. A training program for educators as well as the production and distribution of training and educational material is also suggested.

### **Manufactures of Goods and Services Related to the Topic**

A fourth “public” to be considered are the manufacturers of goods and services related to lighting. It would be important to inform

them about the business changes they could implement that would contribute socially and scientifically to the mitigation of light pollution. Actions of this nature could be carried out by providing incentives and giving certificates.

### **Priorities for International Cooperation**

It is important to secure the cooperation of the amateur astronomer community that is present all over the world and in every country who show strong interest in protecting our dark skies.

# El derecho a los cielos oscuros: resultados y conclusiones

Como resultado de dos días de ponencias individuales y un día de reflexión colectiva en grupos de trabajo, los expertos presentes en la Reunión Internacional “El derecho a los cielos oscuros” establecieron las siguientes líneas de acción para salvaguardar y proteger la visibilidad de nuestros cielos oscuros.

## Medición de la contaminación lumínica y monitoreo internacional

Reconociendo que los cielos oscuros son un importante recurso tanto científico como cultural, y con la finalidad de promover la preservación de los cielos oscuros a nivel visible y de sus respectivas longitudes de onda de radio con objetivos científicos y culturales, el grupo de especialistas reunidos en la Ciudad de México recomienda el desarrollo de un conjunto de sistemas estandarizados para medir y supervisar la contaminación lumínica. Este sistema debería proporcionar información cuantitativa sobre el estado y el avance del brillo en el cielo y de la interferencia radial, así como de su impacto en zonas de importancia astronómica; asimismo debería incluir un sistema de monitoreo de su influencia y/o impacto sobre la salud de los seres humanos y otros sistemas biológicos en general, asegurando la capacidad de las generaciones presentes y futuras para apreciar las estrellas, junto con promover el empleo de un uso más eficiente de energía para el desarrollo sostenible.

Esta información podría ser transmitida a agencias gubernamentales para sustentar su acción a nivel local y nacional, así como a la UNESCO y otras organizaciones encargadas de conservar el patrimonio. La información y conocimiento generados pueden contribuir a la implementación de planes de conservación y de manejo de espacios especialmente idóneos para la observación, así como coadyuvar a la preservación de la visibilidad de los cielos oscuros en áreas naturales y culturales protegidas.

El desarrollo de este conjunto de sistemas estandarizados de monitoreo es una necesidad particularmente urgente para los observatorios astronómicos y zonas aledañas, debido al reciente aumento de la contaminación lumínica provocada por el desarrollo urbano y productivo creciente en todas las latitudes del planeta.

Como premisa fundamental en el establecimiento de dichos estándares, se recomienda ampliamente establecer un control de la proliferación de iluminación sin armadura de cualquier tipo o bien de instalaciones eléctricas de emisiones azules (p. ej., temperaturas de color mayores a 3,000 K). El/los sistema(s) de monitoreo establecido/s debería/n tener la capacidad de medir temperatura de color, resplandor y direccionalidad.

## Prioridades para la cooperación internacional

La cooperación internacional es uno de los garantes fundamentales para el desarrollo de un conjunto estandarizado de sistemas de monitoreo, aplicable a escala mundial. En este sentido, la importancia de las organizaciones culturales, científicas, medioambientales, gubernamentales y comerciales resulta fundamental.

Entre los actores que están llamados a poder desarrollar colaboraciones en el ámbito de la cooperación internacional destacan los siguientes (ordenados aleatoriamente):

- La Organización de las Naciones Unidas para la Educación, la Ciencia y la Cultura (UNESCO), la Oficina de Protección de la Calidad del Cielo de Norte de Chile (OPCC) y la Oficina Técnica para la Protección de la Calidad del Cielo (OTPC)
- Unión Astronómica Internacional (UAI)
- Otras instituciones ligadas a los cielos oscuros, tales como la Asociación Internacional para los Cielos Oscuros (IDA), la Fundación Starlight, CieloBuiro, Cel Fosc, entre otras
- Observatorios profesionales
- Sociedades astronómicas profesionales
- Agencias espaciales
- Parques nacionales
- Sociedades astronómicas de aficionados
- Asociaciones de especialistas en conservación y manejo del patrimonio



- Gobiernos nacionales, estatales y locales
- Organizaciones para la protección del medio ambiente
- Planificadores urbanos
- Expertos en salud
- Profesionales y asociaciones de iluminación
- Empresas de iluminación
- Empresas de energía
- Museos
- Archivos
- Centros académicos especializados en ciencias sociales

### Plan de acción

1. Es sumamente recomendable la conformación de un equipo internacional (con la participación y quizá el liderazgo de la UAI y/o de otras agencias, siempre en cooperación con otras organizaciones astronómicas) con la finalidad de establecer un glosario consensuado, así como un sistema común y un estándar de caracteres idóneos, susceptibles de permitir la instalación en el futuro de observatorios astronómicos. Los elementos de sistema de medida propuestos incluyen, entre otros:

- cobertura de todo el cielo
- información de color
- resolución espacial
- datos satelitales (agencias espaciales e iniciativa privada)
- archivos y bases de datos abiertos
- software estándar y de código abierto para archivar, analizar y compartir resultados

Este sistema debería incluir fuentes complementarias de medición, tales como estudios aéreos.

Con respecto a la estandarización de las técnicas y los protocolos para la obtención de datos de la calidad del cielo oscuro, se sugiere revisar el trabajo de Loss of the Night Network (LoNNe).<sup>1</sup> Este esfuerzo, resultado de una colaboración financiada con fondos europeos, en operación desde el 2012, genera una red donde 40 organizaciones pueden compartir sus ex-

periencias, con el objetivo de promover la cooperación entre estos agentes y asegurar un intercambio de habilidades y para diseñar procedimientos estándar.

En cuanto a la armonización de los datos de monitoreo (principalmente SQM), se insta a revisar el trabajo de la Coordinación Italiana para la Recolección de Datos sobre Contaminación Lumínica (CORDILIT, por sus siglas en italiano)<sup>2</sup> La red CORDILIT, que ha operado en Italia desde 2011, consiste en una infraestructura ligera a la cual se le agregan datos de estaciones desplegadas en varias partes del país. El núcleo de la red fue iniciado por dos organizaciones de la sociedad civil, Veneto Stellato y Attivarti.org (en conjunto con el proyecto BuioMetria Participativa). Desde entonces, se han unido a la red otra serie de conocedores interesados y de científicos, incluyendo al Consejo Nacional de Investigación de Italia. Todos los datos generados por esta red son difundidos con licencia abierta en línea.

2. También se recomienda que la puesta en práctica de dichos sistemas se dé con la menor dilación para proporcionar la información necesaria a las autoridades gubernamentales de los diferentes niveles de gobierno e internacionales, con el objetivo de apoyar y animar el desarrollo de marcos legales y sociales para la protección de las áreas con importancia astronómica ante la proliferación incesante de los procesos urbanos, y de servir en los procesos de toma de decisiones en sistemas de gobernanza multinivel.
3. Al mismo tiempo, se recomienda promover actividades de concientización sobre la necesidad de conservar los cielos oscuros por su valor científico, medioambiental, cultural y de salud pública. Estas acciones podrán dirigirse al público en general, a agencias del sistema de Naciones Unidas, a agencias gubernamentales y a organizaciones internacionales, así como a organizaciones no gubernamentales y de la sociedad civil, sin olvidar al sector privado-empresarial, al sector educativo y a la academia en su conjunto.

Específicamente en el marco de acción de la UNESCO, el grupo de especialistas recomienda la conformación de un grupo de tra-

1. Enlace al sitio oficial: <[www.cost-lonne.eu](http://www.cost-lonne.eu)>.

2. Enlace al sitio oficial: <[www.cordilit.org](http://www.cordilit.org)>.

bajo que genere un reporte sobre la materia con la finalidad de ser incluido en el *Informe Mundial de la UNESCO sobre la Ciencia*. Este reporte deberá incorporar los siguientes elementos:

- Sociedad: involucramiento de la sociedad civil para reforzar la noción de ciudadanía (nacional y mundial). Varias iniciativas ciudadanas de carácter científico pueden implementarse, tales como mediciones domésticas del cielo y su socialización y comparación con las mediciones en diferentes partes del mundo.
- Cultura:
  - Ciudades Creativas (UNESCO), como comunidades de defensa y conservación de los cielos oscuros.
  - Ciudades y desarrollo sostenible (patrimonio y eficiencia; aproximaciones de largo plazo), impacto sobre la sostenibilidad a largo plazo del entorno y en el mundo, inclusión de los cielos oscuros en los manuales de la UNESCO sobre educación para el desarrollo sostenible.

- Módulos educativos que generen conocimiento infantil del cielo. Los especialistas han constatado que un porcentaje cada vez más amplio de niños nunca ha visto o apreciado la bóveda celeste. Una práctica relacionada con este tema podría desarrollarse en los Geoparques Mundiales declarados por la UNESCO.<sup>3</sup>
- Herramientas pedagógicas capaces de generar un concepto atractivo y comprensivo de los cielos oscuros, que comunique su importancia a la sociedad en su conjunto con un mensaje claro, amigable y contundente. Se recomienda la preparación y distribución de materiales informativos en las escuelas, acompañados de guías para los maestros. Un ejemplo de ello es el *Quality Lighting Teaching Kit*<sup>4</sup> realizado por el National Optical Astronomy Observatory. Este kit contiene herramientas para desarrollar actividades prácticas que permiten explorar diversos aspectos relacionados con la iluminación.
- Actividades para el público general: muchas aplicaciones

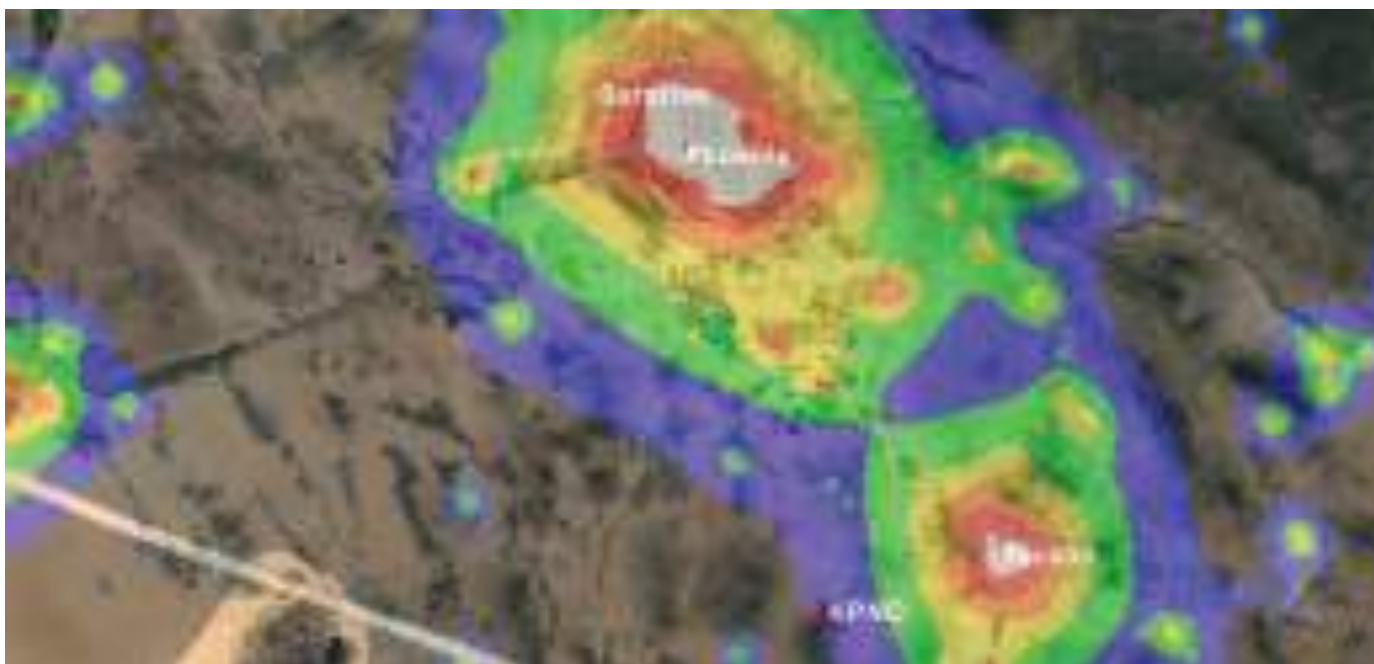


Figura 1. Luz de Tucson, Arizona en relación con el KPNO. © Google Earth, con datos de Google, INEGI, SIO, NOAA, U.S. Navy, NGA y GEBCO, con anotaciones de Fernando Avila Castro y datos de Cinzano *et al.*

3. Para más información sobre los Geoparques Mundiales de la UNESCO, véase: <[www.unesco.org/new/es/office-in-montevideo/ciencias-naturales/earth-sciences/geoparques](http://www.unesco.org/new/es/office-in-montevideo/ciencias-naturales/earth-sciences/geoparques)>.

4. Véase: <<http://www.noao.edu/education/qltkit.php>>.

para teléfonos móviles se pueden utilizar para medir el brillo del cielo en cualquier emplazamiento. La IDA administra un sitio web en el que estas mediciones se pueden registrar y comparar con otros sitios.

### Legislación y normativas técnicas

Se reconoce que los estándares de iluminación serán diferentes de acuerdo con el tipo de uso de los espacios públicos, las áreas industriales, los complejos deportivos y recreativos, así como en las zonas protegidas. Estos estándares también variarán en las diferentes partes del mundo, donde las soluciones tecnológicas, las necesidades y los recursos serán diversos. Más que intentar establecer un estándar sumamente detallado e independiente del área o el tipo de uso que se haga de ésta, se recomienda establecer una norma genérica que promueva mantenerse dentro del 20% de nivel mínimo recomendado, de acuerdo con los criterios establecidos por algunas organizaciones internacionales, tales como IDA, IESNA, CIE y Starlight. Se reconoce que estos estándares y normas deberían ser de riguroso cumplimiento, con el objetivo de reducir de forma efectiva la contaminación lumínica. Se enfatiza la necesidad de que todos los países deben esforzarse por promover las mejores prácticas y comunicarlas en términos de cooperación internacional.

Los especialistas consideran de mayor utilidad establecer legislaciones específicas a nivel nacional y local. A continuación se presenta una serie de recomendaciones y soluciones legislativas que pueden ser aplicadas localmente, especialmente para la construcción de códigos de iluminación exterior. Esta lista no es exhaustiva:

1. Requerir el uso del mínimo de iluminación necesaria para la ejecución de una tarea. Permanecer dentro del 20% del nivel mínimo recomendado.
2. Reforzar el establecimiento de un límite de iluminación per cápita, con el objetivo de conseguir un nivel máximo de 1,000 lm por habitante. El nivel de iluminación instalado en los países desarrollados en 1970 podría considerarse como el máximo nivel posible.
3. Uniformar la iluminación de exteriores (en espacios públicos y privados). El flujo vehicular y peatonal pueden verse afectados por transiciones abruptas entre áreas oscuras e iluminadas. La

respuesta ocular de las pupilas puede comprometerse al atravesar áreas con poca y mucha luz, generando una posible amenaza para conductores y personas con vulnerabilidad visual.

4. Requerir el uso de armazones y coberturas adecuadas en el alumbrado (destacando posibles diferencias entre áreas industriales y residenciales).
5. Requerir el apagado del alumbrado público en las áreas donde no es necesaria la iluminación durante horas específicas, p. ej., estacionamientos, anuncios publicitarios, fuentes decorativas, monumentos y parques.
6. Requerir que la Correlación Color-Temperatura (CCT) se limite a 3,000 K y que se utilicen fuentes de espectro reducido para reducir los posibles impactos en la salud y la vida silvestre (p. ej., LED-PC ámbar).
7. Delimitación de zonas de amortiguamiento alrededor de áreas protegidas (con una posible extensión de 200 km de diámetro). Modelos científicos demuestran que la luz emitida en las grandes urbes puede viajar cientos de kilómetros debido a la dispersión atmosférica. Este fenómeno ha sido observado en el Observatorio Nacional Kitt Peak (KPNO), donde la luz de la ciudad de Tucson, a 100 kilómetros de distancia, ha comenzado a afectar al Observatorio. De forma similar, las ciudades de Mexicali, Ensenada, Tijuana y San Diego pueden convertirse en una posible amenaza para el Observatorio Astronómico Nacional de Baja California (OAN-SPM). Considerando que algunas de estas ciudades tienen una población superior al millón de habitantes y que están a una distancia de menos de 200 km, el área de amortiguamiento propuesta se convierte en una forma de contingencia necesaria frente al ritmo incesante del desarrollo urbano (véanse figuras 1 y 2).
8. Instalación de sistemas de iluminación adaptables que reduzcan sustancialmente (10 veces o más) los niveles de iluminación cuando un área no está en uso. Esto reduce costos y energía.
9. Eliminación de LEDs de amplio espectro e inversión e instalación de LEDs de espectro reducido y con menor costo.

Actualmente no existen opciones disponibles para que los ciudadanos iluminen de forma segura y ecológica las áreas exteriores. Por ende, se necesitan desarrollar opciones para una mejor iluminación exterior tanto a nivel industrial como residencial.

Recomendamos que los gobiernos nacionales y locales, así como las compañías eléctricas, tomen acciones para incentivar la iluminación segura de las áreas urbanas o rurales que puedan beneficiar a los consumidores.

Es recomendable buscar ejemplos de legislaciones existentes en otros ámbitos que hayan contribuido al mejoramiento de factores ambientales, tales como legislaciones de la calidad del aire o del agua. Se deben explorar estos ejemplos para encontrar paralelismos e insumos para las legislaciones de protección de los cielos oscuros.

Finalmente, los expertos destacan como un factor clave motivar el desarrollo de adaptaciones específicas a las normativas genéricas y que incluyan además soluciones locales. Atraer a diversos actores para la búsqueda de soluciones puede contribuir a fortalecer la innovación y con ello encontrar soluciones novedosas para enfrentar los excesos lumínicos.

### Cumplimiento

Se recomienda usar todas las tecnologías disponibles y futuras para monitorear el cumplimiento de cualquier recomendación dispuesta en nuevos acuerdos. Por ejemplo, una red de fotómetros para medir la calidad del cielo (SQM) a nivel global podría ser incorporar datos satelitales de alta resolución que incluyan a su vez información color/espectral de estos datos, ya que el fotómetro y el satélite no detectan la diferencia entre fuentes distintas y los satélites no reconocen la luz azul.<sup>5</sup> Estos datos, recolectados periódicamente, pueden ser utilizados para analizar los resultados y ser presentados de tal manera que informen este esfuerzo. Se recomienda que, en cualquier documentación que se produzca al respecto, se incluyan buenas prácticas con información específica de la ciudad, la industria o el gobierno que tomaron la iniciativa.

### Comunicación a la sociedad y educación

Es necesario que el público en general, todos los habitantes de los núcleos poblados, sean conscientes de la necesidad de preservar sus cielos oscuros. Esta necesidad no puede ser expresada como una preocupación científica, única de los astrónomos, o técnica, de los especialistas. Debe de ser entendida como un ejercicio efectivo de ciudadanía.

Se recomienda la proyección de una serie de reuniones o talleres para definir estrategias, contenidos y herramientas especiales de comunicación y educativas para cuatro perfiles específicos de públicos:

1. Autoridades y tomadores de decisiones en todas las disciplinas involucradas;
2. Público general;
3. Niños y jóvenes;
4. Productores de bienes y servicios relacionados con la materia.

### Autoridades y tomadores de decisiones en varias ramas de interés

En términos de actores ligados a la economía, es necesario subrayar los beneficios financieros que puede acarrear la mitigación de la contaminación lumínica. En la mayoría de los casos, una iluminación más eficiente se traduce en una inversión más efectiva y en un abatimiento de costos. En términos de seguridad, existe una confusión generalizada de que más luz equivale a más seguridad y, por ende, menos luz es igual a inseguridad. Sin embargo, no existe una relación directa entre la oscuridad del cielo y la inseguridad. De hecho, en muchos casos la iluminación excesiva puede generar un resplandor que disminuya la visibilidad y que, en última instancia, constituye una amenaza.

Se ha demostrado que el exceso de iluminación puede ser tóxico y dañino para la salud, y que una iluminación correcta puede contribuir a la disminución de emisiones de bióxido de carbono. El control de la iluminación también puede auxiliar en la protección de los animales que desarrollan sus formas de vida en ambientes nocturnos.

Éstas son las principales líneas de acción —cultura, economía, seguridad, bienestar y medio ambiente— que necesitan ser comunicadas a las autoridades y tomadores de decisiones. Esta comunicación se puede facilitar a través de la UNESCO o de otras organizaciones internacionales, a través del reconocimiento, la generación de incentivos o la creación de grupos de trabajo especializados científico-técnicos, sirviéndose de estrategias de comunicación que impliquen una presencia bien organizada en la web, que sirva a su vez para la generación de conocimiento y respeto por los cielos oscuros nocturnos.

5. Esto significa que detectan un decremento de la contaminación lumínica cuando ésta va en aumento, debido a la migración de lámparas de sodio de alta presión a LED blancos.

### Público general

Es posible generar atención del público general de la misma manera que con las autoridades. Los mismos beneficios económicos, de seguridad, bienestar y del medioambiente pueden resultar de interés público. Adicionalmente, se debería resaltar la importancia de regenerar la relación de la gente con el cielo. Resulta fundamental analizar los flujos de información en las redes sociales.

La educación del público general se puede conseguir por medio de la cooperación de todas las organizaciones preexistentes relacionadas con la protección del medioambiente. Usar esta red en beneficio de los cielos oscuros puede ser significativamente importante. Se recomienda la producción y distribución de material informativo para atraer al público por medio de actividades lúdicas y mediante la creación de sitios web para propiciar colaboración en la materia. Las instituciones convocadas en la Ciudad de México están dispuestas a desarrollar un portal informativo sobre los temas tratados y, en específico, sobre las recomendaciones aquí presentadas.

### Niños y jóvenes

En los dos grupos anteriores se enfatizó la importancia de la recolección y divulgación de información relevante; sin embargo, en el caso de los niños y los jóvenes, la educación es el factor determinante para generar convicción y compromiso duraderos. Se recomienda que el conocimiento del cielo y el universo sean incluidos en la currícula de la educación primaria, secundaria y superior, enfatizando especialmente la importancia de la par-

ticipación pública en la preservación de los valores culturales y científicos relacionados:

- El cielo oscuro como un puente entre los seres humanos;
- El cielo oscuro como una base para promover acciones de aprendizaje multidisciplinario;
- El cielo oscuro como patrimonio de toda la humanidad.

Para que lo anterior tenga éxito, los esfuerzos para concientizar a los niños y los jóvenes deben establecerse en conjunto con las autoridades educativas. Por ello, también se sugiere la creación de programas de capacitación y la producción y distribución de materiales educativos.

### Productores de bienes y servicios relacionados con la materia

El cuarto grupo que se debe considerar son los productores de bienes y servicios relacionados con la iluminación. Sería importante informarlos acerca de las adecuaciones que pueden implementar para contribuir social y científicamente a la disminución de la contaminación lumínica. Acciones de esta índole podrían llevarse a cabo por medio de la entrega de incentivos y certificados.

### Prioridades para la cooperación internacional

Es importante asegurar la cooperación de la comunidad de astrónomos aficionados: esta comunidad se encuentra presente en todos los países del mundo y tiene un fuerte interés en proteger nuestros cielos oscuros.





Oficina en México



## REPORT OF THE COUNCIL ON SCIENCE AND PUBLIC HEALTH

CSAPH Report 2-A-16

Subject: Human and Environmental Effects of Light Emitting Diode (LED) Community Lighting

Presented by: Louis J. Kraus, MD, Chair

Referred to: Reference Committee E  
(Theodore Zanker, MD, Chair)

## 1 INTRODUCTION

2  
3 With the advent of highly efficient and bright light emitting diode (LED) lighting, strong economic  
4 arguments exist to overhaul the street lighting of U.S. roadways.<sup>1-3</sup> Valid and compelling reasons  
5 driving the conversion from conventional lighting include the inherent energy efficiency and longer  
6 lamp life of LED lighting, leading to savings in energy use and reduced operating costs, including  
7 taxes and maintenance, as well as lower air pollution burden from reduced reliance on fossil-based  
8 carbon fuels.

9  
10 Not all LED light is optimal, however, when used as street lighting. Improper design of the lighting  
11 fixture can result in glare, creating a road hazard condition.<sup>4,5</sup> LED lighting also is available in  
12 various color correlated temperatures. Many early designs of white LED lighting generated a color  
13 spectrum with excessive blue wavelength. This feature further contributes to disability glare, i.e.,  
14 visual impairment due to stray light, as blue wavelengths are associated with more scattering in the  
15 human eye, and sufficiently intense blue spectrum damages retinas.<sup>6,7</sup> The excessive blue spectrum  
16 also is environmentally disruptive for many nocturnal species. Accordingly, significant human and  
17 environmental concerns are associated with short wavelength (blue) LED emission. Currently,  
18 approximately 10% of existing U.S. street lighting has been converted to solid state LED  
19 technology, with efforts underway to accelerate this conversion. The Council is undertaking this  
20 report to assist in advising communities on selecting among LED lighting options in order to  
21 minimize potentially harmful human health and environmental effects.

## 22 METHODS

23  
24 English language reports published between 2005 and 2016 were selected from a search of the  
25 PubMed and Google Scholar databases using the MeSH terms “light,” “lighting methods,”  
26 “color,” “photoc stimulation,” and “adverse effects,” in combination with “circadian  
27 rhythm/physiology/radiation effects,” “radiation dosage/effects,” “sleep/physiology,” “ecosystem,”  
28 “environment,” and “environmental monitoring.” Additional searches using the text terms “LED”  
29 and “community,” “street,” and “roadway lighting” were conducted. Additional information and  
30 perspective were supplied by recognized experts in the field.

## 31 ADVANTGAGES AND DISADVANAGES OF LED STREET LIGHTS

32  
33 © 2016 American Medical Association. All rights reserved.

34  
Action of the AMA House of Delegates 2016 Annual Meeting: Council on Science and Public  
Health Report 2 Recommendations Adopted and Remainder of Report Filed.

The main reason for converting to LED street lighting is energy efficiency; LED lighting can reduce energy consumption by up to 50% compared with conventional high pressure sodium (HPS) lighting. LED lighting has no warm up requirement with a rapid “turn on and off” at full intensity. In the event of a power outage, LED lights can turn on instantly when power is restored, as opposed to sodium-based lighting requiring prolonged warm up periods. LED lighting also has the inherent capability to be dimmed or tuned, so that during off peak usage times (e.g., 1 to 5 AM), further energy savings can be achieved by reducing illumination levels. LED lighting also has a much longer lifetime (15 to 20 years, or 50,000 hours), reducing maintenance costs by decreasing the frequency of fixture or bulb replacement. That lifespan exceeds that of conventional HPS lighting by 2-4 times. Also, LED lighting has no mercury or lead, and does not release any toxic substances if damaged, unlike mercury or HPS lighting. The light output is very consistent across cold or warm temperature gradients. LED lights also do not require any internal reflectors or glass covers, allowing higher efficiency as well, if designed properly.<sup>8,9</sup>

Despite the benefits of LED lighting, some potential disadvantages are apparent. The initial cost is higher than conventional lighting; several years of energy savings may be required to recoup that initial expense.<sup>10</sup> The spectral characteristics of LED lighting also can be problematic. LED lighting is inherently narrow bandwidth, with “white” being obtained by adding phosphor coating layers to a high energy (such as blue) LED. These phosphor layers can wear with time leading to a higher spectral response than was designed or intended. Manufacturers address this problem with more resistant coatings, blocking filters, or use of lower color temperature LEDs. With proper design, higher spectral responses can be minimized. LED lighting does not tend to abruptly “burn out,” rather it dims slowly over many years. An LED fixture generally needs to be replaced after it has dimmed by 30% from initial specifications, usually after about 15 to 20 years.<sup>1,11</sup>

Depending on the design, a large amount blue light is emitted from some LEDs that appear white to the naked eye. The excess blue and green emissions from some LEDs lead to increased light pollution, as these wavelengths scatter more within the eye and have detrimental environmental and glare effects. LED’s light emissions are characterized by their correlated color temperature (CCT) index.<sup>12,13</sup> The first generation of LED outdoor lighting and units that are still widely being installed are “4000K” LED units. This nomenclature (Kelvin scale) reflects the equivalent color of a heated metal object to that temperature. The LEDs are cool to the touch and the nomenclature has nothing to do with the operating temperature of the LED itself. By comparison, the CCT associated with daylight light levels is equivalent to 6500K, and high pressure sodium lighting (the current standard) has a CCT of 2100K. Twenty-nine percent of the spectrum of 4000K LED lighting is emitted as blue light, which the human eye perceives as a harsh white color. Due to the point-source nature of LED lighting, studies have shown that this intense blue point source leads to discomfort and disability glare.<sup>14</sup>

More recently engineered LED lighting is now available at 3000K or lower. At 3000K, the human eye still perceives the light as “white,” but it is slightly warmer in tone, and has about 21% of its emission in the blue-appearing part of the spectrum. This emission is still very blue for the nighttime environment, but is a significant improvement over the 4000K lighting because it reduces discomfort and disability glare. Because of different coatings, the energy efficiency of 3000K lighting is only 3% less than 4000K, but the light is more pleasing to humans and has less of an impact on wildlife.

#### *Glare*

Disability glare is defined by the Department of Transportation (DOT) as the following:

1 “Disability glare occurs when the introduction of stray light into the eye reduces the ability to  
2 resolve spatial detail. It is an objective impairment in visual performance.”  
3 Classic models of this type of glare attribute the deleterious effects to intraocular light scatter in the  
4 eye. Scattering produces a veiling luminance over the retina, which effectively reduces the contrast  
5 of stimulus images formed on the retina. The disabling effect of the veiling luminance has serious  
6 implications for nighttime driving visibility.<sup>15</sup>  
7

8 Although LED lighting is cost efficient and inherently directional, it paradoxically can lead to  
9 worse glare than conventional lighting. This glare can be greatly minimized by proper lighting  
10 design and engineering. Glare can be magnified by improper color temperature of the LED, such as  
11 blue-rich LED lighting. LEDs are very intense point sources that cause vision discomfort when  
12 viewed by the human eye, especially by older drivers. This effect is magnified by higher color  
13 temperature LEDs, because blue light scatters more within the human eye, leading to increased  
14 disability glare.<sup>16</sup>  
15

16 In addition to disability glare and its impact on drivers, many residents are unhappy with bright  
17 LED lights. In many localities where 4000K and higher lighting has been installed, community  
18 complaints of glare and a “prison atmosphere” by the high intensity blue-rich lighting are common.  
19 Residents in Seattle, WA have demanded shielding, complaining they need heavy drapes to be  
20 comfortable in their own homes at night.<sup>17</sup> Residents in Davis, CA demanded and succeeded in  
21 getting a complete replacement of the originally installed 4000K LED lights with the 3000K  
22 version throughout the town at great expense.<sup>18</sup> In Cambridge, MA, 4000K lighting with dimming  
23 controls was installed to mitigate the harsh blue-rich lighting late at night. Even in places with a  
24 high level of ambient nighttime lighting, such as Queens in New York City, many complaints were  
25 made about the harshness and glare from 4000K lighting.<sup>19</sup> In contrast, 3000K lighting has been  
26 much better received by citizens in general.  
27

### 28 *Unshielded LED Lighting* 29

30 Unshielded LED lighting causes significant discomfort from glare. A French government report  
31 published in 2013 stated that due to the point source nature of LED lighting, the luminance level of  
32 unshielded LED lighting is sufficiently high to cause visual discomfort regardless of the position,  
33 as long as it is in the field of vision. As the emission surfaces of LEDs are highly concentrated  
34 point sources, the luminance of each individual source easily exceeds the level of visual  
35 discomfort, in some cases by a factor of 1000.<sup>17</sup>  
36

37 Discomfort and disability glare can decrease visual acuity, decreasing safety and creating a road  
38 hazard. Various testing measures have been devised to determine and quantify the level of glare  
39 and vision impairment by poorly designed LED lighting.<sup>20</sup> Lighting installations are typically  
40 tested by measuring foot-candles per square meter on the ground. This is useful for determining the  
41 efficiency and evenness of lighting installations. This method, however, does not take into account  
42 the human biological response to the point source. It is well known that unshielded light sources  
43 cause pupillary constriction, leading to worse nighttime vision between lighting fixtures and  
44 causing a “veil of illuminance” beyond the lighting fixture. This leads to worse vision than if the  
45 light never existed at all, defeating the purpose of the lighting fixture. Ideally LED lighting  
46 installations should be tested in real life scenarios with effects on visual acuity evaluated in order to  
47 ascertain the best designs for public safety.  
48

### 49 *Proper Shielding* 50

1 With any LED lighting, proper attention should be paid to the design and engineering features.  
2 LED lighting is inherently a bright point source and can cause eye fatigue and disability glare if it  
3 is allowed to directly shine into human eyes from roadway lighting. This is mitigated by proper  
4 design, shielding and installation ensuring that no light shines above 80 degrees from the  
5 horizontal. Proper shielding also should be used to prevent light trespass into homes alongside the  
6 road, a common cause of citizen complaints. Unlike current HPS street lighting, LEDs have the  
7 ability to be controlled electronically and dimmed from a central location. Providing this additional  
8 control increases the installation cost, but may be worthwhile because it increases long term energy  
9 savings and minimizes detrimental human and environmental lighting effects. In environmentally  
10 sensitive or rural areas where wildlife can be especially affected (e.g., near national parks or bio-  
11 rich zones where nocturnal animals need such protection), strong consideration should be made for  
12 lower emission LEDs (e.g., 3000K or lower lighting with effective shielding). Strong consideration  
13 also should be given to the use of filters to block blue wavelengths (as used in Hawaii), or to the  
14 use of inherent amber LEDs, such as those deployed in Quebec. Blue light scatters more widely  
15 (the reason the daytime sky is “blue”), and unshielded blue-rich lighting that travels along the  
16 horizontal plane increases glare and dramatically increases the nighttime sky glow caused by  
17 excessive light pollution.

#### 18 19 POTENTIAL HEALTH EFFECTS OF “WHITE” LED STREET LIGHTING

20  
21 Much has been learned over the past decade about the potential adverse health effects of electric  
22 light exposure, particularly at night.<sup>21-25</sup> The core concern is disruption of circadian rhythmicity.  
23 With waning ambient light, and in the absence of electric lighting, humans begin the transition to  
24 nighttime physiology at about dusk; melatonin blood concentrations rise, body temperature drops,  
25 sleepiness grows, and hunger abates, along with several other responses.

26  
27 A number of controlled laboratory studies have shown delays in the normal transition to nighttime  
28 physiology from evening exposure to tablet computer screens, backlit e-readers, and room light  
29 typical of residential settings.<sup>26-28</sup> These effects are wavelength and intensity dependent,  
30 implicating bright, short wavelength (blue) electric light sources as disrupting transition. These  
31 effects are not seen with dimmer, longer wavelength light (as from wood fires or low wattage  
32 incandescent bulbs). In human studies, a short-term detriment in sleep quality has been observed  
33 after exposure to short wavelength light before bedtime. Although data are still emerging, some  
34 evidence supports a long-term increase in the risk for cancer, diabetes, cardiovascular disease and  
35 obesity from chronic sleep disruption or shiftwork and associated with exposure to brighter light  
36 sources in the evening or night.<sup>25,29</sup>

37  
38 Electric lights differ in terms of their circadian impact.<sup>30</sup> Understanding the neuroscience of  
39 circadian light perception can help optimize the design of electric lighting to minimize circadian  
40 disruption and improve visual effectiveness. White LED streetlights are currently being marketed  
41 to cities and towns throughout the country in the name of energy efficiency and long term cost  
42 savings, but such lights have a spectrum containing a strong spike at the wavelength that most  
43 effectively suppresses melatonin during the night. It is estimated that a “white” LED lamp is at  
44 least 5 times more powerful in influencing circadian physiology than a high pressure sodium light  
45 based on melatonin suppression.<sup>31</sup> Recent large surveys found that brighter residential nighttime  
46 lighting is associated with reduced sleep time, dissatisfaction with sleep quality, nighttime  
47 awakenings, excessive sleepiness, impaired daytime functioning, and obesity.<sup>29,32</sup> Thus, white LED  
48 street lighting patterns also could contribute to the risk of chronic disease in the populations of  
49 cities in which they have been installed. Measurements at street level from white LED street lamps  
50 are needed to more accurately assess the potential circadian impact of evening/nighttime exposure  
51 to these lights.





## ENVIRONMENTAL EFFECTS OF LED LIGHTING

The detrimental effects of inefficient lighting are not limited to humans; 60% of animals are nocturnal and are potentially adversely affected by exposure to nighttime electrical lighting. Many birds navigate by the moon and star reflections at night; excessive nighttime lighting can lead to reflections on glass high rise towers and other objects, leading to confusion, collisions and death.<sup>33</sup> Many insects need a dark environment to procreate, the most obvious example being lightning bugs that cannot “see” each other when light pollution is pronounced. Other environmentally beneficial insects are attracted to blue-rich lighting, circling under them until they are exhausted and die.<sup>34,35</sup> Unshielded lighting on beach areas has led to a massive drop in turtle populations as hatchlings are disoriented by electrical light and sky glow, preventing them from reaching the water safely.<sup>35-37</sup> Excessive outdoor lighting diverts the hatchlings inland to their demise. Even bridge lighting that is “too blue” has been shown to inhibit upstream migration of certain fish species such as salmon returning to spawn. One such overly lit bridge in Washington State now is shut off during salmon spawning season.

Recognizing the detrimental effects of light pollution on nocturnal species, U.S. national parks have adopted best lighting practices and now require minimal and shielded lighting. Light pollution along the borders of national parks leads to detrimental effects on the local bio-environment. For example, the glow of Miami, FL extends throughout the Everglades National Park. Proper shielding and proper color temperature of the lighting installations can greatly minimize these types of harmful effects on our environment.

## CONCLUSION

Current AMA Policy supports efforts to reduce light pollution. Specific to street lighting, Policy H-135.932 supports the implementation of technologies to reduce glare from roadway lighting. Thus, the Council recommends that communities considering conversion to energy efficient LED street lighting use lower CCT lights that will minimize potential health and environmental effects. The Council previously reviewed the adverse health effects of nighttime lighting, and concluded that pervasive use of nighttime lighting disrupts various biological processes, creating potentially harmful health effects related to disability glare and sleep disturbance.<sup>25</sup>

## RECOMMENDATIONS

The Council on Science and Public Health recommends that the following statements be adopted, and the remainder of the report filed.

1. That our American Medical Association (AMA) support the proper conversion to community-based Light Emitting Diode (LED) lighting, which reduces energy consumption and decreases the use of fossil fuels. (New HOD Policy)
2. That our AMA encourage minimizing and controlling blue-rich environmental lighting by using the lowest emission of blue light possible to reduce glare. (New HOD Policy)
3. That our AMA encourage the use of 3000K or lower lighting for outdoor installations such as roadways. All LED lighting should be properly shielded to minimize glare and detrimental human and environmental effects, and consideration should be given to utilize the ability of LED lighting to be dimmed for off-peak time periods. (New HOD Policy)

Fiscal Note: Less than \$500

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PONTIFICIA UNIVERSIDAD  
CATOLICA  
DE VALPARAISO



# **Carlos Manuel Dinamarca Cubillos**

## **Cálculo del Flujo Luminoso Superior emitido por un sistema de iluminación mediante software DIALux**

**Informe Proyecto de Título de Ingeniero Eléctrico**



**Escuela de Ingeniería Eléctrica**



## Cálculo del Flujo Luminoso Superior emitido por un sistema de iluminación mediante software DIALux

Carlos Manuel Dinamarca Cubillos

Tesis para el grado de Ingeniero Eléctrico,  
aprobada por la comisión de la  
Escuela de Ingeniería Eléctrica de la  
Pontificia Universidad Católica de Valparaíso  
conformada por

Sr. Enrique Vicente Piraino Davidson  
Profesor Guía

Sr. Sebastián Fingerhuth Massmann  
Secretario Académico

Valparaíso, 28 de febrero de 2017

*Este trabajo de tesis se la dedico primeramente a mis queridos padres Luis y Lucía que gracias a su cariño, amor y ejemplo han hecho de mí una persona con valores para poder desenvolverme como persona, padre y profesional.*

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*Valparaíso, 28 de febrero de 2017*

*C. D*

## Resumen

En el presente trabajo de tesis propone la metodología para calcular el flujo luminoso superior emitido por un sistema de iluminación, se crean las bases y los procedimientos necesarios para calcular los niveles de iluminación y posteriormente el cálculo de flujo luminoso.

El estudio se desarrolló utilizando informes técnicos de niveles de iluminación a nivel del suelo realizados por el Laboratorio de Fotometría y Control de Calidad de la Pontificia Universidad Católica de Valparaíso, donde se buscó encontrar similitud en los resultados de las mediciones con los calculados en el software de cálculo DIALux, luego se calcularon los niveles de iluminación en el hemisferio superior y finalmente se calculó el flujo luminoso.

Palabras claves: flujo luminoso, iluminancia, DIALux, cálculo, medición.

In the present work of thesis establishes the methodology to calculate the upper luminous flux emitted by a system of illumination, the bases and the necessary procedures are created to calculate the levels of illumination and later the calculation of luminous flux.

The work was developed using technical reports of levels of illumination at ground level performed by the laboratory of photometry and quality control of the Pontificia Universidad Católica de Valparaíso, where it was sought to find similarity in the results of the measurements with those calculated in the software DIALux, then the levels of illumination in the upper hemisphere were calculated and finally the luminous flux was calculated.



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# Introducción

En el presente trabajo se ha planteado el estudio del flujo luminoso superior emitido por un sistema de iluminación por medio de una herramienta informática de simulación como es el software DIALux; de tal manera que podamos analizar dinámicamente diferentes zonas que por lo general serían difíciles de estudiar en terreno en la mayoría de los casos.

El estudio en terreno de flujo luminoso superior de cualquier sitio, no es algo comúnmente practicado debido a que se requiere de costosos dispositivos (Drones, Luxómetros de alta gama) para poder llevar a cabo dicho trabajo, también se requiere de destreza para dominar el vuelo del dispositivo que permita medir en el hemisferio superior, además no existe ningún procedimiento o metodología normada para lograr medir o calcular el flujo luminoso (en el caso de simulación). Una alternativa adecuada para esta problemática es utilizar un software que ejecute un algoritmo en base a un modelo matemático que permita simular distintas zonas de interés, esto permite efectuar estudios sobre el comportamiento fotométrico de un sistema de iluminación total, el que incluye todo tipos de factores que influyan en los cálculos (reflexión, luminarias, distintos superficies, etc.), sin necesidad de ejecutar mediciones en terreno para definir el proceso o metodología que permita calcular el flujo luminoso superior que un sistema de iluminación emita hacia el hemisferio superior.

Se debe considerar que la metodología que se diseñará podrá ser aplicable en cualquier sistema de iluminación exterior y además es independiente de la finalidad que tengan los cálculos, ya sea medición de contaminación lumínica, eficiencia energética, estudio de la reflexión en ciertas áreas, etc.

Para lograr lo anterior, se deberá hacer un exhaustivo estudio de las recomendaciones internacionales existentes en la actualidad, estas recomendaciones son desarrolladas por grupos de expertos en el área luminotécnica que conforman la International Commission on Illumination, Comisión Internacional de Iluminación (CIE) en español, estas recomendaciones son la base para ejecutar estudios luminotécnicos en la actualidad, son utilizadas por importantes laboratorios en todo el mundo y el laboratorio de Fotometría y Control de Calidad de la Pontificia Universidad Católica de Valparaíso no es la excepción. Debido a esto y a su importancia en el ámbito de la iluminación es que se utilizarán como base para todo el análisis de este trabajo. El

estudio de estas recomendaciones nos permitirá extraer la información más relevante que acate al proyecto, no se descartará la posibilidad de efectuar modificaciones para cumplir con los objetivos del proyecto, con el foco de que el trabajo final nos permita obtener datos duros y representativos de las zonas que se estudiarán.

Mediante el software de cálculo será posible realizar diferentes simulaciones de comportamiento de distintas áreas y sectores en estudio, permitiendo variar las simulaciones con las variables que permita modificar el programa, gracias a esto es que podemos simular distintas situaciones que nos permitan llegar a datos cercanos obtenidos en trabajo reales en terreno.

Para el modelado y simulación de las zonas de estudio se utilizará un software de simulación de iluminación, DIALux. Con el propósito de sacar datos prácticos se utilizará el informe técnico emitido por el laboratorio de Fotometría y Control de Calidad, bajo siglas que se mantienen en anonimato debido a su confidencialidad.

La simulación se basará en una aproximación visual muy parecida a la que está implementada en terreno, se tomará en cuenta todos los datos de medidas realizadas en las zonas y obtenidas de los informes técnicos anteriormente descritos, que puedan incidir en los resultados finales (distancia de postes, altura de postes, suelos similares y superficies parecidas), todo esto para efectos de diseño del sector simulado. Luego se procederá a la simulación a nivel del suelo que nos permitirá saber si el diseño elaborado tiene la representatividad esperada (magnitud de mediciones en terreno sean similares a las simuladas en DIALux), en seguida de obtener los resultados esperados se procederá a calcular las iluminancias en el hemisferio superior, después de eso se podrá calcular el flujo luminoso superior del sistema de iluminación en estudio.

Para poder calcular el flujo luminoso superior necesariamente se deben obtener los resultados de las iluminancias obtenidas de las simulaciones, pero antes de esto ya se debe contar con la metodología necesaria para lograr calcular el flujo luminoso, ya sea esta un punto, varios o una rejilla de cálculo ubicada en el hemisferio superior del sistema de iluminación.

# 1 Antecedentes generales y propuesta

## 1.1 Objetivos del proyecto.

### 1.1.1 Objetivo general.

El objetivo general del proyecto es desarrollar un sistema que permita la evaluación del flujo luminoso que una instalación exterior emite hacia la bóveda celeste.

### 1.1.2 Objetivo específico

Mediante el uso del software DIALux, simular escenarios similares a los medidos en terreno para emplearlos como base y así establecer una metodología que permita calcular el flujo luminoso emitido por un sistema de iluminación hacia el hemisferio superior.

## 1.2 Conceptos Importantes

### 1.2.1 Energía Lumínica

La energía lumínica es la energía que procede de la luz y viaja a través de esta. Al momento de desplazarse, se comporta como una onda electromagnética. Pero también actúa como una partícula, ya que es capaz de interactuar con la materia. La unidad del Sistema Internacional de medidas que sirve para medir esta clase de energía es el lumen segundo. Esta medida indica la cantidad de energía lumínica emitida durante cierto período [1].

La energía luminosa no debe confundirse con la energía radiante, ya que no todas las longitudes de onda transportan la misma cantidad de energía visible. Su fórmula es:

$$Q = F * t [lm * s] \quad (1-1)$$

### 1.2.2 Flujo Luminoso

El flujo luminoso es la potencia emitida por una fuente de luz en forma de radiación visible y evaluada según su capacidad de producir sensación luminosa. Su unidad es el Lumen [2]. Su fórmula es:



$$F = I * \omega [lm] \quad (1-2)$$

Donde:

I es la intensidad luminosa, su unidad en el Sistema Internacional de medidas es candelas, cuyo símbolo es cd.

$\omega$  es el ángulo sólido, su unidad en el Sistema Internacional de medidas es estereorradián, cuyo símbolo es sr.

### 1.2.3 Intensidad Luminosa

En fotometría, la intensidad luminosa se define como la cantidad de flujo luminoso que emite una fuente por unidad de ángulo sólido. Su unidad de medida en el Sistema Internacional de Unidades es la candela (cd).

Matemáticamente, su expresión es la siguiente:

$$I = F / \omega [cd] \quad (1-3)$$

### 1.2.4 Ángulo sólido

El ángulo sólido es el ángulo espacial que abarca un objeto visto desde un punto dado, que se corresponde con la zona del espacio limitada por una superficie cónica. Mide el tamaño aparente de ese objeto. La unidad del ángulo sólido en el Sistema Internacional de medidas es el estereorradián, cuyo símbolo es sr. Es el área del casquete esférico, en una esfera de radio unidad, abarcado por un cono cuyo vértice está en el centro de la esfera. Es una magnitud adimensional que se calcula mediante la siguiente ecuación:

$$\omega = S / R^2 [-] \quad (1-4)$$

Donde:

R es el radio de la esfera.

S es la superficie proyectada sobre la esfera [3].

### 1.2.5 Iluminancia

La iluminancia (E) es la cantidad de flujo luminoso que incide sobre una superficie por unidad de área.

Matemáticamente se expresa de la siguiente manera:

$$E = F / S [lx] \quad (1-5)$$

Donde:

F es el flujo luminoso.

S es el área en la que proyecta el flujo luminoso.

### 1.2.6 Iluminancia Promedio ( $E_{prom}$ )

Es la media de un conjunto de iluminancias obtenidas de una rejilla de cálculo.

El cálculo de  $E_{prom}$  se realiza después de haber calculado un conjunto de iluminancias puntuales (rejilla de cálculo, la siguiente ecuación determina  $E_{prom}$ .

$$E_{prom} = (\sum E_i) / n \text{ [lx]} \quad (1-6)$$

Donde:

$E_i$  es la iluminancia calculada en el punto i.

n es el número de puntos de cálculo realizados en un área en particular

### 1.2.7 Mínima ( $E_{min}$ )

Es el mínimo valor de iluminancia puntual obtenida desde una rejilla de cálculo.

### 1.2.8 Uniformidad Promedio

Cociente entre la Iluminancia Mínima y la Iluminancia Promedio que nos permite saber qué tan bien está distribuida la luz en un área específica.

La uniformidad se puede calcular según la siguiente ecuación.

$$U_{prom} = E_{min} / E_{prom} \text{ [-]} \quad (1-7)$$

### 1.2.9 Propiedades ópticas de los cuerpos

Cuando una radiación luminosa incide en un cuerpo real se provocan tres fenómenos esenciales, estos se ilustran a continuación.

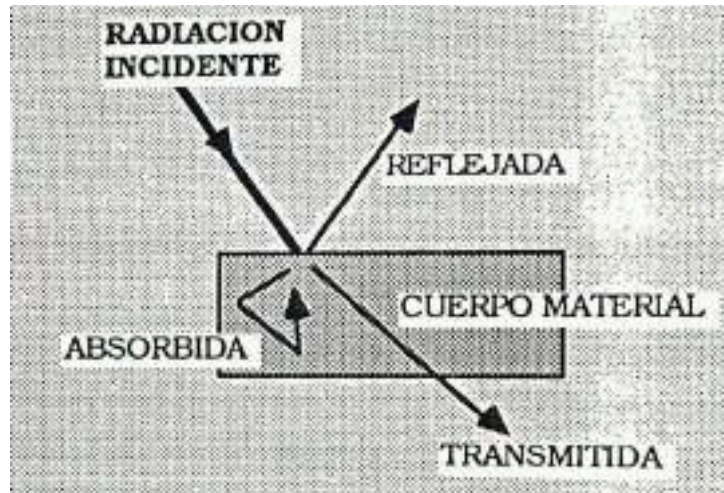


Figura 1-1. Propiedades ópticas de los cuerpos.

### Reflexión

La reflexión es un fenómeno que tiene lugar cuando un rayo luz que tiene incidencia sobre cierto material es reflejado, en términos simples es una modificación de la dirección de la luz incidente. En la siguiente imagen se muestran distintos tipos de reflexión.

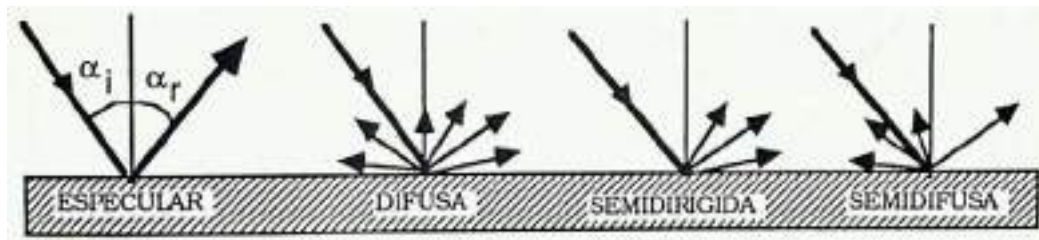


Figura 1-2. Tipos de reflexión [4].

### Transmisión

La transmisión es la propagación de las radiaciones a través de los cuerpos transparentes o translúcidos.

### Absorción

La absorción de la radiación electromagnética es el proceso por el cual dicha radiación es captada por la materia. Cuando la absorción se produce dentro del rango de la luz visible, recibe el nombre de absorción óptica. Esta radiación, al ser absorbida puede ser reemitida, como en el caso de la fluorescencia, o transformada en otro tipo de energía, como calor o energía eléctrica.

#### 1.2.10 Sistema de iluminación

Llamaremos sistema de iluminación a la combinación de fuentes de luz, materiales y texturas que independiente de cómo proyectan luz, ya sea por de forma directa, indirecta, por emisión,

reflexión o transmisión aportan flujo luminoso a un área específica. La figura 1-3 muestra un sistema de iluminación básico con sus aportes directos e indirectos de luz.

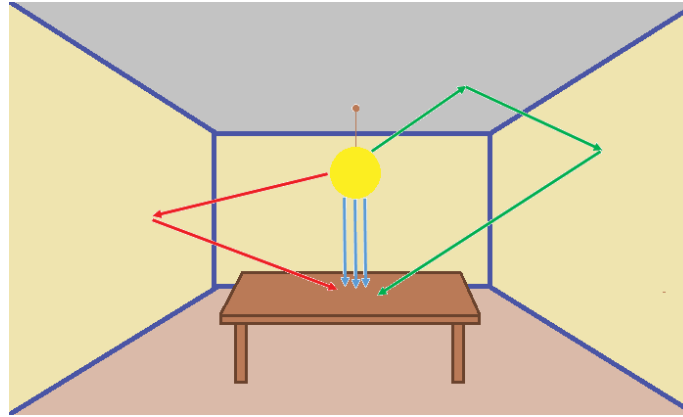


Figura 1-3. Sistema de iluminación

### 1.2.11 Factor de mantenimiento

Es la relación de la iluminancia promedio en el plano de trabajo después de un periodo determinado de uso de una instalación, y la iluminancia promedio obtenida al empezar a funcionar la misma como nueva. En la práctica a mayor factor de mantenimiento (más cercano a 1), mayor iluminancia media obtenida en la simulación [5].

### 1.2.12 Representatividad

En éste trabajo de título se denomina representatividad a la similitud de resultados que se obtiene en una simulación comparada con los resultados obtenidos en terreno.

Para determinar que tan representativa es una simulación, se utiliza el intervalo de confianza, estadísticamente se llama intervalo de confianza a un par de números entre los cuales se estima que estará cierto valor desconocido con una determinada probabilidad de acierto, esta probabilidad de acierto la define el margen de error y este se puede definir para cualquier nivel de confiabilidad deseado, pero por lo general se emplean el 90%, 95% o 99% (para un nivel de confiabilidad del 90% su margen de error es el 10%, para un nivel de confiabilidad del 95% su margen de error es el 5%, etc.) [6].

En estadística un nivel de confianza de 95% indica que 19 de 20 muestras (95%) de la misma población estarán dentro de los intervalos de confianza que se definan, pero para la aplicación de este trabajo de título, se buscará que la simulación se encuentre dentro de un margen de error no superior al 10% de los registros obtenidos en terreno. Por ejemplo, la iluminancia promedio obtenida en las mediciones en terreno es 12 [lx], el valor que calculará se espera esté dentro del intervalo de confianza 10,8 [lx] y 13,2 [lx], lo que nos dará a lo menos un 90% de confiabilidad en la simulación versus medición en terreno y por consiguiente la representatividad buscada en la simulación.

Para efectos prácticos, se buscará representatividad en iluminancia promedio e iluminancia mínima en cada simulación, si esta no se encuentra dentro de los parámetros, se deberá iterar hasta encontrar la representatividad, si esta no se logra encontrar se descartará del estudio la simulación.

### **1.3 Estado del Arte**

En la presente sección se presenta la problemática propuesta que se quiere abordar. Finalmente exhibe un estado del arte considerando los trabajos actuales relacionados de alguna manera a la inspección de flujo luminoso emitido hacia el hemisferio superior.

#### **1.3.1 Problemática**

Debido a que en la actualidad existe la necesidad de cuantificar el flujo luminoso emitido por un sistema de iluminación hacia el hemisferio superior, independiente del objetivo de éste, ya sea por problemas de eficiencia energética, eficacia en la iluminación de un sector, contaminación lumínica de una zona, etc; se requiere de una metodología para lograr cuantificar este flujo luminoso.

#### **1.3.2 Solución al problema**

Para poder atacar la problemática se requiere tener un conocimiento acabado acerca de los métodos utilizados para medir flujo luminoso en la actualidad.

En segundo lugar se hace necesario dominar el uso software DIALux, el que nos permitirá simular distintos escenarios y así lograr calcular las distintas magnitudes.

#### **1.3.3 Trabajos Actuales: Road Lighting Calculations (CIE 140-2000) [7]**

La Comisión Internacional de Iluminación en su versión 140 del año 2000 establece las matrices para el cálculo de la iluminación en carreteras. Para esto fija los puntos de cálculo normalizados para la iluminancia y la luminancia de calzada.

La rejilla de cálculo se compone de puntos que en sentido longitudinal cubrirá el tramo de superficie iluminada comprendido entre dos luminarias consecutivas y en sentido transversal, deberá abarcar el ancho de área aplicable, tal como se representa en la figura 1-3.



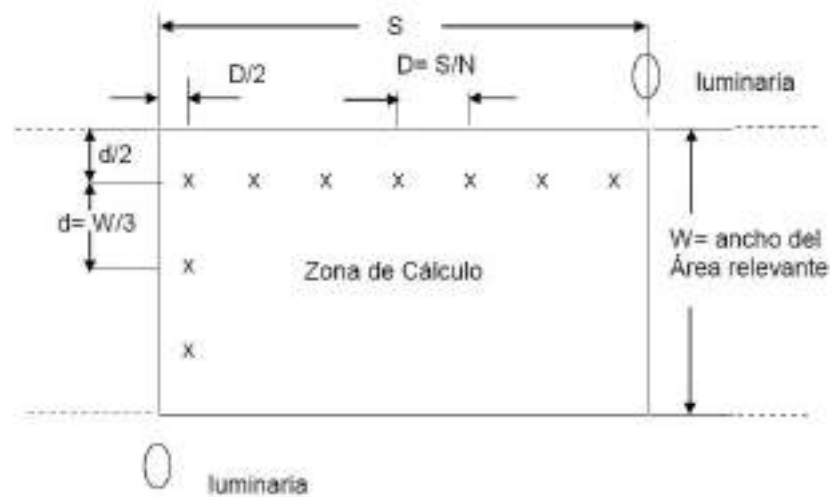


Figura 1-4. Rejilla de cálculo.

Los puntos de cálculo se deben espaciar uniformemente en el campo de cálculo, y la cantidad debe seleccionarse de la siguiente manera. En dirección longitudinal el espaciamiento se determina a partir de la siguiente ecuación.

$$D = S/N \quad (1-8)$$

Donde:

D, es el espaciamiento entre los puntos en la dirección longitudinal [m].

S, es el espaciamiento entre luminarias [m].

N, es el número de puntos de cálculo en dirección longitudinal, con los siguientes valores:

Para  $S \leq 30$  m.  $N = 10$

Para  $S \geq 30$  m. N es el entero más pequeño para que se obtenga D menor o igual a 3 m

Debe tenerse en cuenta que la primera fila de puntos se localiza a una distancia igual a D/2 más allá de primera luminaria.

En dirección transversal se toman tres puntos considerando el ancho total de la calzada,

$$d = W_r / 3 \quad (1-9)$$

Donde:

d, es el espaciamiento entre los puntos en la dirección transversal [m].

$W_r$ , es el ancho de la calzada del área aplicable [m].

### 1.3.4 Trabajos Actuales: Guide on the limitation of the effects of obtrusive light from outdoor lighting installations (CIE 150-2003) [8]

En español “Guía sobre la limitación de los efectos de la luz intrusiva de las instalaciones de iluminación exterior” la que explica como calcular la relación de luz hacia arriba (ULR) mediante un software de cálculo que NO permita el cálculo de esta relación.

Este método permite llegar a una aproximación ULR, este se hace en base a 2 rejillas de cálculo (bajo y sobre las luminarias). Esta recomendación toma como ejemplo áreas generales de instalaciones de iluminación deportiva y se explica a continuación.

Recomienda que las rejillas de cálculo deberán cubrir toda el área más un 5% en cada extremo.

La rejilla inferior debe ser posicionada a 1[m] por debajo del nivel más bajo del proyector montado más bajo del área de medición. El software entregara la iluminancia media resultante de esta rejilla y se denominará como  $E_d$ .

La otra malla de cálculo adquirirá las mismas dimensiones de la rejilla inferior, esta se elevará a 1[m] por encima de la carcasa del reflector. El programa entregara la iluminancia media resultante y se denominará como  $E_u$ .

Luego de obtener estos dos valores, se puede calcular la relación de luz hacia arriba a partir de la siguiente ecuación:

$$ULR = E_u / (E_u + E_d) \quad (1-10)$$

La figura 1-5 resume todo lo anterior.

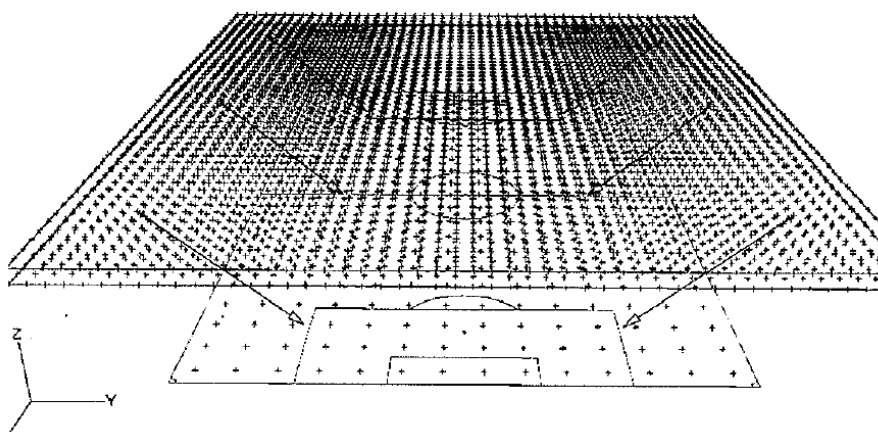


Figura 1-5. Rejillas para el cálculo de ULR.

## 1.4 Software de cálculo DIALux

DIALux es un software de cálculo luminotécnico utilizado por diseñadores de iluminación, consultores, arquitectos, técnicos de iluminación, etc. Puede ser utilizado para el cálculo de iluminación interior y exterior. Permite la importación de archivos de Autocad para su estudio. Se caracteriza por ser capaz de calcular los niveles de iluminación debidos a luz directa e indirecta. El software asume que la luz que es proyectada sobre una superficie, es absorbida en un porcentaje dependiendo del tipo de material de ésta, pero que debido a sus características de reflexión también puede ser una fuente de luz [9].

Los programas de cálculo de iluminación llevan usándose desde hace varias décadas, por lo que se ha podido comprobar la exactitud de los resultados. No obstante, hay que destacar que las causas de desviaciones más frecuentes son:

- Desviación de los datos teóricos de luminosidad de la lámpara con los reales.
- Fuente de alimentación en el uso real, en comparación con laboratorios.
- Desviación en la temperatura de funcionamiento
- Desviación en el grado de reflexión de las superficies

El software permite efectuar la partición de fuentes lineales y extensas, así como de las superficies con el objeto de disponer de cálculos más exactos y precisos considerando únicamente fuentes puntuales.

La versión de software DIALux que se utilizará es la versión 4.13, en las figuras 1-5 y 1-6 se logran apreciar el logo y la interfaz del programa.



Figura 1-6. Logo DIALux.

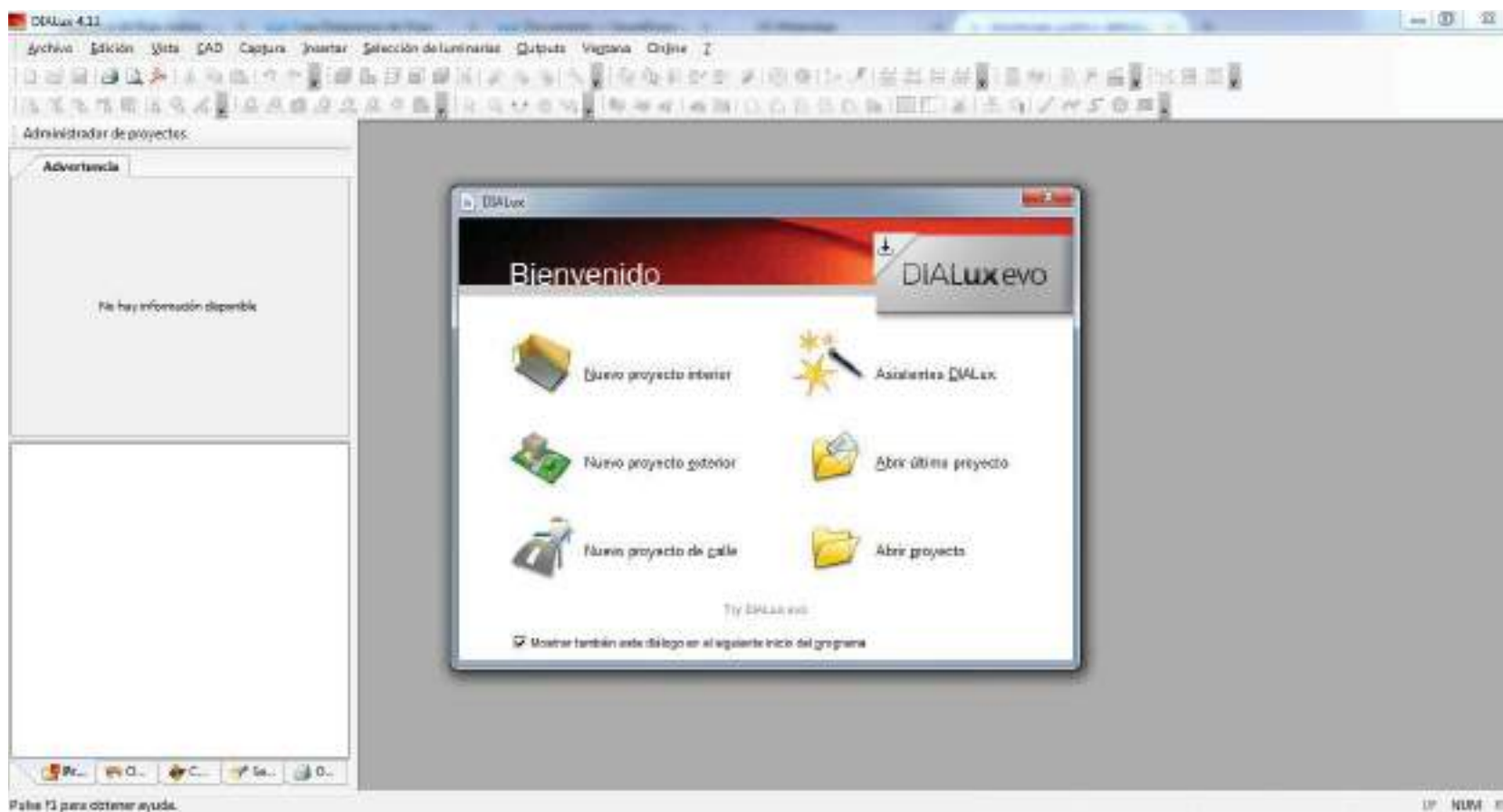


Figura 1-7. Pantalla de bienvenida de DIALux.

Las siguientes imágenes exponen los distintos paneles y pestañas que componen el software de cálculo, los que nos permiten diseñar las zonas de estudio.



Figura 1-8. Menú de trabajo.

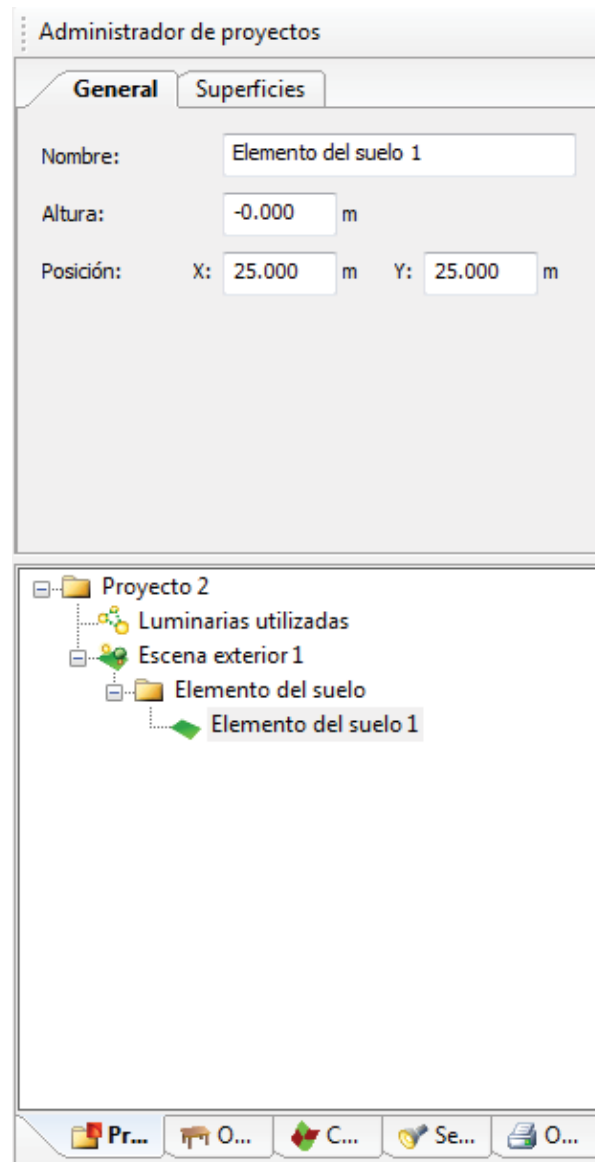


Figura 1-9. Administrador de proyectos.



## 1 Antecedentes generales y propuesta

En el administrador de proyectos nos permite insertar o modificar los objetos y elementos para realizar los cálculos (pistas, luminarias, texturas, viviendas, etc), estos se muestran en las siguientes figuras.

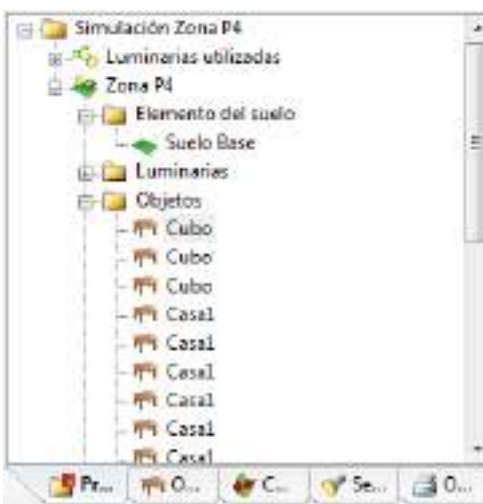


Figura 1-10. Pestaña proyecto (mapa de elementos insertados).



Figura 1-11. Pestaña objetos (permite la inserción de objetos).

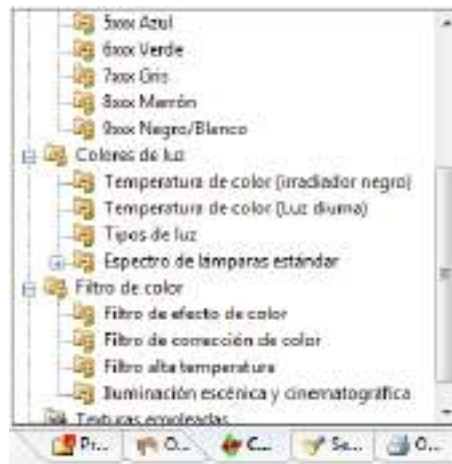


Figura 1-12. Pestaña colores (permite la modificación de texturas).

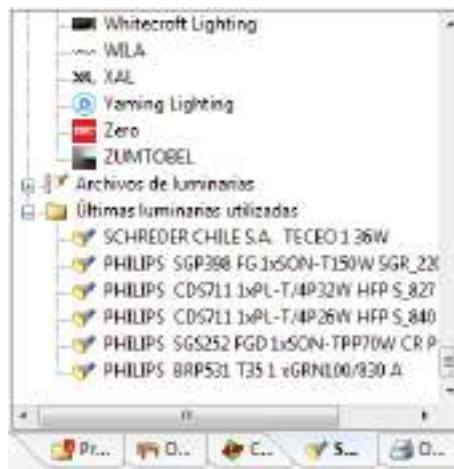


Figura 1-13. Pestaña selección de luminarias (permite inserción de luminarias).



Figura 1-14. Pestaña Output (permite obtener valores de los cálculos).

## 2 Solución y marco teórico

En este capítulo se describe y explica la metodología que se empleará para lograr calcular el flujo luminoso emitido por un sistema de iluminación.

### 2.1 Zonas de aplicación

Las zonas de aplicación de la metodología serán principalmente sistemas de iluminación exterior, vías de tránsito vehicular, plazas, paseos peatonales, estadios, avenidas, etc. Las siguientes figuras ilustran ejemplos de las áreas de aplicación.



Figura 2-1. Zona de aplicación (Vías de tránsito vehicular).



Figura 2-2. Zona de aplicación (Plazas).



Figura 2-3. Zona de aplicación (Paseos peatonales).



Figura 2-4. Zona de aplicación (Estadios).



Figura 2-5. Zona de aplicación (Avenidas).



## 2.2 Solución propuesta

Utilizando el informe de fotometría normalizada elaborado por el Laboratorio de Fotometría y Control de Calidad de la Pontificia Universidad Católica de Valparaíso cuya sigla se reserva, se busca simular y lograr obtener cálculos similares a los obtenidos en mediciones en terreno, en dicho informe se realizaron mediciones a nivel del suelo en cuatro zonas de la comuna de Rengo, Santiago de Chile.

El objetivo es lograr llegar a un modelamiento estética y físicamente semejantes a los de la realidad, luego de conseguir dicho propósito se procederá a realizar las iteraciones necesarias para llegar a obtener resultados aproximados a los obtenidos en terreno (a nivel del suelo).

Finalmente se procederá a crear una metodología que tendrá como base las recomendaciones internacionales CIE 140-2000 y CIE 150-2003.

## 2.3 Marco teórico

En esta sección se explica cuáles serán las zonas que se analizarán y como se llevará a cabo la metodología.

### 2.3.1 Informe Técnico

En el informe técnico, el solicitante (empresa que requiere el informe) requirió que se realizaran mediciones de iluminancia o niveles de iluminación en cuatro zonas de la Región Metropolitana, las que se indican a continuación:

- Zona P1: Calle Stgo Aldea, entre calles Urriola y Estrada.
- Zona P2: Calle Amulen, entre calles Kalefaun y Luis Jorquera.
- Zona P3: Pasaje 4, entre Pasaje 6 y Pasaje 8.
- Zona P4: Pasaje Las Rosas, entre Las Margaritas y Las Dalías.

Para cada zona, se mide en terreno la iluminancia en cada punto de una rejilla de medición conformada según lo establece la normativa CIE 140-2000 "Road Lighting Calculations". Para las Zonas P1, P2, P3 y P4, se consideró una malla conformada por una cantidad de puntos en el largo dada por una separación de 3[m] entre puntos y 3 puntos en el ancho por cada pista. Las mediciones se realizaron con el Luxómetro digital Tektronix LumaColor J17 (Sensor J1811) [10]. La siguiente tabla detalla las características de las zonas del informe técnico.

Tabla 2-1: Características zonas medidas en informe técnico.

|                                          | <b>Zona P1</b>    | <b>Zona P2</b> | <b>Zona P3</b> | <b>Zona P4</b> |
|------------------------------------------|-------------------|----------------|----------------|----------------|
| <b>Puntos Longitudinales [u]</b>         | 13                | 12             | 13             | 11             |
| <b>Puntos Transversales</b>              | 6                 | 6              | 3              | 3              |
| <b>Separación entre postes [m]</b>       | 36,4              | 34,8           | 36             | 32             |
| <b>Ancho de la calle [m]</b>             | 6                 | 7,1            | 3              | 3              |
| <b>N° de pistas</b>                      | 2                 | 2              | 1              | 1              |
| <b>Altura luminarias [m]</b>             | 9                 | 9              | 9              | 9              |
| <b>Luminaria<br/>(Potencia - Óptica)</b> | 90W -<br>Óptica 1 | 55W - Óptica 1 | 36W - Óptica 1 | 36W - Óptica 2 |

### 2.3.2 Metodología de trabajo

La metodología de trabajo será simple y sistemática. Para comenzar se consultó a publicaciones académicas y recomendaciones internacionales de la CIE relevantes a la medición o cálculo de flujo luminoso superior. La propuesta es una combinación de los temas consultados que cuyo fin es proponer una metodología que permita el calcular el flujo luminoso superior. Todo el trabajo será probado y respaldado por simulaciones en un ordenador a través del software DIALux 4.13. Si bien el trabajo contempla el ajuste de los sistemas de iluminación de las distintas zonas, con el único objetivo de que los datos obtenidos de la simulación sean lo más cercano a la realidad para así lograr la representatividad de lo simulado en el software con lo que se midió en terreno.

Esta propuesta contempla un procedimiento paso a paso para calcular de los niveles de iluminación y posteriormente efectuar el cálculo de flujo luminoso superior. Esta metodología será utilizable en cualquier zona donde se requiera calcular el flujo luminoso emitido hacia el hemisferio superior. En la siguiente ilustración se muestra el diagrama de flujo que resume la metodología de trabajo que se empleará para elaborar la propuesta de metodología final para el cálculo de flujo luminoso superior, en la cual se definirá la cantidad de puntos de la rejilla de cálculo y las dimensiones de la misma.

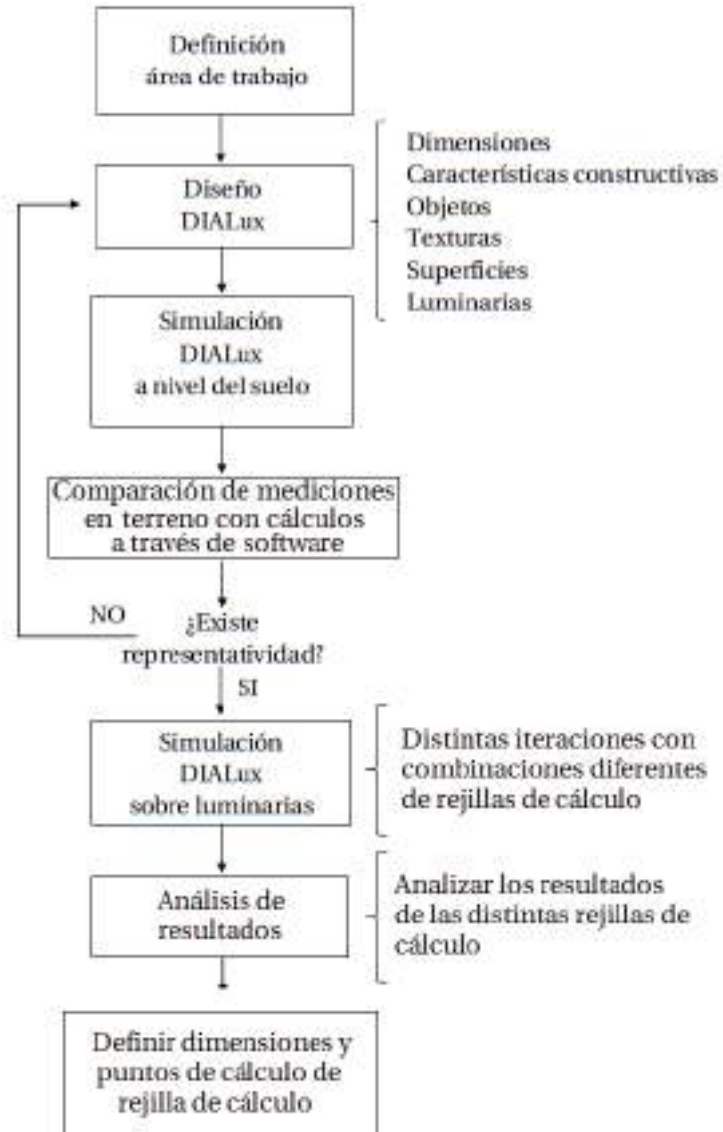


Figura 2-6. Diagrama de flujo de la metodología de trabajo.

Se contemplará que existe representatividad cuando el margen error (%) de  $E_{prom}$  y  $E_{min}$  no superen el 10%.

## 3 Desarrollo

El presente capítulo expone la metodología aplicada para el cálculo de flujo luminoso superior [11].

### 3.1 Diseño en DIALux

Esta sección resume el paso a paso del diseño final de las zonas en estudio.

#### 3.1.1 Configuración zona de trabajo

Tras abrir DIALux aparece una pantalla de bienvenida igual a la que ilustra la figura 3-1, debemos elegir “Nuevo proyecto exterior”, la figura 3-1 se expone esta acción.



Figura 3-1. Nuevo proyecto exterior.

Luego aparecerá la zona de trabajo que muestra la figura 3-2. Al cuadro que aparece en el centro se le llama elemento de suelo.

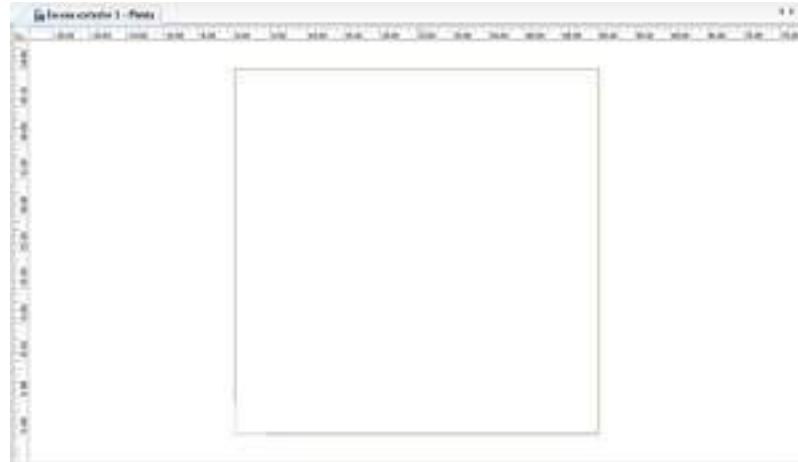


Figura 3-2. Zona de trabajo en DIALux.

Luego de esto haciendo clic derecho en el elemento de suelo y seleccionando “Editar elemento del suelo” se pueden modificar las dimensiones y posición de este. La pantalla que aparece al instante de cliquear es la que se ilustra a continuación.



Figura 3-3. Edición del elemento de suelo.

En el caso de este proyecto se utilizó una zona de trabajo 200x100 [m] para cada una de las simulaciones del informe técnico.

### 3.1.2 Cantidad de luminarias a simular

Para saber cuántas luminarias se utilizarán para realizar las simulaciones, es necesario analizar cuánto aportarán en la magnitud de los resultados las luminarias cercanas al sector donde se ubicará la rejilla de cálculo a nivel del suelo. Para hacer este análisis se elegirá una zona más simple que nos entrega la tabla 2-1, en la cual se emplearán 2 y 4 luminarias.

Luego de examinar la tabla 2-1 se elige la zona P4 básicamente por su simplicidad. La tabla 3-1 muestra los objetos que se usarán para realizar la simulación a nivel del suelo.



Tabla 3-1: Resumen objetos utilizados para simular zona P4.

|                           | Cantidad [-] | Largo [m] | Ancho [m] | Alto [m] | Ubicación<br>respecto eje z [m] |
|---------------------------|--------------|-----------|-----------|----------|---------------------------------|
| <b>Zona de trabajo</b>    | 1            | 200       | 100       | 0        | 0                               |
| <b>Calzada</b>            | 1            | 108       | 3         | 0,001    | 0                               |
| <b>Veredas</b>            | 2            | 108       | 1,5       | 0,001    | 0                               |
| <b>Viviendas</b>          | 18           | 11,4      | 12,085    | 4,5      | 0                               |
| <b>Luminarias</b>         | <b>2 y 4</b> | -         | -         | 9        | 0                               |
| <b>Rejilla de cálculo</b> | 1            | 32        | 3         | -        | 0,001                           |

Las siguientes ilustraciones exponen el aspecto final de la simulación.

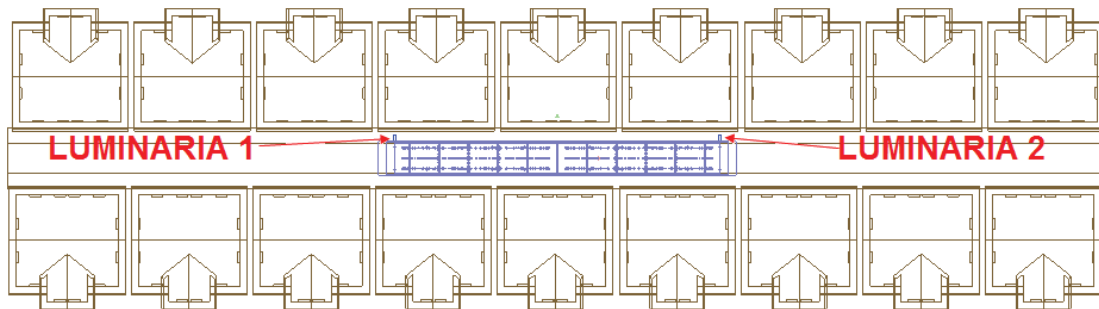


Figura 3-4. Vista de planta (2 luminarias).

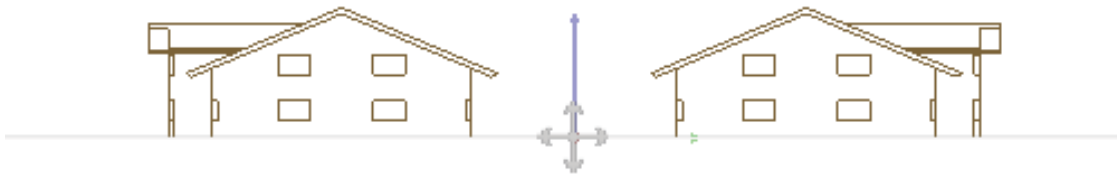


Figura 3-5. Vista frontal.

### Simulaciones para definir cantidad de luminarias

Luego de realizar las simulaciones correspondientes se muestra en las siguientes tablas los resultados obtenidos en DIALux con 2 y 4 luminarias respectivamente, finalmente se expone una tabla comparativa. Ambas simulaciones fueron ejecutadas con una rejilla de cálculo de 11 puntos longitudinales y 3 puntos transversales a nivel del suelo.

Tabla 3-2: Resultados a nivel del suelo con 2 luminarias.

|          | 1     | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11    |
|----------|-------|------|------|------|------|------|------|------|------|------|-------|
| <b>A</b> | 11,00 | 9,52 | 7,17 | 5,30 | 4,34 | 4,07 | 4,34 | 5,30 | 7,17 | 9,52 | 11,00 |
| <b>B</b> | 11,00 | 9,53 | 7,26 | 5,47 | 4,56 | 4,29 | 4,56 | 5,48 | 7,28 | 9,55 | 11,00 |
| <b>C</b> | 10,00 | 9,17 | 7,16 | 5,54 | 4,72 | 4,29 | 4,72 | 5,56 | 7,21 | 9,21 | 10,00 |

Todos los datos en [lx]

Tabla 3-3: Resultados a nivel del suelo con 4 luminarias.

|          | 1     | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11    |
|----------|-------|------|------|------|------|------|------|------|------|------|-------|
| <b>A</b> | 11,00 | 9,69 | 7,27 | 5,36 | 4,38 | 4,09 | 4,38 | 5,36 | 7,26 | 9,68 | 11,00 |
| <b>B</b> | 11,00 | 9,71 | 7,36 | 5,53 | 4,60 | 4,32 | 4,60 | 5,54 | 7,38 | 9,73 | 11,00 |
| <b>C</b> | 11,00 | 9,35 | 7,27 | 5,61 | 4,76 | 4,53 | 4,76 | 5,63 | 7,32 | 9,40 | 11,00 |

Todos los datos en [lx]

Tabla 3-4: Tabla comparativa de iluminancias y uniformidad media con 2 y 4 luminarias.

|                   | Zona P4 2 luminarias | Zona P4 4 luminarias | Variación (%) |
|-------------------|----------------------|----------------------|---------------|
| <b>Eprom [lx]</b> | 7,20                 | 7,32                 | 1,64          |
| <b>Emin [lx]</b>  | 4,07                 | 4,09                 | 0,49          |
| <b>Uprom [-]</b>  | 0,56                 | 0,56                 | 0,00          |

Analizando la tabla 3-4 se puede concluir que la variación de resultados obtenidos no son influyentes en los resultados finales, ya que su variación no supera el 2%. Por ende para el posterior análisis se utilizarán solo 2 luminarias por zona.

### 3.1.3 Altura de cálculos

Con respecto a la altura que se ubicará la malla de cálculo, se tendrá en cuenta la recomendación internacional CIE 150-2003, la que alude el método para realizar cálculos de la relación de luz hacia arriba (ULR) en software (capítulo 5.5.2 – CIE150-2003), esta recomendación fue resumida en la sección 1.2.4 de este informe.

De esta recomendación se tomara en cuenta solo la rejilla superior, que se ubica a 1[m] por encima de la luminaria más alta de la zona de medición. La siguiente ilustración exhibe una vista lateral de la zona, detallando las luminarias y la altura de la rejilla de cálculo.

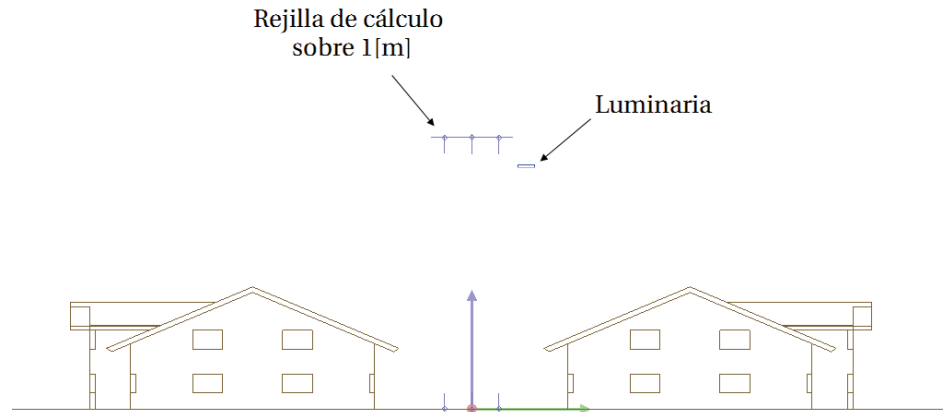


Figura 3-6. Vista lateral con malla de cálculo sobre 1[m].

#### 3.1.4 Dimensiones rejilla en hemisferios superior

Las dimensiones de las rejillas que se simularan serán iguales a las que se calculan a nivel del suelo, además se contemplará el ensanchamiento de la zona en un 5% y un 10%.

#### 3.1.5 Cantidad de puntos de cálculo

La cantidad de puntos de cálculo que se utilizarán en los cálculos, se definirá mediante todas las posibles iteraciones que se hagan con la visión de que estas representen el área de cálculo y entreguen valores con un delta mínimo en la variación de estos resultados.

### 3.2 Análisis informe técnico

Para definir la metodología final se hace necesario realizar simulaciones en todas las zonas del presente informe técnico.

#### 3.2.1 Zona P1

##### Materiales en terreno y materiales simulados

Las características de la zona P1 se presentan en la siguientes tablas nos indican los materiales en terreno y los que se utilizarán en la simulación. Los objetos utilizados para simular son los que se indican a continuación.

Tabla 3-5: Tabla de materiales en terreno y simulados en zona P1.

|                  | MATERIALES             |                                                              |         |
|------------------|------------------------|--------------------------------------------------------------|---------|
|                  | Terreno                | Simulación                                                   | Rho (%) |
| <b>Calzada</b>   | Concreto               | Cemento crudo claro                                          | 68      |
| <b>Veredas</b>   | Pasto                  | Hierba                                                       | 29      |
| <b>Viviendas</b> | Variedad de materiales | Cemento, Piedra de cantera, Madera, Ladrillo                 | 23-49   |
| <b>Techos</b>    | Variedad de materiales | Teja roja, Baldosa cóncava, Pizarra cuadrangular, Teja plana | 30-49   |

Tabla 3-6: Resumen objetos utilizados para simular zona P1.

|                           | Cantidad [-] | Largo [m] | Ancho [m] | Alto [m] | Ubicación respecto eje z [m] |
|---------------------------|--------------|-----------|-----------|----------|------------------------------|
| <b>Zona de trabajo</b>    | 1            | 200       | 100       | 0,000    | 0                            |
| <b>Calzada</b>            | 1            | 108       | 6         | 0,001    | 0                            |
| <b>Veredas</b>            | 2            | 108       | 1,5       | 0,001    | 0                            |
| <b>Viviendas</b>          | 18           | 11,4      | 12,085    | 4,5      | 0                            |
| <b>Luminarias</b>         | 2            | -         | -         | 9        | 0                            |
| <b>Rejilla de cálculo</b> | 1            | 36,4      | 6         | -        | 0,001                        |

##### Luminaria utilizada

En el informe técnico y según la información suministrada por el solicitante de las mediciones en terreno, las luminarias dispuestas en terreno en zona P1 son de 90W óptica 1. En la simulación se utilizarán las mismas luminarias. A continuación en la siguiente figura se observa la curva de distribución luminosa de la luminaria.

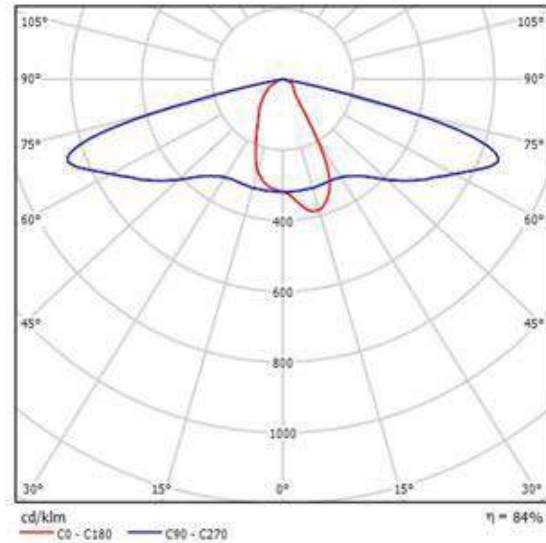


Figura 3-7. Distribución luminosa luminaria 90W óptica 1.

### Aspecto final de la simulación

Ya diseñados los aspectos físicos y definidos los colores y texturas del proyecto, se logra obtener un modelo bastante acercado a lo visto en terreno, las siguientes imágenes muestran una fotografía del informe y una vista 3D de la simulación.



Figura 3-8. Fotografía en terreno zona P1.





Figura 3-9. Vista 3D de la simulación en zona P1.

### Simulación a nivel del suelo

Como indica el diagrama de flujo de la figura 2-6, luego de diseñar la zona se simulará a nivel del suelo con el único objetivo de tener representatividad de los datos calculados con los medidos en terreno.

Las mediciones hechas en terreno arrojan los resultados obtenidos de una rejilla medición de 13x6 puntos, los que se exponen en la siguiente tabla.

Tabla 3-7: Medición en terreno zona P1.

|                |          | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   | 12   | 13   |
|----------------|----------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| <b>PISTA 1</b> | <b>A</b> | 43,8 | 35,5 | 23,9 | 17,9 | 14,5 | 13,5 | 13,5 | 15,0 | 17,8 | 20,2 | 27,0 | 36,7 | 30,8 |
|                | <b>B</b> | 46,4 | 39,1 | 27,9 | 21,3 | 18,2 | 16,7 | 16,5 | 17,5 | 21,0 | 27,8 | 32,5 | 38,8 | 44,3 |
|                | <b>C</b> | 49,9 | 43,3 | 34,0 | 25,5 | 20,5 | 17,7 | 17,3 | 18,5 | 22,1 | 27,8 | 35,9 | 44,5 | 51,2 |
| <b>PISTA 2</b> | <b>A</b> | 52,1 | 40,4 | 33,3 | 25,4 | 20,7 | 17,3 | 16,7 | 17,9 | 20,3 | 24,0 | 32,4 | 44,2 | 52,9 |
|                | <b>B</b> | 45,3 | 39,1 | 28,9 | 21,4 | 18,5 | 16,1 | 15,2 | 15,6 | 16,8 | 20,7 | 27,6 | 37,5 | 45,4 |
|                | <b>C</b> | 32,8 | 29,4 | 22,4 | 17,7 | 14,9 | 13,1 | 11,9 | 11,3 | 12,9 | 16,1 | 20,7 | 27,4 | 33,7 |

Todos los datos en [lx]

El objetivo de la simulación en suelo es llegar a valores similares a los obtenidos en la tabla 3-7, luego de hacer las modificaciones pertinentes se logró llegar a resultados parecidos a los obtenidos en las mediciones en terreno, la tabla 3-8 muestra la similitud de los datos.

Tabla 3-8: Simulación zona P1.

|                |          | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13 |
|----------------|----------|----|----|----|----|----|----|----|----|----|----|----|----|----|
| <b>PISTA 1</b> | <b>A</b> | 45 | 35 | 25 | 20 | 16 | 14 | 14 | 14 | 16 | 20 | 25 | 35 | 45 |
|                | <b>B</b> | 48 | 38 | 30 | 24 | 19 | 16 | 15 | 16 | 19 | 24 | 30 | 38 | 48 |
|                | <b>C</b> | 51 | 42 | 32 | 24 | 19 | 16 | 15 | 16 | 19 | 24 | 32 | 42 | 51 |
| <b>PISTA 2</b> | <b>A</b> | 50 | 39 | 29 | 22 | 18 | 15 | 14 | 15 | 18 | 22 | 29 | 39 | 50 |
|                | <b>B</b> | 42 | 33 | 24 | 19 | 15 | 14 | 13 | 14 | 15 | 19 | 25 | 33 | 42 |
|                | <b>C</b> | 30 | 24 | 19 | 15 | 12 | 11 | 11 | 11 | 12 | 15 | 19 | 24 | 30 |

Todos los datos en [lx]

Para obtener estos resultados se modificó el factor de mantenimiento, después de bastantes iteraciones el factor de mantenimiento empleado para los cálculos fue de 0,98.

Al analizar las tablas 3-7 y 3-8 se ve una gran similitud en la magnitud valores obtenidos en la medición en terreno y simulación en DIALux, ahora se comparan los valores entregados en el informe y el software los cuales son expuestos en la siguiente tabla comparativa.

Tabla 3-9: Tabla comparativa de zona P1 en terreno y simulada.

|                  | <b>Zona P1 en terreno</b> | <b>Zona P1 simulada</b> | <b>Margen de error (%)</b> |
|------------------|---------------------------|-------------------------|----------------------------|
| <b>Emed [lx]</b> | 26,87                     | 25,00                   | 6,95                       |
| <b>Emin [lx]</b> | 11,25                     | 11,00                   | 2,22                       |

En la tabla 3-9 se corrobora que los resultados obtenidos debidos de las iluminancias medidas y calculadas de la zona P4, son prácticamente iguales por lo que se cumple con el objetivo, además su margen de error no supera el 7%, por ende se logra con la representatividad buscada en la zona P1. Ahora según el diagrama de flujo se procede a la simulación sobre las luminarias.

### Simulación sobre luminarias

Siguiendo con la metodología queda simular sobre las luminarias, la cual se realizará con rejillas situadas en el hemisferio superior posicionadas a 1[m] sobre las luminarias. Primeramente se realizarán simulaciones en una misma área en la cual se cambiará la cantidad de puntos de cálculo, luego se modificará la cantidad de puntos longitudinales y posteriormente se variará la cantidad de puntos transversales. Luego de identificar la cantidad de puntos longitudinales y transversales se hará una modificación del área de cálculo en un 5%, tal como indica la CIE150-2003 y después se modificará en un 10% esta área.

### Variación de puntos longitudinales

Las siguientes tablas mostrarán las distintas iteraciones que se realizaron al variar los puntos longitudinales (los puntos transversales son siempre 6). La primera fila muestra la cantidad de puntos longitudinales, la primera columna indica la pista y la segunda columna muestra la cantidad de puntos transversales.

Todos los resultados expuestos en las tablas fueron calculados en el hemisferio superior a 1[m] sobre las luminarias.

Tabla 3-10: Cálculos en rejilla 1x6.

| 1                  |          |      |
|--------------------|----------|------|
| <b>PISTA<br/>1</b> | <b>A</b> | 4,35 |
|                    | <b>B</b> | 4,54 |
|                    | <b>C</b> | 4,66 |
| <b>PISTA<br/>2</b> | <b>A</b> | 4,69 |
|                    | <b>B</b> | 4,65 |
|                    | <b>C</b> | 4,52 |

Todos los datos en [lx]

Tabla 3-11: Cálculos en rejilla 2x6.

| 1      2           |          |      |      |
|--------------------|----------|------|------|
| <b>PISTA<br/>1</b> | <b>A</b> | 5,50 | 5,51 |
|                    | <b>B</b> | 5,78 | 5,77 |
|                    | <b>C</b> | 5,98 | 5,96 |
| <b>PISTA<br/>2</b> | <b>A</b> | 6,10 | 6,07 |
|                    | <b>B</b> | 6,13 | 6,08 |
|                    | <b>C</b> | 5,93 | 5,99 |

Todos los datos en [lx]

Tabla 3-12: Cálculos en rejilla 3x6.

| 1      2      3    |          |      |      |      |
|--------------------|----------|------|------|------|
| <b>PISTA<br/>1</b> | <b>A</b> | 6,22 | 4,35 | 6,21 |
|                    | <b>B</b> | 6,60 | 4,54 | 6,57 |
|                    | <b>C</b> | 6,86 | 4,66 | 6,80 |
| <b>PISTA<br/>2</b> | <b>A</b> | 7,02 | 4,69 | 6,93 |
|                    | <b>B</b> | 7,02 | 4,65 | 6,94 |
|                    | <b>C</b> | 6,93 | 4,52 | 6,83 |

Todos los datos en [lx]

Tabla 3-13: Cálculos en rejilla 4x6.

| 1      2      3      4 |          |      |      |      |      |
|------------------------|----------|------|------|------|------|
| <b>PISTA<br/>1</b>     | <b>A</b> | 6,50 | 4,77 | 4,78 | 6,48 |
|                        | <b>B</b> | 6,91 | 5,01 | 5,01 | 6,86 |
|                        | <b>C</b> | 7,17 | 5,15 | 5,15 | 7,10 |
| <b>PISTA<br/>2</b>     | <b>A</b> | 7,33 | 5,21 | 5,20 | 7,24 |
|                        | <b>B</b> | 7,36 | 5,19 | 5,17 | 7,25 |
|                        | <b>C</b> | 7,34 | 5,07 | 5,04 | 7,20 |

Todos los datos en [lx]

Tabla 3-14: Cálculos en rejilla 5x6.

|                |          | 1    | 2    | 3    | 4    | 5    |
|----------------|----------|------|------|------|------|------|
| <b>PISTA 1</b> | <b>A</b> | 6,47 | 5,17 | 4,35 | 5,19 | 6,43 |
|                | <b>B</b> | 6,87 | 5,45 | 4,54 | 5,45 | 6,81 |
|                | <b>C</b> | 7,14 | 5,62 | 4,66 | 5,61 | 7,05 |
| <b>PISTA 2</b> | <b>A</b> | 7,31 | 5,72 | 4,69 | 5,69 | 7,19 |
|                | <b>B</b> | 7,34 | 5,72 | 4,65 | 5,69 | 7,20 |
|                | <b>C</b> | 7,37 | 5,62 | 4,52 | 5,58 | 7,08 |

Todos los datos en [lx]

Tabla 3-15: Cálculos en rejilla 6x6.

|                |          | 1    | 2    | 3    | 4    | 5    | 6    |
|----------------|----------|------|------|------|------|------|------|
| <b>PISTA 1</b> | <b>A</b> | 6,55 | 5,50 | 4,62 | 4,63 | 5,51 | 6,50 |
|                | <b>B</b> | 6,98 | 5,78 | 4,85 | 4,85 | 5,77 | 6,90 |
|                | <b>C</b> | 7,26 | 5,98 | 4,97 | 4,97 | 5,96 | 7,16 |
| <b>PISTA 2</b> | <b>A</b> | 7,43 | 6,10 | 5,02 | 5,01 | 6,07 | 7,28 |
|                | <b>B</b> | 7,46 | 6,13 | 4,99 | 4,98 | 6,08 | 7,31 |
|                | <b>C</b> | 7,34 | 5,93 | 4,86 | 4,84 | 5,99 | 7,16 |

Todos los datos en [lx]

Tabla 3-16: Cálculos en rejilla 7x6.

|                |          | 1    | 2    | 3    | 4    | 5    | 6    | 7    |
|----------------|----------|------|------|------|------|------|------|------|
| <b>PISTA 1</b> | <b>A</b> | 6,61 | 5,92 | 4,86 | 4,35 | 4,86 | 5,93 | 6,55 |
|                | <b>B</b> | 7,04 | 6,25 | 5,10 | 4,54 | 5,10 | 6,23 | 6,95 |
|                | <b>C</b> | 7,32 | 6,42 | 5,25 | 4,66 | 5,24 | 6,40 | 7,21 |
| <b>PISTA 2</b> | <b>A</b> | 7,45 | 6,57 | 5,32 | 4,69 | 5,30 | 6,52 | 7,32 |
|                | <b>B</b> | 7,52 | 6,63 | 5,30 | 4,65 | 5,28 | 6,57 | 7,35 |
|                | <b>C</b> | 7,40 | 6,44 | 5,19 | 4,52 | 5,16 | 6,37 | 7,20 |

Todos los datos en [lx]

Tabla 3-17: Cálculos en rejilla 8x6.

|                |          | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    |
|----------------|----------|------|------|------|------|------|------|------|------|
| <b>PISTA 1</b> | <b>A</b> | 6,65 | 6,07 | 5,10 | 4,57 | 4,58 | 5,11 | 6,07 | 6,58 |
|                | <b>B</b> | 7,08 | 6,43 | 5,36 | 4,79 | 4,79 | 5,36 | 6,41 | 6,98 |
|                | <b>C</b> | 7,36 | 6,67 | 5,53 | 4,91 | 4,91 | 5,53 | 6,64 | 7,25 |
| <b>PISTA 2</b> | <b>A</b> | 7,51 | 6,83 | 5,62 | 4,96 | 4,95 | 5,60 | 6,77 | 7,37 |
|                | <b>B</b> | 7,54 | 6,86 | 5,62 | 4,92 | 4,91 | 5,59 | 6,79 | 7,38 |
|                | <b>C</b> | 7,44 | 6,71 | 5,52 | 4,79 | 4,77 | 5,48 | 6,62 | 7,24 |

Todos los datos en [lx]

Tabla 3-18: Cálculos en rejilla 9x6.

|                |          | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    |
|----------------|----------|------|------|------|------|------|------|------|------|------|
| <b>PISTA 1</b> | <b>A</b> | 6,67 | 6,22 | 5,32 | 4,72 | 4,35 | 4,72 | 5,33 | 6,21 | 6,60 |
|                | <b>B</b> | 7,11 | 6,60 | 5,61 | 4,95 | 4,54 | 4,95 | 5,61 | 6,57 | 7,01 |
|                | <b>C</b> | 7,40 | 6,86 | 5,79 | 5,08 | 4,66 | 5,08 | 5,78 | 6,80 | 7,27 |
| <b>PISTA 2</b> | <b>A</b> | 7,55 | 7,02 | 5,90 | 5,14 | 4,69 | 5,13 | 5,87 | 6,93 | 7,40 |
|                | <b>B</b> | 7,54 | 7,02 | 5,90 | 5,12 | 4,65 | 5,10 | 5,87 | 6,94 | 7,38 |
|                | <b>C</b> | 7,47 | 6,93 | 5,81 | 4,99 | 4,52 | 4,97 | 5,76 | 6,83 | 7,26 |

Todos los datos en [lx]

Tabla 3-19: Cálculos en rejilla 10x6.

|                |          | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   |
|----------------|----------|------|------|------|------|------|------|------|------|------|------|
| <b>PISTA 1</b> | <b>A</b> | 6,69 | 6,34 | 5,50 | 4,89 | 4,55 | 4,55 | 4,90 | 5,51 | 6,33 | 6,61 |
|                | <b>B</b> | 7,13 | 6,73 | 5,78 | 5,14 | 4,76 | 4,77 | 5,14 | 5,77 | 6,69 | 7,02 |
|                | <b>C</b> | 7,41 | 6,98 | 5,98 | 5,29 | 4,89 | 4,89 | 5,28 | 5,96 | 6,93 | 7,29 |
| <b>PISTA 2</b> | <b>A</b> | 7,53 | 7,13 | 6,10 | 5,36 | 4,94 | 4,93 | 5,34 | 6,07 | 7,06 | 7,40 |
|                | <b>B</b> | 7,56 | 7,16 | 6,13 | 5,35 | 4,89 | 4,88 | 5,33 | 6,08 | 7,07 | 7,40 |
|                | <b>C</b> | 7,47 | 7,10 | 5,93 | 5,23 | 4,75 | 4,74 | 5,20 | 5,99 | 6,99 | 7,25 |

Todos los datos en [lx]

Tabla 3-20: Cálculos en rejilla 11x6.

|                |          | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   |
|----------------|----------|------|------|------|------|------|------|------|------|------|------|------|
| <b>PISTA 1</b> | <b>A</b> | 6,71 | 6,43 | 5,66 | 5,06 | 4,65 | 4,35 | 4,65 | 5,07 | 5,67 | 6,41 | 6,63 |
|                | <b>B</b> | 7,14 | 6,83 | 6,13 | 5,33 | 4,87 | 4,54 | 4,87 | 5,33 | 6,11 | 6,79 | 7,03 |
|                | <b>C</b> | 7,43 | 7,09 | 6,34 | 5,50 | 5,00 | 4,66 | 4,99 | 5,49 | 6,32 | 7,03 | 7,30 |
| <b>PISTA 2</b> | <b>A</b> | 7,55 | 7,24 | 6,47 | 5,58 | 5,05 | 4,69 | 5,04 | 5,56 | 6,44 | 7,16 | 7,41 |
|                | <b>B</b> | 7,60 | 7,27 | 6,50 | 5,57 | 5,02 | 4,65 | 5,01 | 5,55 | 6,45 | 7,17 | 7,41 |
|                | <b>C</b> | 7,50 | 7,24 | 6,15 | 5,47 | 4,89 | 4,52 | 4,87 | 5,43 | 6,08 | 7,10 | 7,27 |

Todos los datos en [lx]

Tabla 3-21: Cálculos en rejilla 12x6.

|                |          | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   | 12   |
|----------------|----------|------|------|------|------|------|------|------|------|------|------|------|------|
| <b>PISTA 1</b> | <b>A</b> | 6,72 | 6,50 | 5,97 | 5,23 | 4,77 | 4,54 | 4,55 | 4,78 | 5,24 | 5,97 | 6,48 | 6,63 |
|                | <b>B</b> | 7,15 | 6,91 | 6,25 | 5,51 | 5,01 | 4,76 | 4,76 | 5,01 | 5,51 | 6,23 | 6,86 | 7,04 |
|                | <b>C</b> | 7,44 | 7,17 | 6,48 | 5,69 | 5,15 | 4,88 | 4,88 | 5,15 | 5,67 | 6,45 | 7,1  | 7,31 |
| <b>PISTA 2</b> | <b>A</b> | 7,56 | 7,33 | 6,62 | 5,78 | 5,21 | 4,92 | 4,92 | 5,20 | 5,76 | 6,58 | 7,24 | 7,43 |
|                | <b>B</b> | 7,58 | 7,36 | 6,66 | 5,79 | 5,19 | 4,88 | 4,87 | 5,17 | 5,75 | 6,60 | 7,25 | 7,43 |
|                | <b>C</b> | 7,52 | 7,34 | 6,51 | 5,69 | 5,07 | 4,74 | 4,73 | 5,04 | 5,64 | 6,43 | 7,2  | 7,28 |

Todos los datos en [lx]



Tabla 3-22: Cálculos en rejilla 13x6.

|                    |          | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   | 12   | 13   |
|--------------------|----------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| <b>PISTA<br/>1</b> | <b>A</b> | 6,72 | 6,37 | 6,03 | 5,37 | 4,91 | 4,61 | 4,35 | 4,61 | 4,92 | 5,39 | 6,03 | 6,35 | 6,64 |
|                    | <b>B</b> | 7,16 | 6,97 | 6,39 | 5,67 | 5,16 | 4,83 | 4,54 | 4,83 | 5,16 | 5,67 | 6,37 | 6,92 | 7,04 |
|                    | <b>C</b> | 7,45 | 7,24 | 6,63 | 5,82 | 5,31 | 4,95 | 4,66 | 4,95 | 5,30 | 5,8  | 6,60 | 7,16 | 7,31 |
| <b>PISTA<br/>2</b> | <b>A</b> | 7,60 | 7,40 | 6,78 | 5,93 | 5,39 | 5    | 4,69 | 4,99 | 5,37 | 5,9  | 6,73 | 7,3  | 7,44 |
|                    | <b>B</b> | 7,59 | 7,43 | 6,81 | 5,98 | 5,37 | 4,97 | 4,65 | 4,95 | 5,35 | 5,94 | 6,75 | 7,31 | 7,41 |
|                    | <b>C</b> | 7,52 | 7,23 | 6,66 | 5,88 | 5,26 | 4,84 | 4,52 | 4,82 | 5,23 | 5,83 | 6,57 | 7,08 | 7,28 |

Todos los datos en [lx]

Tabla 3-23: Cálculos en rejilla 14x6.

|                    |          | 1   | 2   | 3   | 4   | 5    | 6    | 7    | 8    | 9    | 10   | 11   | 12   | 13   | 14   |
|--------------------|----------|-----|-----|-----|-----|------|------|------|------|------|------|------|------|------|------|
| <b>PISTA<br/>1</b> | <b>A</b> | 6,7 | 6,4 | 6,1 | 5,5 | 5,04 | 4,7  | 4,54 | 4,54 | 4,71 | 5,05 | 5,51 | 6,14 | 6,39 | 6,64 |
|                    | <b>B</b> | 7,2 | 6,8 | 6,5 | 5,8 | 5,31 | 4,93 | 4,75 | 4,75 | 4,93 | 5,31 | 5,77 | 6,48 | 6,77 | 7,05 |
|                    | <b>C</b> | 7,5 | 7,1 | 6,8 | 6   | 5,47 | 5,07 | 4,87 | 4,87 | 5,06 | 5,47 | 5,96 | 6,71 | 7,01 | 7,32 |
| <b>PISTA<br/>2</b> | <b>A</b> | 7,6 | 7,3 | 6,9 | 6,1 | 5,56 | 5,12 | 4,91 | 4,91 | 5,11 | 5,54 | 6,07 | 6,85 | 7,15 | 7,46 |
|                    | <b>B</b> | 7,6 | 7,3 | 6,9 | 6,1 | 5,55 | 5,1  | 4,87 | 4,86 | 5,08 | 5,52 | 6,08 | 6,84 | 7,16 | 7,42 |
|                    | <b>C</b> | 7,6 | 7,3 | 6,8 | 5,9 | 5,44 | 4,97 | 4,73 | 4,72 | 4,95 | 5,41 | 5,99 | 6,71 | 7,14 | 7,31 |

Todos los datos en [lx]

Tabla 3-24: Cálculos en rejilla 15x6.

|                |          | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   | 12   | 13   | 14   | 15   |
|----------------|----------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| <b>PISTA 1</b> | <b>A</b> | 6,73 | 6,47 | 6,22 | 5,62 | 5,17 | 4,81 | 4,58 | 4,35 | 4,59 | 4,82 | 5,19 | 5,63 | 6,21 | 6,43 | 6,64 |
|                | <b>B</b> | 7,17 | 6,87 | 6,6  | 6,07 | 5,45 | 5,05 | 4,8  | 4,54 | 4,8  | 5,05 | 5,45 | 6,06 | 6,57 | 6,81 | 7,05 |
|                | <b>C</b> | 7,46 | 7,14 | 6,86 | 6,28 | 5,62 | 5,19 | 4,92 | 4,66 | 4,92 | 5,19 | 5,61 | 6,26 | 6,8  | 7,05 | 7,32 |
| <b>PISTA 2</b> | <b>A</b> | 7,63 | 7,31 | 7,02 | 6,41 | 5,72 | 5,26 | 4,97 | 4,69 | 4,96 | 5,25 | 5,69 | 6,38 | 6,93 | 7,19 | 7,46 |
|                | <b>B</b> | 7,53 | 7,34 | 7,02 | 6,44 | 5,72 | 5,24 | 4,93 | 4,65 | 4,92 | 5,22 | 5,69 | 6,39 | 6,94 | 7,2  | 7,35 |
|                | <b>C</b> | 7,37 | 7,37 | 6,93 | 6,09 | 5,62 | 5,12 | 4,8  | 4,52 | 4,79 | 5,1  | 5,58 | 6,13 | 6,83 | 7,08 | 7,12 |

Todos los datos en [lx]

Tabla 3-25: Cálculos en rejilla 16x6.

|                |          | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   | 12   | 13   | 14   | 15   | 16   |
|----------------|----------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| <b>PISTA 1</b> | <b>A</b> | 6,7  | 6,5  | 6,3  | 5,89 | 5,29 | 4,92 | 4,66 | 4,53 | 4,53 | 4,66 | 4,93 | 5,31 | 5,89 | 6,29 | 6,46 | 6,65 |
|                | <b>B</b> | 7,17 | 6,91 | 6,68 | 6,2  | 5,58 | 5,18 | 4,88 | 4,74 | 4,75 | 4,88 | 5,17 | 5,59 | 6,19 | 6,65 | 6,85 | 7,05 |
|                | <b>C</b> | 7,46 | 7,18 | 6,93 | 6,42 | 5,76 | 5,33 | 5,01 | 4,87 | 4,86 | 5,01 | 5,32 | 5,75 | 6,4  | 6,88 | 7,1  | 7,32 |
| <b>PISTA 2</b> | <b>A</b> | 7,61 | 7,35 | 7,08 | 6,56 | 5,87 | 5,41 | 5,06 | 4,91 | 4,9  | 5,05 | 5,38 | 5,84 | 6,52 | 7,01 | 7,23 | 7,45 |
|                | <b>B</b> | 7,53 | 7,39 | 7,11 | 6,58 | 5,87 | 5,39 | 5,03 | 4,86 | 4,85 | 5,02 | 5,37 | 5,84 | 6,53 | 7,02 | 7,24 | 7,35 |
|                | <b>C</b> | 7,36 | 7,42 | 7,04 | 6,4  | 5,78 | 5,28 | 4,91 | 4,72 | 4,71 | 4,89 | 5,24 | 5,73 | 6,33 | 6,93 | 7,11 | 7,12 |

Todos los datos en [lx]

Tabla 3-26: Cálculos en rejilla 17x6.

|                |          | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   | 12   | 13   | 14   | 15   | 16   | 17   |
|----------------|----------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| <b>PISTA 1</b> | <b>A</b> | 6,74 | 6,53 | 6,36 | 5,99 | 5,4  | 5,03 | 4,74 | 4,57 | 4,35 | 4,57 | 4,75 | 5,04 | 5,42 | 5,99 | 6,35 | 6,48 | 6,65 |
|                | <b>B</b> | 7,17 | 6,95 | 6,75 | 6,27 | 5,71 | 5,3  | 4,98 | 4,78 | 4,54 | 4,78 | 4,98 | 5,29 | 5,7  | 6,25 | 6,71 | 6,87 | 7,05 |
|                | <b>C</b> | 7,47 | 7,23 | 7    | 6,5  | 5,85 | 5,46 | 5,12 | 4,9  | 4,66 | 4,9  | 5,11 | 5,45 | 5,84 | 6,47 | 6,95 | 7,13 | 7,32 |
| <b>PISTA 2</b> | <b>A</b> | 7,61 | 7,39 | 7,16 | 6,65 | 5,97 | 5,54 | 5,18 | 4,95 | 4,69 | 4,94 | 5,16 | 5,52 | 5,94 | 6,6  | 7,08 | 7,27 | 7,45 |
|                | <b>B</b> | 7,57 | 7,42 | 7,18 | 6,68 | 6,01 | 5,53 | 5,15 | 4,91 | 4,65 | 4,9  | 5,13 | 5,51 | 5,98 | 6,62 | 7,09 | 7,28 | 7,37 |
|                | <b>C</b> | 7,36 | 7,46 | 7,13 | 6,53 | 5,92 | 5,43 | 5,03 | 4,78 | 4,52 | 4,77 | 5    | 5,39 | 5,87 | 6,46 | 7,01 | 7,14 | 7,12 |

Todos los datos en [lx]

Tabla 3-27: Cálculos en rejilla 18x6.

|                |          | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   | 12   | 13   | 14   | 15   | 16   | 17   | 18   |
|----------------|----------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| <b>PISTA 1</b> | <b>A</b> | 6,74 | 6,55 | 6,41 | 6,02 | 5,5  | 5,14 | 4,84 | 4,62 | 4,53 | 4,54 | 4,63 | 4,84 | 5,15 | 5,51 | 6,02 | 6,4  | 6,5  | 6,65 |
|                | <b>B</b> | 7,18 | 6,98 | 6,81 | 6,37 | 5,78 | 5,41 | 5,08 | 4,85 | 4,74 | 4,74 | 4,85 | 5,08 | 5,41 | 5,77 | 6,35 | 6,77 | 6,9  | 7,06 |
|                | <b>C</b> | 7,47 | 7,26 | 7,07 | 6,61 | 5,98 | 5,58 | 5,22 | 4,97 | 4,86 | 4,86 | 4,97 | 5,22 | 5,57 | 5,96 | 6,58 | 7,01 | 7,16 | 7,32 |
| <b>PISTA 2</b> | <b>A</b> | 7,59 | 7,43 | 7,22 | 6,76 | 6,1  | 5,68 | 5,29 | 5,02 | 4,9  | 4,9  | 5,01 | 5,28 | 5,65 | 6,07 | 6,71 | 7,14 | 7,28 | 7,44 |
|                | <b>B</b> | 7,57 | 7,46 | 7,25 | 6,79 | 6,13 | 5,67 | 5,28 | 4,99 | 4,85 | 4,85 | 4,98 | 5,25 | 5,64 | 6,08 | 6,73 | 7,15 | 7,31 | 7,37 |
|                | <b>C</b> | 7,36 | 7,34 | 7,21 | 6,64 | 5,93 | 5,57 | 5,16 | 4,86 | 4,72 | 4,71 | 4,84 | 5,13 | 5,53 | 5,99 | 6,55 | 7,08 | 7,16 | 7,12 |

Todos los datos en [lx]

Tabla 3-28: Cálculos en rejilla 19x6.

|                |          | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   | 12   | 13   | 14   | 15   | 16   | 17   | 18   | 19   |
|----------------|----------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| <b>PISTA 1</b> | <b>A</b> | 6,75 | 6,57 | 6,46 | 6,1  | 5,6  | 5,24 | 4,93 | 4,7  | 4,56 | 4,35 | 4,56 | 4,7  | 4,94 | 5,25 | 5,6  | 6,09 | 6,44 | 6,52 | 6,65 |
|                | <b>B</b> | 7,18 | 7    | 6,86 | 6,46 | 5,88 | 5,53 | 5,18 | 4,93 | 4,77 | 4,54 | 4,77 | 4,92 | 5,18 | 5,53 | 5,87 | 6,44 | 6,82 | 6,91 | 7,06 |
|                | <b>C</b> | 7,47 | 7,28 | 7,12 | 6,7  | 6,25 | 5,7  | 5,34 | 5,06 | 4,9  | 4,66 | 4,89 | 5,05 | 5,33 | 5,69 | 6,23 | 6,67 | 7,06 | 7,18 | 7,32 |
| <b>PISTA 2</b> | <b>A</b> | 7,59 | 7,43 | 7,28 | 6,85 | 6,38 | 5,8  | 5,42 | 5,12 | 4,94 | 4,69 | 4,94 | 5,1  | 5,4  | 5,78 | 6,34 | 6,8  | 7,2  | 7,31 | 7,43 |
|                | <b>B</b> | 7,57 | 7,48 | 7,31 | 6,89 | 6,24 | 5,8  | 5,4  | 5,09 | 4,9  | 4,65 | 4,89 | 5,07 | 5,38 | 5,77 | 6,2  | 6,82 | 7,2  | 7,32 | 7,39 |
|                | <b>C</b> | 7,21 | 7,36 | 7,28 | 6,75 | 6,05 | 5,71 | 5,29 | 4,96 | 4,76 | 4,52 | 4,75 | 4,94 | 5,26 | 5,66 | 6,1  | 6,66 | 7,15 | 7,17 | 6,96 |

Todos los datos en [lx]

Tabla 3-29: Cálculos en rejilla 20x6.

|                |          | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   | 12   | 13   | 14   | 15   | 16   | 17   | 18   | 19   | 20   |
|----------------|----------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| <b>PISTA 1</b> | <b>A</b> | 6,74 | 6,59 | 6,5  | 6,16 | 5,84 | 5,34 | 5,02 | 4,77 | 4,6  | 4,53 | 4,53 | 4,61 | 4,78 | 5,03 | 5,35 | 5,85 | 6,16 | 6,48 | 6,54 | 6,65 |
|                | <b>B</b> | 7,18 | 7,02 | 6,91 | 6,53 | 6,15 | 5,63 | 5,29 | 5,01 | 4,82 | 4,74 | 4,74 | 4,82 | 5,01 | 5,28 | 5,63 | 6,13 | 6,5  | 6,86 | 6,93 | 7,06 |
|                | <b>C</b> | 7,47 | 7,3  | 7,17 | 6,79 | 6,36 | 5,77 | 5,45 | 5,15 | 4,95 | 4,86 | 4,86 | 4,94 | 5,15 | 5,44 | 5,76 | 6,34 | 6,75 | 7,1  | 7,19 | 7,32 |
| <b>PISTA 2</b> | <b>A</b> | 7,59 | 7,45 | 7,33 | 6,95 | 6,5  | 5,88 | 5,53 | 5,21 | 4,99 | 4,9  | 4,89 | 4,99 | 5,2  | 5,51 | 5,86 | 6,46 | 6,89 | 7,24 | 7,32 | 7,43 |
|                | <b>B</b> | 7,61 | 7,5  | 7,36 | 6,94 | 6,52 | 5,93 | 5,52 | 5,19 | 4,96 | 4,85 | 4,85 | 4,95 | 5,17 | 5,5  | 5,89 | 6,47 | 6,87 | 7,25 | 7,34 | 7,37 |
|                | <b>C</b> | 7,21 | 7,38 | 7,34 | 6,85 | 6,33 | 5,83 | 5,42 | 5,07 | 4,83 | 4,71 | 4,71 | 4,81 | 5,04 | 5,38 | 5,78 | 6,26 | 6,75 | 7,2  | 7,19 | 6,96 |

Todos los datos en [lx]

Tabla 3-30: Cálculos en rejilla 13x2.

|          | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   | 12   | 13   |
|----------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| <b>A</b> | 7,16 | 6,97 | 6,39 | 5,67 | 5,16 | 4,83 | 4,54 | 4,83 | 5,16 | 5,67 | 6,37 | 6,92 | 7,04 |
| <b>B</b> | 7,59 | 7,43 | 6,81 | 5,98 | 5,37 | 4,97 | 4,65 | 4,95 | 5,35 | 5,94 | 6,75 | 7,31 | 7,41 |

Todos los datos en [lx]

Tabla 3-31: Cálculos en rejilla 13x3.

|          | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   | 12   | 13   |
|----------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| <b>A</b> | 6,95 | 6,58 | 6,22 | 5,54 | 5,05 | 4,73 | 4,46 | 4,73 | 5,05 | 5,54 | 6,22 | 6,54 | 6,85 |
| <b>B</b> | 7,55 | 7,34 | 6,72 | 5,89 | 5,36 | 4,99 | 4,68 | 4,98 | 5,35 | 5,86 | 6,68 | 7,25 | 7,4  |
| <b>C</b> | 7,59 | 7,19 | 6,73 | 5,94 | 5,33 | 4,91 | 4,6  | 4,9  | 5,3  | 5,9  | 6,68 | 7,06 | 7,34 |

Todos los datos en [lx]

Tabla 3-32: Cálculos en rejilla 13x4.

|          | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   | 12   | 13   |
|----------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| <b>A</b> | 6,84 | 6,48 | 6,13 | 5,45 | 4,98 | 4,67 | 4,4  | 4,67 | 4,98 | 5,46 | 6,13 | 6,45 | 6,75 |
| <b>B</b> | 7,4  | 7,2  | 6,59 | 5,79 | 5,3  | 4,94 | 4,65 | 4,94 | 5,29 | 5,78 | 6,56 | 7,13 | 7,27 |
| <b>C</b> | 7,63 | 7,43 | 6,82 | 5,96 | 5,41 | 5,02 | 4,71 | 5,01 | 5,39 | 5,93 | 6,76 | 7,33 | 7,47 |
| <b>D</b> | 7,56 | 7,26 | 6,7  | 5,92 | 5,3  | 4,88 | 4,56 | 4,86 | 5,27 | 5,87 | 6,61 | 7,03 | 7,32 |

Todos los datos en [lx]

Tabla 3-33: Cálculos en rejilla 13x5.

|          | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   | 12   | 13   |
|----------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| <b>A</b> | 6,77 | 6,42 | 6,07 | 5,41 | 4,94 | 4,63 | 4,37 | 4,64 | 4,94 | 5,42 | 6,07 | 6,39 | 6,68 |
| <b>B</b> | 7,24 | 7,05 | 6,46 | 5,73 | 5,21 | 4,87 | 4,58 | 4,86 | 5,2  | 5,72 | 6,44 | 6,99 | 7,13 |
| <b>C</b> | 7,55 | 7,34 | 6,72 | 5,89 | 5,36 | 4,99 | 4,68 | 4,98 | 5,35 | 5,86 | 6,68 | 7,25 | 7,4  |
| <b>D</b> | 7,6  | 7,43 | 6,81 | 5,98 | 5,39 | 4,98 | 4,67 | 4,97 | 5,37 | 5,94 | 6,75 | 7,32 | 7,43 |
| <b>E</b> | 7,53 | 7,25 | 6,68 | 5,9  | 5,28 | 4,85 | 4,54 | 4,84 | 5,24 | 5,85 | 6,59 | 7    | 7,3  |

Todos los datos en [lx]

Tabla 3-34: Cálculos en rejilla 13x6.

|          | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   | 12   | 13   |
|----------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| <b>A</b> | 6,72 | 6,37 | 6,03 | 5,37 | 4,91 | 4,61 | 4,35 | 4,61 | 4,92 | 5,39 | 6,03 | 6,35 | 6,64 |
| <b>B</b> | 7,16 | 6,97 | 6,39 | 5,67 | 5,16 | 4,83 | 4,54 | 4,83 | 5,16 | 5,67 | 6,37 | 6,92 | 7,04 |
| <b>C</b> | 7,45 | 7,24 | 6,63 | 5,82 | 5,31 | 4,95 | 4,66 | 4,95 | 5,3  | 5,8  | 6,6  | 7,16 | 7,31 |
| <b>D</b> | 7,6  | 7,4  | 6,78 | 5,93 | 5,39 | 5    | 4,69 | 4,99 | 5,37 | 5,9  | 6,73 | 7,3  | 7,44 |
| <b>E</b> | 7,59 | 7,43 | 6,81 | 5,98 | 5,37 | 4,97 | 4,65 | 4,95 | 5,35 | 5,94 | 6,75 | 7,31 | 7,41 |
| <b>F</b> | 7,52 | 7,23 | 6,66 | 5,88 | 5,26 | 4,84 | 4,52 | 4,82 | 5,23 | 5,83 | 6,57 | 7,08 | 7,28 |

Todos los datos en [lx]

Tabla 3-35: Cálculos en rejilla 13x7.

|          | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   | 12   | 13   |
|----------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| <b>A</b> | 6,69 | 6,34 | 6,01 | 5,35 | 4,89 | 4,59 | 4,33 | 4,6  | 4,9  | 5,36 | 6,01 | 6,32 | 6,6  |
| <b>B</b> | 7,07 | 6,89 | 6,32 | 5,62 | 5,11 | 4,79 | 4,51 | 4,79 | 5,11 | 5,62 | 6,3  | 6,85 | 6,97 |
| <b>C</b> | 7,37 | 7,17 | 6,57 | 5,77 | 5,28 | 4,93 | 4,63 | 4,93 | 5,27 | 5,76 | 6,54 | 7,1  | 7,25 |
| <b>D</b> | 7,55 | 7,34 | 6,72 | 5,89 | 5,36 | 4,99 | 4,68 | 4,98 | 5,35 | 5,86 | 6,68 | 7,25 | 7,4  |
| <b>E</b> | 7,64 | 7,44 | 6,82 | 5,97 | 5,41 | 5,01 | 4,7  | 5    | 5,39 | 5,94 | 6,77 | 7,34 | 7,47 |
| <b>F</b> | 7,59 | 7,41 | 6,8  | 5,96 | 5,36 | 4,95 | 4,63 | 4,93 | 5,33 | 5,92 | 6,73 | 7,29 | 7,4  |
| <b>G</b> | 7,51 | 7,22 | 6,65 | 5,87 | 5,25 | 4,82 | 4,51 | 4,81 | 5,22 | 5,82 | 6,56 | 7,07 | 7,27 |

Todos los datos en [lx]

Tabla 3-36: Cálculos en rejilla 13x8.

|          | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   | 12   | 13   |
|----------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| <b>A</b> | 6,66 | 6,32 | 5,98 | 5,33 | 4,87 | 4,57 | 4,32 | 4,58 | 4,88 | 5,35 | 5,99 | 6,29 | 6,58 |
| <b>B</b> | 7,01 | 6,63 | 6,27 | 5,57 | 5,08 | 4,75 | 4,48 | 4,75 | 5,08 | 5,58 | 6,26 | 6,59 | 6,9  |
| <b>C</b> | 7,27 | 7,08 | 6,48 | 5,7  | 5,22 | 4,88 | 4,59 | 4,88 | 5,21 | 5,74 | 6,45 | 7,01 | 7,15 |
| <b>D</b> | 7,48 | 7,27 | 6,65 | 5,84 | 5,33 | 4,96 | 4,66 | 4,96 | 5,32 | 5,82 | 6,62 | 7,19 | 7,34 |
| <b>E</b> | 7,61 | 7,39 | 6,77 | 5,93 | 5,39 | 5    | 4,69 | 4,99 | 5,37 | 5,9  | 6,72 | 7,29 | 7,45 |
| <b>F</b> | 7,6  | 7,43 | 6,81 | 5,95 | 5,39 | 4,99 | 4,68 | 4,98 | 5,37 | 5,95 | 6,75 | 7,32 | 7,43 |
| <b>G</b> | 7,58 | 7,2  | 6,74 | 5,95 | 5,34 | 4,93 | 4,61 | 4,91 | 5,32 | 5,91 | 6,7  | 7,08 | 7,37 |
| <b>H</b> | 7,5  | 7,22 | 6,64 | 5,87 | 5,24 | 4,81 | 4,5  | 4,8  | 5,21 | 5,81 | 6,55 | 7,06 | 7,26 |

Todos los datos en [lx]

La tabla 3-39 resume los valores calculados por DIALux.

Tabla 3-37: Resumen Variación de puntos transversales.

| Rejilla<br>(Ptos long x Ptos transv.) | Resultados    |              |              |
|---------------------------------------|---------------|--------------|--------------|
|                                       | Eprom<br>[lx] | Emin<br>[lx] | Uprom<br>[-] |
| <b>13x1</b>                           | 6,16          | 4,68         | 0,76         |
| <b>13x2</b>                           | 6,05          | 4,54         | 0,75         |
| <b>13x3</b>                           | 6,00          | 4,46         | 0,74         |
| <b>13x4</b>                           | 6,00          | 4,40         | 0,73         |
| <b>13x5</b>                           | 6,00          | 4,37         | 0,73         |
| <b>13x6</b>                           | 6,00          | 4,35         | 0,72         |
| <b>13x7</b>                           | 6,00          | 4,33         | 0,72         |
| <b>13x8</b>                           | 5,99          | 4,32         | 0,72         |



### Análisis de resultados

En esta sección se tomará la decisión de la cantidad de puntos que usará la rejilla de cálculo para calcular flujo luminoso superior.

### Análisis puntos longitudinales

Las siguiente tres imágenes son gráficos que muestran el comportamiento de los resultados obtenidos de las simulaciones detallados en la tabla 3-30 realizadas en las distintas rejillas de cálculo.

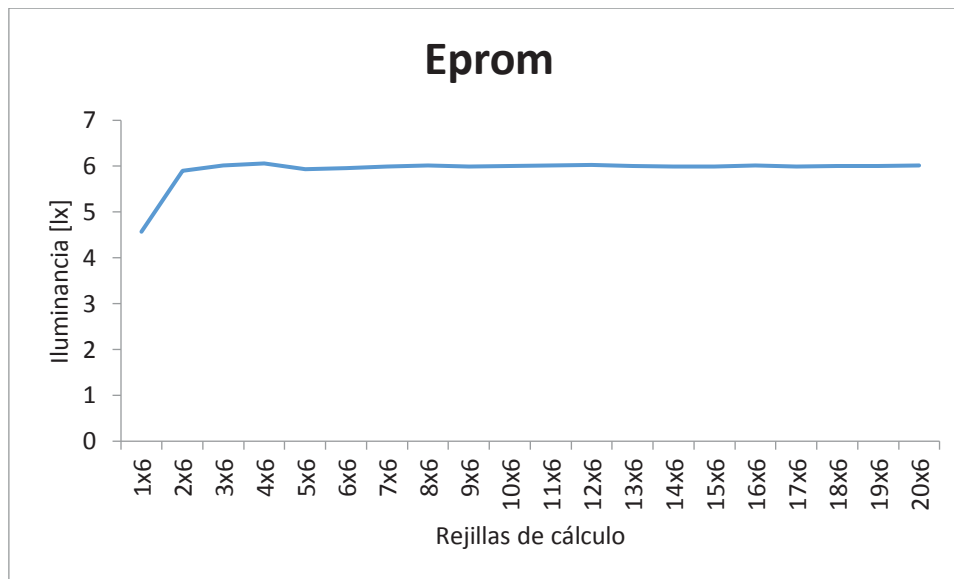


Figura 3-10. Representación gráfica de tabla 3-30 (Eprom), zona P1.

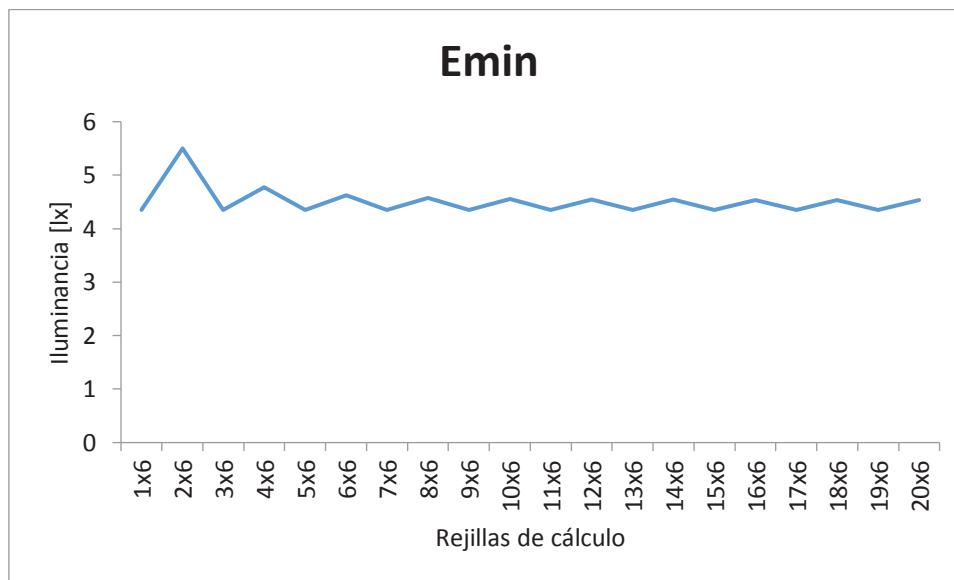


Figura 3-11. Representación gráfica de tabla 3-30 (Emin), zona P1.

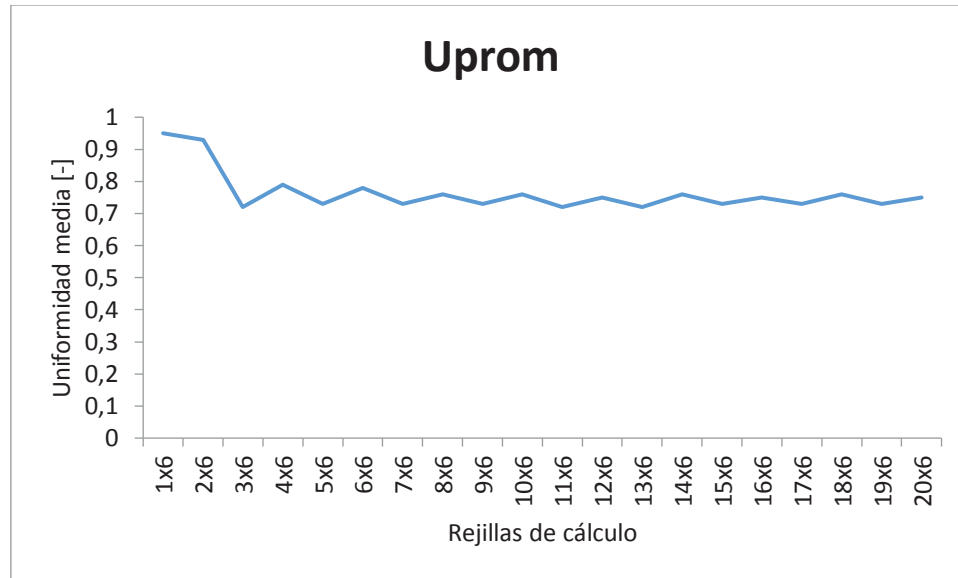


Figura 3-12. Representación gráfica de tabla 3-30 (Uprom), zona P1.

#### Análisis puntos transversales

Las siguientes ilustraciones se exhiben gráficos que muestran el comportamiento de los resultados obtenidos de las simulaciones (tabla 3-39) realizadas en las distintas rejillas de cálculo.

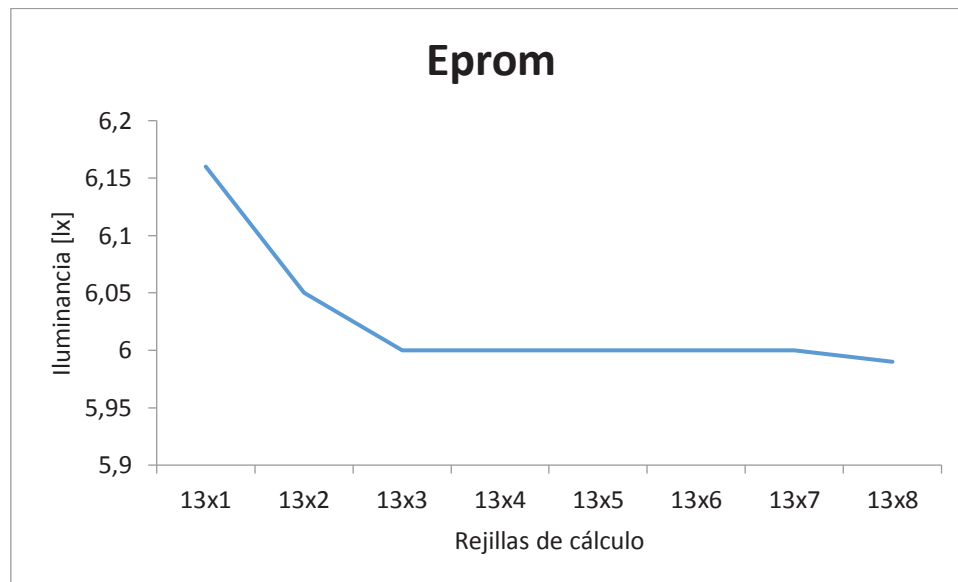


Figura 3-13. Representación gráfica de tabla 3-39 (Eprom), zona P1.

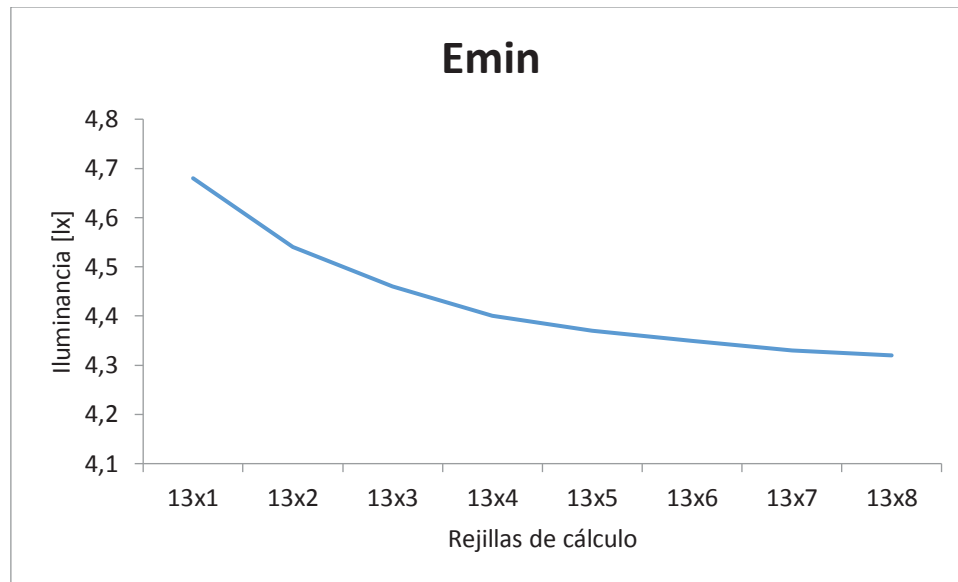


Figura 3-14. Representación gráfica de tabla 3-39 (Emin), zona P1.

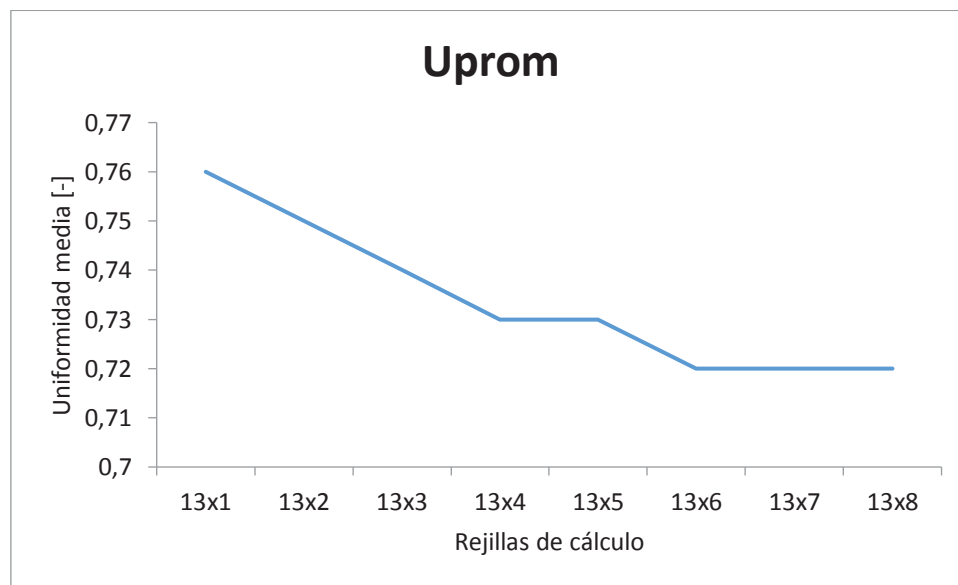


Figura 3-15. Representación gráfica de tabla 3-39 (Uprom), zona P1.

**Ensanchamiento (5% y 10%)**

Para este análisis se tendrá en cuenta la utilización de solo 5 puntos longitudinales y 6 puntos transversales. La siguiente tabla muestra los resultados obtenidos de DIALux.

Tabla 3-38: Resumen variación de ensanchamiento de área de cálculo.

|                   | <b>Sin Ensanchamiento<br/>Rejilla (5x6)</b> | <b>Ensanchamiento<br/>5%</b> | <b>Ensanchamiento<br/>10%</b> |
|-------------------|---------------------------------------------|------------------------------|-------------------------------|
| <b>Eprom [lx]</b> | 5,94                                        | 6,00                         | 6,05                          |
| <b>Emin [lx]</b>  | 4,35                                        | 4,32                         | 4,29                          |
| <b>Uprom [-]</b>  | 0,73                                        | 0,72                         | 0,71                          |

**Conclusiones análisis zona P1**

Luego de analizar gráficamente el estudio hecho de puntos longitudinales y transversales que tendrá la metodología se puede concluir que:

- La cantidad de longitudinales que nos llevan a obtener una menor variación y llegar a un estado casi estable son cinco.
- La cantidad de transversales que nos llevan a una aproximación de los resultados esperados son seis, quiere decir que para efectos de simulación se deben tomar en cuenta puntos de cálculo distanciados a 1[m].
- Considerando que la variación del ancho es casi despreciable, de todas formas se toma en cuenta la recomendación internacional CIE150-2003 que indica un ensanchamiento de un 5% en los extremos del área de cálculo.

### 3.2.2 Zona P2

#### Materiales en terreno y materiales simulados

Las características de la zona P2 se presentan en la siguientes tablas nos indican los materiales en terreno y los que se utilizarán en la simulación. Los objetos utilizados para simular son los que se indican a continuación.

Tabla 3-39: Tabla de materiales en terreno y simulados en zona P2.

|                  | MATERIALES             |                                                              |         |
|------------------|------------------------|--------------------------------------------------------------|---------|
|                  | Terreno                | Simulación                                                   | Rho (%) |
| <b>Calzada</b>   | Asfalto                | Asfalto                                                      | 30      |
| <b>Veredas</b>   | Tierra                 | Arena (1)                                                    | 51      |
| <b>Viviendas</b> | Variedad de materiales | Cemento, Piedra de cantera, Madera, Ladrillo                 | 23-49   |
| <b>Techos</b>    | Variedad de materiales | Teja roja, Baldosa cóncava, Pizarra cuadrangular, Teja plana | 30-49   |

(1) En el caso de las veredas que son de tierra se simuló con Arena, ya que DIALux carece de esta textura.

Tabla 3-40: Resumen objetos utilizados para simular zona P2.

|                           | Cantidad [-] | Largo [m] | Ancho [m] | Alto [m] | Ubicación respecto eje z [m] |
|---------------------------|--------------|-----------|-----------|----------|------------------------------|
| <b>Zona de trabajo</b>    | 1            | 200       | 100       | 0,000    | 0                            |
| <b>Calzada</b>            | 1            | 108       | 6         | 0,001    | 0                            |
| <b>Veredas</b>            | 2            | 108       | 1,5       | 0,001    | 0                            |
| <b>Viviendas</b>          | 18           | 11,4      | 12,085    | 4,5      | 0                            |
| <b>Luminarias</b>         | 2            | -         | -         | 9        | 0                            |
| <b>Rejilla de cálculo</b> | 1            | 34,8      | 7,1       | -        | 0,001                        |

#### Luminaria utilizada

En el informe técnico y según la información suministrada por el solicitante de las mediciones en terreno, las luminarias dispuestas en terreno en zona P2 son de 55W óptica 1. En la simulación se utilizarán las mismas luminarias. A continuación en la siguiente figura se observa la curva de distribución luminosa de la luminaria.



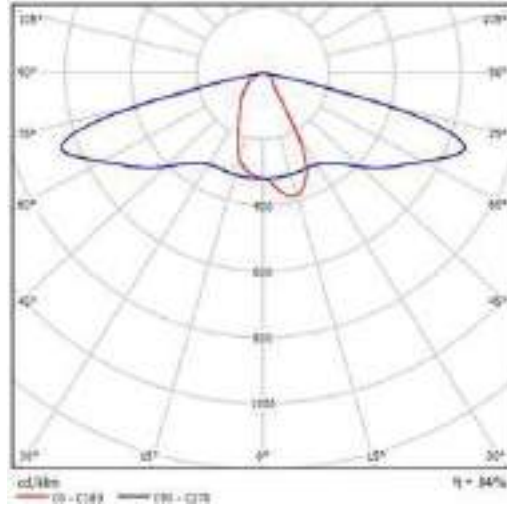


Figura 3-16. Distribución luminosa luminaria 55W óptica 1.

### Aspecto final de la simulación

Ya diseñados los aspectos físicos y definidos los colores y texturas del proyecto, se logra obtener un modelo bastante acercado a lo visto en terreno, las siguientes imágenes muestran una fotografía del informe y una vista 3D de la simulación.



Figura 3-17. Fotografía en terreno zona P2.

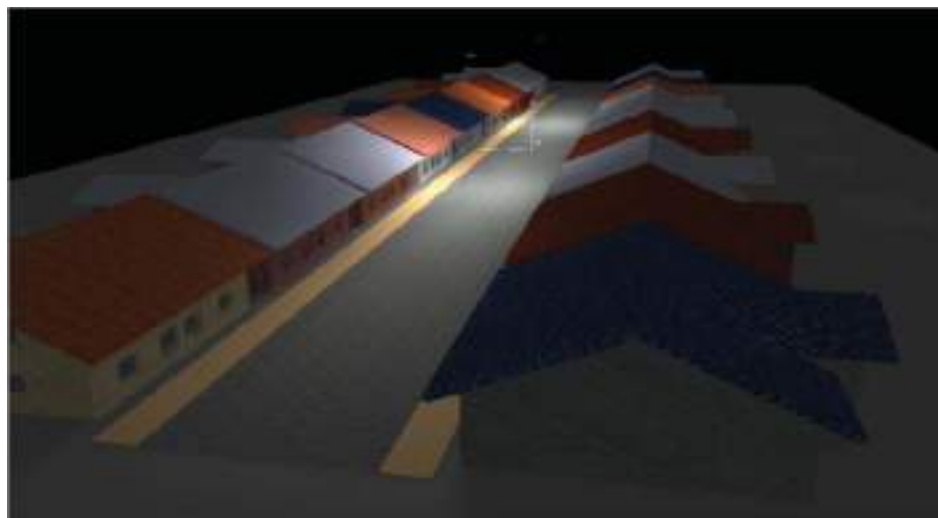


Figura 3-18. Vista 3D de la simulación en zona P2.

### Simulación a nivel del suelo

Como indica el diagrama de flujo de la figura 2-6, luego de diseñar la zona se simulará a nivel del suelo con el único objetivo de tener representatividad de los datos calculados con los medidos en terreno.

Las mediciones hechas en terreno arrojan los resultados obtenidos de una rejilla medición de 12x6 puntos, los que se exponen en la siguiente tabla.

Tabla 3-41: Medición en terreno zona P2.

|                |          | 1     | 2     | 3     | 4     | 5    | 6    | 7    | 8    | 9     | 10    | 11    | 12    |
|----------------|----------|-------|-------|-------|-------|------|------|------|------|-------|-------|-------|-------|
| <b>PISTA 1</b> | <b>A</b> | 21,13 | 16,82 | 11,82 | 7,9   | 6,04 | 4,97 | 4,88 | 5,67 | 7,67  | 11,21 | 16,64 | 21,18 |
|                | <b>B</b> | 23,72 | 19,31 | 13,8  | 9,74  | 7,63 | 6,43 | 6,32 | 7,21 | 8,78  | 13,17 | 19,04 | 23,97 |
|                | <b>C</b> | 25,34 | 21,19 | 15,63 | 11,53 | 9,14 | 7,83 | 7,63 | 8,7  | 10,8  | 14,88 | 20,71 | 25,93 |
| <b>PISTA 2</b> | <b>A</b> | 24,75 | 21,43 | 16,34 | 12,68 | 9,9  | 8,39 | 8,08 | 9,1  | 11,35 | 15,04 | 20,83 | 25,75 |
|                | <b>B</b> | 21,64 | 19,26 | 15,38 | 12,27 | 9,81 | 8,38 | 8,04 | 8,93 | 11,02 | 14,23 | 19,06 | 22,74 |
|                | <b>C</b> | 17,8  | 16,01 | 13,12 | 10,84 | 9,29 | 7,63 | 7,97 | 8,24 | 9,99  | 12,29 | 15,81 | 18,81 |

Todos los datos en [lx]

El objetivo de la simulación en suelo es llegar a valores similares a los obtenidos en la tabla 3-43, luego de hacer las modificaciones pertinentes se logró llegar a resultados parecidos a los obtenidos en las mediciones en terreno, la tabla 3-44 muestra la similitud de los datos.

Tabla 3-42: Simulación zona P2.

|                |          | 1  | 2  | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11 | 12 |
|----------------|----------|----|----|------|------|------|------|------|------|------|------|----|----|
| <b>PISTA 1</b> | <b>A</b> | 21 | 16 | 11   | 8,32 | 6,95 | 6,44 | 6,44 | 6,95 | 8,31 | 11   | 16 | 21 |
|                | <b>B</b> | 23 | 18 | 13   | 11   | 8,94 | 7,97 | 7,98 | 8,96 | 11   | 13   | 18 | 23 |
|                | <b>C</b> | 25 | 20 | 16   | 12   | 9,35 | 8,14 | 8,14 | 9,37 | 12   | 16   | 20 | 25 |
| <b>PISTA 2</b> | <b>A</b> | 25 | 20 | 14   | 11   | 8,93 | 7,87 | 7,88 | 8,94 | 11   | 14   | 20 | 25 |
|                | <b>B</b> | 20 | 16 | 12   | 9,12 | 7,69 | 7,01 | 7,01 | 7,71 | 9,15 | 12   | 16 | 20 |
|                | <b>C</b> | 13 | 11 | 8,26 | 6,64 | 5,47 | 5,18 | 5,18 | 5,48 | 6,68 | 8,31 | 11 | 13 |

Todos los datos en [lx]

Para obtener estos resultados se modificó el factor de mantenimiento, después de bastantes iteraciones el factor de mantenimiento empleado para los cálculos fue de 0,80. La siguiente tabla muestra un resumen de los datos medidos en terreno y los resultados de la simulación.

Tabla 3-43: Tabla comparativa de zona P2 en terreno y simulada.

|                  | <b>Zona P2 en terreno</b> | <b>Zona P2 simulada</b> | <b>Margen de error (%)</b> |
|------------------|---------------------------|-------------------------|----------------------------|
| <b>Emed [lx]</b> | 13,56                     | 12,51                   | 7,74                       |
| <b>Emin [lx]</b> | 4,88                      | 5,18                    | 6,15                       |

Al analizar la tabla 3-45 se observa que se logra obtener la representatividad de la zona, ya que sus márgenes de error no superan 10% en ninguno de los casos, es por esto que se procede a la simulación sobre las luminarias.

### Simulación sobre luminarias

Siguiendo con la metodología queda simular sobre las luminarias, la cual se realizará con rejillas ubicadas en el hemisferio superior posicionadas a 1[m] sobre las luminarias. Se realizará un estudio análogo al ejecutado en la zona P1 en la sección 3.2.1.

### Variación de puntos longitudinales

Para determinar la cantidad de puntos longitudinales que se utilizarán en la metodología, se utilizó una rejilla de cálculo de 34,8 [m] de largo y 7,1 [m] de ancho, se dejó constante el número de puntos transversales y se alteró el número de puntos longitudinales de la siguiente manera.

Rejilla n° 1: 1x6

Rejilla n° 2: 2x6

Rejilla n° 3: 3x6

...

Rejilla n° 20: 20x6

En la siguiente tabla detalla el resumen de los valores calculados por DIALux, aplicando esta combinación de rejillas.

Tabla 3-44: Resumen variación de puntos longitudinales a 1[m] sobre luminarias en zona P2.

| Rejilla<br>(Ptos. long. x Ptos. transv.) | Resultados    |              |                   |
|------------------------------------------|---------------|--------------|-------------------|
|                                          | Eprom<br>[lx] | Emin<br>[lx] | Emin/Eprom<br>[-] |
| 1x6                                      | 1,56          | 1,44         | 0,93              |
| 2x6                                      | 1,79          | 1,60         | 0,90              |
| 3x6                                      | 1,80          | 1,44         | 0,80              |
| 4x6                                      | 1,80          | 1,48         | 0,82              |
| 5x6                                      | 1,80          | 1,44         | 0,80              |
| 6x6                                      | 1,80          | 1,46         | 0,81              |
| 7x6                                      | 1,81          | 1,44         | 0,80              |
| 8x6                                      | 1,82          | 1,45         | 0,80              |
| 9x6                                      | 1,82          | 1,44         | 0,79              |
| 10x6                                     | 1,81          | 1,45         | 0,80              |
| 11x6                                     | 1,82          | 1,44         | 0,79              |
| 12x6                                     | 1,82          | 1,44         | 0,79              |
| 13x6                                     | 1,81          | 1,44         | 0,80              |
| 14x6                                     | 1,81          | 1,44         | 0,80              |
| 15x6                                     | 1,81          | 1,44         | 0,80              |
| 16x6                                     | 1,81          | 1,44         | 0,80              |
| 17x6                                     | 1,81          | 1,44         | 0,80              |
| 18x6                                     | 1,81          | 1,44         | 0,80              |
| 19x6                                     | 1,81          | 1,44         | 0,80              |
| 20x6                                     | 1,81          | 1,44         | 0,80              |

### Variación de puntos transversales

Para determinar la cantidad de puntos transversales que se utilizarán en la metodología, se utilizó una rejilla de cálculo de 34,8 [m] de largo y 7,1 [m] de ancho, se dejó constante el número de puntos longitudinales y se alteró el número de puntos transversales de la siguiente manera.

Rejilla n° 1: 12x1

Rejilla n° 2: 12x2

Rejilla n° 3: 12x3

...

Rejilla n° 8: 12x8

En la siguiente tabla detalla el resumen de los valores calculados por DIALux, aplicando esta combinación de rejillas.

Tabla 3-45: Resumen variación de puntos transversales a 1[m] sobre luminarias en zona P2.

| Rejilla<br>(Ptos long x Ptos transv.) | Resultados    |              |                   |
|---------------------------------------|---------------|--------------|-------------------|
|                                       | Eprom<br>[lx] | Emin<br>[lx] | Emin/Eprom<br>[-] |
| 12x1                                  | 1,87          | 1,62         | 0,86              |
| 12x2                                  | 1,82          | 1,53         | 0,84              |
| 12x3                                  | 1,82          | 1,49         | 0,82              |
| 12x4                                  | 1,82          | 1,47         | 0,81              |
| 12x5                                  | 1,82          | 1,45         | 0,80              |
| 12x6                                  | 1,82          | 1,44         | 0,79              |
| 12x7                                  | 1,81          | 1,44         | 0,79              |
| 12x8                                  | 1,81          | 1,43         | 0,79              |

### Análisis de resultados

En esta sección se tomará la decisión de la cantidad de puntos que usará la rejilla de cálculo para calcular flujo luminoso superior.

### Análisis puntos longitudinales

Las siguiente tres imágenes son gráficos que muestran el comportamiento de los resultados obtenidos de las simulaciones (tabla 3-46) realizadas en las distintas rejillas de cálculo.

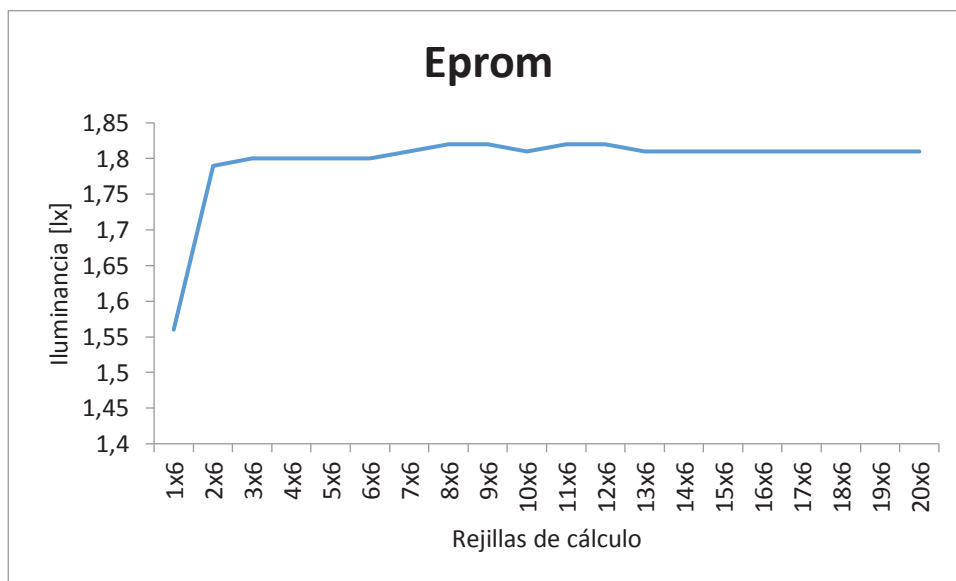


Figura 3-19. Representación gráfica de tabla 3-46 (Eprom), zona P2.



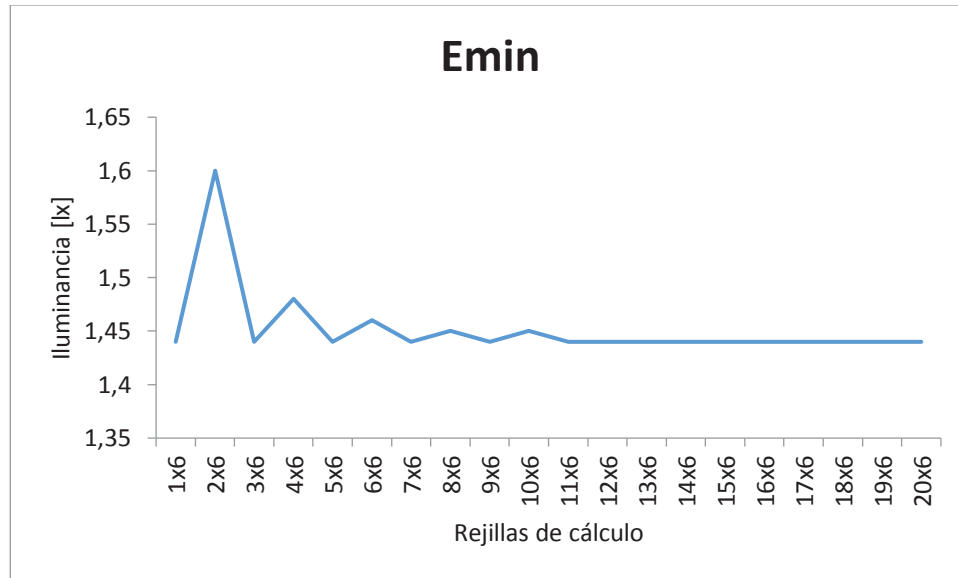


Figura 3-20. Representación gráfica de tabla 3-46 (Emin), zona P2.

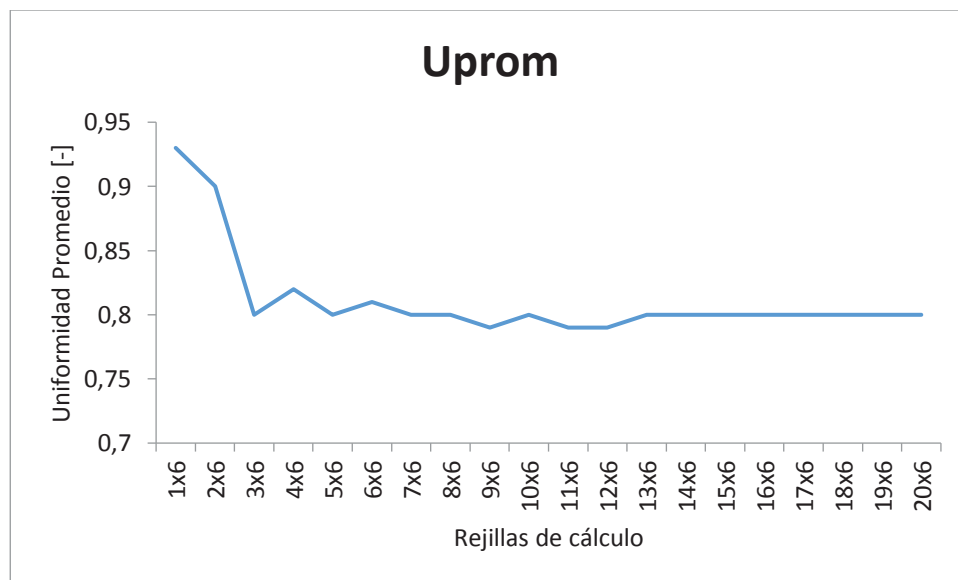


Figura 3-21. Representación gráfica de tabla 3-46 (Uprom), zona P2.

### Análisis puntos transversales

Las siguientes ilustraciones se exhiben gráficos que muestran el comportamiento de los resultados obtenidos de las simulaciones (tabla 3-47) realizadas en las distintas rejillas de cálculo.

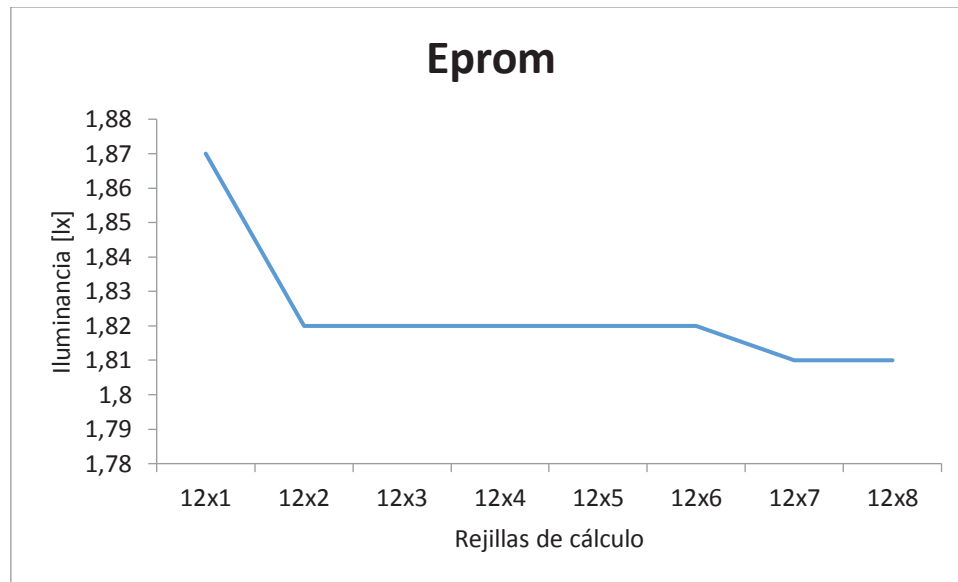


Figura 3-22. Representación gráfica de tabla 3-47 (Eprom), zona P2.

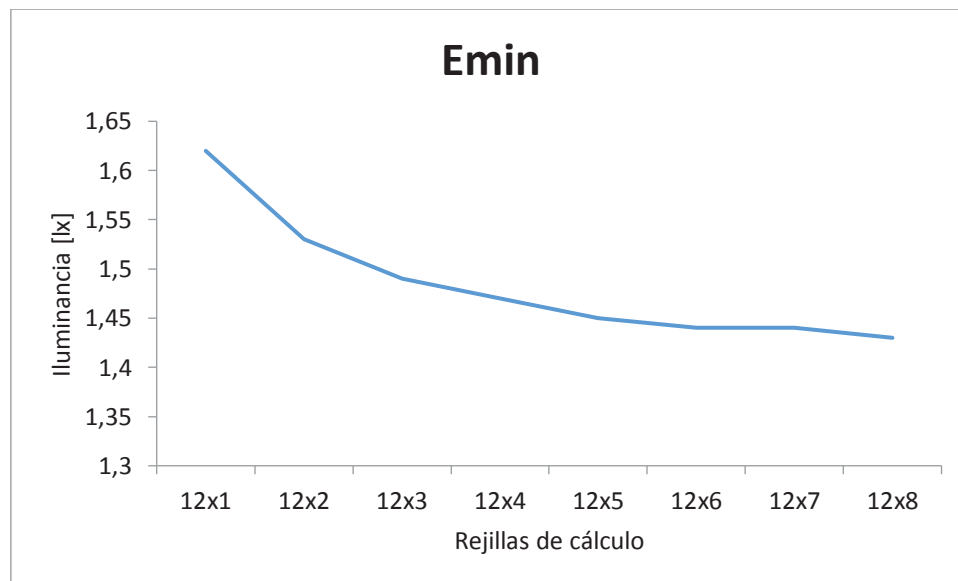


Figura 3-23. Representación gráfica de tabla 3-47 (Emin), zona P2.

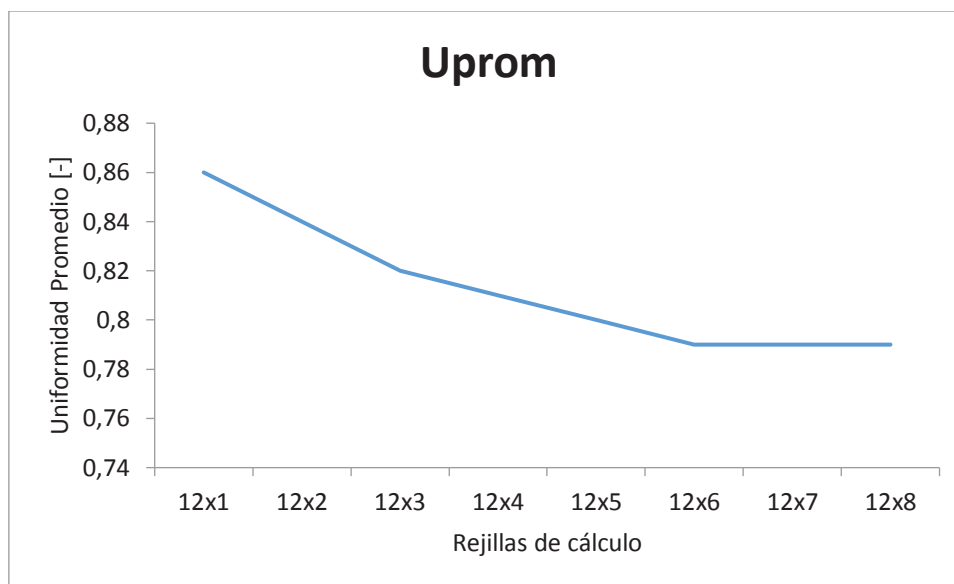


Figura 3-24. Representación gráfica de tabla 3-47 (Uprom), zona P2.

**Ensanchamiento (5% y 10%)**

Para este análisis se tendrá en cuenta la utilización de solo 5 puntos longitudinales y 6 puntos transversales. La siguiente tabla muestra los resultados obtenidos de DIALux.

Tabla 3-46: Resumen variación de ensanchamiento de área de cálculo.

|                       | Sin Ensanchamiento<br>Rejilla (5x6) | Ensanchamiento<br>5% | Ensanchamiento<br>10% |
|-----------------------|-------------------------------------|----------------------|-----------------------|
| <b>Eprom [lx]</b>     | 1,80                                | 1,83                 | 1,85                  |
| <b>Emin [lx]</b>      | 1,44                                | 1,43                 | 1,42                  |
| <b>Emin/Eprom [-]</b> | 0,80                                | 0,78                 | 0,77                  |

**Conclusiones análisis zona P2**

Luego de analizar gráficamente el estudio hecho de puntos longitudinales y transversales que tendrá la metodología se puede concluir que:

- La cantidad de longitudinales que nos llevan a obtener una menor variación y llegar a un estado casi estable son cinco.
- La cantidad de transversales que nos llevan a una aproximación de los resultados esperados son seis, quiere decir que para efectos de simulación se deben tomar en cuenta puntos de cálculo distanciados a 1[m].
- Considerando que la variación del ancho es casi despreciable, se toma en cuenta la recomendación internacional CIE150-2003 que indica un ensanchamiento de un 5% en los extremos del área de cálculo.

### 3.2.3 Zona P3

#### Materiales en terreno y materiales simulados

Las características de la zona P3 se presentan en la siguientes tablas nos indican los materiales en terreno y los que se utilizarán en la simulación, los objetos utilizados para simular.

Tabla 3-47: Tabla de materiales en terreno y simulados en zona P3.

|                  | MATERIALES             |                                                              |         |
|------------------|------------------------|--------------------------------------------------------------|---------|
|                  | Terreno                | Simulación                                                   | Rho (%) |
| <b>Calzada</b>   | Concreto               | Hormigón grueso crudo                                        | 43      |
| <b>Veredas</b>   | Cemento                | Hormigón-18 Cemento Grueso                                   | 54      |
| <b>Viviendas</b> | Variedad de materiales | Cemento, Piedra de cantera, Madera, Ladrillo                 | 23-49   |
| <b>Techos</b>    | Variedad de materiales | Teja roja, Baldosa cóncava, Pizarra cuadrangular, Teja plana | 30-49   |

Tabla 3-48: Resumen objetos utilizados para simular zona P3.

|                           | Cantidad [-] | Largo [m] | Ancho [m] | Alto [m] | Ubicación respecto eje z [m] |
|---------------------------|--------------|-----------|-----------|----------|------------------------------|
| <b>Zona de trabajo</b>    | 1            | 200       | 100       | 0,000    | 0                            |
| <b>Calzada</b>            | 1            | 108       | 6         | 0,001    | 0                            |
| <b>Veredas</b>            | 2            | 108       | 1,5       | 0,001    | 0                            |
| <b>Viviendas</b>          | 18           | 11,4      | 12,085    | 4,5      | 0                            |
| <b>Luminarias</b>         | 2            | -         | -         | 7,5      | 0                            |
| <b>Rejilla de cálculo</b> | 1            | 36        | 3         | -        | 0,001                        |

#### Luminaria utilizada

En el informe técnico y según la información suministrada por el solicitante de las mediciones en terreno, las luminarias dispuestas en terreno en zona P3 son de 36W óptica 1. En la simulación se utilizarán las mismas luminarias. A continuación en la siguiente figura se observa la curva de distribución luminosa de la luminaria.

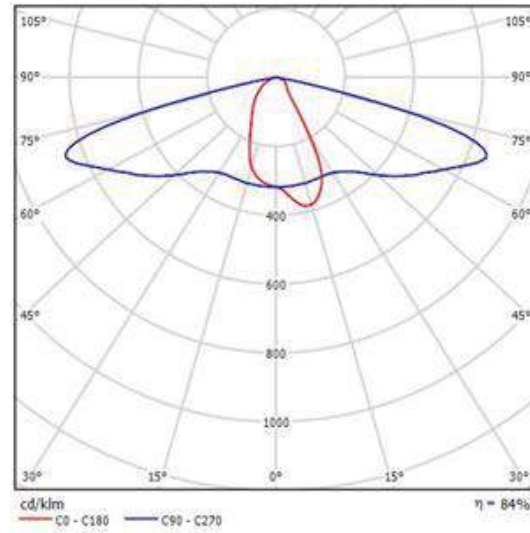


Figura 3-25. Distribución luminosa luminaria 36W óptica 1.

### Aspecto final de la simulación

Ya diseñados los aspectos físicos y definidos los colores y texturas del proyecto, se logra obtener un modelo bastante acercado a lo visto en terreno, las siguientes imágenes muestran una fotografía del informe y una vista 3D de la simulación.



Figura 3-26. Fotografía en terreno zona P3.



Figura 3-27. Vista 3D de la simulación en zona P3.

### Simulación a nivel del suelo

Siguiendo la metodología de trabajo la que indica que luego de diseñar la zona se simulará a nivel del suelo con el único objetivo de tener representatividad de los datos calculados con los medidos en terreno.

Las mediciones hechas en terreno arrojan los resultados obtenidos de una rejilla medición de 13x3 puntos, los que se exponen en la siguiente tabla.

Tabla 3-49: Medición en terreno zona P3.

|   | 1     | 2     | 3     | 4     | 5    | 6    | 7    | 8    | 9    | 10    | 11    | 12    | 13    |
|---|-------|-------|-------|-------|------|------|------|------|------|-------|-------|-------|-------|
| A | 21,68 | 18,05 | 13,47 | 10,4  | 7,81 | 6,5  | 6,24 | 6,73 | 8,22 | 10,88 | 14,63 | 18,54 | 22,38 |
| B | 22,71 | 19,17 | 13,91 | 10,11 | 7,66 | 6,22 | 5,85 | 6,14 | 7,13 | 9,56  | 13,06 | 20,58 | 23,89 |
| C | 20,6  | 16,98 | 12,05 | 8,83  | 6,66 | 5,26 | 4,65 | 4,67 | 5,88 | 7,99  | 10,5  | 17,9  | 21,43 |

Todos los datos en [lx]

El objetivo de la simulación en suelo es llegar a valores similares a los obtenidos en la tabla 3-51, luego de hacer las modificaciones pertinentes se logró llegar a magnitudes similares en la simulación con las obtenidas en terreno, la tabla 3-52 muestra la similitud de los datos.

Tabla 3-50: Simulación zona P3.

|   | 1  | 2  | 3  | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11 | 12 | 13 |
|---|----|----|----|------|------|------|------|------|------|------|----|----|----|
| A | 21 | 16 | 11 | 8,38 | 6,28 | 5,31 | 5,06 | 5,31 | 6,27 | 8,37 | 11 | 16 | 21 |
| B | 23 | 17 | 12 | 8,73 | 6,39 | 5,33 | 5,06 | 5,33 | 6,39 | 8,74 | 12 | 17 | 23 |
| C | 22 | 16 | 11 | 7,96 | 6,13 | 5,15 | 4,86 | 5,15 | 6,14 | 7,99 | 11 | 16 | 22 |

Todos los datos en [lx]

Para obtener estos resultados se modificó el factor de mantenimiento y la altura de las luminarias, después de bastantes iteraciones el factor de mantenimiento empleado para los cálculos fue de



0,80 y la altura de las luminarias fue de 7,5 m. La siguiente tabla muestra un resumen de los datos medidos en terreno y los resultados de la simulación.

Tabla 3-51: Tabla comparativa de zona P3 en terreno y simulada.

|                   | <b>Zona P3 en terreno</b> | <b>Zona P3 simulada</b> | <b>Margen de error (%)</b> |
|-------------------|---------------------------|-------------------------|----------------------------|
| <b>Eprom [lx]</b> | 12,18                     | 11,09                   | 8,95                       |
| <b>Emin [lx]</b>  | 4,65                      | 4,86                    | 4,51                       |

Luego de analizar la tabla 3-53 se observa que se logra obtener la representatividad de la zona, ya que sus márgenes de error no superan 10% en ninguno de los casos, es por esto que se procede a la simulación sobre las luminarias.

### **Simulación sobre luminarias**

Siguiendo con la metodología queda simular sobre las luminarias, la cual se realizará con rejillas ubicadas en el hemisferio superior posicionadas a 1[m] sobre las luminarias. Se realizará un estudio análogo al ejecutado en la zona P1 en la sección 3.2.1.

### **Variación de puntos longitudinales**

Para determinar la cantidad de puntos longitudinales que se utilizarán en la metodología, se utilizó una rejilla de cálculo de 36 [m] de largo y 3 [m] de ancho, se dejó constante el número de puntos transversales y se alteró el número de puntos longitudinales de la siguiente manera.

Rejilla n° 1: 1x3

Rejilla n° 2: 2x3

Rejilla n° 3: 3x3

...

Rejilla n° 20: 20x3

En la siguiente tabla detalla el resumen de los valores calculados por DIALux, aplicando esta combinación de rejillas.

Tabla 3-52: Resumen variación de puntos longitudinales a 1[m] sobre luminarias en zona P3.

| Rejilla<br>(Ptos. long. x Ptos. transv.) | Resultados    |              |              |
|------------------------------------------|---------------|--------------|--------------|
|                                          | Eprom<br>[lx] | Emin<br>[lx] | Uprom<br>[-] |
| 1x3                                      | 1,43          | 1,42         | 0,99         |
| 2x3                                      | 1,77          | 1,72         | 0,97         |
| 3x3                                      | 1,86          | 1,42         | 0,76         |
| 4x3                                      | 1,90          | 1,51         | 0,79         |
| 5x3                                      | 1,91          | 1,42         | 0,74         |
| 6x3                                      | 1,91          | 1,46         | 0,76         |
| 7x3                                      | 1,91          | 1,42         | 0,74         |
| 8x3                                      | 1,90          | 1,44         | 0,76         |
| 9x3                                      | 1,90          | 1,42         | 0,75         |
| 10x3                                     | 1,90          | 1,43         | 0,75         |
| 11x3                                     | 1,90          | 1,42         | 0,75         |
| 12x3                                     | 1,89          | 1,43         | 0,75         |
| 13x3                                     | 1,90          | 1,42         | 0,75         |
| 14x3                                     | 1,90          | 1,42         | 0,75         |
| 15x3                                     | 1,90          | 1,42         | 0,75         |
| 16x3                                     | 1,90          | 1,42         | 0,75         |
| 17x3                                     | 1,90          | 1,42         | 0,75         |
| 18x3                                     | 1,90          | 1,42         | 0,75         |
| 19x3                                     | 1,90          | 1,42         | 0,75         |
| 20x3                                     | 1,90          | 1,42         | 0,75         |

### Variación de puntos transversales

Para determinar la cantidad de puntos transversales que se utilizarán en la metodología, se utilizó una rejilla de cálculo de 36 [m] de largo y 3 [m] de ancho, se dejó constante el número de puntos longitudinales y se alteró el número de puntos transversales de la siguiente manera.

Rejilla n° 1: 13x1

Rejilla n° 2: 13x2

Rejilla n° 3: 13x3

...

Rejilla n° 8: 13x8

En la siguiente tabla detalla el resumen de los valores calculados por DIALux, aplicando esta combinación de rejillas.

Tabla 3-53: Resumen variación de puntos transversales a 1[m] sobre luminarias en zona P2.

| Rejilla<br>(Ptos long x Ptos transv.) | Resultados    |              |              |
|---------------------------------------|---------------|--------------|--------------|
|                                       | Eprom<br>[lx] | Emin<br>[lx] | Uprom<br>[-] |
| 13x1                                  | 1,92          | 1,44         | 0,75         |
| 13x2                                  | 1,91          | 1,42         | 0,75         |
| 13x3                                  | 1,90          | 1,42         | 0,75         |
| 13x4                                  | 1,91          | 1,42         | 0,75         |
| 13x5                                  | 1,91          | 1,42         | 0,75         |
| 13x6                                  | 1,90          | 1,41         | 0,74         |
| 13x7                                  | 1,90          | 1,41         | 0,74         |
| 13x8                                  | 1,90          | 1,41         | 0,74         |

### Análisis de resultados

En esta sección se tomará la decisión de la cantidad de puntos que usará la rejilla de cálculo para calcular flujo luminoso superior.

### Análisis puntos longitudinales

Las siguiente tres imágenes son gráficos que muestran el comportamiento de los resultados obtenidos de las simulaciones (tabla 3-54) realizadas en las distintas rejillas de cálculo.

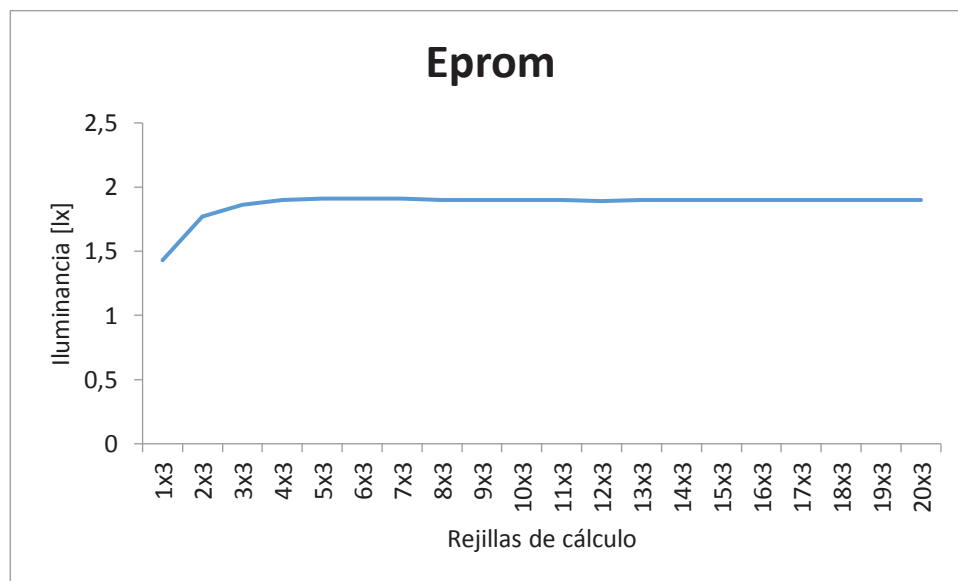


Figura 3-28. Representación gráfica de tabla 3-54 (Eprom), zona P3.

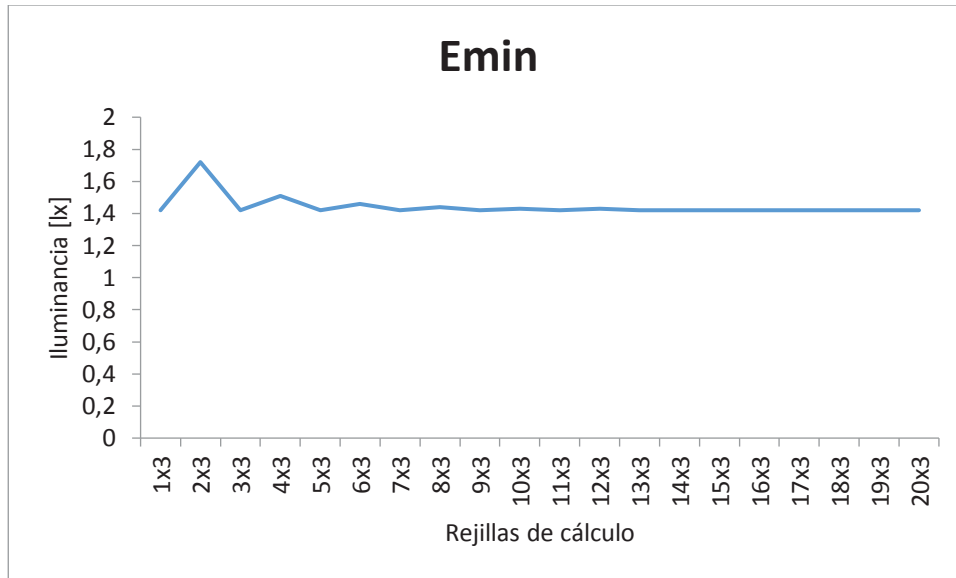


Figura 3-29. Representación gráfica de tabla 3-54 (Emin), zona P3.

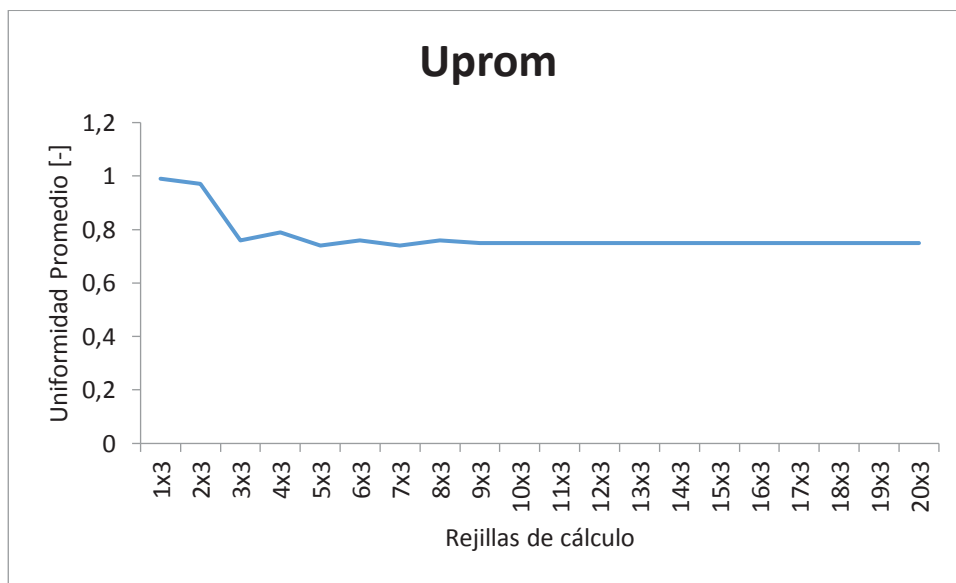


Figura 3-30. Representación gráfica de tabla 3-54 (Uprom), zona P3.

### Análisis puntos transversales

Las siguientes ilustraciones se exhiben gráficos que muestran el comportamiento de los resultados obtenidos de las simulaciones (tabla 3-55) realizadas en las distintas rejillas de cálculo.

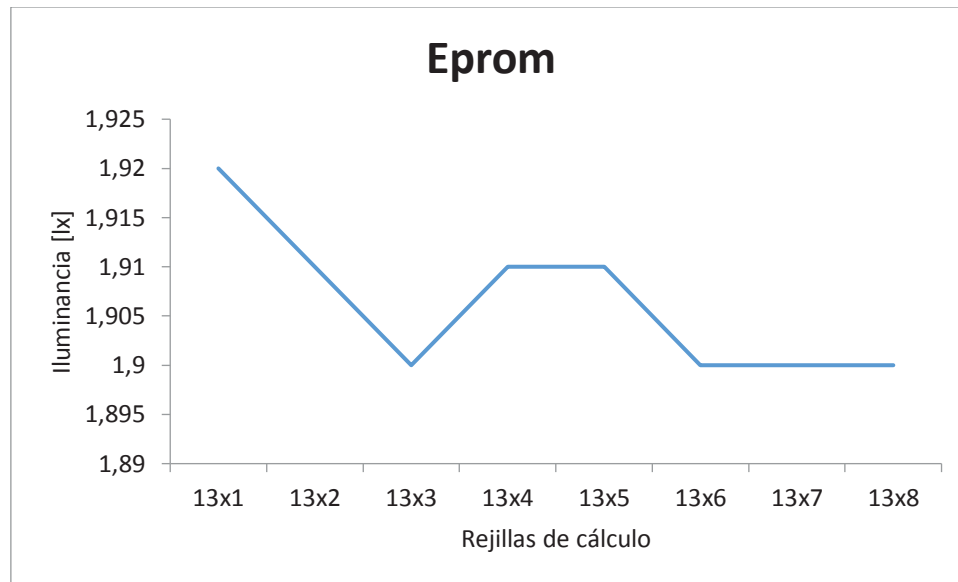


Figura 3-31. Representación gráfica de tabla 3-55 (Eprom), zona P3.

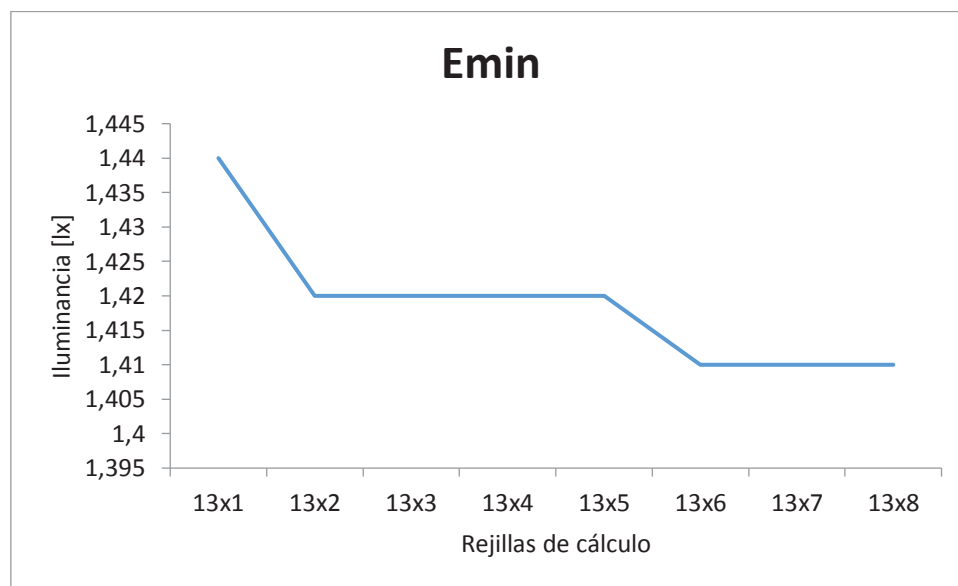


Figura 3-32. Representación gráfica de tabla 3-55 (Emin), zona P3.

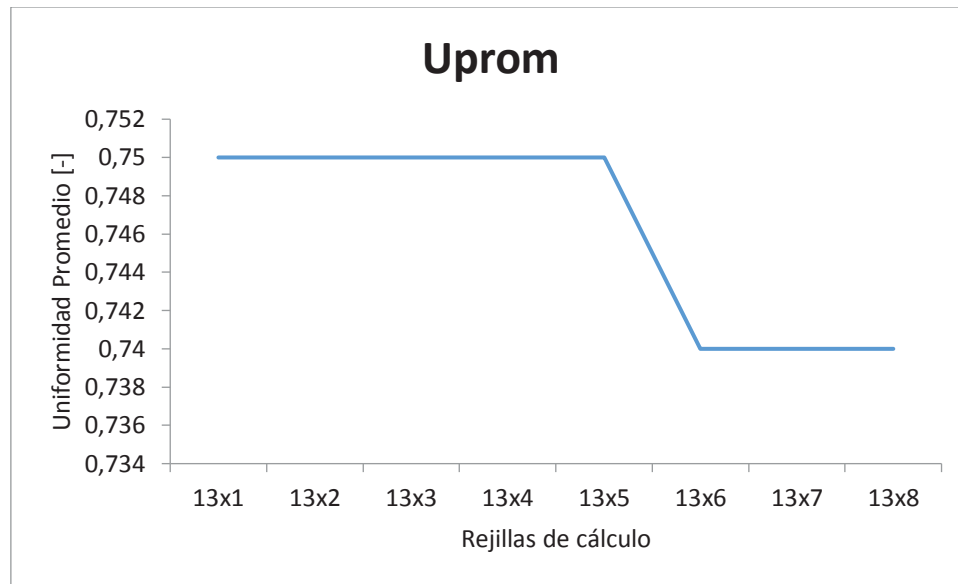


Figura 3-33. Representación gráfica de tabla 3-55 (Uprom), zona P3.

**Ensanchamiento (5% y 10%)**

Para este análisis se tendrá en cuenta la utilización de solo 5 puntos longitudinales y 3 puntos transversales. La siguiente tabla muestra los resultados obtenidos de DIALux.

Tabla 3-54: Resumen variación de ensanchamiento de área de cálculo.

|                   | Sin Ensanchamiento<br>Rejilla (5x3) | Ensanchamiento<br>5% | Ensanchamiento<br>10% |
|-------------------|-------------------------------------|----------------------|-----------------------|
| <b>Eprom [lx]</b> | 1,91                                | 1,95                 | 1,98                  |
| <b>Emin [lx]</b>  | 1,42                                | 1,42                 | 1,42                  |
| <b>Uprom [-]</b>  | 0,74                                | 0,73                 | 0,72                  |

**Conclusiones análisis zona P3**

Luego de analizar gráficamente el estudio hecho de puntos longitudinales y transversales que tendrá la metodología se puede concluir que:

- La cantidad de longitudinales que nos llevan a obtener una menor variación y llegar a un estado casi estable son cinco.
- La cantidad de transversales que nos llevan a una aproximación de los resultados esperados son seis, quiere decir que para efectos de simulación se deben tomar en cuenta puntos de cálculo distanciados a 1[m].
- Considerando que la variación del ancho es casi despreciable, se toma en cuenta la recomendación internacional CIE150-2003 que indica un ensanchamiento de un 5% en los extremos del área de cálculo.



### 3.2.4 Zona P4

#### Materiales en terreno y materiales simulados

Las características de la zona P4 se presentan en la siguientes tablas nos indican los materiales en terreno y los que se utilizarán en la simulación. Los objetos utilizados para simular son los que se indican a continuación.

Tabla 3-55: Tabla de materiales en terreno y simulados en zona P4.

|                  | MATERIALES             |                                                              |         |
|------------------|------------------------|--------------------------------------------------------------|---------|
|                  | Terreno                | Simulación                                                   | Rho (%) |
| <b>Calzada</b>   | Hormigón               | Hormigón crudo grueso                                        | 43      |
| <b>Veredas</b>   | Tierra                 | Arena (2)                                                    | 51      |
| <b>Viviendas</b> | Variedad de materiales | Cemento, Piedra de cantera, Madera, Ladrillo                 | 23-49   |
| <b>Techos</b>    | Variedad de materiales | Teja roja, Baldosa cóncava, Pizarra cuadrangular, Teja plana | 30-49   |

(2) En el caso de las veredas que son de tierra se simuló con Arena, ya que DIALux carece de esta textura.

Tabla 3-56: Resumen objetos utilizados para simular zona P4.

|                           | Cantidad [-] | Largo [m] | Ancho [m] | Alto [m] | Ubicación respecto eje z [m] |
|---------------------------|--------------|-----------|-----------|----------|------------------------------|
| <b>Zona de trabajo</b>    | 1            | 200       | 100       | 0,000    | 0                            |
| <b>Calzada</b>            | 1            | 108       | 3         | 0,001    | 0                            |
| <b>Veredas</b>            | 2            | 108       | 1,5       | 0,001    | 0                            |
| <b>Viviendas</b>          | 18           | 11,4      | 12,085    | 4,5      | 0                            |
| <b>Luminarias</b>         | 2            | -         | -         | 9        | 0                            |
| <b>Rejilla de cálculo</b> | 1            | 32        | 3         | -        | 0,001                        |

#### Luminaria utilizada

En el informe técnico y según la información suministrada por el solicitante de las mediciones en terreno, las luminarias dispuestas en terreno en zona P4 son de 36W óptica 2. En la simulación se utilizarán las mismas luminarias. A continuación en la siguiente figura se observa la curva de distribución luminosa de la luminaria.

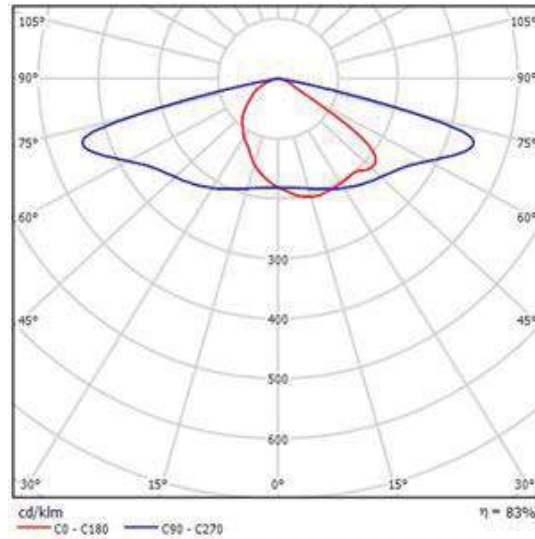


Figura 3-34. Distribución luminosa luminaria 36W óptica 2.

### Aspecto final de la simulación

Ya diseñados los aspectos físicos y definidos los colores y texturas del proyecto, se logra obtener un modelo bastante acercado a lo visto en terreno, las siguientes imágenes muestran una fotografía del informe y una vista 3D de la simulación.

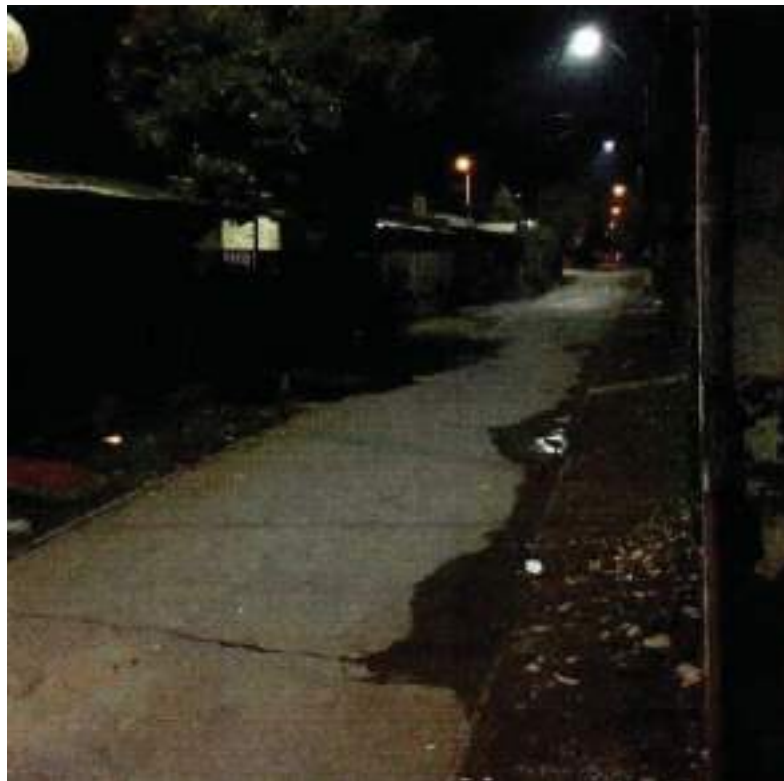


Figura 3-35. Fotografía en terreno zona P4.

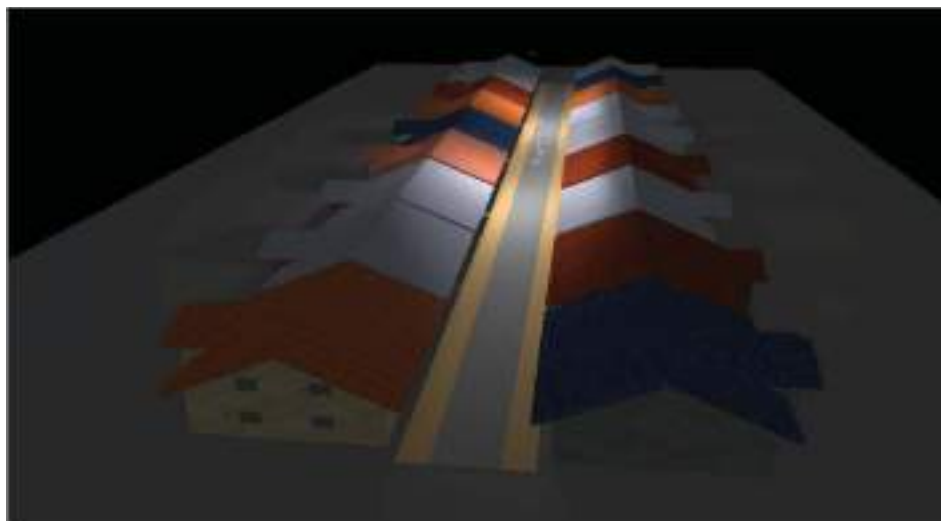


Figura 3-36. Vista 3D de la simulación en zona P4.

### Simulación a nivel del suelo

Como indica el diagrama de flujo de las figura 2-6, luego de diseñar la zona se simulará a nivel del suelo con el único objetivo de tener representatividad de los datos calculados con los medidos en terreno.

Las mediciones hechas en terreno arrojan los resultados obtenidos de una rejilla medición de 11x3 puntos, los que se exponen en la siguiente tabla.

Tabla 3-57: Medición en terreno zona P4 a nivel del suelo.

|   | 1     | 2     | 3    | 4    | 5    | 6    | 7       | 8       | 9    | 10    | 11    |
|---|-------|-------|------|------|------|------|---------|---------|------|-------|-------|
| A | 10,88 | 9,07  | 6,79 | 5,09 | 4,41 | 4,05 | 4,45    | 5,61    | 7,45 | 9,72  | 11,35 |
| B | 11,57 | 10,08 | 7,26 | 5,54 | 4,92 | 4,43 | 4,79    | 6,01    | 7,67 | 10,43 | 11,85 |
| C | 11,11 | 10,07 | 7,69 | 5,92 | 5    | 4,82 | 1,63(3) | 1,48(3) | 8,15 | 10,73 | 12,12 |

(3) Valores excluidos del cálculo por no ser representativos.  
Todos los datos en [lx]

El objetivo de la simulación en suelo es llegar a valores similares a los obtenidos en la tabla 3-59, luego de hacer las modificaciones pertinentes se logró llegar a resultados parecidos a los obtenidos en las mediciones en terreno, la tabla 3-60 muestra la similitud de los datos.

Tabla 3-58: Simulación en zona P4 a nivel del suelo.

|   | 1  | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11 |
|---|----|------|------|------|------|------|------|------|------|------|----|
| A | 11 | 9,73 | 7,32 | 5,42 | 4,44 | 4,15 | 4,44 | 5,42 | 7,32 | 9,72 | 11 |
| B | 11 | 9,74 | 7,41 | 5,59 | 4,66 | 4,38 | 4,66 | 5,6  | 7,43 | 9,76 | 11 |
| C | 11 | 9,36 | 7,31 | 5,66 | 4,82 | 4,59 | 4,82 | 5,68 | 7,36 | 9,41 | 11 |

Todos los datos en [lx]

Para obtener estos resultados se modificó el factor de mantenimiento, después de bastantes iteraciones el factor de mantenimiento empleado para los cálculos fue de 0,95. La siguiente tabla comparativa muestra los datos medidos en terreno y los resultados de la simulación.

Tabla 3-59: Tabla comparativa de zona P4 en terreno y simulada a nivel del suelo.

|                  | <b>Zona P4 en terreno</b> | <b>Zona P4 simulada</b> | <b>Margen de error (%)</b> |
|------------------|---------------------------|-------------------------|----------------------------|
| <b>Emed [lx]</b> | 7,34                      | 7,35                    | 0,14                       |
| <b>Emin [lx]</b> | 4,05                      | 4,15                    | 2,47                       |

Analizando la tabla 3-58 se observa que se logra obtener la representatividad en la zona, ya que sus márgenes de error no superan 3% en ninguno de los casos, es por esto que se procede a la simulación sobre las luminarias.

### **Simulación sobre luminarias**

Siguiendo paso a paso con la metodología de trabajo queda simular sobre las luminarias, la cual se realizará con rejillas ubicadas en el hemisferio superior posicionadas a 1[m] sobre las luminarias. Se realizará un estudio análogo al hecho en la zona P1 en la sección 3.2.1.

### **Variación de puntos longitudinales**

Para determinar la cantidad de puntos longitudinales que se utilizarán en la metodología, se utilizó una rejilla de cálculo de 32 [m] de largo y 3 [m] de ancho, se dejó constante el número de puntos transversales y se alteró el número de puntos longitudinales de la siguiente manera.

Rejilla n° 1: 1x3

Rejilla n° 2: 2x3

Rejilla n° 3: 3x3

...

Rejilla n° 20: 20x3

En la siguiente tabla detalla el resumen de los valores calculados por DIALux, aplicando esta combinación de rejillas.

Tabla 3-60: Resumen variación de puntos longitudinales a 1[m] sobre luminarias en zona P4.

| Rejilla<br>(Ptos. long. x Ptos. transv.) | Resultados    |              |                   |
|------------------------------------------|---------------|--------------|-------------------|
|                                          | Eprom<br>[lx] | Emin<br>[lx] | Emin/Eprom<br>[-] |
| 1x3                                      | 1,77          | 1,73         | 0,98              |
| 2x3                                      | 2,07          | 1,99         | 0,96              |
| 3x3                                      | 2,04          | 1,73         | 0,85              |
| 4x3                                      | 2,04          | 1,81         | 0,89              |
| 5x3                                      | 2,04          | 1,73         | 0,85              |
| 6x3                                      | 2,04          | 1,76         | 0,87              |
| 7x3                                      | 2,03          | 1,73         | 0,85              |
| 8x3                                      | 2,04          | 1,75         | 0,86              |
| 9x3                                      | 2,03          | 1,73         | 0,85              |
| 10x3                                     | 2,03          | 1,74         | 0,86              |
| 11x3                                     | 2,03          | 1,73         | 0,85              |
| 12x3                                     | 2,03          | 1,74         | 0,86              |
| 13x3                                     | 2,03          | 1,73         | 0,85              |
| 14x3                                     | 2,03          | 1,74         | 0,85              |
| 15x3                                     | 2,03          | 1,73         | 0,85              |
| 16x3                                     | 2,03          | 1,73         | 0,85              |
| 17x3                                     | 2,03          | 1,73         | 0,85              |
| 18x3                                     | 2,03          | 1,73         | 0,85              |
| 19x3                                     | 2,03          | 1,73         | 0,85              |
| 20x3                                     | 2,03          | 1,73         | 0,85              |

### Variación de puntos transversales

Para determinar la cantidad de puntos transversales que se utilizarán en la metodología, se utilizó una rejilla de cálculo de 32 [m] de largo y 3 [m] de ancho, se dejó constante el número de puntos longitudinales y se alteró el número de puntos transversales de la siguiente manera.

Rejilla n° 1: 11x1

Rejilla n° 2: 11x2

Rejilla n° 3: 11x3

...

Rejilla n° 8: 11x8

En la siguiente tabla detalla el resumen de los valores calculados por DIALux, aplicando esta combinación de rejillas.

Tabla 3-61: Resumen variación de puntos transversales en zona P4.

| Rejilla<br>(Ptos long x Ptos transv.) | Resultados    |              |                   |
|---------------------------------------|---------------|--------------|-------------------|
|                                       | Eprom<br>[lx] | Emin<br>[lx] | Emin/Eprom<br>[-] |
| 11x1                                  | 2,03          | 1,77         | 0,87              |
| 11x2                                  | 2,03          | 1,75         | 0,86              |
| 11x3                                  | 2,03          | 1,73         | 0,85              |
| 11x4                                  | 2,03          | 1,73         | 0,85              |
| 11x5                                  | 2,03          | 1,72         | 0,85              |
| 11x6                                  | 2,03          | 1,72         | 0,85              |
| 11x7                                  | 2,03          | 1,72         | 0,84              |
| 11x8                                  | 2,03          | 1,71         | 0,84              |

### Análisis de resultados

En esta sección se tomará la decisión de la cantidad de puntos que usará la rejilla de cálculo para calcular flujo luminoso superior.

### Análisis puntos longitudinales

Las siguiente tres imágenes son gráficos que muestran el comportamiento de los resultados obtenidos de las simulaciones (tabla 3-62) realizadas en las distintas rejillas de cálculo.

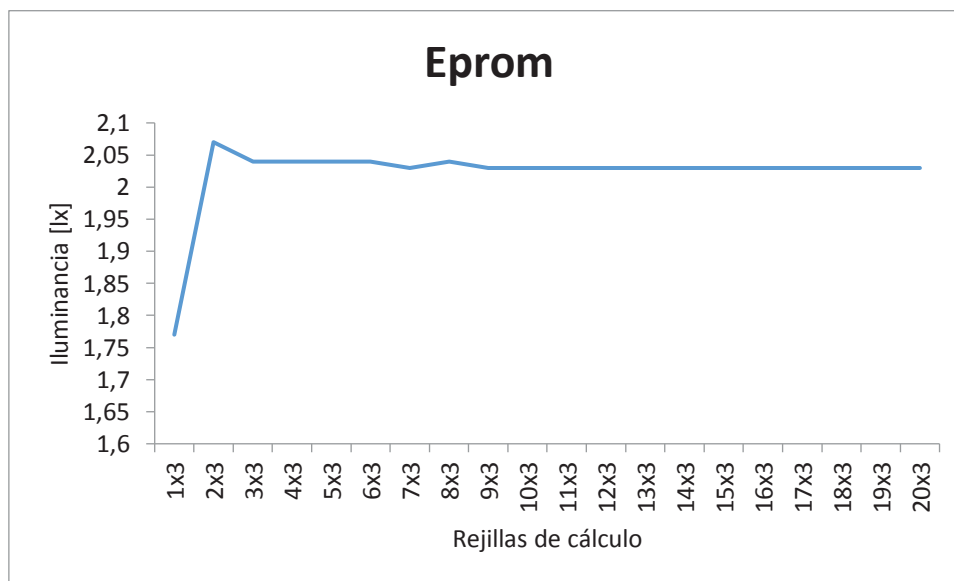


Figura 3-37. Representación gráfica de tabla 3-62 (Eprom), zona P4.



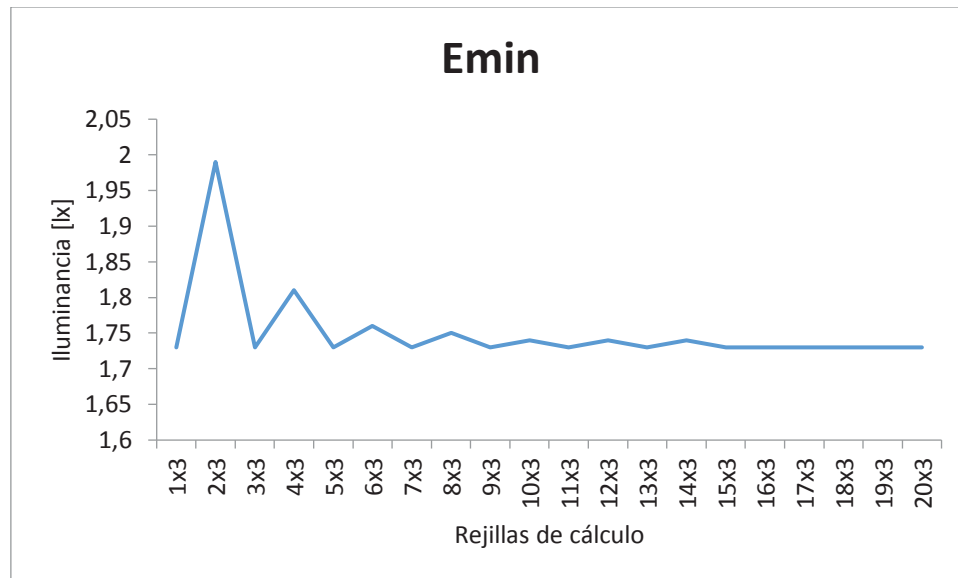


Figura 3-38. Representación gráfica de tabla 3-62 (Emin), zona P4.

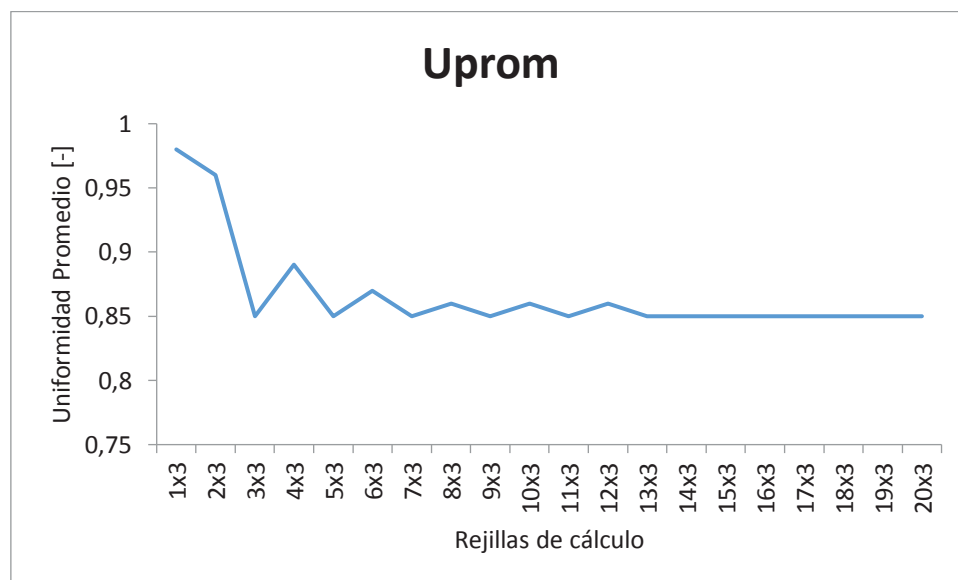


Figura 3-39. Representación gráfica de tabla 3-62 (Uprom), zona P4.

### Análisis puntos transversales

Las siguientes ilustraciones se exhiben gráficos que muestran el comportamiento de los resultados obtenidos de las simulaciones (tabla 3-63) realizadas en las distintas rejillas de cálculo.

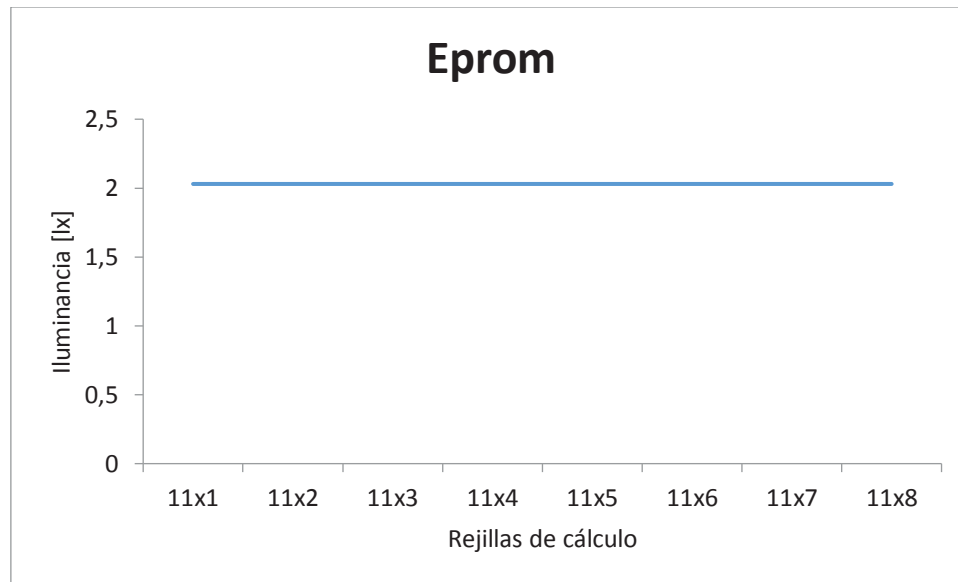


Figura 3-40. Representación gráfica de tabla 3-63 (Eprom), zona P4.

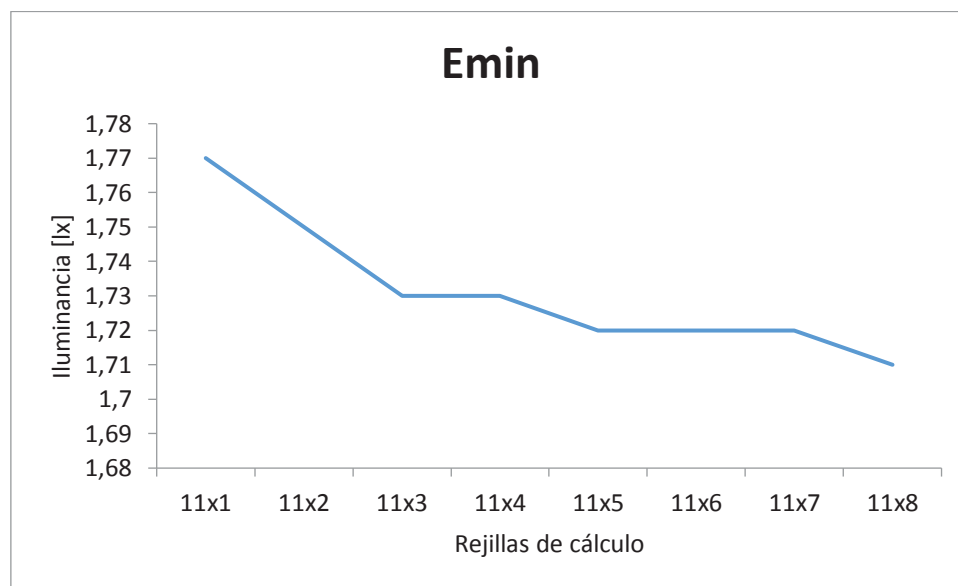


Figura 3-41. Representación gráfica de tabla 3-63 (Emin), zona P4.

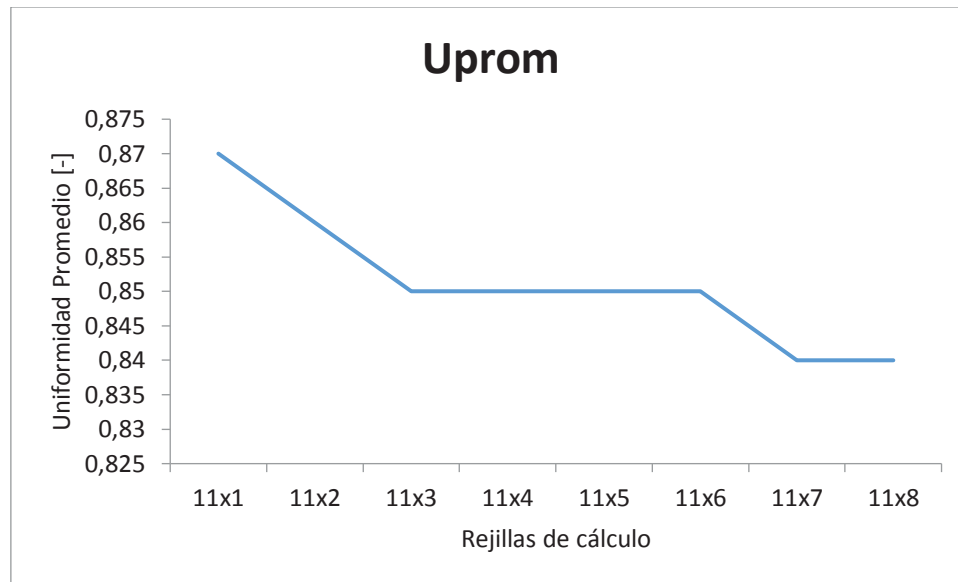


Figura 3-42. Representación gráfica de tabla 3-63 (Uprom), zona P4.

### Ensanchamiento (5% y 10%)

Para este análisis se tendrá en cuenta la utilización de solo 5 puntos longitudinales y 3 puntos transversales. La siguiente tabla muestra los resultados obtenidos de DIALux.

Tabla 3-62: Resumen variación de ensanchamiento de área de cálculo en el hemisferio superior.

|                   | Sin Ensanchamiento<br>Rejilla (5x3) | Ensanchamiento<br>5% | Ensanchamiento<br>10% |
|-------------------|-------------------------------------|----------------------|-----------------------|
| <b>Eprom [lx]</b> | 2,04                                | 2,05                 | 2,06                  |
| <b>Emin [lx]</b>  | 1,73                                | 1,73                 | 1,73                  |
| <b>Uprom [-]</b>  | 0,85                                | 0,85                 | 0,84                  |

### Conclusiones análisis zona P4

Luego de analizar gráficamente el estudio hecho de puntos longitudinales y transversales que tendrá la metodología se puede concluir que:

- La cantidad de longitudinales que nos llevan a obtener una menor variación y llegar a un estado casi estable son cinco.
- La cantidad de transversales que nos llevan a una aproximación de los resultados esperados son seis, quiere decir que para efectos de simulación se deben tomar en cuenta puntos de cálculo distanciados a 1[m].

Considerando que la variación del ancho es casi despreciable, de todas formas se toma en cuenta la recomendación internacional CIE150-2003 que indica un ensanchamiento de un 5% en los extremos del área de cálculo.

### 3.2.5 Conclusión del análisis del informe técnico

En esta sección se definirá la cantidad de puntos de cálculo y el área de cálculo.

#### Puntos longitudinales y transversales

Luego de analizar gráficamente el estudio realizado con distintas rejillas de cálculo ubicadas sobre 1[m] de las luminarias, con el objeto de definir la cantidad de puntos longitudinales y transversales que tendrá la metodología, se puede concluir que:

- La cantidad de puntos longitudinales que nos llevan a una aproximación de los resultados esperados son cinco, dicha cantidad de puntos se evidencian a continuación:
  - o En las 4 zonas que se realizó el análisis (zona P1, zona P2, zona P3 y zona P4) se logra llegar a una estabilidad en la curva con escasamente 5 puntos longitudinales en el caso del análisis gráfico de Eprom.
  - o El análisis gráfico de Emin, también logra estabilidad en 5 puntos longitudinales.
  - o En el análisis gráfico de Uprom, se corrobora que en 5 puntos longitudinales se logra estabilidad.
- La cantidad de puntos transversales que nos estabiliza la curva de Eprom, Emin y Uprom, son n puntos dependiendo del ancho de la zona analizada. Los n puntos deben estar separados equidistantemente a 1[m] el uno del otro.

Debido de las conclusiones anteriores se establece como estándar una rejilla de cálculo en el hemisferio superior con 5 puntos en sentido longitudinal y n puntos de cálculo en sentido transversal dependiendo del ancho de la superficie de simulación de estos, separados a 1[m] el uno del otro

#### Largo y ancho de las áreas de cálculo.

##### Cálculos a nivel del suelo

El área en la que se efectuarán los cálculos a nivel del suelo se definirá de forma similar a como lo establece en la recomendación internacional CIE 140-2000, esta indica que el largo se define como la distancia de dos luminarias consecutivas y el ancho se define con el ancho del área de cálculo. Por ejemplo, si es una calzada, el ancho lo define la misma calzada, si es una plaza, el ancho lo define la misma plaza, etc.

##### Cálculos en el hemisferio superior

El área en la que se efectuarán los cálculos para obtener los valores en DIALux será definida al igual como se establece en la recomendación internacional CIE 150-2003, esta indica que se considera un ensanchamiento en los extremos de la rejilla de cálculo en un 5% de cada extremo.

El largo y ancho base, los cuales sufrirán el ensanchamiento, se obtienen del largo y ancho de la superficie de cálculo a nivel del suelo.

A continuación en la figura 3-38 se ilustra un resumen con las áreas bases que se considerarán en calzadas de tránsito vehicular con y sin bandejón central.

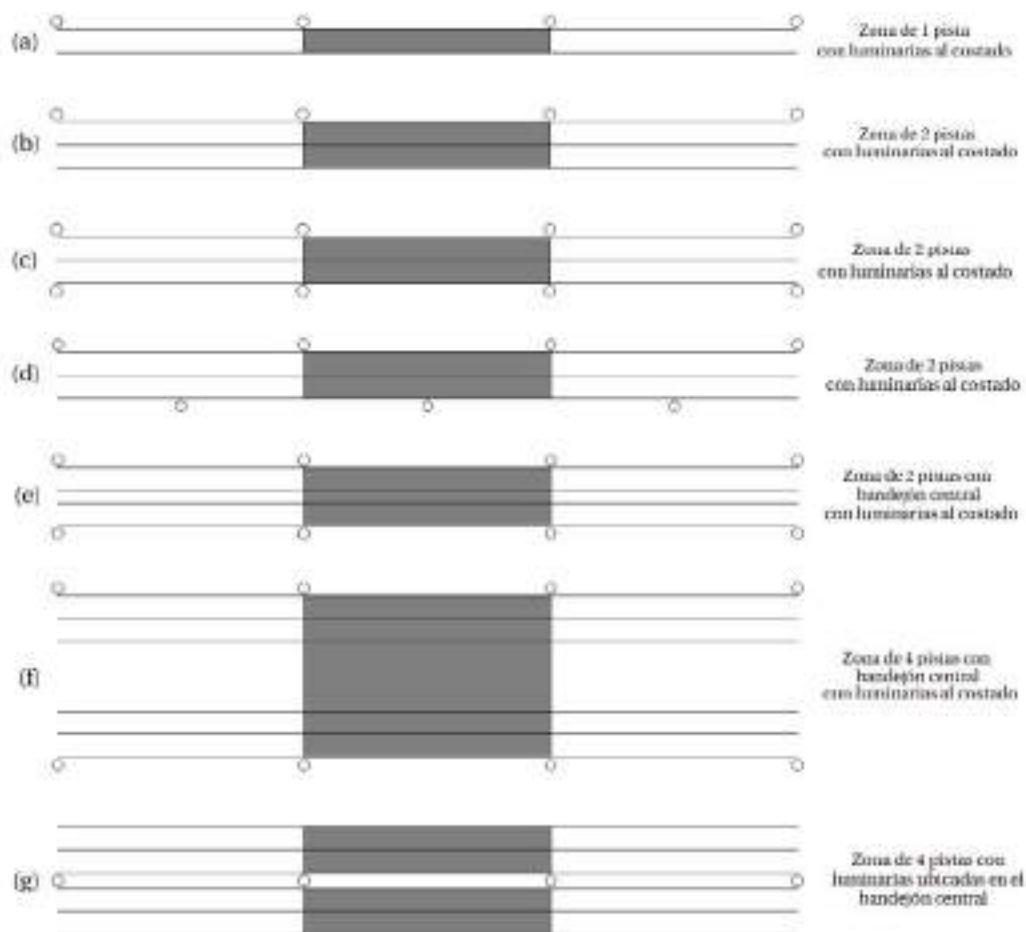


Figura 3-43. Áreas de cálculo base.

### 3.3 Prueba de la metodología

Se considera necesario realizar una prueba global de la metodología, para esto se considera un área que abarque la mayor cantidad de factores, la zona elegida es avenida Brasil entre las calles General Cruz y Freire, justo al frente de la facultad de ingeniería de la PUCV.

#### 3.3.1 Simulación Avenida Brasil

Las siguientes ilustraciones muestran avenida Brasil en la realidad y simulada en DIALux respectivamente.



Figura 3-44. Av. Brasil vista con Google Street.



Figura 3-45. Av. Brasil simulada.



La figura 3-41 muestra la ubicación de las rejillas de cálculo, se contemplan 3 rejillas una a nivel del suelo de 13x30, las otras dos están situadas en el hemisferio, la primera es de 13x30 y la segunda de 5x30, esta última para comprobar los cálculos solo con 5 puntos longitudinales, ambas sobre 1[m] sobre las luminarias.

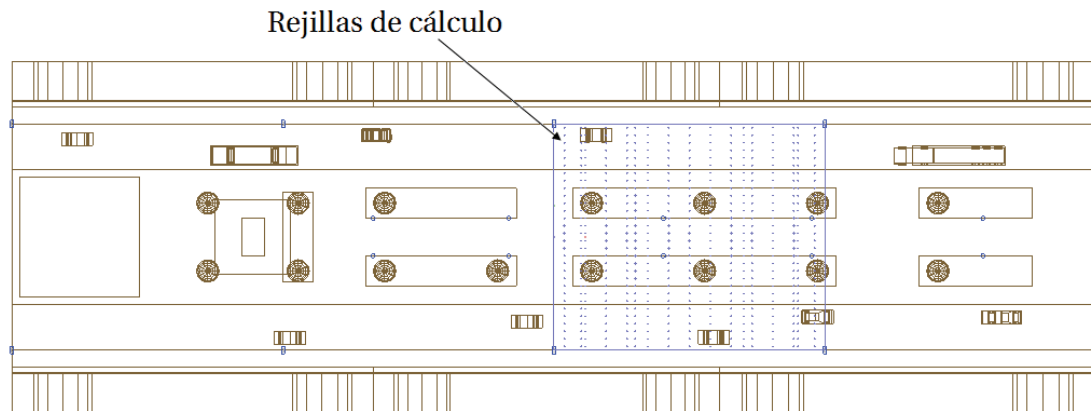


Figura 3-46. Vista de planta Av. Brasil.

### 3.3.2 Resultados simulación

Las siguientes tablas exponen las iluminancias calculadas por el software.

Tabla 3-63: Iluminancia puntuales a nivel del suelo (rejilla 13x30).

|           | 1    | 2           | 3           | 4  | 5    | 6    | 7           | 8           | 9    | 10   | 11 | 12 | 13          |
|-----------|------|-------------|-------------|----|------|------|-------------|-------------|------|------|----|----|-------------|
| <b>A</b>  | 26   | 21          | 15          | 11 | 7,89 | 6,55 | 6,21        | 6,76        | 8,26 | 11   | 15 | 21 | 26          |
| <b>B</b>  | 31   | 0,95<br>(4) | 1,28<br>(4) | 14 | 9,44 | 7,58 | 7,19        | 7,82        | 9,8  | 14   | 20 | 26 | 31          |
| <b>C</b>  | 36   | 1,53<br>(4) | 2,22<br>(4) | 17 | 11   | 8,72 | 8,28        | 8,98        | 11   | 17   | 24 | 32 | 36          |
| <b>D</b>  | 39   | 34          | 25          | 18 | 12   | 9,49 | 9,05        | 9,74        | 12   | 18   | 25 | 34 | 39          |
| <b>E</b>  | 39   | 33          | 24          | 18 | 12   | 9,77 | 9,49        | 10          | 13   | 18   | 24 | 32 | 38          |
| <b>F</b>  | 36   | 29          | 21          | 16 | 12   | 10   | 9,69        | 10          | 12   | 16   | 21 | 29 | 36          |
| <b>G</b>  | 31   | 24          | 18          | 14 | 12   | 10   | 9,91        | 10          | 11   | 14   | 18 | 24 | 31          |
| <b>H</b>  | 26   | 20          | 14          | 12 | 11   | 11   | 10          | 9,75        | 10   | 12   | 15 | 21 | 27          |
| <b>I</b>  | 22   | 17          | 12          | 11 | 12   | 12   | 11          | 9,52        | 9,5  | 10   | 13 | 19 | 24          |
| <b>J</b>  | 17   | 14          | 11          | 11 | 13   | 14   | 12          | 8,88        | 8,67 | 9,38 | 12 | 18 | 22          |
| <b>K</b>  | 14   | 12          | 9,31        | 11 | 16   | 17   | 13          | 9,33        | 8,16 | 8,66 | 12 | 19 | 22          |
| <b>L</b>  | 11   | 9,73        | 8,24        | 11 | 18   | 16   | 15          | 9,3         | 7,63 | 8,1  | 12 | 19 | 18          |
| <b>M</b>  | 9,93 | 8,64        | 7,47        | 11 | 18   | 14   | 16          | 9,25        | 6,85 | 7,75 | 12 | 19 | 14          |
| <b>N</b>  | 9,21 | 8,01        | 7,11        | 11 | 19   | 15   | 17          | 9,33        | 7,03 | 7,57 | 12 | 21 | 13          |
| <b>O</b>  | 8,94 | 7,75        | 5,08<br>(4) | 12 | 20   | 21   | 17          | 9,35        | 6,97 | 7,56 | 12 | 21 | 19          |
| <b>P</b>  | 9,04 | 7,81        | 5,18<br>(4) | 12 | 20   | 23   | 17          | 9,46        | 7,03 | 7,64 | 12 | 21 | 21          |
| <b>Q</b>  | 9,42 | 8,11        | 7,36        | 11 | 20   | 19   | 17          | 9,61        | 7,16 | 7,74 | 12 | 21 | 17          |
| <b>R</b>  | 10   | 8,8         | 7,7         | 11 | 19   | 15   | 17          | 9,59        | 7    | 7,95 | 12 | 21 | 16          |
| <b>S</b>  | 12   | 9,97        | 8,47        | 12 | 19   | 15   | 16          | 9,7         | 7,79 | 8,31 | 13 | 22 | 17          |
| <b>T</b>  | 14   | 12          | 9,58        | 12 | 18   | 17   | 15          | 9,81        | 8,33 | 8,91 | 13 | 21 | 22          |
| <b>U</b>  | 18   | 15          | 11          | 12 | 15   | 16   | 13          | 9,21        | 8,92 | 9,72 | 13 | 21 | 24          |
| <b>V</b>  | 22   | 17          | 12          | 12 | 13   | 14   | 12          | 10          | 9,79 | 11   | 14 | 21 | 26          |
| <b>W</b>  | 27   | 20          | 15          | 13 | 13   | 12   | 11          | 10          | 11   | 12   | 16 | 22 | 29          |
| <b>X</b>  | 32   | 25          | 18          | 15 | 13   | 11   | 11          | 10          | 12   | 15   | 19 | 26 | 32          |
| <b>Y</b>  | 36   | 30          | 22          | 17 | 13   | 11   | 10          | 11          | 12   | 17   | 22 | 30 | 2,81<br>(4) |
| <b>Z</b>  | 39   | 33          | 24          | 18 | 13   | 10   | 9,89        | 10          | 13   | 18   | 24 | 33 | 1,16<br>(4) |
| <b>AA</b> | 39   | 34          | 26          | 19 | 13   | 9,79 | 9,28        | 9,77        | 13   | 19   | 26 | 34 | 39          |
| <b>AB</b> | 36   | 32          | 24          | 17 | 11   | 8,95 | 5,06<br>(4) | 1,3<br>(4)  | 10   | 16   | 24 | 32 | 36          |
| <b>AC</b> | 31   | 26          | 20          | 14 | 9,65 | 7,82 | 4,36<br>(4) | 0,18<br>(4) | 8,13 | 13   | 20 | 26 | 31          |
| <b>AD</b> | 26   | 21          | 15          | 11 | 8,14 | 6,79 | 6,26        | 6,38        | 8,15 | 11   | 15 | 21 | 25          |

(4) Valores excluidos del cálculo por no ser representativos  
Todos los datos en [lx]

Los valores excluidos en la tabla 3-65 se deben a que no se logra calcular el total de la iluminancia que incide en el punto. La principal causa por la que no se logra calcular debidamente la iluminancia es porque la luz es intervenida por algún objeto o elemento, éste se interpone entre la fuente de luz y el punto de cálculo.

Tabla 3-64: Iluminancia puntuales sobre 1 [m] de las luminarias (rejilla 13x30).

|           | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    | 10   | 11   | 12   | 13   |
|-----------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| <b>A</b>  | 4,78 | 4,69 | 4,46 | 4,17 | 4,02 | 3,98 | 3,91 | 3,94 | 4,11 | 4,56 | 5,19 | 5,8  | 6,07 |
| <b>B</b>  | 4,96 | 4,67 | 4,5  | 4,25 | 4,09 | 4,04 | 4,01 | 4,02 | 4,2  | 4,59 | 5,11 | 5,62 | 6,11 |
| <b>C</b>  | 5,07 | 4,84 | 4,71 | 4,47 | 4,27 | 4,14 | 4,13 | 4,08 | 4,3  | 4,58 | 5,05 | 5,44 | 5,74 |
| <b>D</b>  | 4,97 | 4,75 | 4,67 | 4,47 | 4,29 | 4,17 | 4,13 | 4,11 | 4,29 | 4,54 | 4,95 | 5,24 | 5,49 |
| <b>E</b>  | 4,77 | 4,65 | 4,62 | 4,44 | 4,29 | 4,13 | 4,12 | 4,12 | 4,25 | 4,37 | 4,74 | 5    | 5,23 |
| <b>F</b>  | 4,56 | 4,48 | 4,49 | 4,35 | 4,22 | 4,06 | 4,04 | 4,13 | 4,1  | 4,27 | 4,53 | 4,84 | 5    |
| <b>G</b>  | 4,42 | 4,34 | 4,43 | 4,32 | 4,12 | 3,94 | 3,95 | 4,03 | 4,08 | 4,15 | 4,43 | 4,62 | 4,78 |
| <b>H</b>  | 4,17 | 4,22 | 4,32 | 4,22 | 4,02 | 3,85 | 3,86 | 3,94 | 4,01 | 4,07 | 4,3  | 4,49 | 4,62 |
| <b>I</b>  | 3,99 | 4,1  | 4,26 | 4,13 | 4,01 | 3,81 | 3,79 | 3,92 | 4    | 3,97 | 4,17 | 4,3  | 4,47 |
| <b>J</b>  | 3,85 | 4,03 | 4,09 | 4,14 | 3,93 | 3,75 | 3,71 | 3,86 | 3,92 | 3,86 | 4,01 | 4,18 | 4,29 |
| <b>K</b>  | 3,91 | 3,91 | 4,09 | 4,11 | 3,86 | 3,67 | 3,66 | 3,88 | 3,94 | 3,83 | 4,05 | 4,17 | 4,24 |
| <b>L</b>  | 3,73 | 3,89 | 3,98 | 4,03 | 3,8  | 3,6  | 3,67 | 3,77 | 3,88 | 3,73 | 3,83 | 4,04 | 4,12 |
| <b>M</b>  | 3,75 | 3,89 | 3,96 | 3,95 | 3,77 | 3,57 | 3,68 | 3,74 | 3,85 | 3,75 | 3,84 | 4,02 | 4,12 |
| <b>N</b>  | 3,74 | 3,81 | 3,94 | 3,97 | 3,77 | 3,56 | 3,69 | 3,75 | 3,79 | 3,7  | 3,88 | 4,09 | 4,1  |
| <b>O</b>  | 3,75 | 3,87 | 3,94 | 3,94 | 3,76 | 3,54 | 3,71 | 3,77 | 3,78 | 3,71 | 3,8  | 4,11 | 4,05 |
| <b>P</b>  | 3,74 | 3,9  | 3,95 | 3,96 | 3,77 | 3,56 | 3,73 | 3,78 | 3,79 | 3,72 | 3,8  | 4,12 | 4,05 |
| <b>Q</b>  | 3,75 | 3,84 | 3,95 | 3,98 | 3,77 | 3,58 | 3,72 | 3,79 | 3,84 | 3,72 | 3,87 | 4,13 | 4,1  |
| <b>R</b>  | 3,76 | 3,95 | 3,96 | 3,97 | 3,77 | 3,6  | 3,74 | 3,81 | 3,95 | 3,8  | 3,84 | 4,01 | 4,11 |
| <b>S</b>  | 3,79 | 3,99 | 4,01 | 4,06 | 3,81 | 3,62 | 3,72 | 3,85 | 3,98 | 3,82 | 3,86 | 4,11 | 4,15 |
| <b>T</b>  | 4,09 | 4,03 | 4,14 | 4,14 | 3,86 | 3,69 | 3,72 | 3,96 | 4,06 | 3,93 | 4,14 | 4,27 | 4,32 |
| <b>U</b>  | 4,07 | 4,18 | 4,14 | 4,16 | 3,93 | 3,78 | 3,79 | 3,95 | 4,07 | 3,98 | 4,11 | 4,3  | 4,38 |
| <b>V</b>  | 4,28 | 4,23 | 4,3  | 4,16 | 4,01 | 3,85 | 3,89 | 4,04 | 4,17 | 4,11 | 4,31 | 4,43 | 4,58 |
| <b>W</b>  | 4,48 | 4,36 | 4,31 | 4,25 | 4,03 | 3,9  | 3,97 | 4,08 | 4,21 | 4,22 | 4,47 | 4,65 | 4,79 |
| <b>X</b>  | 4,74 | 4,56 | 4,48 | 4,33 | 4,13 | 3,98 | 4,06 | 4,2  | 4,31 | 4,31 | 4,6  | 4,79 | 4,97 |
| <b>Y</b>  | 4,91 | 4,71 | 4,54 | 4,35 | 4,19 | 4,06 | 4,1  | 4,24 | 4,34 | 4,44 | 4,72 | 5    | 5,19 |
| <b>Z</b>  | 5,22 | 4,87 | 4,65 | 4,43 | 4,24 | 4,12 | 4,17 | 4,23 | 4,4  | 4,55 | 4,93 | 5,17 | 5,41 |
| <b>AA</b> | 5,39 | 4,99 | 4,71 | 4,46 | 4,25 | 4,15 | 4,17 | 4,21 | 4,43 | 4,61 | 5,01 | 5,31 | 5,63 |
| <b>AB</b> | 5,51 | 5,07 | 4,74 | 4,47 | 4,23 | 4,11 | 4,16 | 4,17 | 4,44 | 4,64 | 5,09 | 5,45 | 5,83 |
| <b>AC</b> | 5,36 | 4,89 | 4,53 | 4,23 | 4,02 | 3,92 | 3,94 | 4    | 4,19 | 4,4  | 4,84 | 5,25 | 5,72 |
| <b>AD</b> | 5,13 | 4,89 | 4,49 | 4,16 | 3,94 | 3,84 | 3,8  | 3,88 | 4,06 | 4,32 | 4,84 | 5,33 | 5,5  |

Todos los datos en [lx]

Tabla 3-65: Iluminancia puntuales sobre las luminarias (rejilla 5x30).

|           | 1    | 2    | 3    | 4    | 5    |
|-----------|------|------|------|------|------|
| <b>A</b>  | 4,73 | 4,09 | 3,91 | 4,39 | 5,89 |
| <b>B</b>  | 4,71 | 4,18 | 4,01 | 4,42 | 5,68 |
| <b>C</b>  | 5,04 | 4,37 | 4,13 | 4,47 | 5,45 |
| <b>D</b>  | 4,91 | 4,4  | 4,13 | 4,46 | 5,29 |
| <b>E</b>  | 4,81 | 4,39 | 4,12 | 4,37 | 5,04 |
| <b>F</b>  | 4,58 | 4,29 | 4,04 | 4,22 | 4,84 |
| <b>G</b>  | 4,39 | 4,23 | 3,95 | 4,16 | 4,68 |
| <b>H</b>  | 4,27 | 4,15 | 3,86 | 4,04 | 4,5  |
| <b>I</b>  | 4,07 | 4,13 | 3,79 | 3,99 | 4,36 |
| <b>J</b>  | 4,02 | 4,04 | 3,71 | 3,87 | 4,18 |
| <b>K</b>  | 3,95 | 4,04 | 3,66 | 3,91 | 4,17 |
| <b>L</b>  | 3,92 | 3,92 | 3,67 | 3,78 | 4,03 |
| <b>M</b>  | 3,81 | 3,93 | 3,68 | 3,78 | 4,09 |
| <b>N</b>  | 3,83 | 3,89 | 3,69 | 3,76 | 4,09 |
| <b>O</b>  | 3,81 | 3,88 | 3,71 | 3,82 | 4,05 |
| <b>P</b>  | 3,83 | 3,9  | 3,73 | 3,83 | 4,04 |
| <b>Q</b>  | 3,88 | 3,9  | 3,72 | 3,8  | 4,08 |
| <b>R</b>  | 3,87 | 3,94 | 3,74 | 3,86 | 4,08 |
| <b>S</b>  | 4,02 | 3,95 | 3,72 | 3,89 | 4,1  |
| <b>T</b>  | 4,09 | 4,06 | 3,72 | 4,03 | 4,24 |
| <b>U</b>  | 4,16 | 4,04 | 3,79 | 4,02 | 4,29 |
| <b>V</b>  | 4,24 | 4,14 | 3,89 | 4,16 | 4,49 |
| <b>W</b>  | 4,45 | 4,16 | 3,97 | 4,24 | 4,66 |
| <b>X</b>  | 4,65 | 4,23 | 4,06 | 4,39 | 4,84 |
| <b>Y</b>  | 4,86 | 4,27 | 4,1  | 4,46 | 5,01 |
| <b>Z</b>  | 5,07 | 4,35 | 4,17 | 4,52 | 5,22 |
| <b>AA</b> | 5,19 | 4,36 | 4,17 | 4,6  | 5,37 |
| <b>AB</b> | 5,31 | 4,34 | 4,16 | 4,61 | 5,5  |
| <b>AC</b> | 4,97 | 4,13 | 3,94 | 4,36 | 5,32 |
| <b>AD</b> | 4,97 | 4,04 | 3,8  | 4,28 | 5,4  |

Todos los datos en [lx]

Tabla 3-66: Resumen cálculos obtenidos en Av. Brasil.

| Altura de cálculo | Rejilla<br>(ptos trans. x ptos long.) | Resultados |           |           |
|-------------------|---------------------------------------|------------|-----------|-----------|
|                   |                                       | Eprom[lx]  | Emin [lx] | Uprom [-] |
| nivel del suelo   | 13x30                                 | 16,02      | 6,21      | 0,39      |
| sobre 1 [m]       | 13x30                                 | 4,24       | 3,54      | 0,83      |
| sobre 1 [m]       | 5x30                                  | 4,26       | 3,66      | 0,86      |

Según los datos que entrega la tabla 3-68 se ratifica que la rejilla de 5 puntos longitudinales y n puntos transversales (en este caso 30 puntos de cálculo) nos entrega resultados confiables para luego calcular el flujo luminoso superior.

### 3.3.3 Cálculo del flujo luminoso superior

Necesariamente y cumpliendo con el objetivo del proyecto se debe calcular el flujo luminoso emitido hacia la bóveda celeste por el sistema de iluminación. Debemos recordar que la Eprom

que calcula el software es la iluminancia promedio de un área en particular, si utilizamos la fórmula 1-5 podemos calcular el flujo luminoso medio emitido hacia el hemisferio superior.

$$E = F/S \quad (1-5)$$

Donde:

- E es la iluminancia
- F el flujo luminoso
- S la superficie o área de cálculo

De la ecuación anterior podemos decir que:

$$F_{prom} = E_{prom} * S$$

Utilizando los valores que nos entrega la tabla 3-68 para calcular el flujo luminoso, esta tabla corresponde a la simulación con una rejilla de cálculo situada en el hemisferio superior a 1[m] sobre las luminarias con 150 puntos de cálculo (5 longitudinales y 30 transversales) y además sabemos que la zona de cálculo comprende un largo de 36[m] por 30[m] de ancho. Podemos decir que el flujo luminoso es:

$$F_{med} = 4,26 * 36 * 30$$

$$F_{med} = 4600,8 \text{ [lm]}$$

Este resultado es la representación del flujo luminoso medio emitido hacia el hemisferio superior por todo el sistema de iluminación en estudio.

## 4 Metodología propuesta

A continuación se detalla la metodología final que se propone para realizar cálculo de flujo luminoso superior en sistemas de iluminación, los pasos a seguir son los siguientes:

- Diseñar en DIALux la zona de estudio lo más cercano a la realidad (modelamiento).
- Definir el largo y ancho de la zona de cálculo.
- Posicionar rejillas de cálculo a nivel de suelo y sobre 1[m] en el hemisferio superior considerando el 5% de ensanchamiento.
- Realizar un cómputo a nivel del suelo tal cual lo indica la CIE 140-2000.
  - o Si se tiene un informe con las iluminancias medidas punto a punto en terreno, utilizarlos para compararlos y ver si los datos calculados son representativos.
  - o Si no existe informe, necesariamente se deberá hacer una medición en terreno.
- Comparar resultados medidos en terreno con los cálculos obtenidos de la simulación (a nivel del suelo). Si estos resultados son similares en las magnitudes y su margen de error no supera el 10%, se considera que la zona tiene representatividad.
- Luego de cumplir con la representatividad, se debe realizar un cálculo en el hemisferio superior, tan solo con 5 puntos longitudinales y n puntos transversales (dependiendo del ancho de la zona de cálculo), considerando el ensanchamiento en un 5% de la región de cálculo utilizada a nivel del suelo.
- Extraer el valor de la iluminancia media resultante.
- Calcular flujo luminoso medio emitido por el conjunto total.

La figura 4-1 muestra un diagrama de flujo que nos permitirá realizar los estudios de flujo luminoso superior en sistemas de iluminación sin equivocaciones.



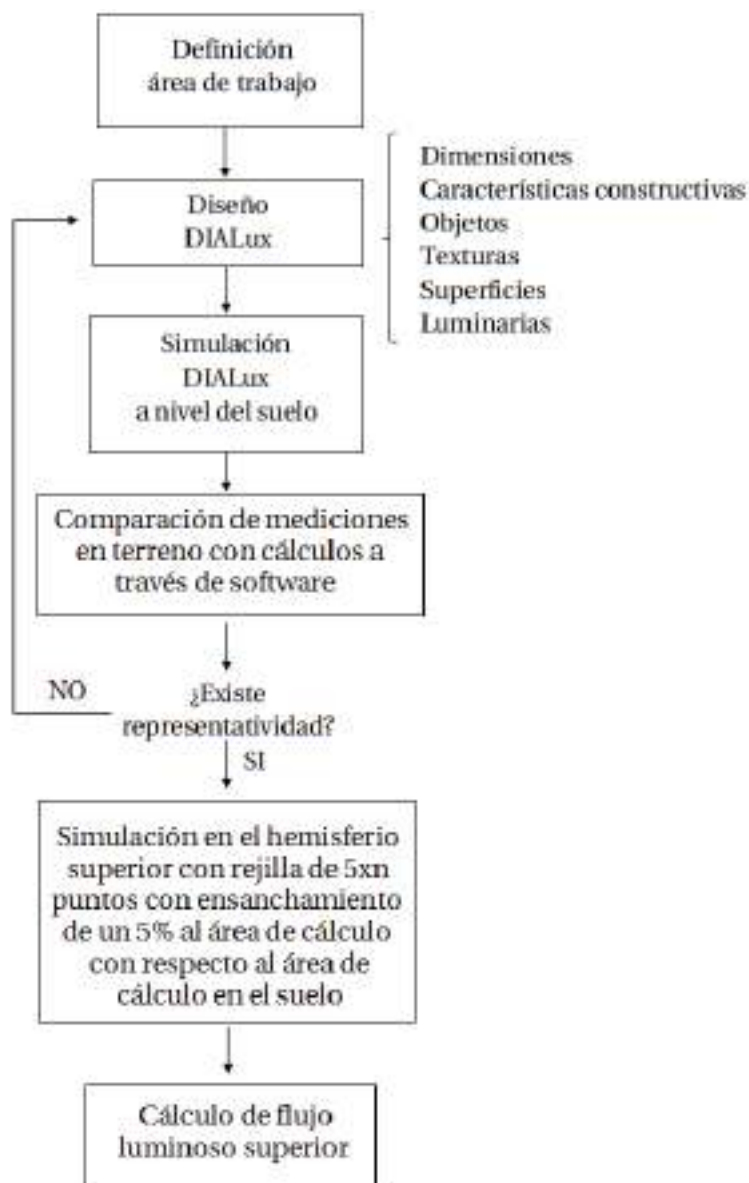


Figura 4-1. Diagrama de flujo de la metodología propuesta.

Se contemplará que existe representatividad cuando el margen error (%) de  $E_{prom}$  y  $E_{min}$  no superen el 10%.

## Conclusiones

En el presente informe podemos concluir que independiente de cuál sea el objetivo del cálculo de flujo luminoso emitido hacia el hemisferio superior (eficiencia energética, contaminación lumínica, estudios de reflexión, etc.), es necesario contar con una metodología que nos permita realizar esta tarea.

Debido a que no existe ningún procedimiento normado, se tuvo que realizar un exhaustivo estudio de las recomendaciones internacionales desarrolladas por la comisión internacional de iluminación. El estudio de diversas recomendaciones CIE dio como fruto la utilización de dos de estas en particular, las recomendaciones CIE 140-2000 y CIE 150-2003. Estas se utilizaron como base de la metodología de trabajo y por consiguiente para confeccionar la metodología propuesta.

En resumen la CIE 140-2000 se utilizó para calcular los niveles de iluminación a nivel del suelo y para definir el largo y ancho de las rejillas, tanto a nivel del suelo como en el hemisferio superior. La rejilla de cálculo ubicada en el hemisferio superior que se utilizó fue una combinación de ambas recomendaciones, la recomendación CIE 140-2000 se usó como base de las dimensiones de la rejilla, a la cual se le modificaron sus dimensiones en un 5% en cada extremo y la CIE 150-2003 se empleó para definir el posicionamiento de esta rejilla a 1[m] sobre el sistema de iluminación.

Para efectos de agotar recursos y así justificar la propuesta final, la metodología de trabajo proponía diversas iteración en las áreas de estudio (zona P1, zona P2, zona P3 y zona P4) contemplando la modificación de sus dimensiones de las rejillas de cálculo y la variación de puntos de cálculo, de este estudio se terminó concluyendo que no es necesario realizar un cálculo sobre luminarias con la misma cantidad de puntos que se calcula a nivel del suelo, en las zonas estudiadas se consideró prudente considerar solo una rejilla de 5xn (5 puntos longitudinales y n transversales) para el cálculo puntual de iluminancia, el detalle de la rejilla posicionada en el hemisferio superior sobre 1[m] del sistema de iluminación se expone a continuación.

- 5 puntos longitudinales, independiente del largo de la zona de cálculo.
- n puntos transversales, dependientes del ancho de la zona de cálculo.
- Ensanchamiento de un 5% en cada extremo del área de cálculo utilizada en los cálculos a nivel del suelo.

La cantidad de puntos que definen la rejilla de cálculo fueron ratificados por la simulación de Avenida Brasil, lo que fue concluyente a la hora de proponer la metodología. Se concluye de lo anterior que debido a la altura en que se posiciona la rejilla de cálculo, esta no contempla todos los ángulos reflejados por las distintas superficies, es por eso que es factible realizar las simulaciones con una cantidad menor de puntos (rejilla de  $5 \times n$ ).

En conclusión y debido al resultado de la combinación de estudio y las recomendaciones CIE, para realizar el cálculo del flujo luminoso que una instalación exterior emite hacia el hemisferio superior se debe utilizar una rejilla posicionada sobre 1[m] de la luminaria más alta en la zona de cálculo y esta debe contar con 5 puntos longitudinales y n puntos transversales que permitan el cálculo de la iluminancia en el punto. Además las simulaciones deben ser acompañadas siempre de una rejilla a nivel del suelo con el objeto de buscar representatividad en la zona.

La idea de disminuir la cantidad de puntos de cálculo es para facilitar el trabajo cuando se requiera hacer mediciones en terreno de flujo luminoso superior, ya que con menos puntos se simplifica significativamente el proceso de medición en terreno.

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**FACULTAD DE ECOLOGÍA Y RECURSOS NATURALES  
ESCUELA DE INGENIERÍA AMBIENTAL  
INTEGRADOR III: PROYECTO DE TÍTULO**

# **“Propuesta de cambio a la norma de emisión que regula la contaminación lumínica en Chile”**

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Santiago 14 de diciembre del 2017



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## 1. Introducción

La inquietud de la sociedad por la contaminación es un tema que cada vez adquiere mayor importancia, lo que se ha traducido en una creciente presión hacia nuevas disposiciones legales, con el fin de proteger la salud de las personas y el medio ambiente. Sin embargo, si no existe un verdadero compromiso por parte de las industrias y sociedad no habrá ley que proteja de la contaminación ni del agotamiento de los limitados recursos y espacios que aún quedan (Salazar, 2004).

Bajo lo estipulado por la ley 19300 (MMA,2010) contaminación se define como “la presencia en el ambiente de sustancias, elementos, energía o combinación de ellos, en concentraciones o concentraciones y permanencia superiores o inferiores, según corresponda, a las establecidas en la legislación vigente”. A partir de esto se pueden distinguir, que existen distintos tipos de contaminación como lo son la contaminación de agua, suelo, aire, acústica y lumínica (Chiluisa,2014). De estas, una de las menos abordada es la contaminación lumínica.

Para mitigar la contaminación lumínica, en diversos países como España e Italia, se han desarrollado normas que regulan la contaminación lumínica en gran parte de su territorio. Por ejemplo, en el caso de España, se encuentra establecido el Real decreto 243/1992, de 13 de marzo, por el que se aprueba el Reglamento de la Ley 31/1988, de 31 de octubre, sobre protección de la calidad astronómica de los Observatorios del Instituto de Astrofísica de Canarias.

Chile no se encuentra alejado de esta realidad, puesto que dentro del marco regulador cuenta con el DS 43/2013, Norma de Emisión que regula la contaminación lumínica. Dicha norma, sin embargo, solo aplica en tres regiones del país: Antofagasta, Atacama y Coquimbo, además de velar solo por la calidad de los cielos nocturnos, sin considerar los efectos en los ecosistemas, lo cual es la base para la normativa medioambiental del país.

Los anteceden expuestos, muestran que la Norma de Emisión chilena que regula la contaminación lumínica presenta serias limitaciones, que van desde las zonas de aplicación

(solo tres regiones) hasta los alcances de su aplicación (solo impacto en la calidad de los cielos). Por tanto, es que la presente investigación pretende comparar la normativa chilena respecto de sus pares internacionales, para así poder establecer como han abordado el problema de la contaminación lumínica en el extranjero, determinando, cuales son los aspectos que consideran esas normas. Se dará énfasis a como esas normas abordan (si lo hacen) los efectos ecológicos de la contaminación lumínica. Finalmente se podrán identificar criterios que puedan ser claves para que la norma chilena pueda incluir el ámbito ecológico en esta, proponiéndose también que el alcance de esta no solo sea sectorial, sino que nacional.

## **1.1.Objetivo**

### **1.1.1 Objetivo general**

Proponer cambios en la norma de emisión DS 43,2013 que regula la contaminación lumínica en Chile, considerando el área territorial de aplicación y los efectos ecológicos de este contaminante.

### **1.1.2 Objetivos Especificos**

- Analizar normativas internacionales para la contaminación lumínica.
- Analizar los antecedentes de los efectos ecológicos de la contaminación lumínica
- Complementar los criterios de la norma de emisión para la regulación de la contaminación lumínica en Chile, considerando el área territorial de aplicación y los efectos ecológicos.

### **1.1.3 Alcance**

Esta investigación abordará el ámbito normativo, en relación a experiencias internacionales para así complementar la normativa chilena vigente que regula las emisiones de luz artificial.

## **2. Revisión bibliográfica**

### **2.1. Contaminación Lumínica**

Desde tiempos remotos, la astronomía ha influido en la cultura de muchos pueblos, siendo la base para establecer tiempos, predicciones, orientación, ritos a los dioses, ciclos lunares, entre otros. Con el paso del tiempo, la imagen de un cielo limpio y estrellado ha ido cambiando. Cuando el hombre tuvo la necesidad de ver más allá de lo que podía ver al caer la noche, éste busco medios para realizar sus objetivos, como lo fue el fuego, pero esto no fue suficiente, cada vez era necesaria aún más luz para satisfacer sus necesidades. Con el tiempo se descubrió la electricidad, nació la primera ampolleta, y luego vino una revolución industrial que remeció al mundo. Aquellos pueblos donde su cultura era basada en los cielos, fueron olvidados por el resto, pero el problema nació cuando estos pueblos vieron impedidas sus actividades culturales por la imposibilidad de observar con claridad el firmamento. El desarrollo a nivel mundial no solo perjudicó a estas culturas, sino que, a gran parte del mundo, cuando se observaron por primera vez imágenes de la Tierra vista de noche desde el espacio. En ellas se pudo observar pequeños puntos de luz en diversas partes del mundo, los cuales con el paso del tiempo se fueron haciendo aún más evidentes. En estas imágenes, América destacaba por el resplandor de luz proveniente de las grandes urbes de la costa oriental, y las enormes zonas industriales de los Grandes Lagos. En el caso de Europa, Gran Bretaña y Países Bajos destacaban por ser los países más visibles desde el espacio. En España, tanto en Madrid como en Barcelona, aparecían dos enormes manchas brillantes de luz (Sacristán, 1995). Este fenómeno luminoso que se pudo evidenciar por medio de estas imágenes satelitales, se conoce como “contaminación lumínica”.

La contaminación lumínica es toda aquella iluminación artificial que interrumpe los patrones naturales de luz y oscuridad, para una gama de actividades humanas (Longcore y Rich, 2004). Los impactos sobre el medio ambiente natural o la visión humana del cielo nocturno llevan al reconocimiento de la "contaminación lumínica ecológica" y la "contaminación lumínica astronómica" (Longcore y Rich, 2004). La resultante de esta contaminación lumínica astronómica, produce que el cielo pierda su natural oscuridad, las estrellas y otros objetos astronómicos desaparecen, haciéndose imposible su estudio o su simple observación. Por otra parte, la proyección de luz artificial en el entorno nocturno es causante de una severa

distorsión en la conducta y los ciclos naturales de los animales y plantas. Es importante destacar que la producción de esta luz desperdiciada también genera gases que incrementan el calentamiento global de la Tierra y otros efectos medioambientales indeseados (Skaf et al., 2010).

## **2.2. Causas de la contaminación lumínica.**

En la vida y las sociedades actuales, la necesidad de iluminar es un factor clave para el diario vivir. En estos espacios y tiempos, no se siguen ritmos naturales de día y noche. Cada vez aumenta la preferencia por realizar actividades humanas en horarios nocturnos, por lo cual, dichas actividades nocturnas necesitan del apoyo del uso de luminarias (farolas, proyectores o focos, etc) que, debido a un mal diseño luminotécnico o a una colocación inapropiada, dejan escapar buena parte del flujo luminoso fuera del área que se necesita iluminar. Una excesiva iluminación, produce asimismo innecesarias pérdidas de luz por reflexión en el suelo y demás objetos sobre iluminados. (García et al, 2012)

La falta de sensibilidad de las personas y sobre todo de las entidades responsables es debida principalmente a una falta de información unida al hecho frecuente de que al vivir durante mucho tiempo con este problema, nos hemos acostumbrado a él y ya no lo percibimos como tal.

## **2.3. Efectos de la contaminación lumínica**

### **2.3.1. Efectos de la contaminación lumínica sobre la calidad de los cielos**

El efecto más característico de la contaminación lumínica es la alteración de la vista al firmamento siendo este un patrimonio, recurso natural y económico. El uso inadecuado de luz artificial dirigida hacia los cielos y su dispersión en la atmosfera ha provocado que la visión a la vía láctea se vea perjudicada, no solo para el ojo humano sino para los observatorios (OPCC, 2017).

El año 2016, se publicó a través de la revista Science Advance el nuevo atlas mundial del brillo artificial nocturno, el cual logro evidenciar el impacto visual mundial de la contaminación lumínica. Como se muestra en la figura 2.1.1 los puntos de colores rojos son aquellos lugares en el mundo en los cuales la vista al firmamento es nula, en esta situación el país más contaminado por la luz es Singapur, donde toda la población vive bajo un cielo tan



brillante que el ojo no puede adaptarse completamente a la visión nocturna. Otras poblaciones que experimentan este nivel de contaminación lumínica son Kuwait (98%), Qatar (97%), Emiratos Árabes Unidos (93%), Arabia Saudita (83%), Corea del Sur (66%), Israel (61%), Argentina (58%), Libia (53%) y Trinidad y Tabago (50%); todos estos países tienen más de la mitad de sus habitantes viviendo bajo cielos extremadamente brillantes (Falchi, 2016).

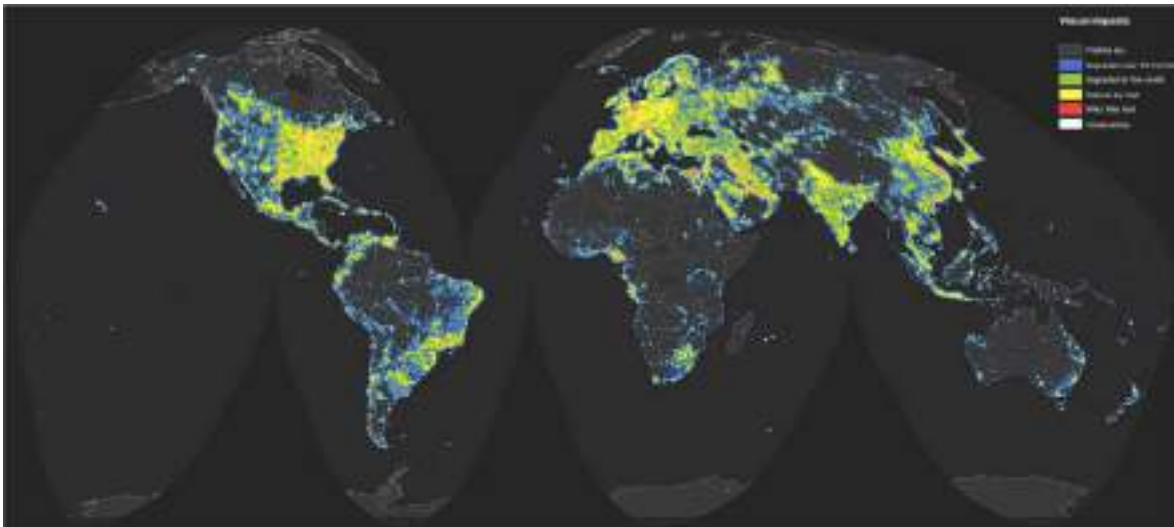


Figura 2.1.1. Mapa mundial del impacto visual de la contaminación lumínica. (Fotografía tomada de Falchi, 2016)

### 2.3.2. Efectos de la contaminación lumínica en la salud humana

Los efectos sobre la salud de las personas producto de la contaminación lumínica han sido complejos de definir, puesto que a pesar de que existen evidencias epidemiológicas concluyentes que apuntan hacia una asociación constante entre la exposición a la luz artificial nocturna interior y problemas de salud tales como el cáncer de mama, dice George Brainard, profesor de neurología del Colegio Médico Superior Jefferson, de la Universidad Thomas Jefferson de Filadelfia, “esa asociación no prueba que la luz artificial provoque el problema. Por otra parte, los estudios de laboratorio controlados demuestran que la exposición a la luz durante la noche puede trastornar la fisiología circadiana y neuroendocrina, acelerando el crecimiento de los tumores.”(Chepesiuk, 2010).

### 2.3.3 Efectos de la contaminación lumínica sobre aspectos socioeconómicos

A menudo la emisión de luz en los distintos alumbrados de exteriores involucra que los niveles de consumo energético aumenten más de lo necesario debido al uso ineficaz del recurso energético, siendo la luz emitida en intensidades, rangos espectrales, horario de funcionamiento y distribución espectral inadecuadas.

El gasto energético del alumbrado público de un municipio representa aproximadamente el 50% del gasto energético total (Capó,2002). La aplicación de medidas correctoras, como el uso de lámparas de sodio o de bajo consumo, luminarias con pantallas que eviten el flujo de luz por encima del plano horizontal o la limitación del horario del funcionamiento de los focos luminosos, entre otros, pueden reducir este gasto en más de un 25% (Figura 2.3.1). Según la Asociación Internacional Dark-Sky, el problema de la contaminación lumínica afecta a dos tercios de la población mundial, y se calcula que en EEUU se gastan 6 millones de toneladas de carbón y 23 millones de barriles de petróleo al año en generar luz que se proyecta al cielo, lo que supone un desperdicio de unos 1.000 millones de dólares.



Figura 2.3.1. Ejemplo de sobreconsumo mall Costanera Center, Santiago de Chile. (Fotografía propia)

### 2.3.4. Efectos de la contaminación lumínica en los ecosistemas

Los efectos ecológicos que provoca la luz artificial se han estudiado cada vez más en profundidad (Chepesiuk, 2010). (Matí)Por ejemplo, la iluminación puede afectar indirectamente a la fotosíntesis, a través del desencadenamiento de otras respuestas fisiológicas en plantas que influyen en la fotosíntesis (Skaf et al., 2010).

También los ecosistemas costeros se pueden ver afectados por la luz artificial antropogénica del lugar. Un ejemplo de esto son las tortugas marinas, estas se ven afectadas debido a que la luz artificial provoca trastornos en su comportamiento (Figura 2.4.1). Estas especies se dirigen hacia las playas en busca de realizar su anidación, pero producto de la iluminación artificial nocturna, las tortugas evitan anidar allí, trayendo consigo también una desorientación por las luces y lo que las hace vagar hacia carreteras o calles cercanas, donde corren el riesgo de ser arrolladas por los vehículos.



Figura 2.4.1. Ambientes de playa vulnerable ante los efectos de la luz antropogénica. (Fotografía tomada de Longcore, 2016)

#### **2.4. Situación actual de la contaminación lumínica en Chile.**

Como se mencionó anteriormente, la normativa existente en Chile, se centra en la calidad de cielos astronómicos de regiones en específico y, ésta nace producto de la preocupación de los astrónomos y científicos del país, que producto de sus investigaciones, que se generaron a partir de simposios y estudios científicos que se realizaron a nivel internacional, se demostró que los cielos astronómicos se perjudicaban por dicha contaminación. Pero también descubrieron que los cielos no eran los únicos que se podían ver afectados producto de la contaminación lumínica, puesto que este fenómeno, afectaba tanto a los seres humanos, el medio ambiente y la economía.

#### **2.4.1. Marco regulador.**

En diciembre del año 2012, se promulgo el Decreto Supremo N° 43, Norma de Emisión que regula la contaminación lumínica en Chile, cuyo objetivo es prevenir la contaminación lumínica de los cielos nocturnos de las regiones de Antofagasta, Atacama y Coquimbo, de manera de proteger la calidad astronómica de dichos cielos, mediante la regulación de la emisión del flujo radiante por parte de fuentes reguladas.

Esta norma establece el ámbito territorial de aplicación correspondiente a las regiones de Antofagasta, Atacama y Coquimbo. Por otro lado, las fuentes emisoras que han de ser reguladas conciernen al Alumbrado de Exteriores, correspondiente al alumbrado ambiental, deportivo y recreacional, funcional, industrial, ornamental y decorativo.

Se exceptúan de esta norma, todo aquello que corresponda a: iluminación por combustión a gas natural u otros combustibles, luminarias destinadas a la iluminación ornamental para festividades, siempre que no se excedan los 1500 lúmenes por cada lámpara, aquellas necesarias para garantizar la navegación marítima y aérea, cumpliendo con condiciones de color, luminarias de los vehículos motorizados, lámparas de emergencia, iluminación de espacios cerrados, proyectores astronómicos y las vitrinas iluminadas desde su interior.

Dicha norma establece límites máximos de emisión en relación a:

- Intensidad luminosa: fija un ángulo gama igual a 90°, que esté comprendida entre 0,00 y 0,49 candelas por cada 1.000 lúmenes del flujo de la lámpara. En el caso del alumbrado deportivo y recreacional se fija un límite de intensidad luminosa máxima de 10 candelas por cada 1.000 lúmenes del flujo de la lámpara, a un ángulo gama de 90°, junto con la adición de una visera que limite la emisión hacia el hemisferio superior. Dicha visera o paralumen deberá presentar un área similar a la de la superficie emisora del reflector, a objeto de cubrir efectivamente el plano superior del proyector o luminaria.

- Radiancia espectral: limita la composición de frecuencias de la luz emitida, concentrándose en el rango de luz visible.
- Reflexión: fija un 20% sobre los valores mínimos de la norma NSG 9 N°71, Iluminación: Diseño de alumbrados públicos en sectores urbanos, de la SEC, o la que lo reemplace.
- Iluminancia: los avisos y letreros luminosos no podrán exceder una iluminancia de  $50 \text{ cd/m}^2$  y no podrán orientarse por sobre la horizontal.

También estipula condiciones de cumplimiento para:

- Avisos y letreros luminosos: estos no podrán ser orientados en ángulos mayores a 0 grados con respecto al plano horizontal que pasa por el centro del área luminosa.
- Cañones de luz o proyectores láser: no podrán apuntarse por sobre ángulos gama mayores a 70 grados, aquellos tipos de proyectores láser o cañones de luz que puedan ser orientados libremente mientras se operan.

En relación al control y fiscalización de esta norma, el control es realizado bajo una certificación del cumplimiento de los límites de emisión, que se realiza previo a la instalación de la iluminaria, y en relación a la fiscalización, ésta, se encuentra a cargo de la superintendencia del medio ambiente.

### 3. Metodología

3.1 Objetivo específico 1: Analizar normativas internacionales para la contaminación lumínica.

Se analizó la normativa internacional (basada en los siguientes países: España, Italia y Eslovenia), en función de las consideraciones y aspectos de estas normativas, enfocándose en aspectos ecológicos, identificando alcance de aplicación, fuentes regulas, límites de emisión, entre otros.

#### 3.1.1 *Búsqueda y selección de información*

Se recopiló información de normativas internacionales pertenecientes a los siguientes países: España, Italia, y Eslovenia. La selección de estos países, se basó en que estos han sido de los que han abordado con mayor profundidad el tema de la contaminación lumínica.

Las normativas se buscaron dentro de las siguientes páginas correspondientes:

- España: Boletín oficial del estado (BOES)
- Italia: Ministerio del Medio Ambiente tutela del territorio del mar.
- Eslovenia: Dark Sky

#### 3.1.2. *Recopilación y análisis de la información*

Los criterios que fueron considerados en la recopilación de información, se basaron en los aspectos generales que cada normativa encontrada consideró, con énfasis en los aspectos ecológicos, con el fin de identificar alcance de aplicación, fuentes reguladas, límites de emisión, prohibiciones, consideraciones hacia la salud de las personas y el medio ambiente, zonificación del territorio y consideraciones especiales según fuese el caso.



3.2. Objetivo específico 2: Analizar los antecedentes de los efectos ecológicos de la contaminación lumínica.

Se analizaron antecedentes en relación a los efectos de la contaminación lumínica en el ámbito ecológico a partir de la identificación de trabajos publicados en revistas científicas, reportes técnicos, tesis entre otros documentos que sean accesibles.

#### *3.2.1 Identificación de efectos ecológicos de la contaminación lumínica*

A partir de investigaciones científicas, reportes técnicos, tesis entre otros documentos que fueron accesibles, se identificaron antecedentes en relación a los efectos ecológicos que produce la contaminación lumínica en diversos ecosistemas.

#### *3.2.2 Descripción y análisis de los efectos ecológicos por contaminación lumínica*

Una vez identificados estos antecedentes, se realizó una lista detallada de los efectos ecológicos encontrados para ulterior describir cada efecto, según lo encontrado, para luego poder analizar los impactos que conllevan estos efectos.

3.3 Objetivo específico 3: Complementar los criterios de la norma de emisión para la regulación de la contaminación lumínica en Chile, considerando el área territorial de aplicación y los efectos ecológicos.

Se integró la información recopilada en los objetivos específicos 1 y 2, en función de proponer, mediante la identificación de propuestas de mejora a la norma chilena, la complementación de ésta, a partir de la integración de los efectos ecológicos y el ámbito territorial, entre otros puntos que se lograron observar.

#### *3.3.1 Comparación de la normativa nacional e internacional*

En relación a lo obtenido en el objetivo específico 1, se comparó la norma nacional con las normativas establecidas en los países antes mencionados. Esta comparación se hizo en base

a los criterios analizados anteriormente: ámbito de aplicación, fuentes reguladas, límites de emisión y otras consideraciones.

### *3.3.2 Complementación de la normativa chilena*

Una vez que se obtuvo la comparación nacional e internacional, se identificaron aquellos aspectos que la norma chilena no contemplaba, para así incluir criterios que la norma chilena no consideraba según los antecedentes entregados por las normativas internacionales.

## 4. Resultados

### 4.1. Normativa internacional sobre contaminación lumínica.

#### 4.1.1. Normativa internacional

La Tabla 4.1.1. muestra un resumen de las diferentes normativas de los países seleccionados.

Es posible observar que en el caso de España e Italia estas normas son particulares para las distintas regiones.

Tabla 4.1.1. Normativa internacional.

| País          | Alcance                                 | Año  | Nombre                                                                                                                                                                                             |
|---------------|-----------------------------------------|------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>España</b> | Comunidad Autónoma de Cantabria.        | 2006 | Ley de Cantabria 6/2006, de 9 de junio, de Prevención de la Contaminación Lumínica.                                                                                                                |
| <b>España</b> | Comunidad Autónoma de Cantabria.        | 2010 | Decreto 48/2010, de 11 de agosto, por el que se aprueba el Reglamento por el que se desarrolla parcialmente la Ley de Cantabria 6/2006, de 9 de junio, de prevención de la contaminación lumínica. |
| <b>España</b> | Comunidad de Castilla y León            | 2010 | Ley 15/2010, de 10 de diciembre, de prevención de la contaminación lumínica y del fomento del ahorro y eficiencia energéticos derivados de instalaciones de iluminación.                           |
| <b>España</b> | Comunidad de Cataluña                   | 2001 | Ley 6/2001, de 31 de mayo, de Ordenación Ambiental del Alumbrado para la Protección del Medio Nocturno.                                                                                            |
| <b>España</b> | Comunidad de Cataluña                   | 2015 | Decreto 190/2015, de 25 de agosto, de desarrollo de la Ley 6/2001, de 31 de mayo, de ordenación ambiental del alumbrado para la protección del medio nocturno.                                     |
| <b>España</b> | Comunidad autónoma de las Illes Balears | 2005 | Ley 3/2005 de 20 de abril, de protección del medio nocturno de las Illes Balears.                                                                                                                  |
| <b>España</b> | Comunidad Foral de Navarra              | 2005 | Ley FORAL 10/2005, De 9 de noviembre, de ordenación del alumbrado para la protección del medio ambiente nocturno.                                                                                  |

|                  |                              |      |                                                                                                                                                                                                                                              |
|------------------|------------------------------|------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>España</b>    | Comunidad Foral de Navarra   | 2005 | Decreto FORAL 199/2007, de 17 de septiembre, por el que se aprueba el Reglamento de desarrollo de la Ley Foral 10/2005, de 9 de noviembre, de ordenación del alumbrado para la protección del medio nocturno.                                |
| <b>Italia</b>    | Región de Véneto             | 2009 | Ley Regional 7 de agosto de 2009, n. 17, "Nuevas normas para la contención de la contaminación luminosa, el ahorro de energía en la iluminación exterior, la protección del medio ambiente y las actividades de observadores astronómicos".  |
| <b>Italia</b>    | Región de Puglia             | 2005 | Ley regional N° 15, 23 de noviembre de 2005, "Medidas urgentes para la contención de la contaminación lumínica y el ahorro energético"                                                                                                       |
| <b>Italia</b>    | Emilia Romagna               | 2003 | Ley regional núm. 19 de 29 de septiembre de 2003, reglas de restauración para ahorros de luz y energía.                                                                                                                                      |
| <b>Italia</b>    | Lombardia                    | 2000 | Ley Regional 27 de marzo de 2000 - N ° 17, Medidas urgentes en el ámbito del ahorro energético para el uso de la iluminación exterior para luchar contra la contaminación lumínica.                                                          |
| <b>Italia</b>    | Región Friuli-Venezia Giulia | 2007 | Ley regional 18/06/2007, No. 015 Medidas urgentes para contener la contaminación lumínica, para ahorrar energía en la iluminación exterior y para la protección del medio ambiente y de la attività svolta de los observadores astronómicos. |
| <b>Eslovenia</b> | Eslovenia                    | 2007 | Ley Eslovena de Contaminación por Luz                                                                                                                                                                                                        |

#### 4.1.2. Análisis comparativo de las leyes de España por comunidad autónoma.

A continuación, la tabla 4.1.2.1. presenta los aspectos mayormente regulados por las comunidades autónomas de España.

Tabla 4.1.2.1. Aspectos regulados por las comunidades autónomas de España.

| Aspectos claves regulados               | Criterios                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
|-----------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Ámbito territorial de aplicación</b> | ➤ Regional                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |
| <b>Fuentes reguladas</b>                | ➤ Fuentes de emisión correspondientes a: <ul style="list-style-type: none"> <li>• Alumbrado de exterior</li> <li>• Alumbrado de interior</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |
| <b>Prohibiciones</b>                    | ✓ Se prohíbe: <ul style="list-style-type: none"> <li>• La iluminación de grandes extensiones de playa o de costa, excepto por razones de seguridad, en caso de emergencia o en los demás supuestos que se determinen reglamentariamente en atención a los usos del alumbrado.</li> <li>• Los artefactos y dispositivos aéreos de publicidad nocturna.</li> <li>• Las luminarias, integrales o monocromáticas, con un flujo de hemisferio superior instalado que supere el diez por ciento de aquél, salvo que iluminen elementos de un especial interés histórico o artístico, de acuerdo con lo que se determine reglamentariamente.</li> <li>• El alumbrado de las pistas de esquí en zonas E1, excepto para acontecimientos deportivos extraordinarios según lo que se establezca por reglamento, y en el resto de zonas por una duración superior a un valor establecido por reglamento. Por reglamento también pueden fijarse las franjas horarias en las que está permitido el alumbrado y otras condiciones adicionales para la protección del medio nocturno y de la fauna (Cataluña).</li> <li>• Las fuentes de luz que, mediante proyectores convencionales o láseres, emitan por encima del plano horizontal, salvo que iluminen elementos de un especial interés histórico, de acuerdo con lo que se determine por vía reglamentaria.</li> </ul> |
| <b>Intensidad luminosa</b>              | 2.500 a 25.000 [cd]                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |
| <b>Radiancia espectral</b>              | No contiene esta información                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
| <b>Reflexión</b>                        | No contiene esta información                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |
| <b>Iluminancia</b>                      | Alumbrado comercial y publicitario: <ul style="list-style-type: none"> <li>✓ 50 a 1000 [cd/m<sup>2</sup>]</li> </ul> Alumbrado ornamental: <ul style="list-style-type: none"> <li>✓ 10 a 150 [cd/m<sup>2</sup>]</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |
| <b>Salud humana</b>                     | Si, a partir de la que son fuentes regulas.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |
| <b>Medio ambiente</b>                   | Si, por medio de la zonificación.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |

|                                    |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |
|------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Zonificación del territorio</b> | <p>-En todos los casos se ordena la división del territorio en cuatro zonas, clasificadas de E1 a E4, en función de la vulnerabilidad a la contaminación lumínica y se prevé el establecimiento de las mismas vía reglamentaria.</p> <p>-En la descripción de zonas E1 no hay diferencias destacables.</p> <p>-Respecto a las zonas E2, E3 y E4, las leyes de Cataluña, Islas Baleares y Cantabria, sólo indican el brillo que cada área puede admitir, siendo este clasificado como reducido, medio y alto respectivamente.</p> <p>-En el caso de Navarra, la definición especifica la clasificación y usos del suelo de cada zona.</p> <p>-Además de las cuatro zonas descritas, todas las leyes definen los denominados puntos de referencia, como espacios que por sus características requieren una especial protección.</p> |
| <b>Consideraciones especiales</b>  | No se contemplan.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |

#### 4.1.3. Análisis comparativo de las leyes de Italia por región.

En la tabla 4.1.3.1. se presentan los aspectos mayormente regulados en las normativas de Italia.

Tabla 4.1.3.1. Aspectos regulados por las regiones de Italia.

| Aspectos claves regulados               | Criterios                                                                                                                                                |
|-----------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Ámbito territorial de aplicación</b> | Regional                                                                                                                                                 |
| <b>Fuentes reguladas</b>                | <p>Fuentes de emisión correspondientes a:</p> <ul style="list-style-type: none"> <li>• Alumbrado de exterior</li> <li>• Alumbrado de interior</li> </ul> |
| <b>Prohibiciones</b>                    | Está prohibido usar permanentemente haces de luz giratoria o fija para el propósito la publicidad.                                                       |
| <b>Intensidad luminosa</b>              | 0 a 0,40 [cd] por 1000 [lm] a 90°                                                                                                                        |
| <b>Radiancia espectral</b>              | No contiene esta información                                                                                                                             |
| <b>Reflexión</b>                        | No contiene esta información                                                                                                                             |
| <b>Iluminancia</b>                      | No contiene esta información                                                                                                                             |
| <b>Salud humana</b>                     | Si, a partir de la que son fuentes regulas.                                                                                                              |
| <b>Medio ambiente</b>                   | Si, por medio de disposiciones relacionadas con áreas protegidas                                                                                         |



|                                           |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |
|-------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <p><b>Zonificación del territorio</b></p> | <ul style="list-style-type: none"> <li>• Se realiza en función de áreas protegidas</li> <li>• Todas las fuentes de luz altamente contaminantes, como globos, linternas o similares, deben ser revisado o equipado con dispositivos adecuados capaces de contener y dirigir el flujo hacia el suelo, sin embargo, no más de 15 cd por 1000 lúmenes a 90 ° o más, así como gafas protectoras transparentes.</li> <li>• Se concede una excepción de acuerdo con indicaciones específicas acordadas entre los municipios interesados y los observadores astrónomos responsables de las fuentes de luz internalizadas y, por lo tanto, en concreto, no contaminantes, para aquellos con una emisión que no exceda los 1500 lúmenes cada uno (hasta un máximo de tres centros con punto de luz único), para aquellos de uso temporal o que normalmente están desconectados por la vigésima hora en el período solar dentro de las veintidós horas durante el período de tiempo de verano, para aquellos programados para ser reemplazados dentro de cuatro años desde la fecha de entrada en vigencia de esta ley. Los letreros luminosos no tienen iluminación propia debe estar iluminado de arriba a abajo. En cualquier caso, todos los tipos de insignias luminosas no específicas y el uso nocturno indispensable debe ser apagado dentro de las veintitrés horas durante el horario de verano y en horas veintidós en el período de tiempo solar.</li> <li>• Faros, torres de faros y focos iluminadores estacionamientos, plazas, yardas, ferrocarriles y cruces de caminos, complejos industriales, instalaciones deportivas y áreas de todo tipo deben tener, con respecto al suelo, una inclinación tal, en relación con las características del sistema, no enviar más de 0 cd por 1000 lúmenes a 90 ° y más.</li> </ul> |
| <p><b>Consideraciones especiales</b></p>  | <p>➤ Si, en base a zonas especiales de protección.</p> <ul style="list-style-type: none"> <li>• Las zonas especiales de protección y protección tendrán un radio mínimo de extensión, sin perjuicio de lo dispuesto en la presente Directiva. Los límites regionales, serán igual a:             <ul style="list-style-type: none"> <li>▪ 30 kilómetros para Observatorios Profesionales;</li> <li>▪ 15 kilómetros para observadores no profesionales de importancia regional y provincial;</li> <li>▪ Extender los límites de las áreas naturales protegidas.</li> </ul> </li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |

#### 4.1.4. Análisis de la ley de Eslovenia

La siguiente tabla muestra los aspectos claves regulados por Eslovenia.

Tabla 4.1.4.1. Aspectos regulados en Eslovenia.

| Aspectos claves regulados               | Criterios                                                                                                                                                                                           |
|-----------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Ámbito territorial de aplicación</b> | Nacional                                                                                                                                                                                            |
| <b>Fuentes reguladas</b>                | Fuentes de emisión correspondientes a: <ul style="list-style-type: none"> <li>• Alumbrado de exterior</li> </ul>                                                                                    |
| <b>Prohibiciones</b>                    | <ul style="list-style-type: none"> <li>• Se prohíben proyectores de cielo.</li> <li>• Iluminar edificios en las paredes donde se encuentran las ventanas de las viviendas residenciales.</li> </ul> |
| <b>Intensidad luminosa</b>              | 0,40 a 15 [cd]                                                                                                                                                                                      |
| <b>Radiancia espectral</b>              | No contiene esta información                                                                                                                                                                        |
| <b>Reflexión</b>                        | No contiene esta información                                                                                                                                                                        |
| <b>Iluminancia</b>                      | No contiene esta información                                                                                                                                                                        |
| <b>Salud humana</b>                     | Si, a partir de la que son fuentes regulas.                                                                                                                                                         |
| <b>Medio ambiente</b>                   | Si, por medio de la protección de especies en peligro de extinción.                                                                                                                                 |
| <b>Zonificación del territorio</b>      | No se contemplan.                                                                                                                                                                                   |
| <b>Consideraciones especiales</b>       | Si, en base a especies en peligro de extinción.                                                                                                                                                     |

#### 4.2. Efectos ecológicos

La Tabla 4.2.1 muestra un resumen de alguno de los diversos efectos ecológicos provocados por la contaminación lumínica.

Tabla 4.2.1. Descripción de los efectos de la contaminación lumínica en el ámbito ecológico.

| Caso de estudio                                    | Descripción                                                                                                                                                                                         | Efecto                                                                                                                                                                                                                                                                                                                                                    | Referencia                |
|----------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------|
| <b><i>Tigriopus californicus</i></b>               | Por medio de esta especie, se estudió como la contaminación lumínica, considerado como un factor antropogénico estresante, puede afectar el medio marino intermarial.                               | La exposición de la especie a dicho factor antropogénico estresante, provoco alteraciones en la fisiología y el comportamiento circadiano de organismo de medio marino intermarial.                                                                                                                                                                       | Nesbit y Christie, (2014) |
| <b>Artrópodos nocturnos</b>                        | Se compararon los números de artrópodos capturados por tres tipos de lámparas: dos lámparas comerciales LED (2700 K), dos lámparas comerciales fluorescentes compactas (CFLs; 2.700K) y un control. | Los resultados sugieren que las fuentes de iluminación de interior con luz de espectro completo, pueden ser diseñados para reducir la atracción de insectos, puesto que toda la luz atrae a los artrópodos, siendo los LED los que generalmente atraen a estas especies al igual que una lámpara fluorescente compacta con la misma temperatura de color. | Longcore et.al, (2015)    |
| <b><i>Amphistegina lobifera</i> (Foraminífera)</b> | Se investiga esta especie, para ver cómo responden a los cambios en los niveles de luz en condiciones de laboratorio controlada.                                                                    | La luz elevada causó en la especie de estudio, una reducción significativa en la supervivencia, blanqueo inducido y el estrés foto-oxidativa, y además causó engrosamiento de capas externas de la especie.                                                                                                                                               | Prazeres et al, (2016)    |
| <b>Aves costeras</b>                               | Se estudió dos tipos de luces en una plataforma de petróleo, una luz comercial fluorescente y una luz especial verde, para determinar cómo se comportan las aves costeras antes estos tipos de luz. | Se pudo encontrar que las luces verdes en la plataforma fueron menos atractivas para las aves y no afectó su orientación, sin embargo, las luces fluorescentes atrajeron un número mayor de aves hacia la plataforma, perjudicando su orientación y en algunos casos condujo a la mortalidad de aves producto del choque dicha plataforma.                | Van de Laar, (2007)       |
| <b>Larvas de anfibios</b>                          | Se estudia dos renacuajos de la misma edad, se someten a distintos niveles de luz, uno se somete a un equivalente de una noche muy oscura y el otro a mayor exposición de luz.                      | El estudio reflejó que, al someter a la especie a una mayor exposición de luz, disminuyó la producción de melatonina, conllevando a la interrupción de la metamorfosis del renacuajo, en cambio la especie sometida a oscuridad no presentó alteraciones en su metamorfosis.                                                                              | Wise y Buchanan, (2006)   |

### 4.3. Complementación de la norma chilena.

La tabla 4.1.3.1. muestra los aspectos regulados en Chile y en el extranjero en función de aquellos aspectos que no se contemplan en la normativa chilena para así poder complementarla.

Tabla 4.3.1. Aspectos regulados a nivel nacional e internacional en relación a criterios que se debieran considerar en Chile.

| Aspectos regulados                      | Contenido en la norma chilena | Complementación                                                                                                                                                                                     |
|-----------------------------------------|-------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Ámbito de aplicación territorial</b> | Si                            | En Chile la norma es aplicada solo en tres regiones, por lo que debería ampliarse a todo el país debido a que ayudaría a prevenir y/o disminuir la contaminación lumínica en sectores no regulados. |
| <b>Fuentes emisoras</b>                 | Si                            | A pesar de que en Chile se regulan las fuentes emisoras de exterior, se debería considerar regular también las fuentes emisoras de interior como se realiza a nivel internacional.                  |
| <b>Prohibiciones</b>                    | No                            | Solo se contemplan cumplimientos.                                                                                                                                                                   |
| <b>Intensidad luminosa</b>              | Si                            | No se consideran cambios                                                                                                                                                                            |
| <b>Radiancia espectral</b>              | Si                            | No se consideran cambios                                                                                                                                                                            |
| <b>Reflexión</b>                        | Si                            | No se consideran cambios                                                                                                                                                                            |
| <b>Iluminancia</b>                      | Si                            | No se consideran cambios                                                                                                                                                                            |
| <b>Salud humana</b>                     | Si                            | Se debería evaluar este aspecto para ser aún más contemplado, para esto se recomienda hacer investigaciones.                                                                                        |
| <b>Medio ambiente</b>                   | No                            | Basado en los antecedentes científicos recopilados, este aspecto se debería ser considerado por los efectos que provoca la contaminación lumínica en las especies                                   |
| <b>Zonificación del territorio</b>      | No                            | Se debería considerar la realización de la zonificación del territorio en base a la vulnerabilidad frente a la contaminación lumínica.                                                              |
| <b>Consideraciones especiales</b>       | No                            | -                                                                                                                                                                                                   |

## 5. Discusión

En base a los resultados obtenidos de la normativa internacional y estudios científicos se encontraron aspectos claves que la norma chilena debería considerar para generar mejoras en dicha normativa. Considerando lo anterior en relación a lo mencionado en la tabla 4.1.3. se pueden considerar como aspectos claves para modificar:

- ✓ *Ambito de aplicación.* Puesto que la norma chilena establece un alcance territorial de aplicación solo para las regiones de Antofagasta, Atacama y Coquimbo, ya que en dichas regiones se encuentra los cielos más limpios de Chile y abarcan un patrimonio astronómico y turístico favorable para estas regiones, gran parte del territorio chileno no regulado ante este contaminante, siendo que el acceso a la electricidad en Chile es del 100%. Considerar ampliar el ámbito de aplicación para todo el territorio chileno, trae consigo la prevención y/o disminución de la contaminación lumínica y sus efectos en sectores que aún no son regulados.
- ✓ *Fuentes de emisión reguladas.* Otro aspecto a considerar, es que dicha norma aplique tanto para alumbrado de exterior como de interior debido a que este último no es considerado dentro de la norma chilena, aspecto que en el extranjero es contemplado debido a los efectos que genera este tipo de alumbrado en la salud de las personas.
- ✓ *Salud humana.* Si bien dentro de la norma este aspecto se considera, cabe señalar que es necesario conocer la experiencia internacional y nacional sobre los efectos que tiene la luz en los seres humanos producto del avance de las nuevas tecnologías de iluminación.
- ✓ *Medio ambiente.* En relación a los estudios analizados sobre los efectos que tiene la contaminación lumínica en el ámbito ecológico, es menester considerar dicho aspecto para prevenir un daño mayor al patrimonio natural que se desea preservar en nuestro país, puesto que la contaminación lumínica dentro de los distintos ecosistemas, puede tener un impacto mensurable sobre la calidad de vida y hábitat tanto en especies y seres humanos. Minimizar los impactos ecológicos en el medio, requiere que esta normativa adopte un proceder para utilizar sólo luz necesaria para las necesidades humanas y ser cautelosos al introducir la luz en o cerca de un paisaje natural. Aunque no hay un compendio de información para cada especie y cada ambiente, se debe

proporcionar evidencia adecuada para la gestión razonable de iluminación en áreas naturales.

- ✓ *Zonificación del territorio.* Si se considera ampliar el ámbito territorial de aplicación de la normativa a nivel nacional, la zonificación es un aspecto que se debe considerar antes de establecer nuevos límites de emisión, puesto que ésta debiera hacerse en base a la vulnerabilidad territorial respecto de la contaminación lumínica, lo que permitiría identificar aquellas zonas que se pudiesen encontrar como zona latente o saturada, lo que implicaría que dichos límites serían aun más estrictos según sea el caso. Como consecuencia, también esto conllevaría a beneficios ecosistémicos, dado que los estudios analizados en este trabajo, evidenciaron que la contaminación lumínica tiene efectos tanto en especies y el ecosistema, mostrándose una asociación existente entre la contaminación lumínica y perturbaciones ecológicas, por lo tanto la normativa chilena debiese incluir en este punto para poder apuntar hacia el desarrollo sustentable del país.

En relación a los límites de emisión no se consideran realizar cambios puesto que en comparación con la normativa internacional, la intensidad luminosa no varía con respecto a lo encontrado en el extranjero. Sin embargo se debería considerar realizar nuevos estudios que evalúen los límites de estos aspectos.

## **6. Conclusión**

En base a la investigación realizada se puede concluir que :

- A nivel internacional, los países analizados evidenciaron que a pesar de ser los que han abordado con mayor profundidad el tema de la contaminación lumínica, demuestran que aún queda mucho por hacer y legislar en materia de contaminación lumínica.
- Los estudios analizados evidencian que la contaminación lumínica tiene efectos tanto en especies y el ecosistema, mostrándose una asociación existente entre la contaminación lumínica y perturbaciones ecológicas.
- En lo que respecta a la norma chilena, la escasa legislación referida a contaminación lumínica sólo se limita a regiones que asientan algún centro de observación



astronómica, pero no pone énfasis en los severos daños que se generan sobre la salud de los seres humanos y en especial sobre el ecosistema.

- Es pertinente considerar ampliar el alcance de aplicación de la norma, incluir las fuentes emisoras de interior, realizar investigaciones sobre los efectos de la luz en la salud de las personas, incluir los aspectos ecologicos y contemplar una zonificación, dado los hallazgos encontrados en los estudios antes mencionados, debido los beneficios antropocéntricos que este aspecto puede traer consigo para las generaciones futuras y para prevenir un daño mayor al patrimonio natural que se desea preservar.

## 7. Recomendaciones

-  Puesto que en el reglamento de dictación de una norma de emisión, dice que solo se puede pueden establecer límites máximos de emisión, se recomienda generar una zonificación en base a la vulnerabilidad territorial para estipular límites en relación a cada zona.
-  También, se recomienda realizar nuevas investigaciones sobre los efectos que tiene la luz sobre la salud de las personas y analizar la perspectiva de estas ante la contaminación lumínica.

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# An Investigation of LED Street Lighting's Impact on Sky Glow

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**Prepared for:**

Solid-State Lighting Program  
Building Technologies Office  
Office of Energy Efficiency and  
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**Prepared by:**

Pacific Northwest National  
Laboratory

# An Investigation of LED Street Lighting's Impact on Sky Glow

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- Jim Brodrick, Lighting Program Manager for the U.S. Department of Energy in the Building Technologies Office, supported this project and provided unending patience.

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<sup>1</sup> PIC is part of the Lab's computing strategy to nurture a culture of computational science by offering cost-effective services and hardware capabilities. For more information about the PIC program, please see the PIC Resources page: <http://pic.pnnl.gov/resources.stm>.

## Executive Summary

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Like all broad-spectrum (i.e., white) light sources, light-emitting diodes (LEDs) produce a portion of their output in shorter wavelengths, which may include varying components of violet, blue, cyan, and other colors. Because shorter wavelengths scatter more readily in the Earth's atmosphere than longer wavelengths, like yellow and red, and because of certain biological sensitivities to shorter wavelengths, a variety of concerns have been raised regarding the potential impact from converting exterior lighting sources with low, short wavelength content, primarily high-pressure sodium (HPS), to broad-spectrum LED. Street lighting is often a focus of these concerns, including potential reduction of night-sky visibility from greater levels of scattered light, commonly referred to as *sky glow*, and potential health issues from exposure to those higher levels of light. This document focuses on potential changes to sky glow that can be expected from LED street lighting conversions, and does not address health concerns.

Multiple factors contribute to the ultimate levels of sky glow in any location. A major consideration is that street lighting, the focus of this document, is only one of many sources of light at night in urban areas. Other sources include building interior lights escaping from exterior windows, architectural and landscape lighting, signage, parking lots and garages, recreational lighting, and vehicular lighting. *The findings in this document consequently represent only the contributions to sky glow from the street lighting system* and may not even address the primary sources of sky glow in locations such as a large urban area. The results and related undertakings planned in any real location should be considered in that context.

While increasing the short wavelength content of exterior lighting sources increases the potential for sky glow, other characteristics of LED street lighting luminaires can reduce or completely offset these effects. The three main characteristics of luminaires that influence sky glow are spectral power distribution (SPD), total lumen output, and luminaire light distribution (and, most importantly, the amount of that distribution emitted as uplight). Each of these characteristics can be specified through the selection of luminaires and should therefore be carefully evaluated as part of the system design.

External factors also influence how much sky glow a given observer sees, such as the observer's location relative to the source of the light (especially their distance from it), the size of the source (i.e., city area), the atmospheric conditions at the time of observation, the heights of poles, surrounding geographical features, and the reflectance of the ground surface. This project has estimated the influence of the first three factors using a model well known throughout the astronomical community, *SkyGlow Simulator*, developed by Miroslav Kocifaj.<sup>2</sup> The influence of each factor was calculated independently during an extended set of computer runs (approximately 200,000). Generalized assumptions were necessary even with this large number of runs to prevent the computation effort from growing even larger, as were significant simplifications to such complex topics as atmospheric aerosol concentration, composition, and physical characterization (i.e., particle size, shape, and distribution).

As in any modeling effort, the results are only as valid as their underlying assumptions, so care was taken to select values for variables that are reasonable and representative of typical conditions and scenarios. The latter

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<sup>2</sup> Miroslav Kocifaj is a senior researcher at the ICA Institute of the Slovak Academy of Sciences.

is key to interpreting the results contained in this report. While any number of hypothetical constructs could be explored, such as updated versions of incumbent technologies (for example, HPS with improved optical control) or “engineered” SPDs designed to optimize specific properties of a light source, the primary focus of this investigation is to examine *representative* street lighting situations that exist across the U.S. today, both the incumbent systems and the LED systems replacing them. The results are thereby intended to represent what is happening in the U.S. rather than what could happen if the study were free to invent alternative characteristics of future street lighting systems.

In a few cases, values were selected because they are commonly used in other atmospheric modeling efforts (such as a uniform ground reflectivity of 15%). In terms of luminaire characteristics, four levels of uplight (0%, 2%, 5%, and 10%) were compared, along with two percentages of lumen output (100% and 50%). The latter were chosen to show the relative influence of lumen output instead of absolute lumen values, given the wide variation of product outputs within even a single installation and the intent of this study to be more generic in its findings. Finally, 10 different SPDs from actual products of different light source types and correlated color temperatures (CCTs) were modeled, along with a hypothetical source whose radiant energy output is equal across the visible spectrum. The equal energy spectrum was included specifically to investigate the influence of individual wavelength bands on sky glow, in 5 nm increments from 380 to 780 nm, to identify which wavelengths contribute more to sky glow under different conditions.

The model calculates sky glow impacts from street lighting in terms of diffuse irradiance ( $\text{W/m}^2$ ) or illuminance (scotopic- $\text{cd/m}^2/\text{sr}$  or scotopic-lux) on the horizontal plane, incident upon an observer for the entire night sky dome. To facilitate comparisons, these results are then reported relative to the baseline conditions as multiples or fractions thereof. Results are reported both as *unweighted* sky glow, which reflect the raw radiant power of the sky glow incident upon the observation point, and scotopically *weighted* sky glow to better account for its visual impact on human observation of the night sky.

Ultimately, sky glow is not determined by any single factor but by the combination of factors present in any given situation. Figures ES.1 and ES.2 show a progression of effects from successively combining the different factors modeled, dividing the results into sky glow impacts for the “near” observer located at the edge of the city (Figure ES.1) and for the “distant” observer located 40 km from the city center (Figure ES.2). Each graphic is further subdivided by unweighted or scotopically weighted results, by atmospheric condition (ATM1-4 representing a range from clear to increasingly turbid atmospheres, ATM5 representing complete cloud cover), and finally by the SPD of the source. The charts also show the sky glow results for an HPS incumbent (displayed as the red dashed line set at 1.0), but do not show results from two additional incumbent sources that were modeled and are contained in the main body of this report, a 4000 K metal halide source and a low-pressure sodium source, nor do they include the hypothetical equal energy spectrum.

The results are displayed in three progressive tiers: the top chart shows the isolated effect of replacing the baseline HPS SPD with the various other LED SPDs modeled with no other modifications; the middle chart adds the effect of reducing luminaire lumen output by half compared to the baseline HPS (a typical result for conversions in the U.S.); and the bottom chart further adds the impact of eliminating uplight from the luminaires, assuming a typical HPS baseline value of 2%. **The bottom charts in both figures thereby represent typical conversion scenarios in the U.S.—an incumbent HPS cobra head product with 2% uplight replaced by each of the LED products listed, at half the light output and 0% uplight.** Note that the values represent static conditions, and so do not include any additional reductions possible through the use of adaptive lighting (e.g., dimming). Such impacts could be significant because contributions to sky glow scale directly with light output.

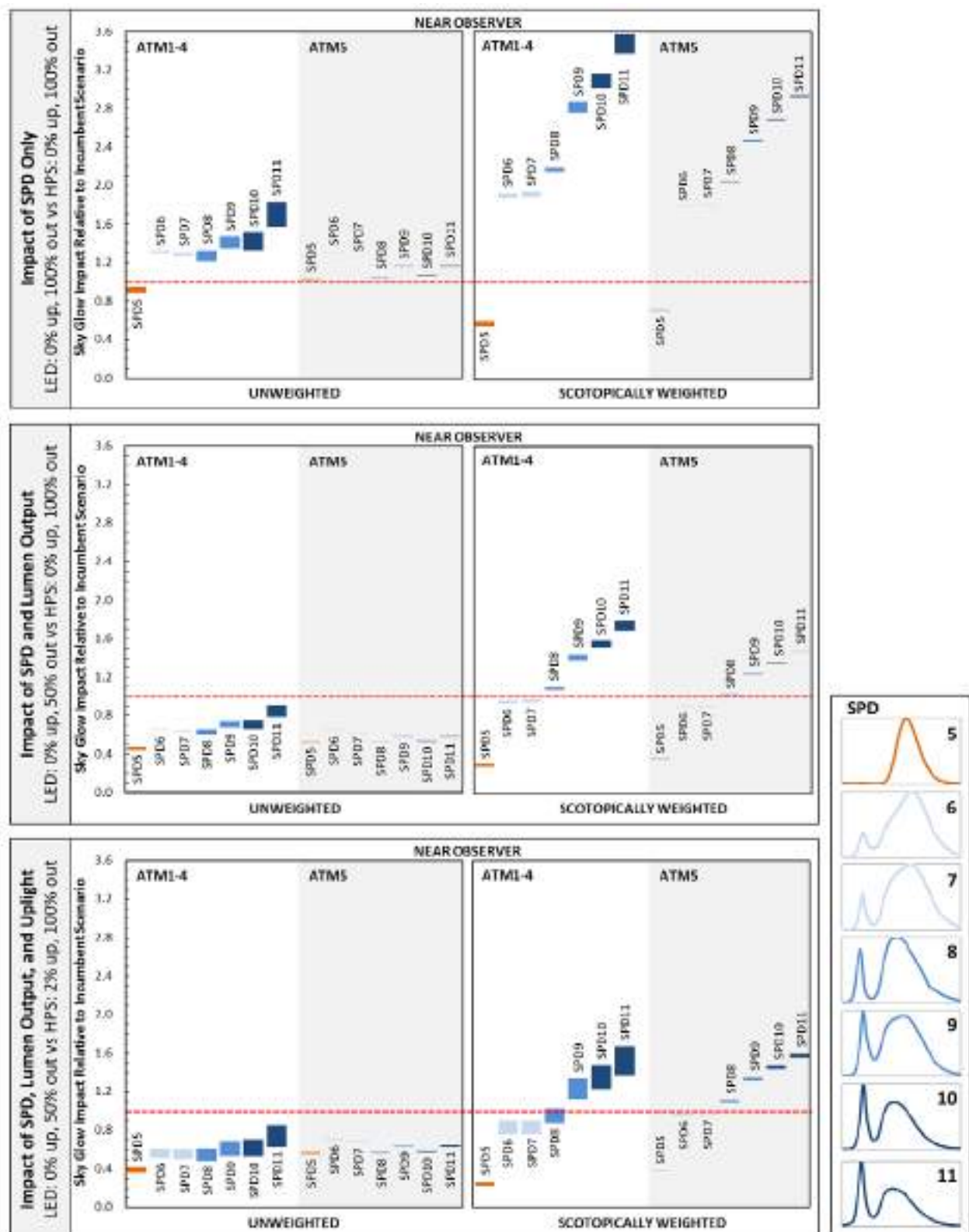


Figure ES.1 Results of the LED street lighting conversions, from the near observer position at the edge of the city. Each plot shows the relative skyglow irradiance contribution from street lights compared to the HPS baseline. The top chart shows the isolated effect of replacing the baseline HPS SPD with that of the various other SPDs modeled; the middle chart adds the effect of reducing luminaire output by half compared to the baseline HPS; the bottom chart further adds the impact of eliminating uplight from the luminaires, assuming a typical HPS baseline value of 2% (note this represents an increase from the first two charts using 0%). The baseline is represented by the dashed red line at the normalized value of 1.0.

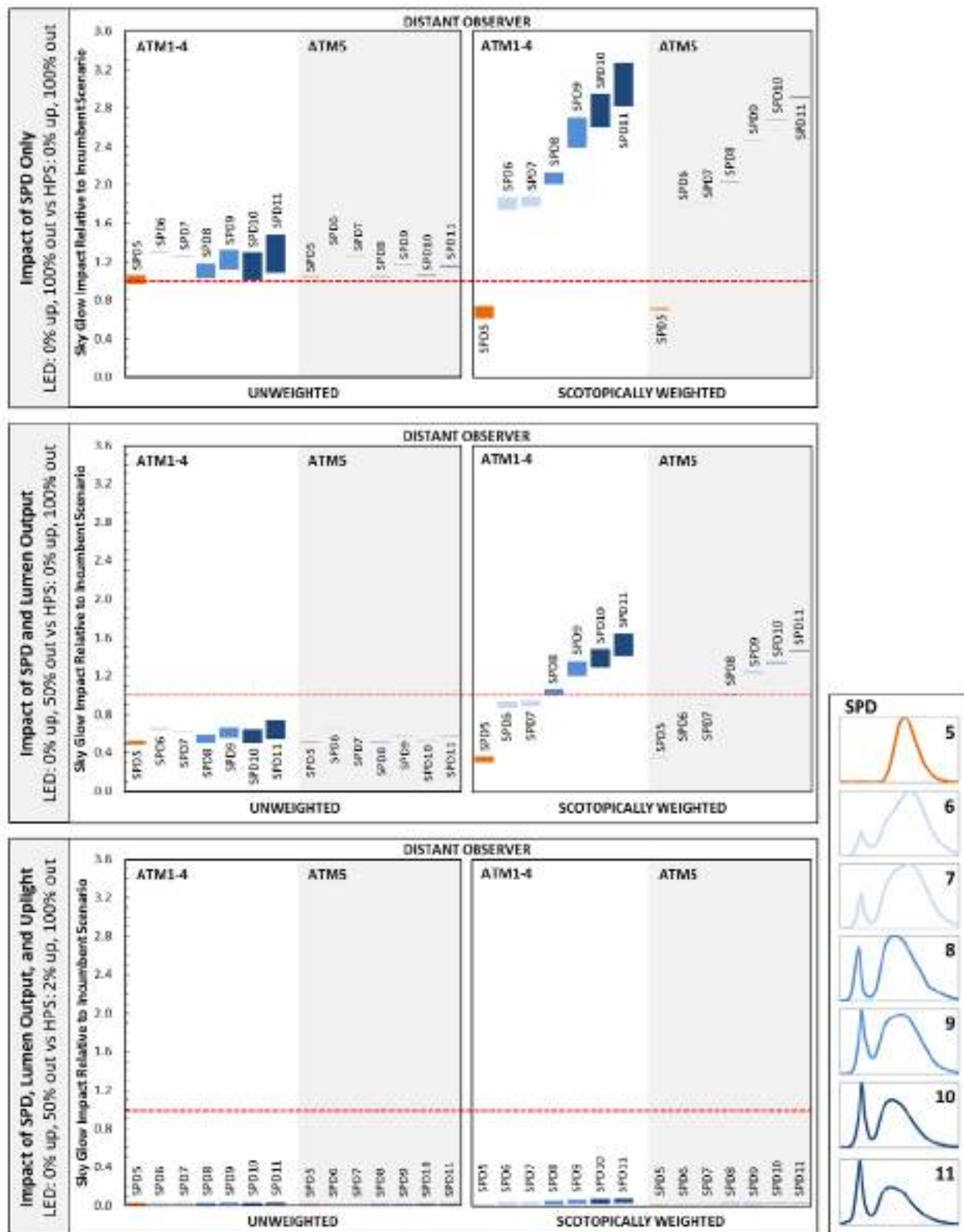


Figure ES.2 Results of the LED street lighting conversions, from the distant observer position 40 km from city center. Each plot shows the relative skyglow irradiance contribution from street lights compared to the HPS baseline. The top chart shows the isolated effect of replacing the baseline HPS SPD with that of the various other SPDs modeled; the middle chart adds the effect of reducing luminaire output by half compared to the baseline HPS; the bottom chart further adds the impact of eliminating uplight from the luminaires, assuming a typical HPS baseline value of 2% (note this represents an increase from the first two charts using 0%). The baseline is represented by the dashed red line at the normalized value of 1.0.

A key finding is that, in a typical U.S. conversion, all of the LED products reduce sky glow when the results are unweighted, for both the near and distant observers. Each bar in the graphs depicts the range of possible sky glow impact, from minimum to maximum, given the fixed conditions noted (atmospheric condition [ATMX], source SPD, and weighting), while allowing all other variables to float within their defined ranges. When the results are instead scotopically weighted to evaluate the effects on human vision (i.e., visibility of the night sky), some LED products reduce sky glow for the near observer and others increase it, compared to the baseline. Another important finding evident in the modeling results is that CCT is not a very reliable indicator of sky glow impacts, especially when scotopic weighting is not applied (evident in the irregular and overlapping performance of the SPDs when ordered by increasing CCT). The overall range of results for LED luminaires across most conditions for the near observer is from about 0.4 to 0.8 times the unweighted baseline HPS sky glow, and 0.2 to 1.6 times the scotopically weighted baseline HPS sky glow. For the distant observer, even at only 40 km (about 25 miles) from the city center, the elimination of uplight from the luminaires has nearly removed (by 95% or more) the contribution to sky glow from the street lighting system, for both the unweighted and scotopically weighted results, under all atmospheric conditions. It should also be noted here, however, that this modeling effort did not consider effects of obstruction by buildings or terrain; in locations where such obstructions already block low-angle uplight, elimination of uplight from the luminaires will not have as dramatic an effect.

Except for installations made in the early years of LED street lighting conversions (roughly prior to 2010), most to date have involved 4000 K CCT products. (Beginning in 2016, some sites also started considering or installing 3000 K products in their conversion projects.) Although this cannot be confirmed without analyzing the specific SPDs for the new LED systems, this study suggests that, for residents near the city, the visible contribution to sky glow from a typical street light conversion (i.e., half the output; 0% uplight) should be no worse than before, and has possibly improved. Unweighted results are more relevant to astronomical instrument observation, so when the modeled conditions are achieved, sky glow from the street lights should be considerably reduced (by roughly one-third to one-half) for any observatories near the city.

Distant from the city, the sky glow contribution from the typical LED street lighting conversion appears to be negligible, at all SPDs, for human observers (e.g., scotopically weighted results) as well as astronomical equipment (e.g., unweighted results). Although the reduction is striking even at this relatively short distance of 40 km, street lighting must again be considered in the context of accounting for only one (now former) source of sky glow from an urban area, as the others remain unaffected.

Near the city, the sky glow contributions from the street lighting system can be further reduced by substituting an LED product with less short wavelength content, as often (though not always) found in lower CCT options, or, as noted, by decreasing the light output through dimming or by eliminating unneeded lights. The designer may want to consider the additional value of pursuing such reductions in the context of the overall system design. These include determining just how much light is needed in a given location and how those needs potentially change over the course of the evening—identifying where light is needed, and just as importantly, where it is not, and selecting the color characteristics of the source that are most appropriate to the specific use (and possibly, how they may change over the course of the evening as well).

The artistry in lighting design is in achieving the optimal balance not only among these elements, but also in accommodating safety and economic considerations, aesthetics, user preference, and any additional issues that must be taken into account. The wide flexibility of LED sources provides many choices to the system designer for pursuing the optimal balance for any given set of circumstances.



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## 1 Introduction

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Humanity began illuminating the night with fire-based sources long before the dawn of civilization. This practice continued, albeit with different fuels and increasingly sophisticated technology, through the millennia until the turn of the 20<sup>th</sup> century, when electric lighting sources became commercially viable. Since then, electric lighting has dominated the nighttime illumination of both interior and exterior spaces. This development founded a structural component of civilization that continues to contribute much to our modern lives, but it has also altered many characteristics of the night environment, and brought with it less desirable effects.

One of these effects is *sky glow*, the visible background luminance (brightness) in the atmosphere above towns and cities that obscures the view of stars from the ground.<sup>1</sup> Many lighting sources contribute to sky glow, from both interior and exterior locations, to the degree that each individual installation allows it. Some amount of sky glow is unavoidable if our nighttime environments are to be illuminated; however, the levels over many modern urban areas (that generally also spill over into neighboring non-urban areas) are not an inherent requirement of nighttime illumination, but often rather a result of insufficient attention to proper design and control of the light needed for a specific application. The underlying reasons do not necessarily reflect carelessness, but may instead derive from decisions made to control costs.

The first several decades of electrically illuminating the night primarily saw the use of broad-spectrum, or “white” light sources, in both interior and exterior applications. Beginning around the 1970s, more narrow-spectrum products like high-pressure sodium (HPS) and low-pressure sodium (LPS) appeared on the market and started to claim market share due to their higher efficiency and improved lumen maintenance relative to the earlier mercury vapor and incandescent sources in common use at the time. In the 1990s, metal halide lamps, which exhibited a better color-rendering white light, were used in some prominent pedestrian areas, although its application was limited by the lamp’s shorter life and lower efficacy compared to HPS. The mid-2000s saw the beginnings of a wider interest in more broad-spectrum sources with the advent of solid-state lighting (SSL) or light-emitting diode (LED) technology. LEDs are favored over the incumbent technologies due not only to their significantly reduced energy use and improved lumen maintenance, but also for their improved color rendition properties and high precision of optical control, among other benefits. It is also useful to note that even at the time LEDs became commercial, many street and roadway lighting systems continued to employ mercury vapor lights and even some incandescent sources in older installations. Thus, some sites have been using essentially the same technology for more than 100 years.

Broad-spectrum light sources emit more radiant energy in the shorter wavelengths of the visible spectrum, which may include varying components of violet, blue, cyan, and other colors, compared to narrower-spectrum sources that emit much more of their output in longer wavelengths like red and yellow. Because shorter wavelengths scatter more readily in the Earth’s atmosphere than longer wavelengths, along with certain biological sensitivities to shorter wavelengths, concerns have been raised regarding the potential impact from converting exterior lighting sources with low, short wavelength content (primarily HPS) to broad-spectrum LED.

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<sup>1</sup> This study calculates sky glow impacts in terms of diffuse irradiance ( $\text{W}/\text{m}^2$ ) or illuminance (scotopic- $\text{cd}/\text{m}^2/\text{sr}$  or scotopic-lux) on the horizontal plane resulting from any incremental brightness of the sky from the natural background, collected from all angles and directions. Radiance is directional and so may vary depending on the observer’s direction of view.

Street lighting is a common focus of these concerns, which include a possible increased loss of night-sky visibility from sky glow and potential health issues from exposure to the associated higher levels of light.

While the science behind short wavelength light and its impacts evolves, significant uncertainty remains regarding how the ongoing transition to LED luminaires will contribute to these situations. Many current impacts have been projected in the literature, but take a highly simplified approach, often directly substituting an assumed spectral power distribution (SPD) of an LED source for that of an HPS source, while holding all other factors (e.g., light output and distribution) constant. Such simplification directly conflicts with actual field experience in the U.S., which reveals that such factors usually change significantly during a lighting conversion.

The U.S. Department of Energy Solid-State Lighting Program has therefore undertaken a review of sky glow models over the last 18 months and consulted with several specialists in atmospheric scatter and sky visibility to identify the most critical factors that influence sky glow. Atmospheric models are complex and often require advanced computers to adequately estimate the effects of different factors on sky glow, particularly as the number of factors considered increases. In this study, the factors considered as contributors to the presence of sky glow include some that are inherent to the street lighting system and others external to it, as given below.

#### Street Light Factors:

- Luminaire light output
- Luminaire light distribution, including amount of uplight
- Spectral content of the emitted light

#### External Factors:

- Atmospheric conditions (clear, cloudy, and a range of humidity, turbidity, and particulate content)
- City size and lighting density
- Observer location relative to the city center
- Certain fixed assumptions, such as reflectance values of the ground surface onto which the light is projected

Other factors not considered here due to the associated computational burden, but that would be relevant for an actual location, include the following:

- Shape of the city and distribution of light sources and their associated intensities
- Variations in atmospheric particulate size, shape, and distribution
- Multiple scattering of wavelengths (only single scattering was taken into account in this study)
- Light extinction (absorption or blocking) effects of buildings, trees, and terrain

This study estimates the typical changes to sky glow in the U.S. occurring as a result of converting HPS street lighting to broader spectrum sources, with particular focus on LEDs, and reports the contributions relative to HPS baseline conditions. *It is important to note that the relative comparisons of sky glow impact apply only to the street lighting system's contribution to the sky glow over a city, and not to the impact that all city light sources have on that sky glow.* Section 9.3 discusses this in more detail. Companion issues regarding the energy and lighting quality tradeoffs typically associated with various means of reducing sky glow are also presented. However, associated biological impacts of the short wavelengths are outside the scope of this study.

## 2 A Brief Background on Sky Glow

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A large body of research exists on the sources, severity, and consequences of sky glow.<sup>2</sup> Many of these studies describe modeling methodologies that incorporate estimates of different light reflectances and scattering properties, or procedures for measuring sky glow to estimate impacts to night sky visibility. A brief discussion of concepts and terms commonly used is helpful for understanding the relevant issues.

### 2.1 Astronomical observation

Stellar brightness is described in units of visual magnitude, an inverse logarithmic scale where smaller numbers are assigned to brighter objects. The scale was first developed by ancient Greek astronomers who subjectively divided stars into six categories of visibility, the brightest assigned a magnitude of 1 and the faintest a value of 6. Fast-forward a couple of millennia and much of our current quantification scheme is still based on this rudimentary method, although much more sophisticated techniques of measurement and calculation have been developed in the time since, including expansion of the scale beyond 1-6.

To be visible, stars and other celestial bodies must offer sufficient contrast from their background. This means that as background luminance or sky brightness increases, an increasing range of objects become obscured from view. On a clear, moonless night in an environment free of light pollution, the stars just at the edge of unaided visibility to a completely dark-adapted human eye can fall between magnitudes 6 and 8. With a telescope, this range can extend to magnitude 20 (positive) and beyond. To illustrate the other end of the scale, our sun is at magnitude -26.7 (negative).

Sky brightness is often described in terms of the *limiting magnitude*, the threshold at which objects with lower brightness (i.e., larger positive magnitude) can no longer be distinguished. The number of visible objects at a given brightness is inversely related to that brightness, so that any increase in limiting magnitude compared to a pristine environment free of background light quickly eliminates many lower-brightness celestial objects from view.

### 2.2 Reported units of measurement

Units of measurement produced by the various methods and devices used to estimate and report sky glow require conversion depending on their intended use. Figure 1 shows a nomogram available from the Dark Skies Awareness<sup>3</sup> website that ties several commonly used metrics together and enables a helpful first-order conversion among them.<sup>4</sup>

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<sup>2</sup> For example, see the list of references provided by Christopher Kyba, which date as far back as 1970 (note this list is no longer maintained): [http://userpage.fu-berlin.de/~kyba/literature/sky\\_glow.html](http://userpage.fu-berlin.de/~kyba/literature/sky_glow.html).

<sup>3</sup> Dark Skies Awareness: <http://www.darkskiesawareness.org/>.

<sup>4</sup> This study uses different measures of sky brightness (irradiance in  $\text{W/m}^2$  and scotopic illuminance in  $\text{scotopic-cd/m}^2/\text{sr}$ ) reaching an observer's point of view from the increased sky brightness in all directions, which do not appear in the nomogram.

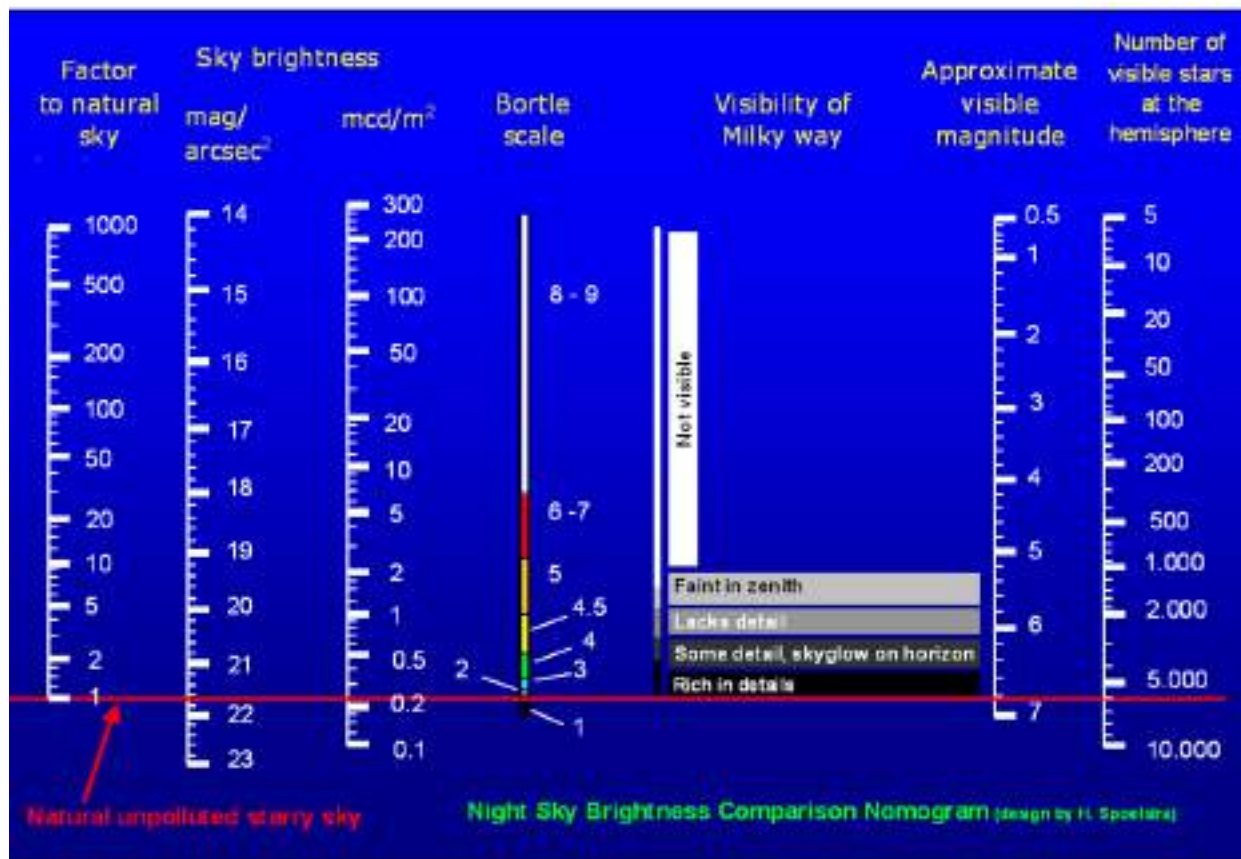


Figure 1 Night sky brightness comparison nomogram. (Source: <http://www.darkskiesawareness.org/nomogram.php>.)

### 2.3 Atmospheric scattering

Sky brightness is increased by both natural (e.g., the Milky Way, the moon, space dust) and anthropogenic light sources, as well as by direct radiation and reflection/scattering from air molecules and airborne aerosols within the atmosphere. Rayleigh scattering occurs when visible light wavelengths encounter particles of a much smaller relative size (e.g., atoms and molecules). Such particles act as single dipoles, given the intensity of scattered radiation is identical in opposite (i.e., forward and backward) directions. The light is scattered diffusely according to a mathematical relationship between the particle size and wavelength, making Rayleigh scattering wavelength-dependent. The nitrogen and oxygen molecules that make up the vast bulk of our atmosphere are of a size that is most relevant to the blue end of the visible spectrum, and thus are responsible for the blue appearance of our sky.<sup>5</sup> This same relationship applies to light produced by electric sources.

In contrast, Mie scattering occurs when the particle size is similar to or larger than the wavelength, as applies to aerosols (e.g., water droplets, dust, smog, salt). As atmospheric aerosol content increases, the amount of scattering also increases but the wavelength dependence of the resulting sky glow decreases. Mie scattering occurs more uniformly across the visible spectrum (giving clouds their characteristic white color) and has a significant forward bias. Backscatter is even more suppressed if particles become irregularly shaped. Mie

<sup>5</sup> Rayleigh scattering for wavelengths at 400 nm is 9.4 times as great as that at 700 nm for equal incident intensity. See: <http://hyperphysics.phy-astr.gsu.edu/hbase/atmos/blusky.html>. Furthermore, our perception of the sky as “blue” is more a result of the sensitivity of the human retina than the sky’s actual wavelength content. Were our eyes sufficiently sensitive to the corresponding wavelengths, the sky would instead appear violet. See: <http://www.spc.noaa.gov/publications/corfid/sunset/>.

scattering's contribution to sky glow is greatest for light projected at angles near the horizon, where small particle forward-scattering directs light back to earth.<sup>6</sup>

Electric light finds its way into the atmosphere via direct emission, scattering, and reflection. Many modern outdoor luminaires now restrict all light emission to below the horizontal plane (through the luminaire design), so that the primary upward component of light from the luminaire results from ground reflection. Reflectance values vary by type of ground cover, but commonly used average values range between 12% and 15%.<sup>7,8</sup> Outdoor luminaires that most commonly cause direct emission to the sky are as follows:

- Traditional drop-lens fixtures designed to distribute light at high angles for extended reach (many, or most of which, are being slowly phased out by state or local ordinances and otherwise updated lighting practices)
- Fixtures pointed into the sky (e.g., some architectural lighting, advertising signage, and angled fixtures like spotlights and sports lighting)
- Decorative fixtures like acorn- or globe-style post-top units, often found in historic districts (see Figure 2)

High-angle downward light (i.e., light emitted within a few degrees below the horizontal plane) that reaches the atmosphere does so primarily through scattering on its extended path toward the ground, but a commonly held position is that this light is typically extinguished by buildings and vegetation before its contribution becomes significant.<sup>9</sup> Some sky glow models therefore ignore the contribution of high-angle downward light entirely, while others similarly discount upward light emitted near the horizontal plane.

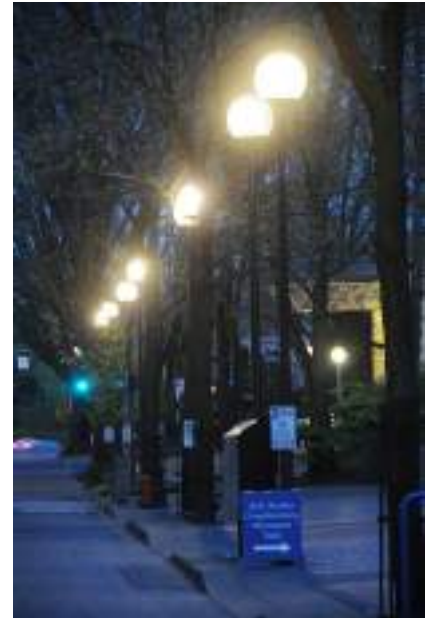


Figure 2 Globe fixtures.

<sup>6</sup> See: <http://hyperphysics.phy-astr.gsu.edu/hbase/atmos/blusky.html> for illustrations of the effects of particle size and incident angles.

<sup>7</sup> R. Stempok. 'Real World Background Luminance for Objects to be Viewed by Night Drivers.' *Electric Power Research Institute (EPRI) RFR 053926*, 2004.

<sup>8</sup> E. Dobos. 'Albedo.' *Encyclopedia of Soil Science*. DOI: 10.1081/E-ESS 120014334, 2003.

<sup>9</sup> C. Luginbuhl et al. 'From the Ground Up II: Sky Glow and Near-Ground Artificial Light Propagation in Flagstaff, Arizona.' *Publications of the Astronomical Society of the Pacific*, vol. 121, 2009, pp. 204-212.



### 3 Luminaire Characteristics Contributing to Sky Glow

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Three main characteristics of the luminaire determine its contribution to sky glow. Each of these elements can be adjusted through their initial specification, and sometimes dynamically throughout their operation, to help control their impact.

#### 3.1 Light distribution

Luminaires are traditionally designed with reflectors and optics to create a particular light distribution that fits the needs of a given application. The resulting distribution typically alters the path of much of the original light output from the source (lamp or LED). Lamp-type sources are often referred to as omni-directional emitters because the lamp yields light output in nearly all directions. Without control of this output using reflectors and lenses, much of the output would be wasted on unintended targets or lost to the night sky, and moreover would likely cause glare for an observer (akin to illuminating a room using a bare bulb).

In contrast, most state-of-the-art LED products emit light out of a single side of the chip to form a directional emission pattern. This light usually still requires some redirection to shape the distribution to the application, but in general the need for redirection is much lower. A distinct advantage of this characteristic is that generally more of the light output goes where it is wanted and less where it is not wanted. Decreasing stray light not only reduces the incidence of light trespass that traditional sources sometimes cause, but also contributes less light to the night sky.

A related improvement of most modern street lighting fixtures (applicable to both LED and conventional sources) is the ability to eliminate virtually all output above the horizontal plane. Older fixtures frequently used drop-lenses to extend the reach of their illumination between mounting poles or into other distant areas, but modern flat lens optics have greatly reduced the need for this approach (Figure 3).



Figure 3 Drop-lens (left) and flat-lens (right) cobra head street light fixtures.

Drop-lens fixtures emit a highly visible portion of their output directly into the sky, as is evident by direct views of the light source from above. In contrast, the light sources in flat-lens fixtures are not usually visible from above (Figure 4).

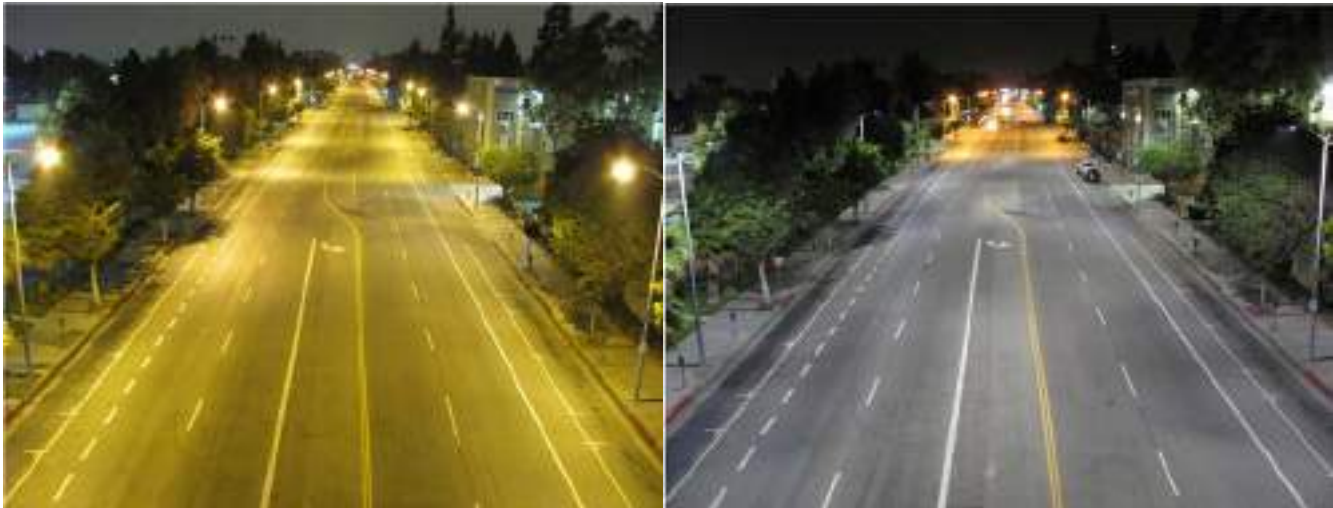


**Figure 4** Absence of uplight from modern luminaires at right compared to older drop-lens fixtures at left. (Photo credit: LABSL)

### 3.2 Luminaire light output

Improvements in uniformity that accompany improved distribution also mean fewer shadows in some areas and lower hot spots from excess illumination in others. Together, these benefits enable LED products to generally meet a given lighting application with far fewer lumens than required by traditional lamp-based products. Light output of LED products is often half, or even less, of the light output of incumbent products they are replacing.

### 3.3 Spectral content

A significant body of literature is evolving on the impacts of light at night with respect to spectral content (as reflected in its SPD). As noted, shorter wavelengths tend to scatter more readily in the atmosphere than longer wavelengths, so the spectral content of a light source directly influences sky glow.

The SPD of a source describes its spectral content in terms of radiant power emitted in each wavelength bin across the spectrum. Although SPDs for a given source technology often share similar characteristics, different products frequently have significant variations in output among wavelength bins and furthermore may incorporate additional chips with different properties to enhance certain colors or other qualities (Figure 5). Most source technologies are therefore inaccurately represented by an assumed set of monolithic properties, especially when products using that technology are available in widely different SPDs, often even at the same CCT. Despite the common use of CCT as an indicator of SPD, the specific spectra contained in the sources are more directly relevant to sky glow than the light's apparent hue.



**Figure 5** PC-amber-cyan-violet flat lens chip array (ledengin.com).

## 4 Selected Sky Glow Model: *SkyGlow Simulator*

### 4.1 Theory

Miroslav Kocifaj developed the model *SkyGlow Simulator* in 2007.<sup>10,11</sup> (An example of the graphical user interface is shown in Figure 6 and the geometrical setup of the model is shown in Figure 7.) The model is scalable and designed for realistically shaped emitters (e.g., cities or defined land surface areas) as an improvement over point-sources. *SkyGlow Simulator* models light emitted by ground sources based on the angular distribution of light (e.g., power per unit solid angle per unit projected source area). The surface area (shape and size) of a city is defined through coordinate vertices (latitude, longitude). To characterize the emitted light, the number of individual light sources is defined, along with their spectral and angular radiative characteristics. The model calculates the total ground emission based on total luminaire input wattage, total light output, or the city population (e.g., lumens per person). Essentially, the model combines ground-based light sources, built of many pixels, with a vertically stratified atmosphere (characterized by specific altitude-dependent volume scattering and absorption coefficients). Each pixel is characterized by the position with respect to the observer, the total radiant flux, and the spectral radiance as a function of zenith angle.

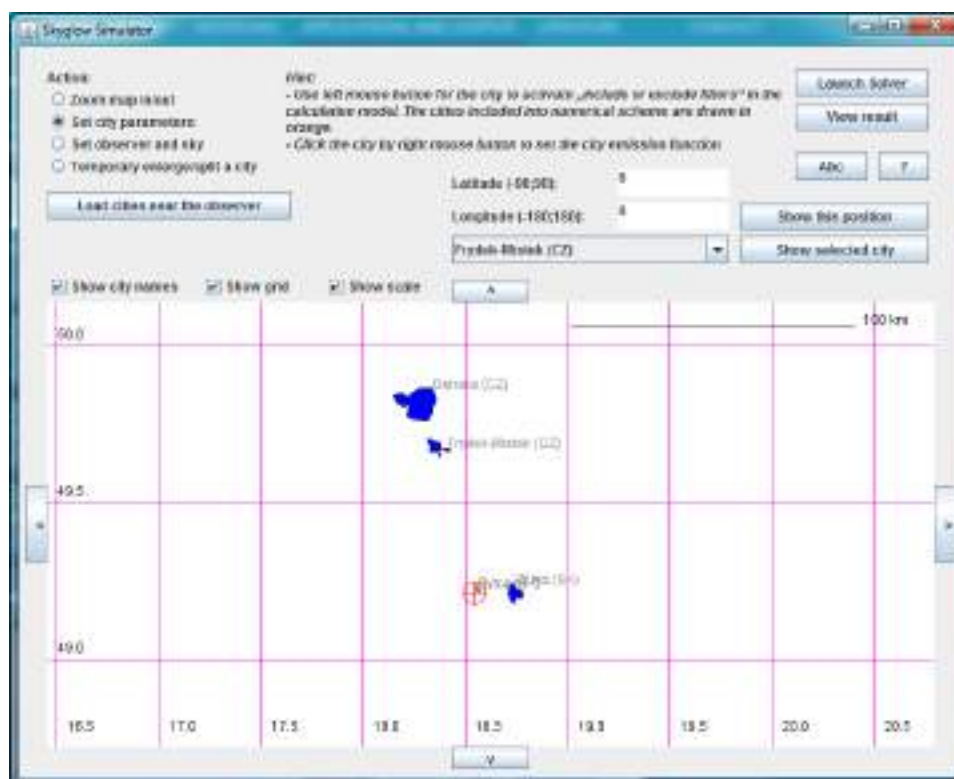


Figure 6 Graphical user interface for the model *SkyGlow Simulator*.

<sup>10</sup> M. Kocifaj. 'Light-pollution model for cloudy and cloudless night skies with ground-based light source.' *Applied Optics*, vol. 46, no. 15, 2007.

<sup>11</sup> *SkyGlow Simulator*: <http://unisky.sav.sk/?lang=en&page=aplikacia&subpage=glow>.



Various atmospheric conditions can be analyzed in the model, including cloudless, overcast, and cloudy skies. The probability that a photon will be scattered into the solid angle of observation is dependent on the optical properties of the atmosphere, characterized by scattering phase functions. Aerosol particles and air molecules are the most important atmospheric constituents responsible for scattering and attenuation of visible radiation. Thus, the overall transmission function reflects the optical properties (absorption, extinction, scattering) of the molecular-aerosol atmosphere. The phase function for molecular scattering is expressed analytically while that for aerosols is obtained numerically; here the molecular scattering is simulated in accordance with Rayleigh theory, and aerosol scattering is approximated by the Henyey–Greenstein function. Aerosols are one of the most unstable atmospheric constituents given that their spatial distribution depends on microphysical properties of aerosols themselves (size/shape distributions, refractive index, and chemical composition). Thus, a set of characteristics is needed (e.g., asymmetry parameter, single scattering albedo, optical thickness of constituents) for the most accurate representation, but most existing models are simplified to an average state of the atmosphere.

The radiative flux due to scattering in a cloud-free atmosphere (or the region underlying the clouds) is calculated separately from the radiant flux directed from a cloud to the observer, based on the spectral reflectance of the cloud.<sup>15</sup> The total intensity (sum of cloudless and cloudy, as applicable) is calculated per zenith (strong correlation) and azimuth (weak dependence) angle, resulting in an angular distribution of the sky glow that is either unweighted (radiance,  $\text{W/m}^2/\text{sr}$ ) or weighted (scotopic luminance,  $\text{scotopic cd/m}^2$ ). The angular distribution is represented by a polar plot (Figure 8).

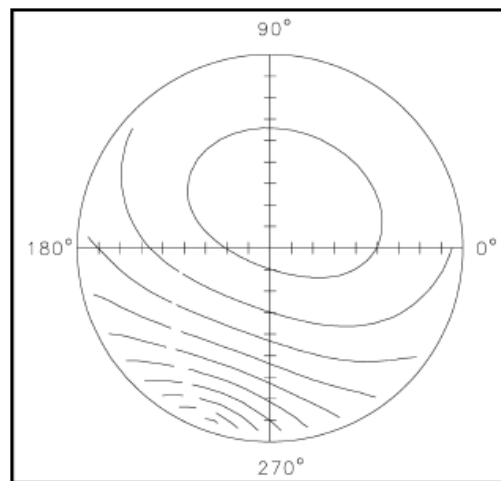


**Figure 8 Sky glow polar plot.** Isolines are drawn in logarithmic scale to overcome changes to luminance over orders of magnitude. The angle along the circle represents the azimuth of the sky element while the zenith angle is measured from the center to the margin.

Additional outputs include diffuse irradiance ( $\text{W/m}^2$ ) or scotopic illuminance ( $\text{scotopic-cd/m}^2/\text{sr}$  or  $\text{scotopic-lux}$ ) on the horizontal surface and the ratio of zenith radiance or luminance to diffuse irradiance or illuminance ( $1/\text{sr}$ ). The diffuse horizontal irradiance/illuminance value is associated with the overall luminous/radiative flux directed to the observer, independent of the direction at which the light beam is propagated. This value thus does not contain information on dominant light beams. The zenith radiance/luminance relative to the horizontal

<sup>15</sup> This theory can only be used for partly cloudy skies as contribution of reflected light depends on shape of cloud; the projected area at a cloud surface changes with the orientation of the normal vector to surface; thus, the numerical implementation must be enhanced to accept geometrical relations.

irradiance/illuminance, however, is inversely proportional to the steradian and can show how much the sky state changes with distance from a city or town, especially at short distances (e.g., up to a few radii from the city center). This study exclusively analyzed the diffuse irradiance and illuminance values on the horizontal surface.<sup>16</sup>

## 4.2 Validation

Three steps of validation for sky glow models include:

- Comparing a complex model with a simpler but more validated one
- Conducting sensitivity studies to test whether the model predicts a well-known behavior of the phenomenon or to obtain an intuitive understanding of its complex non-linear behavior
- Comparing calculated values with actual measurements

*SkyGlow Simulator* (formerly denoted MSNsR<sub>Au</sub>) was compared against ILLUMINA in 2012 and was found to be:

“...well optimized for large-scale simulations. In particular, the grid size is adapted dynamically depending on the distance between a light source and a hypothetical observer. This enables rapid numerical modelling for large territories. MSNsR<sub>Au</sub> is also well suited for the mass modelling of night-sky radiances after ground-based light sources are hypothetically changed. This enables an optimum design of public lighting systems and a time-efficient evaluation of the optical effects related to different lamp spectra or different lamp distributions...Thus a choice of an appropriate model depends mainly on AOD [aerosol optical depth] and CPU requirements.”<sup>17</sup>

The second and third steps were addressed through an investigation of the impact of changing spatial and spectral ground-lamp distributions on the hemispherical spectral sky radiance for different observer distances at two observatories: Vartovka and Stará Lesná in Slovakia.<sup>18</sup> Measurements were taken at Frýdek-Místek in August 2009, which verified and validated the model's performance (Figure 9): “Bear in mind that the focus of the model is not on absolute values in mcd/ m<sup>2</sup>, but on the (normalized) sky luminance...found that theory fits the measured luminance very well since the mean deviation  $\sigma$  is below 2%.”<sup>19</sup>

<sup>16</sup> M. Kocifaj. ‘Retrieval of angular emission function from whole-city light sources using night-sky brightness measurements.’ *Optica*, vol. 4, no. 2, 2017, pp. 255-262: <https://doi.org/10.1364/OPTICA.4.000255>.

<sup>17</sup> M. Aube and M. Kocifaj. ‘Using two light-pollution models to investigate artificial sky radiances at Canary Islands observatories.’ *Monthly Notices of the Royal Astronomical Society*, vol. 422, 2012, pp. 819-830.

<sup>18</sup> M. Kocifaj, M. Aube, and I. Kohut. ‘The effect of spatial and spectral heterogeneity of ground-based light sources on night-sky radiances.’ *Monthly Notices of the Royal Astronomical Society*, vol. 409, 2010, pp. 1203-1212.

<sup>19</sup> M. Kocifaj. ‘Night sky luminance under clear sky conditions: Theory vs. experiment’. *Journal of Quantitative Spectroscopy & Radiative Transfer*, vol. 139, 2014, pp. 43-51.



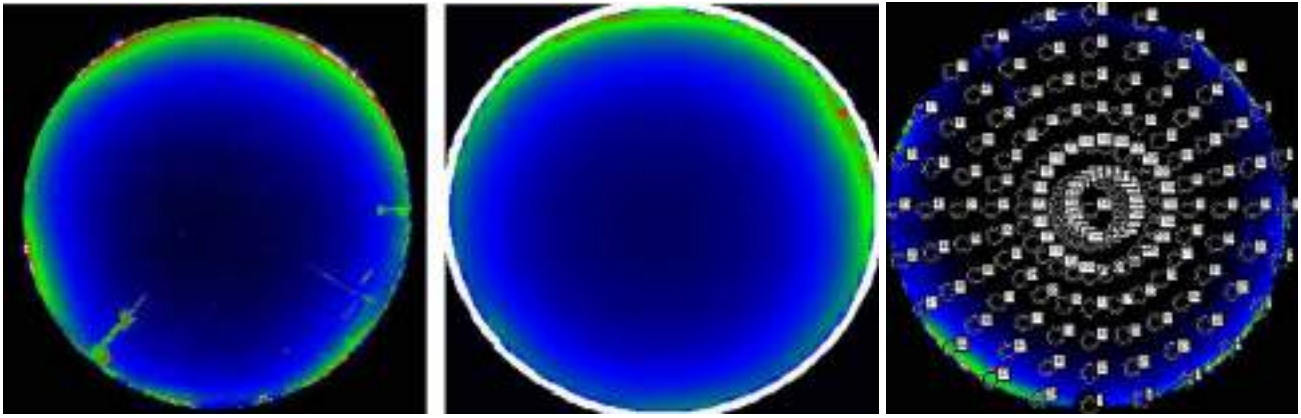


**Figure 9** From left to right: measurement of zenith-normalized luminance, reconstructed data of zenith-normalized luminance, and indices and positions of measured sky elements (e.g., where measurements were taken). The luminance values are relative to zenith (assigned a value of 1), with blue indicating 3 times zenith, green 12 times, and red 40 times.

## 5 Modeled Results

### 5.1 General concepts

This section discusses general terms and concepts to assist with practical understanding of the modeled results, which follow:

- The tables and figures display the relative impacts of individual variables compared to a stated baseline street lighting system unless otherwise indicated. The ranges (e.g., minimum, maximum) and other statistical values (e.g., 1<sup>st</sup> quartile, median, 3<sup>rd</sup> quartile) are calculated between two states of a particular variable (e.g., two uplight percentages), while altering the other factors across their entire ranges. When reviewing relative values, it should be kept in mind that a 10% reduction in a large number, as often applies to an effect in a nearby observer's location, may exceed a 90% reduction of a smaller number, such as an effect that might occur at a distance, in terms of absolute impact.
- Absolute sky glow calculations were performed, producing results reported in diffuse horizontal irradiance ( $\text{W/m}^2$ ) from the night sky as measured on the ground, in the range of light visible to humans (380 through 780 nm).<sup>20</sup> This is referred to as “unweighted” irradiance because no weighting function such as human visual sensitivity is applied to the calculated values. The results were then also weighted by the human scotopic visibility function,  $V'(\lambda)$ , to yield scotopic illuminance values (scotopic-cd/m<sup>2</sup>/sr or scotopic-lux) that better represent light visible to the dark-adapted human eye. In each case, the impacts reported in this document take the form of multipliers compared to a baseline value, to indicate the relative impacts.
- The differences between unweighted and scotopically weighted results indicate the potential influence of those results on a) astronomical instrument observations or the response of plants and animals, and b) night sky visibility, respectively. For the light spectra studied in this report, a large difference between the same results when unweighted and weighted indicates a significant presence of short wavelengths around the peak of rod vision (507 nm); little or no difference means a lower presence of such wavelengths.
- Physical parameters often have direct and significant influence; for example, larger cities covering more area tend to produce higher levels of light corresponding to higher total light output, resulting in increased sky glow that extends over longer distances.
- Some other basic physical principles:
  - Shorter wavelengths (e.g., violet, blue) scatter more readily than longer wavelengths (e.g., yellow, red) due to the atmosphere's molecular composition<sup>21</sup>; shorter wavelengths thereby have greater influence on sky glow near the source, but rapidly attenuate with distance. Because longer wavelengths are less affected by the molecular elements of the atmosphere, under clear conditions they travel farther and thus have greater influence on sky glow seen by distant observers.<sup>22</sup>

<sup>20</sup> Horizontal all-sky irradiance was judged the best metric for purposes of this report, but others like maximum vertical illuminance may also be critical for select sites like environmental preserves. See, for example: D. Duriscoe. 'Photometric indicators of visual night sky quality derived from all-sky brightness maps.' *Journal of Quantitative Spectroscopy & Radiative Transfer*, vol. 181, 2016, pp. 33-45.

<sup>21</sup> See, for example: <http://www.spc.noaa.gov/publications/corfid/sunset/>.

<sup>22</sup> M. Kocifaj. 'A numerical experiment on light pollution from distant sources.' *Monthly Notices of the Royal Astronomical Society*, vol. 415, 2011, pp. 3609–3615.

- Water droplets and aerosols like dust, soot, and salt have different effects on the sky radiance because of their much larger sizes and irregular shapes compared to oxygen and nitrogen molecules, the primary scattering agents in a clear sky.<sup>23,24</sup> Different compounds may also possess different absorption/reflection properties. Higher aerosol loading more uniformly reduces the propagation of all wavelengths, compared to clear conditions.
- Light reaches the sky from a combination of light emitted directly upward (above the 90° horizontal plane) from the luminaire and light emitted downward (below 90°), some of which is then scattered upward or reflected from the ground or other objects (e.g., buildings).
- Some globe and other decorative fixtures emit light straight up (i.e., at *zenith*), but for most standard cobra head products representing the bulk of installed street lighting fixtures, “uplight” primarily refers to light emitted at a relatively small (0° to 10°) angle above a horizontal plane drawn level with the aperture of the light source. Light emitted from a drop-lens cobra head street light at higher angles tends to be at much lower intensity than that emitted near horizontal.
- Light emitted or reflected toward zenith travels the shortest path through the atmosphere (the average scale height up to which the uniform molecular atmosphere extends is about 8 km) before exiting to space, thus encountering fewer scattering agents than light traveling at lower angles with correspondingly longer atmospheric paths.<sup>25</sup> Light traveling toward zenith thereby tends to produce less sky glow (under non-cloudy conditions) than light at lower angles.
- Clouds often amplify sky glow for observers within the defined city area, as determined by a complex function of cloud optics and geometry, as well as the position of an individual observer relative to the cloud array.
- Light traveling through the atmosphere is ultimately either absorbed by aerosols, particulates, buildings, or terrain, or exits to space. The scattering effects as the light follows its path are a function of the elements investigated in this study as well as others not covered, such as the complex variations in particulate size and shape listed earlier.

The atmosphere represents a virtually infinite combination of elements when considering the movement of light, particles, or fluids it contains; characteristic inaccuracies are widely recognized in even such common activities as forecasting the weather. Significant simplifications are required in any related modeling effort, and even then models used for these purposes are necessarily both mathematically complex and data intensive.

As this document is designed more to inform the general lighting community (than, for example, the atmospheric or astronomical modeling communities), the descriptions of the modeling methods and results are more tailored toward lighting professionals. The intent is to facilitate a general understanding of the impact of light in the atmosphere resulting from various street lighting scenarios, and how the different characteristics of that light (luminous flux, SPD, and percent uplight) influence sky glow.<sup>26</sup> The effects of each variable considered

<sup>23</sup> For instance, water droplets have spherical or spheroidal forms, thus showing an enhanced backscatter, while dust-like particles are usually of irregular shapes with weak backscatter and various side-scatter features. Soot particles absorb very efficiently, thus they are less efficient in redirecting scattered light back to the ground. On the other hand, salt particles are composed of non-absorbing (or weakly absorbing) species and thus scatter very efficiently.

<sup>24</sup> M. Kocifaj et al. ‘The effect of spatial and spectral heterogeneity of ground-based light sources on night-sky radiances.’ *Monthly Notices of the Royal Astronomical Society*, vol. 409, 2010, pp. 1203–1212.

<sup>25</sup> L. M. Celnikier. ‘Understanding the physics of meteoritic descent.’ *American Journal of Physics*, vol. 63, no. 520, 1995, pp. 524–535.

<sup>26</sup> Correlated Color Temperature (CCT) is often used as a proxy for spectral content in discussions about sky glow, but is an imprecise measure. Many different combinations of wavelengths can be used to produce a given color appearance, or CCT. This study relies on actual SPDs in interpreting the calculations because the potential differences among products even at the same CCT may result in wide variations in atmospheric effects.

in this study are described in general terms below, with emphasis on the conditions where the effects are significant:

- Three hypothetical cities were defined, spanning a small city to a large metropolis, believed to be reasonable representations of typical U.S. cities. The information about each is included in Table 1. All cities are unique in their particular shape and dimensions, introducing significant variation among actual locations. To keep the current effort manageable, however, each hypothetical city was simplified to a uniform, circular shape. There is a noticeable range in lighting density, which reflects differences in city design; City2 has the lowest density and meets the qualification as an International Dark-Sky City.

**Table 1** Characteristics of hypothetical cities modeled.

|       | Radius<br>(km) | City Area<br>(km <sup>2</sup> ) | No. Fixtures | Lighting Density<br>(fixtures per km <sup>2</sup> ) |
|-------|----------------|---------------------------------|--------------|-----------------------------------------------------|
| City1 | 1.4            | 7                               | 342          | 52                                                  |
| City2 | 7.2            | 164                             | 3,500        | 21                                                  |
| City3 | 8.6            | 232                             | 39,884       | 172                                                 |

- Two observer distances were selected, the first at the city perimeter (but still within the city, hereafter referred to as the “near observer”) and the second 40 km from the center of the city (well outside the city, hereafter referred to as the “distant observer”). For consistency, the observer positions were uniformly located due east of the city center, at the same cardinal direction relative to center.
- Garstang’s city emission function<sup>27</sup> was used to model how light propagates into the atmosphere. Among the variables that can be specified in the model, two address the direction of light emitted from light sources: 1) the fraction of light emitted downward and isotropically reflected (assuming a uniform 15% ground reflectance), and 2) the fraction of light radiated directly upward (above 90°). Per Garstang’s function, if the luminaire emits no light upward, then the only light reaching the sky is that reflected from the ground according to a cosine function (represented by the dashed line in Figure 10). If there is uplight, the direct uplight is emitted according to the function represented by the dotted line; the solid line represents the combined product of the downward-reflected and upward-emitted quantities.

<sup>27</sup> R. H. Garstang. ‘Model for Artificial Night-Sky Illumination.’ *Publications of the Astronomical Society of the Pacific*, vol. 98, no. 601, 1986, pp. 364-375.

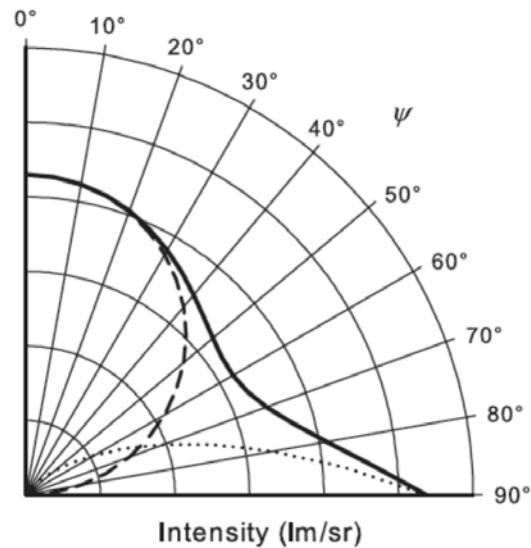


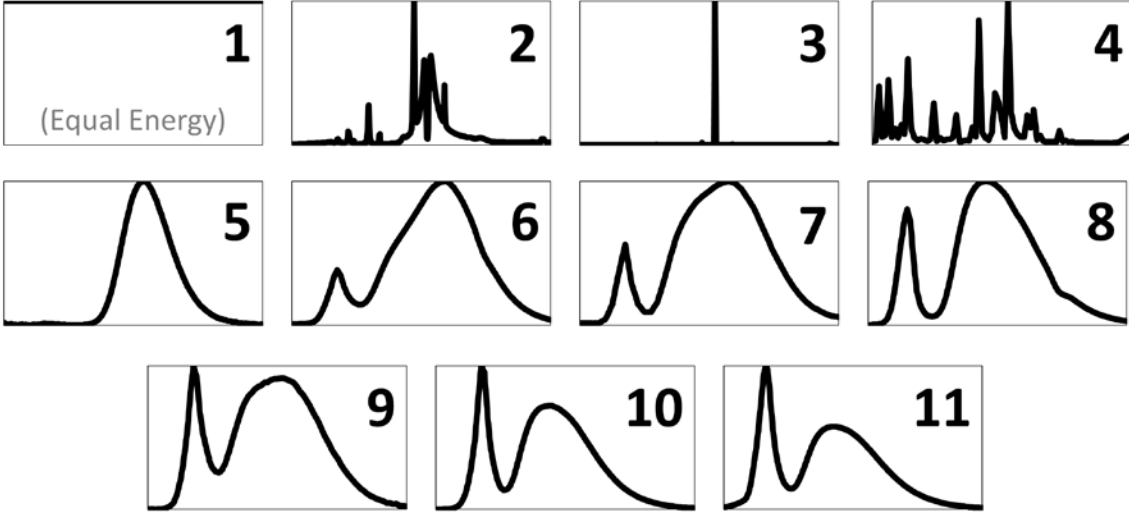
**Figure 10 Garstang's city emission function.** If the luminaire emits no light upward, then the only light reaching the sky is that reflected from the ground according to a cosine function (represented by the dashed line). If there is uplight, the direct uplight is emitted according to the function represented by the dotted line; the solid line represents the combined product of the downward reflected and upward emitted quantities.

- Light output, SPD, and percent uplight are the variables used to specify the fixture characteristics in the model. The effect of light output was tested using normalized values of 500 and 1,000 lm/fixture.<sup>28</sup> These values were run and compared for every scenario (e.g., for all source types/technologies). The 11 SPDs listed in Table 2 were selected to represent incumbent technologies and various LEDs. An equal energy SPD (all wavelengths emitted at equal energy) was included to compare associated sky glow effects on a granular wavelength basis, in 5 nm spectral bands. The scotopic-to-photopic (S/P) ratios relative to HPS for the LEDs ranged from 0.70 to 3.13, and are listed here because this metric is referenced as a means to evaluate light sources for sky glow potential in some approaches to street lighting design.<sup>29</sup> Generally, light sources with more emission around 507 nm (the peak of the human scotopic luminous efficiency function) will have higher S/P ratios.

<sup>28</sup> These particular values were selected to test the relative influence of output rather than to calculate absolute output values, given the wide variation of product outputs within even a single installation and the intent of this study to be more generic in its findings.

<sup>29</sup> Because the photopic and scotopic luminous efficiency functions are different, when applied to a particular SPD they will thus yield different values for photopic and scotopic lumens. The ratio of these two values is the scotopic-to-photopic (S/P) ratio.

**Table 2** The 11 selected SPDs, normalized to a maximum output of 1, along with their corresponding CCT values and S/P ratios (relative to HPS).

| Input SPDs (normalized to maximum output of 1)                                     |                  |      |      |                 |                  |      |      |      |      |       |       |
|------------------------------------------------------------------------------------|------------------|------|------|-----------------|------------------|------|------|------|------|-------|-------|
|  |                  |      |      |                 |                  |      |      |      |      |       |       |
| Specifications and Calculated Metrics/Values                                       |                  |      |      |                 |                  |      |      |      |      |       |       |
|                                                                                    | SPD1             | SPD2 | SPD3 | SPD4            | SPD5             | SPD6 | SPD7 | SPD8 | SPD9 | SPD10 | SPD11 |
| Source type                                                                        | N/A <sup>A</sup> | HPS  | LPS  | MH <sup>B</sup> | LED <sup>C</sup> | LED  | LED  | LED  | LED  | LED   | LED   |
| CCT (K)                                                                            | 5455             | 2041 | 1778 | 3924            | 1872             | 2704 | 2981 | 3940 | 4101 | 5197  | 6101  |
| photopic lux                                                                       | 1000             | 1000 | 1000 | 1000            | 1000             | 1000 | 1000 | 1000 | 1000 | 1000  | 1000  |
| scotopic lux                                                                       | 2265             | 629  | 218  | 1381            | 445              | 1173 | 1188 | 1345 | 1650 | 1797  | 1970  |
| S/P ratio (relative to HPS)                                                        | 3.60             | 1.00 | 0.35 | 2.19            | 0.71             | 1.86 | 1.89 | 2.14 | 2.62 | 2.85  | 3.13  |

<sup>A</sup> Equal energy

<sup>B</sup> Metal halide

<sup>C</sup> Phosphor-converted (PC) Amber LED

- Four uplight values were selected for comparison: 0% uplight roughly represents what were formerly referred to as “full cut-off” fixtures<sup>30</sup>; the values of 2% and 5% represent the percent uplight of typical and relatively poor drop-lens cobra head street lights, respectively<sup>31</sup>; and 10% approximates a good optical quality acorn post-top light. The 10% value also allows for cross-model comparison since many other sky glow models assume 10% uplight from street lights.<sup>32</sup>
- The atmospheric conditions modeled include four that are “cloudless” with varying degrees of turbidity, and one of cloud cover (see Table 3). For all conditions, there were no light blocking objects near the horizon. NASA’s AERONET station data was used as a reference source for various atmospheric

<sup>30</sup> The term has since been deprecated by the Illuminating Engineering Society.

<sup>31</sup> A survey conducted by PNNL in February 2017 of 10 HPS drop-lens cobra head street light products from major manufacturers found a range of uplight between 0.1% and 5.1%, with an average of 2.4%.

<sup>32</sup> It is important to note that obstacle blocking was not accounted for in this effort, which may have increased the impact of higher uplight values. Depending on the particular environment, a portion of the uplight (mainly the light travelling emitted near the horizon) could be blocked and absorbed by obstacles, so that eliminating uplight in the luminaires will not have as dramatic of effect. See: M. Aubé. ‘Physical Behaviour of Anthropogenic Light Propagation into the Nocturnal Environment.’ *Philosophical Transactions of the Royal Society - B*, vol. 370, no. 1667, 2015.



conditions in the U.S.<sup>33</sup> These conditions are loosely based on U.S. cities with the intent to represent a realistic range of conditions.

- The results are reported in both unweighted and scotopically weighted terms to enable their use in analyzing a variety of human, instrument, and non-human biological impacts.

**Table 3 Atmospheric conditions modeled.**

| Atmospheric conditions |                                                              | ATM1                    | ATM2 | ATM3 | ATM4 | ATM5            |
|------------------------|--------------------------------------------------------------|-------------------------|------|------|------|-----------------|
| Clouds                 |                                                              | No                      | No   | No   | No   | Yes             |
| Cloud                  | Altitude of the cloud base (km)                              | N/A                     | N/A  | N/A  | N/A  | 1               |
| Details                | Spectral albedo (select data file)                           | N/A                     | N/A  | N/A  | N/A  | Altocumulus.cld |
| Aerosols               | Reference aerosol optical thickness <sup>A,B</sup> at 500 nm | 0.1                     | 0.1  | 0.5  | 0.5  | 0.5             |
|                        | Angstrom exponent <sup>A</sup>                               | 0.3                     | 1.5  | 0.3  | 1.5  | 1.0             |
|                        | Scale height for the molecular atmosphere (km)               | 8.0                     | 8.0  | 8.0  | 8.0  | 8.0             |
|                        | Vertical gradient of the aerosol concentration (1/km)        | 0.65                    | 0.65 | 0.65 | 0.65 | 0.65            |
| Data files for         | single scattering albedo                                     | constant_background.ssa |      |      |      |                 |
|                        | asymmetry parameter                                          | constant_background.ssa |      |      |      |                 |
| Horizon                | No light blocking objects near horizon                       |                         |      |      |      |                 |

<sup>A</sup> Aerosol optical thickness is an expression of particle density; the Angstrom exponent is an expression of particle size.

<sup>B</sup> Aerosol optical thickness is a term used in the model; most U.S. sources appear to use the term aerosol optical depth.

## 5.2 Atmosphere

Atmospheric conditions play a significant role in both the level and the distribution of sky glow. Clouds have the greatest effect for observers within the city because they act as immediate reflectors, sending reflected light back to the ground. At the same time, these clouds confine light locally, effectively reducing the light observed at some distance from the city. Under cloudy conditions, therefore, distant observers only receive light that is scattered through a long cloud layer and/or directly emitted at angles only slightly above horizontal.

The size, shape, and density of aerosol particles collectively influence the *turbidity*, which influences the behavior of light traveling through the atmosphere. Although the intensity of scattered light generally increases as atmospheric turbidity increases, that greater aerosol optical depth (AOD) also causes more rapid decay of the intensity of the emitted light beam. Scattering and extinction work in opposite directions, complicating the effect of aerosols on sky glow. Furthermore, optical properties of the aerosol layer depend on particle type and size. Black soot in the air, for example, absorbs much of any incident light and thus creates a darker sky glow, whereas salt aerosols found in coastal regions tend to be diffuse reflectors, making the sky brighter and reducing the contrast of the stars.

Figure 11 illustrates the significant impact to sky glow from dense atmospheres, either highly turbid with many different aerosol particle sizes (ATM3-4) or with complete cloud cover (ATM5). Clearer skies with lighter aerosol dosing (ATM2) display almost none of the same effects, being more closely clustered around the baseline value (ATM1 – assigned the relative value of 1.0 in the charts).

<sup>33</sup> Aerosol Robotic Network (AERONET): <https://aeronet.gsfc.nasa.gov/>.

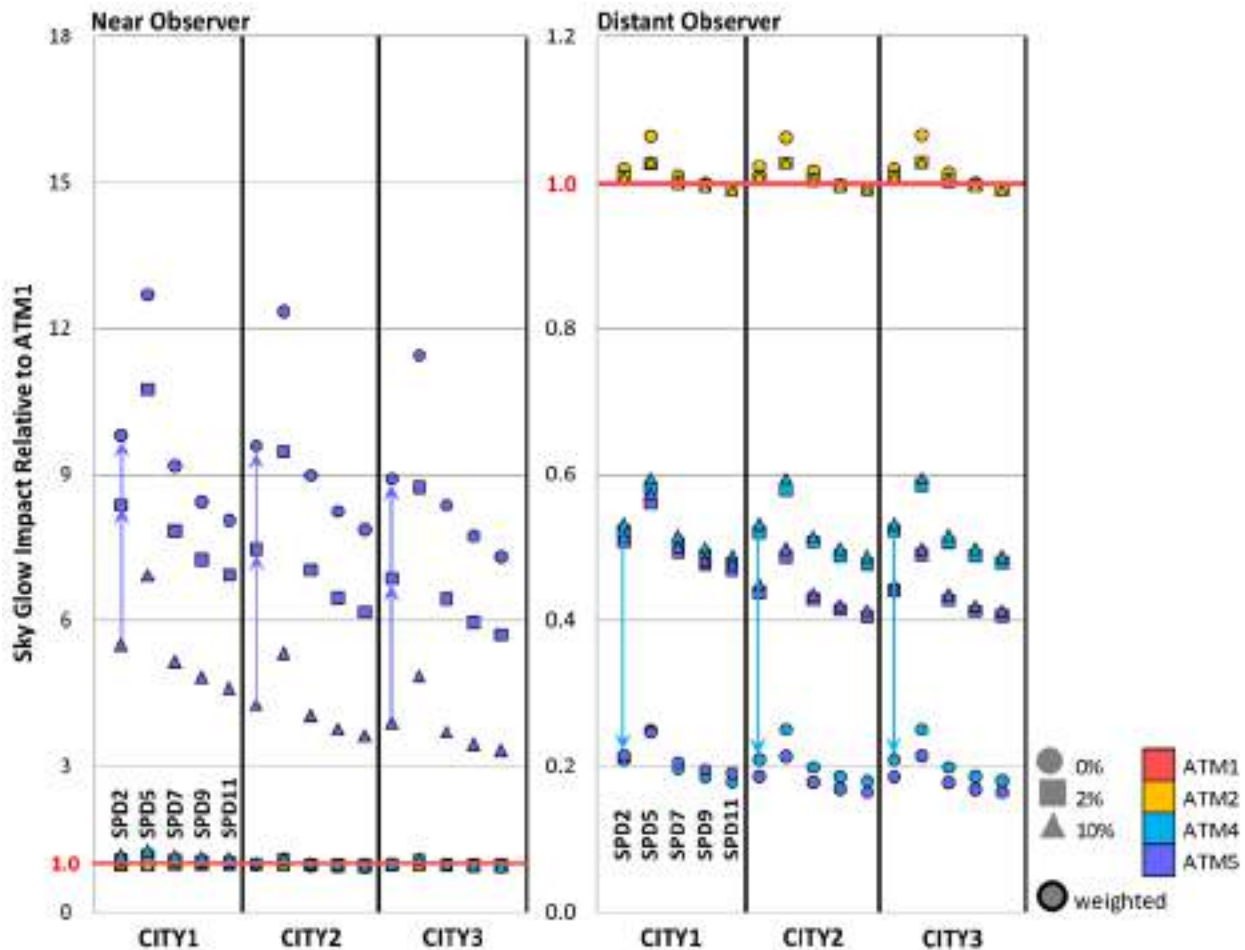


**Figure 11** Relative impacts of the atmospheric conditions for the near and distant observer positions. The relative impacts (note the different scales) of select atmospheric conditions (ATM2, ATM4, and ATM5) compared to ATM1 (indicated as red line) are graphed for each city and five select SPDs based on their percent uplift (0%, 2%, 10%). Only the scotopically weighted results are graphed. The graph on the left, for the near observer, shows the significant increase in sky glow due to clouds, including the increase in sky glow that comes from decreasing uplift, denoted by the direction of the arrows (for the cloudy condition only). The graph on the right, for the distant observer, shows the influence of more turbulent and cloudy atmospheres in decreasing sky glow. Unlike the graph for the near observer, decreasing the percent uplift decreases sky glow, also denoted by the arrows. (For a complete version of the graph, see Appendix B.)

The atmosphere also affects the impact of uplift from the luminaire. For a near observer under clear conditions, increasing uplift slightly increases sky glow because of the associated increase in scatter, but under cloudy conditions, increased uplift from the luminaire actually reduces the visible sky glow. This contradiction occurs for two reasons: under cloudy conditions, the downward portion of light from the luminaire bounces multiple times between the ground and the overhead clouds, effectively trapping and dissipating it; also, most of the increased uplift is emitted at low elevation angles and undergoes a long trajectory before reaching the cloud base, and thus does not reach the near observer.

For the near observer, the brightness of the night environment noticeably increases under cloudy conditions, increasing even more when luminaires direct all their output downward (i.e., have no uplift). For an observer outside the city, however, the brightness of the night environment decreases as turbidity and clouds increase. Decreasing the uplift reduces sky glow for the distant observer under all atmospheric conditions.

### 5.3 City characteristics

Three main drivers of sky glow are related to city characteristics: the city area, total light output, and the range of light emission angles that affect other areas within the city. In general, the larger the city, the more complicated the propagation of light and associated scattering in the atmosphere, and the greater the propensity for light from the opposite side of the city (relative to the observer) to propagate at low elevation angles and along longer optical paths. Distant observers receive a collection of light from different angles, depending on their distance relative to the dimensions of the city.

### 5.4 Street lights: light output, percent uplight, SPD

#### 5.4.1 Light output

This study compared the effects of light output using two output levels, one twice the value of the other. As the values of all the other input variables were modified in the sky glow calculations, the relationship between light output and sky glow remained linear, such that whenever the street lighting levels were doubled, the resulting sky glow contribution from the street lights also precisely doubled. Conversely, reducing light output reduces the sky glow proportionally.

#### 5.4.2 Percent uplight

The percent uplight fraction was varied in the modeling from 0% to 2%, 5%, and 10%. At 0% uplight, all light in the sky is due to ground reflection and is distributed according to its assumed cosine reflectance function. The other values create a hybrid cosine and low-angle emission pattern (refer to Figure 10).

Figure 12 portrays the modeled impacts of percent uplight. From left to right, each bar shows the minimum, 1<sup>st</sup> quartile, median, 3<sup>rd</sup> quartile, and maximum values for all combinations of modeled variables, with the colored areas representing the data between the 1<sup>st</sup> and 3<sup>rd</sup> quartiles. These are shown relative to a baseline (represented by the red line at value 1.0) for each comparison of identical conditions, varying only the 2%, 5%, or 10% uplight variable. The charts show that reducing uplight decreases sky glow under all conditions, except for the near observer under cloudy skies. Reducing percent uplight counterintuitively increases sky glow under the cloudy condition when the observer is within the city. (See the discussion on atmosphere in Section 5.2.)

The reduction in sky glow resulting from eliminating uplight is particularly pronounced for the distant observer. Shown at the far left of the bottom charts, sky glow for the distant observer has been reduced by at least 95% compared to the baseline condition of 2% uplight. Assuming no obstructions due to buildings, trees, terrain or other factors that change the baseline results for comparison, *eliminating uplight has by far the single largest influence of any variable to reduce sky glow for distant observers.*

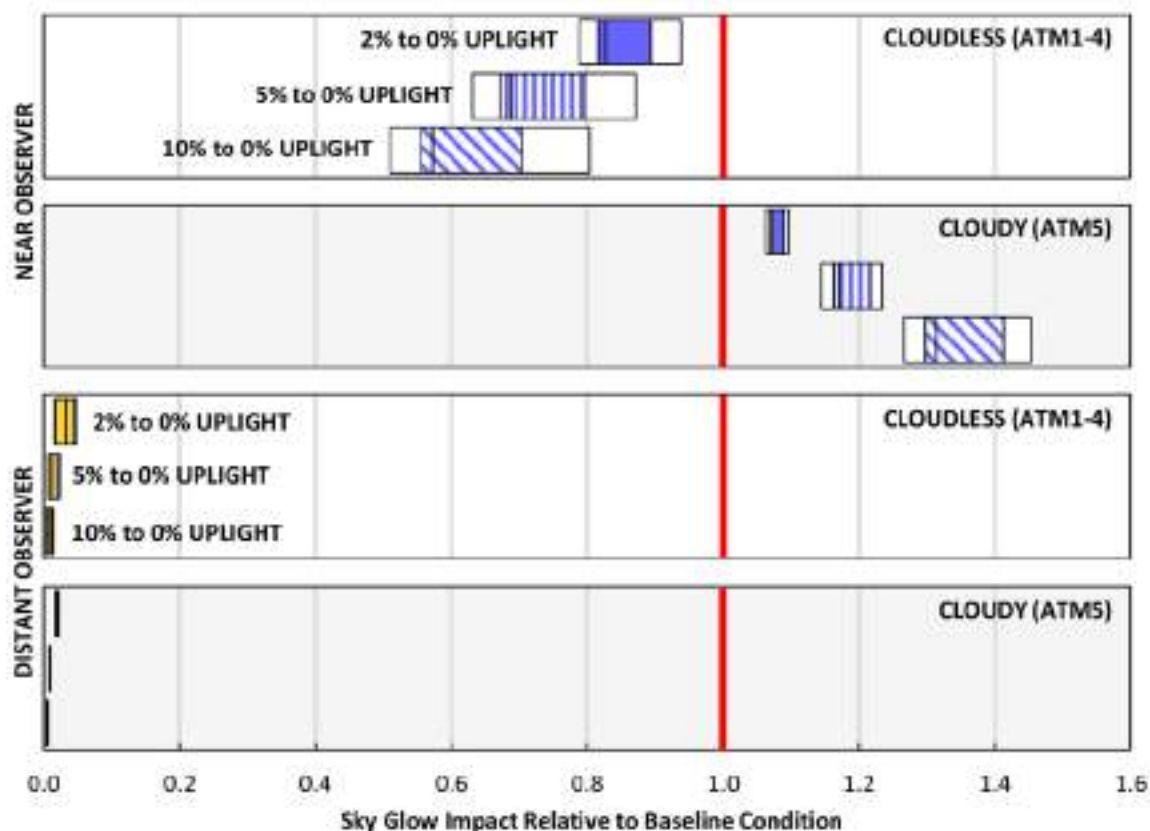


**Figure 12** Impact of reducing percent uplight under cloudless sky and cloudy conditions. The top graph is for the cloudless (ATM1-4) conditions while the bottom is for the cloudy (ATM5) condition. The blue bars are for the near observer position while the yellow-orange are for the distant observer position. The solid bars show the impact of changing from 2% to 0% uplight, the vertically hatched bars show the impact of changing from 5% to 0% uplight, and the diagonally hatched bars show the impact from 10% to 0% uplight. Thus, a value of 0.5 indicates that reducing uplight to 0% from the corresponding baseline results in 0.5 times the sky glow.

#### 5.4.3 Spectral power distribution

Table 4 shows the range of impacts of SPD relative to HPS, for all cities and all atmospheric conditions. The table identifies the SPDs by number, with the corresponding CCT values and relative S/P ratios in Table 2. Figure 13 shows the actual SPDs. According to the median values shown in bold, all SPDs increase sky glow compared to HPS except for LPS and PC Amber LED, and scotopic weighting further emphasizes these impacts. These results are due to the increased scatter of the short to very short wavelengths for the *unweighted* results. The more pronounced impact of short wavelength scatter in the *scotopically weighted* results is due to the human eye's increased sensitivity to wavelengths near the peak of the scotopic sensitivity curve (507 nm). Note that the impacts reported are driven by the specific SPD of each respective product. While unweighted sky glow values increase for all light sources with higher contents of very short wavelengths (i.e., violet), the associated influence of very short wavelengths ends when scotopically weighted because the human eye is less sensitive to wavelengths below about 420 nm.

**Table 4** Relative impact of SPD on sky glow compared to HPS for both unweighted and scotopically weighted results, between the two observer positions. HPS (SPD2) is represented by the value of 1. Cells highlighted in yellow are close to 1 in value; values decreasing from 1 become more greenish while those increasing from one become more reddish.

|       | Unweighted Results |        |     |                  |        |     | Scotopically-Weighted Results |        |     |                  |        |     |
|-------|--------------------|--------|-----|------------------|--------|-----|-------------------------------|--------|-----|------------------|--------|-----|
|       | Near Observer      |        |     | Distant Observer |        |     | Near Observer                 |        |     | Distant Observer |        |     |
|       | MIN                | MEDIAN | MAX | MIN              | MEDIAN | MAX | MIN                           | MEDIAN | MAX | MIN              | MEDIAN | MAX |
| SPD1  | 2.0                | 2.5    | 2.9 | 2.0              | 2.2    | 2.4 | 3.4                           | 3.9    | 4.2 | 3.2              | 3.6    | 3.9 |
| SPD3  | 0.7                | 0.7    | 0.8 | 0.7              | 0.7    | 0.8 | 0.3                           | 0.3    | 0.4 | 0.3              | 0.4    | 0.4 |
| SPD4  | 1.2                | 1.7    | 2.1 | 1.1              | 1.4    | 1.7 | 2.1                           | 2.3    | 2.4 | 2.0              | 2.2    | 2.3 |
| SPD5  | 0.9                | 0.9    | 1.0 | 0.9              | 1.0    | 1.1 | 0.5                           | 0.6    | 0.7 | 0.6              | 0.6    | 0.7 |
| SPD6  | 1.3                | 1.3    | 1.3 | 1.3              | 1.3    | 1.3 | 1.8                           | 1.9    | 1.9 | 1.7              | 1.8    | 1.9 |
| SPD7  | 1.2                | 1.3    | 1.3 | 1.2              | 1.3    | 1.3 | 1.8                           | 1.9    | 1.9 | 1.8              | 1.8    | 1.9 |
| SPD8  | 1.0                | 1.2    | 1.3 | 1.0              | 1.1    | 1.2 | 2.0                           | 2.2    | 2.2 | 2.0              | 2.1    | 2.1 |
| SPD9  | 1.2                | 1.4    | 1.5 | 1.1              | 1.2    | 1.3 | 2.5                           | 2.8    | 2.9 | 2.4              | 2.6    | 2.7 |
| SPD10 | 1.1                | 1.3    | 1.5 | 1.0              | 1.2    | 1.3 | 2.7                           | 3.0    | 3.2 | 2.6              | 2.8    | 3.0 |
| SPD11 | 1.2                | 1.6    | 1.8 | 1.1              | 1.3    | 1.5 | 2.9                           | 3.4    | 3.6 | 2.8              | 3.1    | 3.3 |

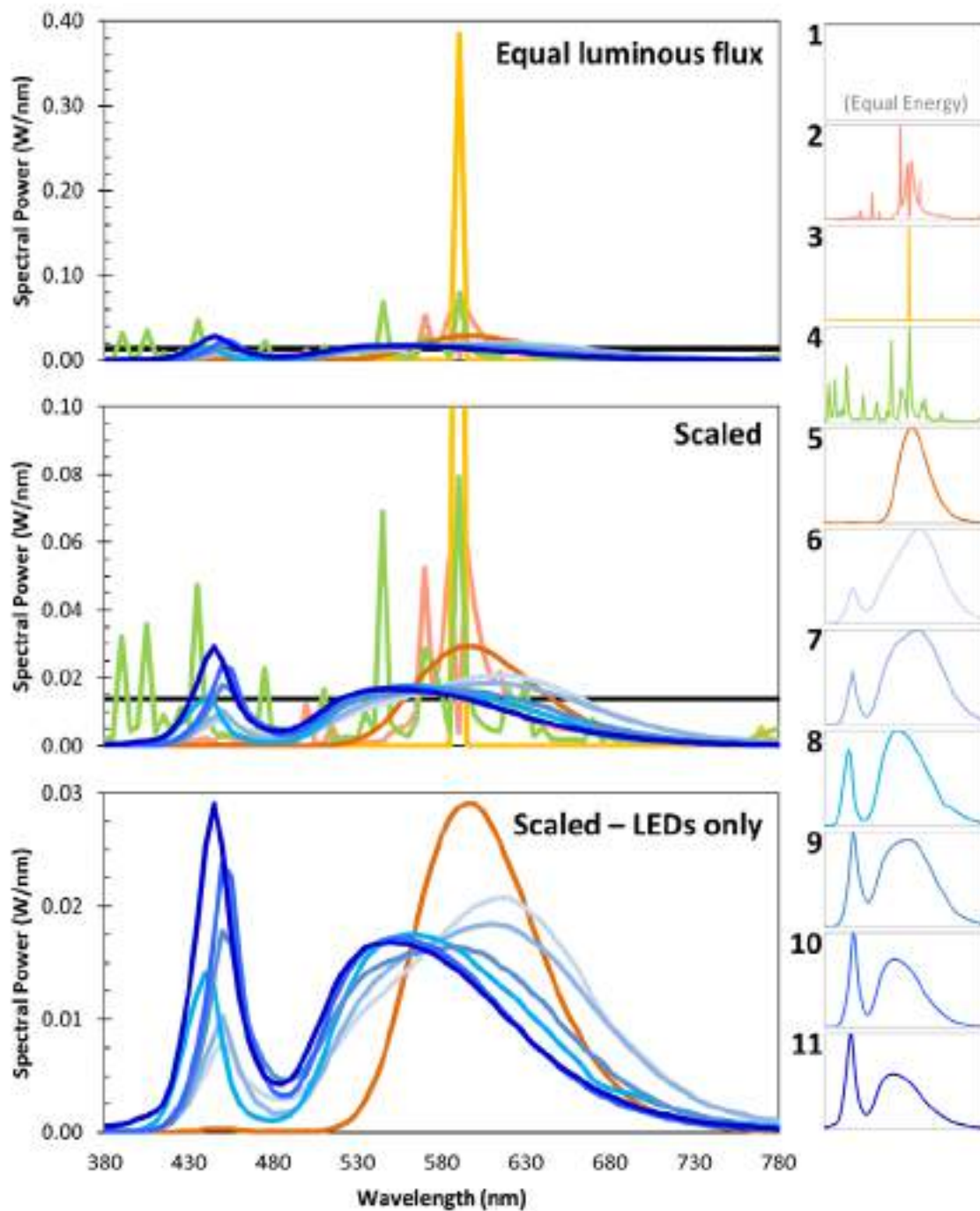


**Figure 13** SPDs of light sources modeled in study, graphed from 380 to 780 nm at equal lumen output. The top chart shows the set of SPDs modeled in this study, displaying the overall range in spectral radiant power for all products. The middle chart zooms in to better reveal the variation among the non-LPS waveforms. The bottom chart shows LEDs only. The significant variation among spectral content is evident in all charts.



Figure 14 shows the same data in the form of bar graphs. The bottom graphs are further divided into atmospheric conditions. Impacts displayed are based on a uniform light output from the source. In these results, city specifications and percent uplight values do not significantly alter the relative impact of each SPD compared to HPS; the impact is more related to the type of result (unweighted versus weighted) and sometimes varies based on observer position (e.g., each SPD has a greater range of impact when the observer is within the city versus outside the city). Scotopic weighting increases the relative sky glow of all light sources except LPS and PC Amber LED.

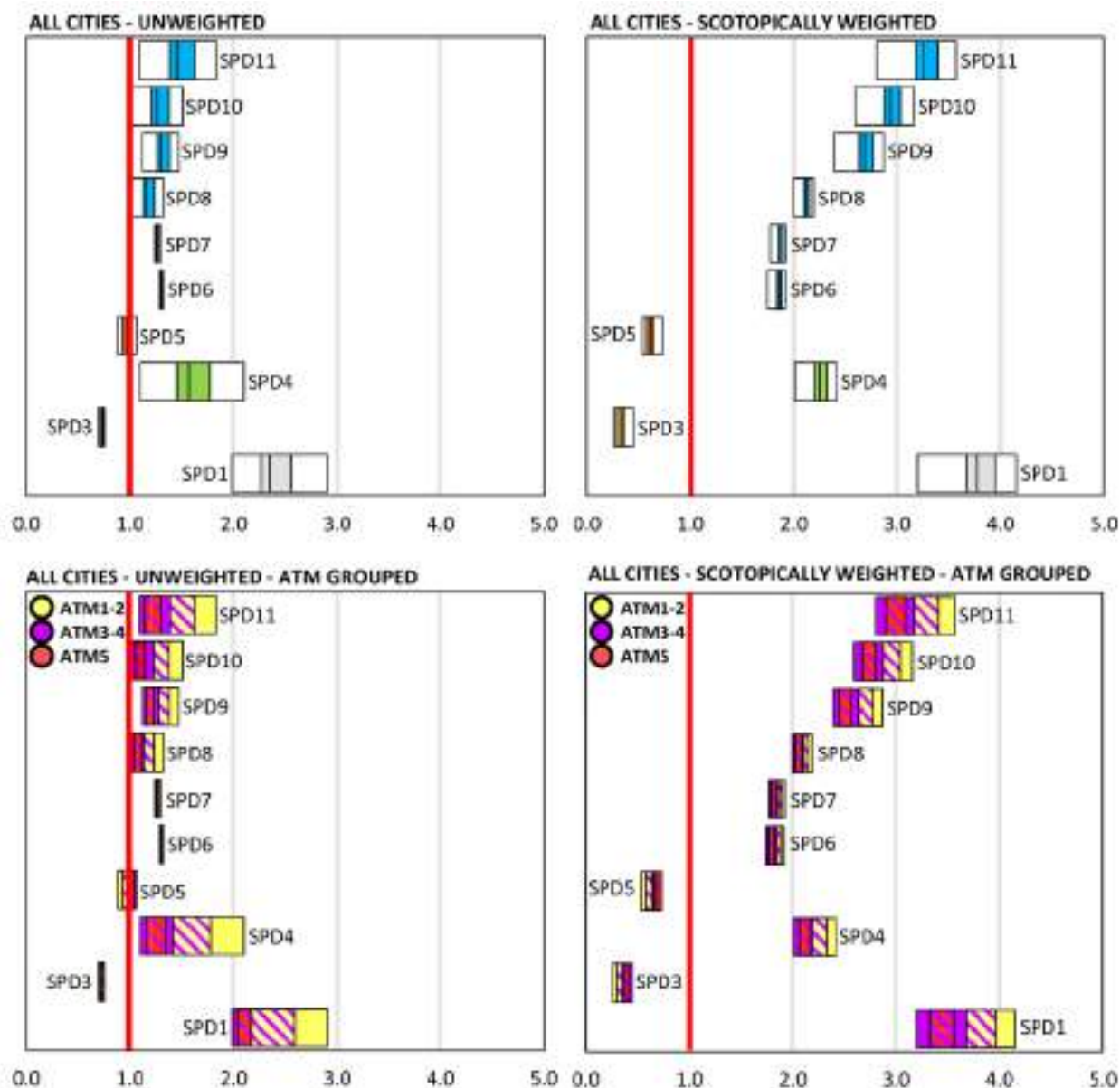


**Figure 14 Relative impact of SPD compared to HPS for both observer positions.** The top graphs show the minimum, 1<sup>st</sup> quartile, median, 3<sup>rd</sup> quartile, and maximum values, with the shaded areas representing data within the 25<sup>th</sup> to 75<sup>th</sup> percentiles. Blue indicates white LED sources while red indicates PC Amber LED, yellow LPS, green metal halide, and gray the Equal Energy spectrum. The bottom graphs are split into atmospheric conditions, showing the minimum and maximum values for ATM1-2, ATM3-4, and ATM5. Hatched shading indicates an overlap in atmospheric conditions. Vertical red lines in all graphs represent the HPS baseline at 1.0.

The atmosphere more readily scatters shorter wavelengths, so that the color of sky glow under cloudless conditions is likely to be bluer than the color of light emitted from the street lighting (just as with natural sunlight, where the sky appears blue compared to the white light coming from the sun). Figure 15 shows the resulting sky glow spectra for an equal energy source (i.e., an SPD with equal energy emitted at all wavelengths), and thereby represents the relative power of each wavelength in the original source that would be present as sky glow for an observer located near the city.<sup>34</sup> Notice that, except for ATM5 (the cloudy atmospheric condition), very short wavelengths predominate in the sky glow spectrum for the near observer, followed by blue and decreasing smoothly through the longer colors of the spectrum, with red wavelengths contributing least. Under cloudy conditions, however, wavelengths are scattered more evenly (due to an effect of the attenuation between the source, cloud height, and observer), so there is less spectral variation (and thus the sky or “cloud” glow spectrum appears closer to that of the original source).

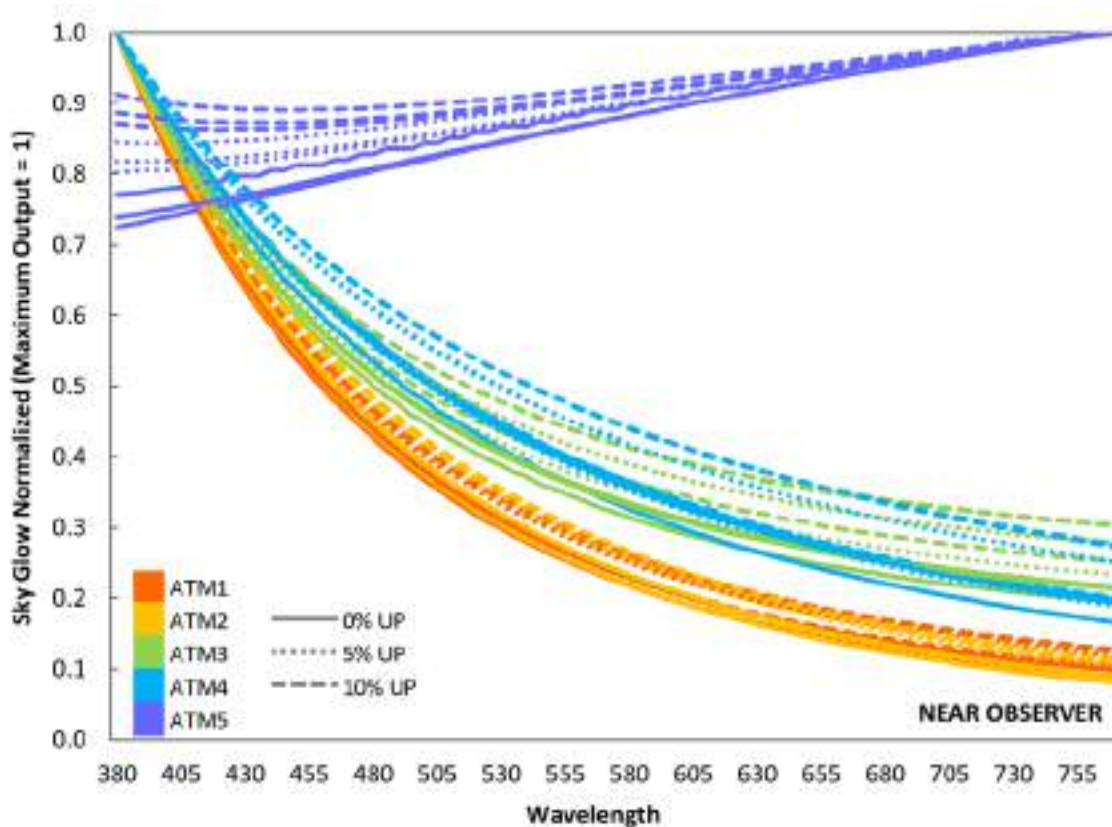


Figure 15 For each city and the near observer position, the relative spectral power distribution of the resulting sky glow for the equal energy SPD based on atmospheric condition and percent uplight.

Shorter wavelengths affect sky glow less for a distant observer than for the nearby observer, because shorter wavelengths are more likely to be scattered or reduced over longer travel distances. This effect becomes even more pronounced when there is cloudiness and turbidity in the atmosphere (Figure 16). While the distant observer in this study is only at 40 km from the city center, the flattening effect on the SPDs of resulting sky glow from the diminished short wavelength content is already visible.

<sup>34</sup> The 2% uplight runs have been omitted from this graphic for simplicity but fall between the 0% and 5% runs.

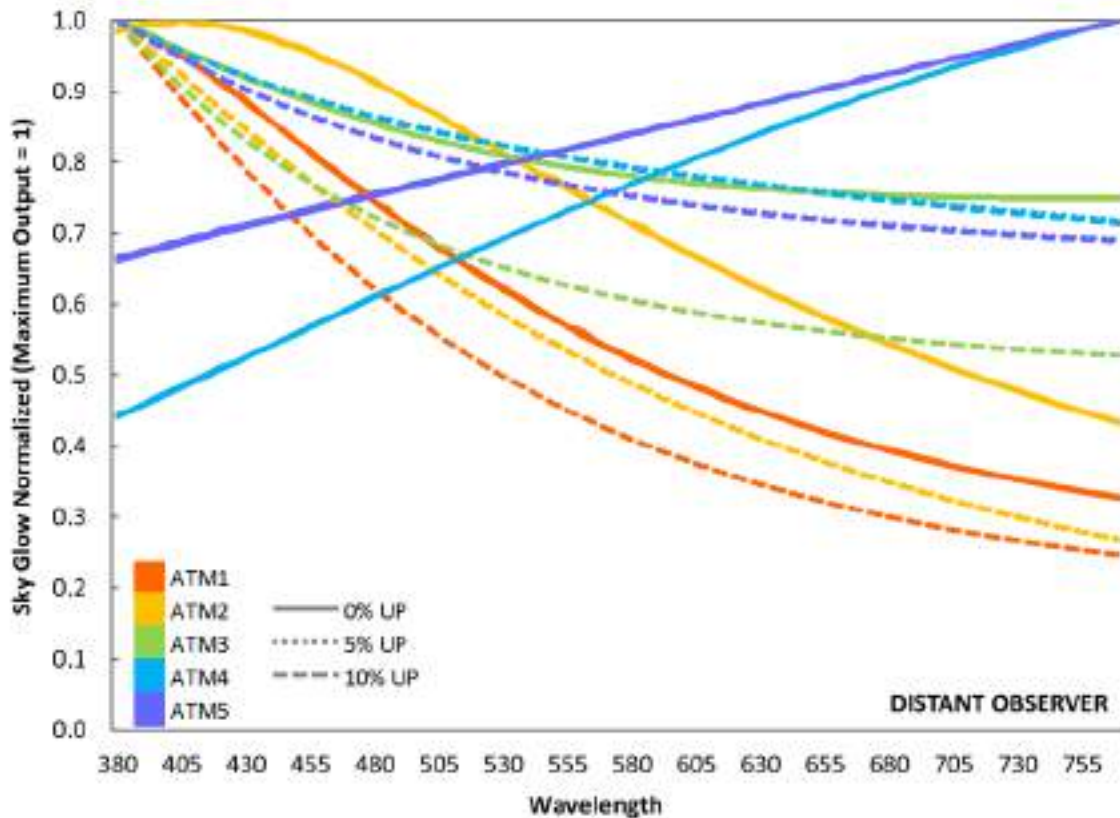


**Figure 16** For each city and the distant observer position, the relative spectral power distribution of the resulting sky glow for the equal energy SPD based on atmospheric condition and percent uplight.

At some point (beyond what was modeled here), the shorter wavelengths will be essentially depleted by scattering and will disappear from the SPD of the continuing light. The very turbid and cloudy atmospheric conditions at 40 km are both already displaying this characteristic because those conditions exert the greatest influence on attenuating short wavelengths near the source, and thus some portion has already been removed by the relatively short distance traveled to the distant observer. Eventually, at some greater distance from the city, all the curves will assume the shape of the two 0% uplight curves for ATM4 and ATM5 in Figure 16. Note also that even at 40 km under cloudy conditions, only uplight emitted at low angles above the horizontal plane reaches the distant observer's position, so the magnitude of radiant power at that location has likely been substantially reduced already.

## 6 Discussion of Individual Contributions

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Individual contributions to sky glow from the different variables range widely. Although such contributions do not naturally occur in isolation—in other words the results observed in an actual location reflect the sum total of the individual influences (some of which are counter to others), it is useful to review them separately to better understand the variables (or “levers”) a planner has at their disposal for influencing the ultimate impact of a system. Combining these individual contributions is the subject of Section 7.

Figure 17 separates the relative impacts of the variables independent of the lighting system (e.g., atmospheric conditions) from those that can be altered through luminaire selection (e.g., SPD, percent uplight, and light output). In Figure 17, atmospheric conditions are relative to ATM1 and SPD is relative to HPS. The percent uplight values represent a change from 2% to 0% uplight and the light output values represent a change from 100% to 50% output.

Relative levels of influence are more important in this graph than are the absolute values of the results, since the overall accuracy of the values is only as valid as the assumptions that underlie them (and as noted, the ultimate impact results from the combination of elements). Nevertheless, comparing the relative sizes of corresponding columns provides a useful indication of the different levels of influence.

A number of observations can be drawn from the graphs:

- Atmospheric conditions have the potential to significantly increase the impact on sky glow for near observers.
- Among the characteristics of the street lighting luminaire, SPD has the greatest potential to increase sky glow if a full range of product options (i.e., from LPS to metal halide and all other products in between) is considered; however, when the actual selection considered is between two products relatively close in characteristics, such as a nominal 3000 K LED versus a 4000 K LED, the range in impacts is much narrower, even when scotopically weighted.
- As modeled in this study, reducing the percent uplight has the greatest potential to significantly decrease sky glow for observers distant from the city. Figure 17 shows that reducing the uplight from 2% to 0% nearly eliminates any increase in sky glow for the distant observer relative to the defined base condition, for all SPDs and lumen output levels.
- While nothing below a 50% reduction in light output was modeled, it should also be noted that sky glow directly scales up or down with light output for all observer positions. This suggests that, for example, during certain hours when lower light levels might be acceptable for local safety and other criteria, the lighting system could be dimmed to any level (including none) to further decrease corresponding sky glow contributions.

While the graphs do not show the impact of city characteristics, namely city area and lighting density (number of lights per unit area), larger cities and increased lighting density significantly increase the impact for observers inside and distant from the city. This comes as no surprise, given that larger cities tend to generate more light that causes sky glow over greater distances.

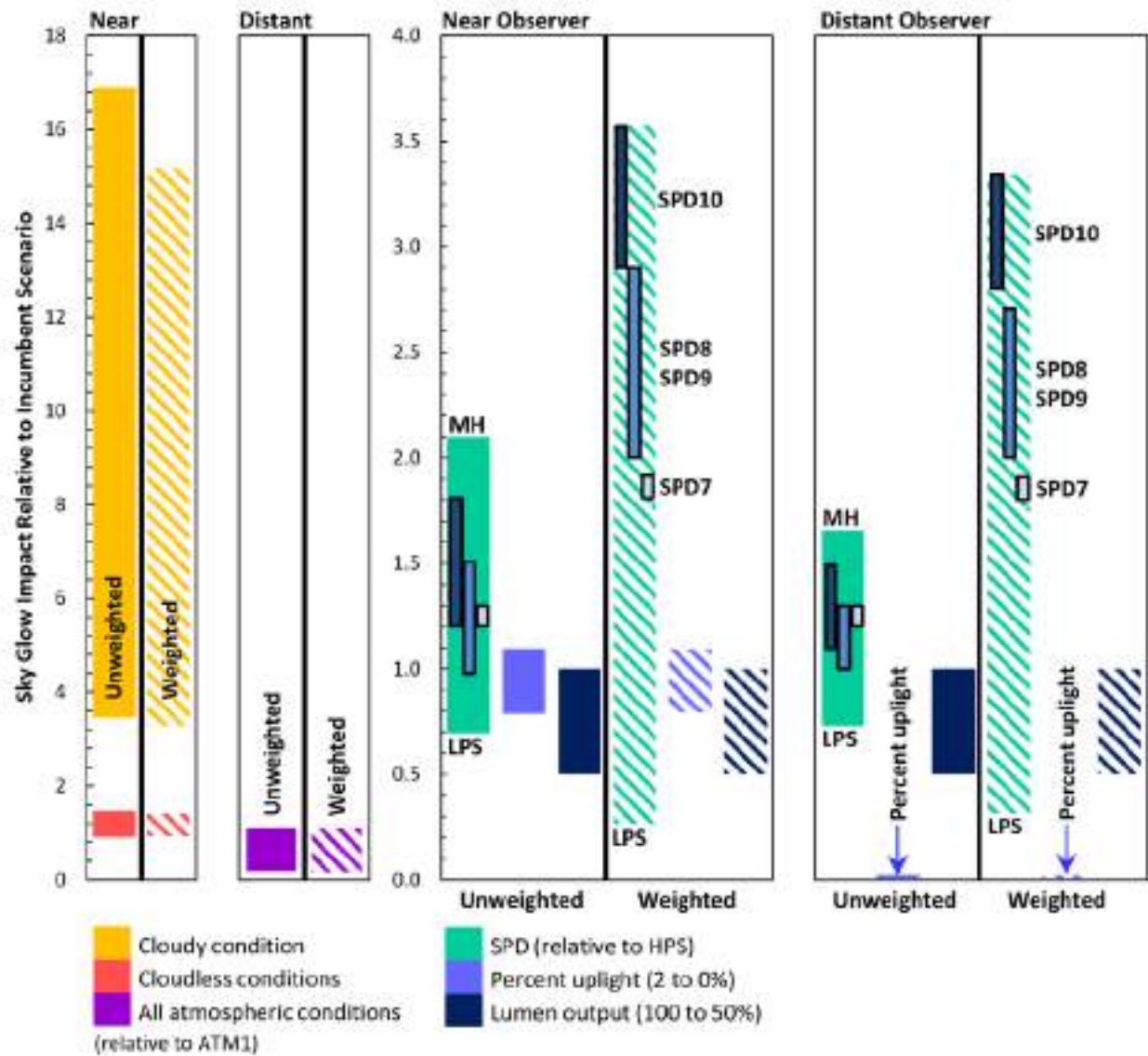


**Figure 17** The relative range in impacts of atmospheric conditions (relative to ATM1) on the left, along with SPD (relative to HPS), percent uplight (switching from 2% to 0%), and light output (changing between 100% and 50% output) on the right. Solid bars represent unweighted results while hatched bars are scotopically weighted. The specific locations of individual LED SPDs are displayed to facilitate comparisons between them; additional SPDs (e.g., LPS and MH) are included to delineate minimum and maximum performance.



## 7 Combined Effects Comparison

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So far, the investigation has focused on the individual influences of different variables on sky glow, whereas the results in an actual conversion come from the particular combination of these elements in a given installation. This section combines the different elements to examine a representative scenario for a typical street lighting conversion in the U.S. today.

The following series of comparisons are in three progressive tiers: the top chart shows the isolated effect of replacing the baseline HPS SPD with the various other LED SPDs modeled with no other modifications; the middle chart adds the effect of reducing luminaire lumen output by half compared to the baseline HPS (a typical result for conversions in the U.S.); and the bottom chart further adds the impact of eliminating uplight from the luminaires, assuming a typical HPS baseline value of 2%. **The bottom charts in both figures thereby represent typical conversion scenarios in the U.S.—an incumbent HPS cobra head product with 2% uplight replaced by each of the LED products listed, at half the light output and 0% uplight.** Figure 18 and Figure 19 show the three iterations for a near observer and a distant observer, respectively, separated into cloudy and cloudless conditions. The impacts are further divided into the different LED SPDs modeled. While the impacts are clearly evident, a few highlights deserve mention:

- When SPD is the only variable considered (as discussed in the previous section isolating individual impacts), all of the modeled LED conversions other than PC Amber LED increase sky glow relative to HPS.
- Scotopically weighting the results significantly increases the impact compared to unweighted results. Generally, the products with higher levels of short wavelength content have greater impact to sky glow due to Rayleigh scattering effects, and significantly increase that impact as atmospheric turbidity increases, since turbidity intensifies scatter. Scotopically weighting the results further increases the calculated sky glow effect for sources with greater short wavelength content by accounting for the human eye's increased sensitivity to short wavelengths.
- Taking the next step and reducing lumen output by half improves the situation, decreasing unweighted sky glow in all of the LED conversions relative to the baseline HPS system. For the scotopically weighted results, sky glow relative to HPS decreased for some of the LED products but increased for others.
- Ultimately, when both reduced lumen output and percent uplight are taken into consideration, all LED products allow for greater potential reductions at the near observer position, although certain conditions may still increase sky glow overall. In the *worst-case scenario* modeled in this study (the LED with the most short wavelength content), scotopically-weighting the results increases the contribution to sky glow from street lights about 60% relative to the HPS baseline, for the near observer position under the highest turbidity. However, even the impacts of this worst case scenario decrease rapidly with distance. For the distant observer (at just 40 km), eliminating the uplight dramatically reduces the sky glow for all SPDs, for both the unweighted and scotopically weighted results alike.



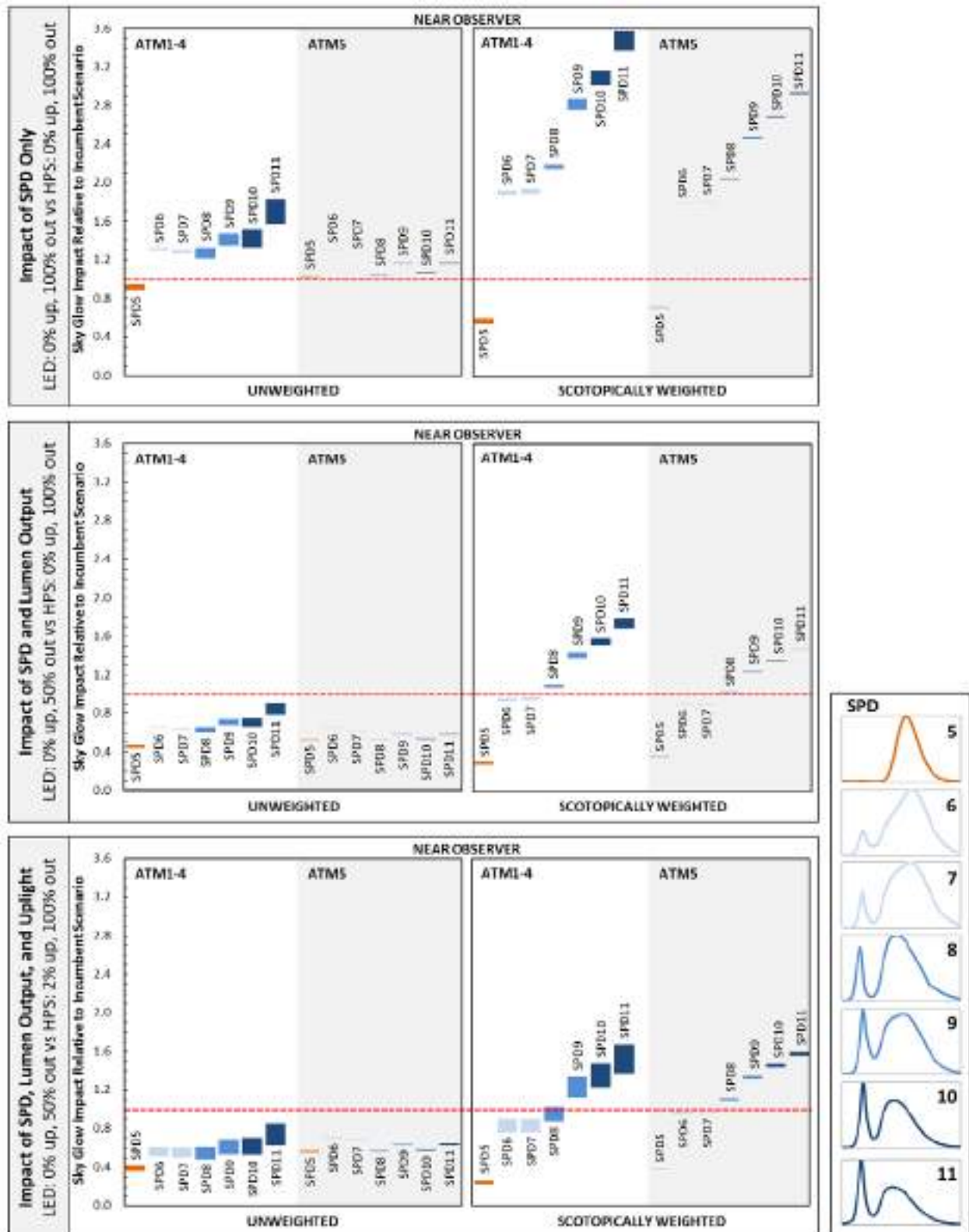


**Figure 18** Combined results of the LED street lighting conversions, from the near observer position at the edge of the city. The top chart shows the isolated effect of replacing the baseline HPS SPD with that of the various other SPDs modeled; the middle chart adds the effect of reducing luminaire output by half compared to the baseline HPS; the bottom chart further adds the impact of eliminating uplight from the luminaires, assuming a typical HPS baseline value of 2% (note this represents an increase from the first two charts using 0%). The baseline is represented by the dashed red line at the normalized value of 1.0.

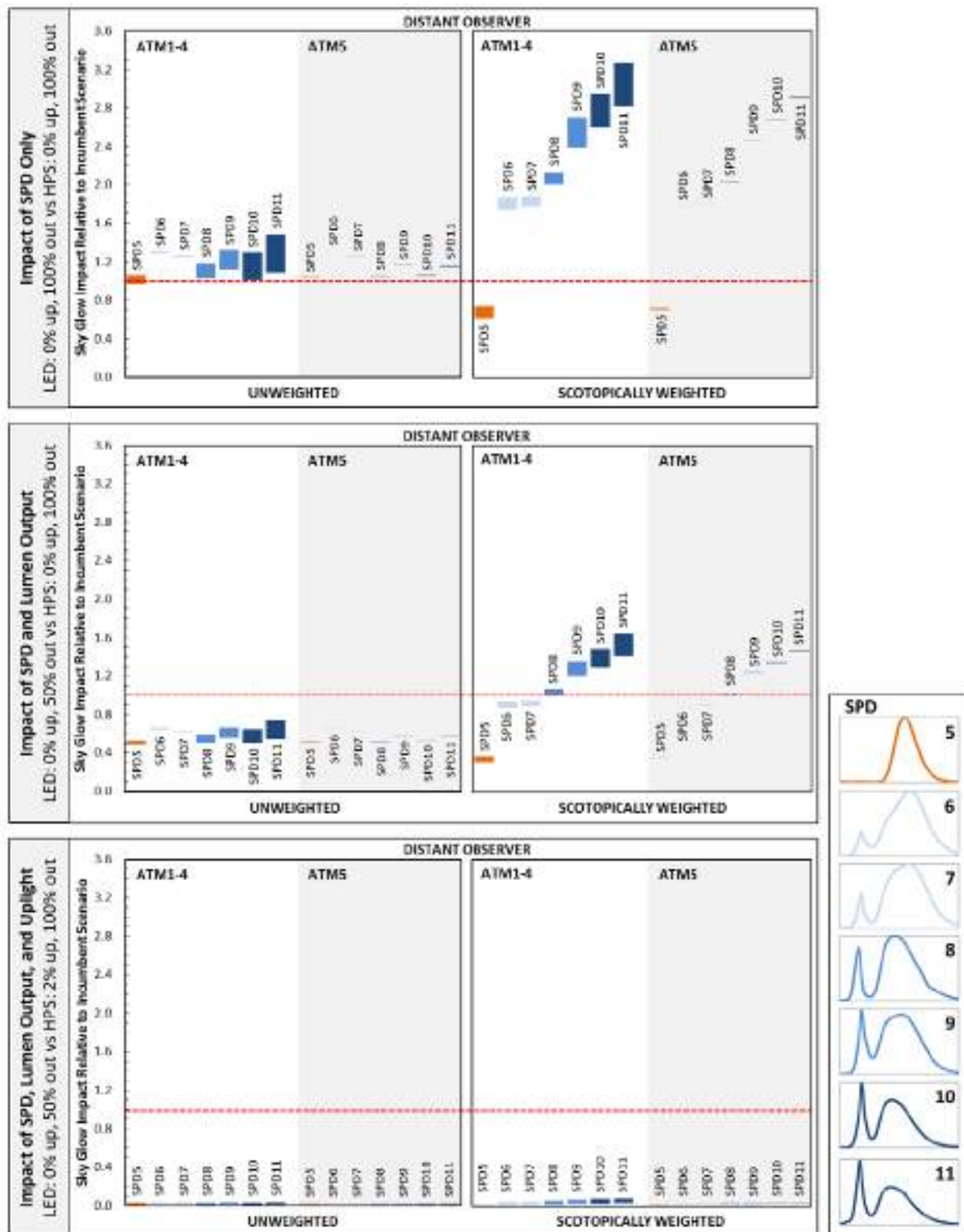


**Figure 19** Combined results of the LED street lighting conversions, from the distant observer position 40 km from city center. The top chart shows the isolated effect of replacing the baseline HPS SPD with that of the various other SPDs modeled; the middle chart adds the effect of reducing luminaire output by half compared to the baseline HPS; the bottom chart further adds the impact of eliminating uplight from the luminaires, assuming a typical HPS baseline value of 2% (note this represents an increase from the first two charts using 0%). The baseline is represented by the dashed red line at the normalized value of 1.0.

## 8 Takeaways from the Results

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Several useful conclusions can be drawn regarding each contributing element modeled in this study.

### 8.1 Light output

- The relationship between light output and sky glow is linear; increases or decreases in the luminaire output levels are matched one-for-one in the resulting contributions to sky glow from the street lighting system. Light output, and thus target light levels on the ground and how they might be varied both spatially (e.g., between roadway and off-roadway areas) and temporally over the course of an evening, are powerful tools for addressing sky glow and related concerns.

### 8.2 Percent uplight

- For a near observer under clear conditions, a reduction from any level of uplight to 0% significantly reduces sky glow. For distant observers, sky glow is quickly attenuated at 0% uplight (although a light dome in the direction of the city may still be visible).
- Under cloudy conditions, the near observer sees more sky glow contributed by reflected downlight than from uplight emitted at small angles above the horizontal plane. This is because the uplight tends to travel out of the area before contributing much sky glow to the immediate area, whereas reflected downlight is essentially trapped in the immediate area between the ground and cloud layer.
- Under clear conditions, transitioning from 10% to 5% uplight has less impact than transitioning from 5% to 0%, signifying that the greatest impact comes from the transition to no uplight.

### 8.3 Spectral power distribution

- Light sources emitting higher levels of short wavelength energy experience more scatter/attenuation in the atmosphere until those wavelengths are depleted. Scotopically weighting the results emphasizes short wavelength content centered on the maximum scotopic sensitivity of 507 nm. Longer wavelengths tend to travel farther and thus have more impact on sky glow for distant observers.
- Higher aerosol contents tend to reduce these differences between short and long wavelengths over distance as they scatter and attenuate wavelengths more uniformly.

### 8.4 Atmospheric conditions

- Cloudy conditions have a large potential impact on sky glow within the defined city area. Clouds reflect, transmit or absorb all wavelengths of light fairly evenly, and the resulting diffusion of the reflected light contributes to the localized sky glow. Clouds eventually prevent any light from reaching a distant observer, although longer wavelengths continue to propagate farther than shorter wavelengths.
- Clear conditions result in more scattering and attenuation of shorter wavelengths than longer ones; for a local observer this means a potentially “bluer” sky glow than the SPD of the original source, but also means that the shorter wavelengths are depleted from a projected beam faster than longer wavelengths. Longer wavelengths thereby affect sky glow more for distant observers, under clear conditions. (As this study only modeled out to a distance of 40 km, the full attenuation of shorter wavelengths does not appear in these results, although the trend is already evident in Figure 16.)

## 8.5 City characteristics

- In this study, city area and lighting density were the main drivers of total light output and associated sky glow specifically related to characteristics of the city, although this study did not consider complex city geographies (instead simplifying each to a circular layout). Reducing luminaire density by eliminating unnecessary luminaires is one approach that cities might pursue to reduce sky glow.

## 8.6 Combined Effects

- The transition to no uplight nearly removes the contribution of street lighting to sky glow for the distant observer (by at least 95%), for all products and atmospheric conditions.<sup>35</sup>
- For a near observer, on an unweighted basis, typical conversions to LEDs that include a 50% reduction in lumen output and elimination of uplight will significantly reduce sky glow compared to an HPS incumbent delivering 2% uplight. Scotopically weighting the results reduces the number of products that can make this claim.
- Cities can use the knowledge of combined effects to balance street light conversions and new street lighting installations to either maintain current levels of sky glow or reduce the total sky glow over time.

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<sup>35</sup> In terms of the all-sky horizontal irradiance ( $\text{W/m}^2$ ) metric selected for use in this investigation.

## 9 Other Considerations

The preceding sections have been presented without any implied preferences or consideration of additional factors that may bear on the selection of the best characteristics of a street lighting system for a given location. In an actual situation, the choices available to owners and users of a street lighting system often involve a mix of benefits and compromises, of which sky glow is only one. A number of such factors must be weighed by the system designer based on the specific site conditions to find the best balance among them.

### 9.1 Energy use

Until very recently, warm-white LEDs exhibited significantly lower efficacies than cool-white LEDs because of Stokes losses during the phosphor conversion of the blue light output by the LED. In general, the greater the amount of blue light conversion by phosphors required to produce increasingly warmer color temperatures, the greater the associated losses. The difference in efficacy between 3000 and 4000 K LED luminaires, for example, has been as high as 25% or more in the past, but is diminishing over time as newer products enter the market. This change is not only a function of improved phosphor materials, but is also due to the development of different approaches that manufacturers can use to alter CCT that may, for instance, preserve efficacy at the expense of some ability to render colors accurately.

Table 5 lists the cutsheet-reported performance of various products that were gathered from manufacturer websites in February 2017. Each row lists a product and its reported performance at the various CCTs in which it was available at that time. The key information in this table is in the final column, which reveals the energy penalty at that time for reducing the color temperature from one value to the next (e.g., from 4000 to 3000 K or from 5000 to 4000 K).

**Table 5** Performance specifications, including power (W), light output (lm), and luminaire efficacy (lm/W) of similar make and model products available at different CCTs.

| Manufacturer/Product                | 3000 K |       |                 | Nominal CCT<br>4000 K |       |      | 5000 K |       |      | Percent Change in Efficacy from |                  |
|-------------------------------------|--------|-------|-----------------|-----------------------|-------|------|--------|-------|------|---------------------------------|------------------|
|                                     | W      | Lm    | Lm/W            | W                     | Lm    | Lm/W | W      | Lm    | Lm/W | 4000 K to 3000 K                | 5000 K to 4000 K |
| GE Lighting <sup>A</sup>            | 15     | 1900  | 127             | 15                    | 2000  | 133  | N/A    | N/A   | N/A  | -5%                             | N/A              |
| Cree <sup>B</sup>                   | 50     | 5000  | 100             | 50                    | 5000  | 100  | N/A    | N/A   | N/A  | 0%                              | N/A              |
| Eaton <sup>C</sup>                  | 59     | 5414  | 92              | 59                    | 6116  | 104  | 59     | 6116  | 104  | -11%                            | 0%               |
| Hubbell <sup>D</sup>                | 269    | 17734 | 66              | 269                   | 22736 | 85   | 269    | 23645 | 88   | -22%                            | -4%              |
| Leotek <sup>E</sup>                 | 29     | 3451  | 118             | 29                    | 3739  | 128  | 29     | 3739  | 128  | -8%                             | 0%               |
| Acuity Brands Lithonia <sup>F</sup> | 72     | 7137  | 99 <sup>G</sup> | 72                    | 7665  | 106  | 72     | 7712  | 107  | -7% <sup>G</sup>                | -1%              |

<sup>A</sup> Evolve ERL1-Type 2 Med

<sup>B</sup> RSW-S1-Type 2 Med

<sup>C</sup> Galleon LED T2 1000mA

<sup>D</sup> WP9L2P70/120LED

<sup>E</sup> GCJ1-20H-3-450S-5000K

<sup>F</sup> DSX0 LED 20C 1000 T2M

<sup>G</sup> The manufacturer reports reducing the CRI of the 3000K version of this product from 80 to 70 to achieve higher efficacy.

Accurate comparison between products at different CCTs is complicated by the various methods manufacturers use to preserve efficacy, as noted above. However, all such tradeoffs in luminaire characteristics and CCT choices should be evaluated at the time of product selection to optimize the benefits for the specific project.

## 9.2 Visual acuity, scene brightness, and possible safety implications

Short wavelengths are a part of the natural day and night spectrum around which our vision has evolved. Reducing the content of short wavelengths may therefore carry tradeoffs in visual performance and perceptions of brightness that need to be considered when designing a street lighting system. The spectrum affects both the luminance contrast and the color contrast of the object, and thus affects the ability to see and recognize the task and situation even when our sensitivity to color is diminished under nighttime light levels.

The source of the visibility and brightness improvement from broader-band spectrum sources is not completely understood. The IES<sup>36</sup> and the CIE<sup>37</sup> acknowledge improvement in off-axis visibility for drivers due to scotopic content in the SPD, probably due to the blue-shifted sensitivity of the rods and the preponderance of rods in the periphery of the retina, but more research will be required to fully explain this phenomenon.

Studies in Seattle<sup>38</sup> and San Jose<sup>39</sup> suggest that color contrast may play a role in a driver's ability to detect an obstacle or pedestrian from a greater distance, enabling earlier braking time. Although more research is again needed, it stands to reason that there may be associated safety implications from reducing or eliminating short wavelengths from a street lighting source.

## 9.3 Sky glow from street lighting in context

Sky glow results from a complex combination of light released to the exterior environment within a region. In addition to street lighting, other sources of light at night include area lighting (e.g., surface parking lots and parking garages, pedestrian pathways and building campuses, recreational parks and athletic fields, and residential porch lights), advertisements and signage, vehicles, exterior building architectural lighting, and building interior lighting escaping from windows and skylights (see Figure 20).



Figure 20 Many sources of light contribute to sky glow.

While a street light would typically have a much higher light output than, for instance, light escaping a single office or storefront window, the uplight component of the latter may be greater due to a complete lack of directional control. Furthermore, the aggregate contribution may be quite substantial, as suggested in Figure 21.

<sup>36</sup> Illuminating Engineering Society. Spectral effects of lighting on visual performance at mesopic light levels, TM-12, 2006.

<sup>37</sup> Commission Internationale de L'Eclairage, "Recommended System for Mesopic Photometry Based on Visual Performance," CIE Report (Vienna Austria), vol. 191, 2010.

<sup>38</sup> Seattle LED Adaptive Lighting Study, 2014: <https://neea.org/docs/default-source/reports/seattle-led-adaptive-lighting-study.pdf?sfvrsn=4>.

<sup>39</sup> City of San Jose Advanced street lighting technologies assessment project, 2010: <http://www.sanjoseca.gov/DocumentCenter/View/18941>.



Building lighting is predominately characterized by broad spectrum sources at 3000 K, and frequently higher, CCTs. Associated sky glow is thereby likely to be significant, but there appears to be a relative lack of focus on this source and its corresponding contributions to date.



**Figure 21 High-angle lighting primarily from building interiors.** All light visible from this point of view is being emitted above the horizontal plane.

Table 6 was assembled in response to recent concerns from the medical community about “blue” wavelength content in LED sources, with a focus on street lighting.<sup>40</sup> The table reveals that blue wavelength content is generally similar among different lighting sources at similar CCTs (though individual products can range somewhat due to differences in their SPDs). Note that the sources listed include many commonly used in interior and exterior applications. All broad-spectrum lighting exposed to the night environment thus has the potential to be of concern, with respect to contributions to sky glow.

The model runs described in this study illustrated that uplight exerts an oversized influence on sky glow and that the influence generally increases with SPDs containing higher levels of short wavelength energy, especially if weighting the results for scotopic visibility. Heavily populated metro areas thereby have potentially substantial contributions to sky glow from non-street lighting sources. This is emphasized following LED lighting conversions where direct uplight from the older street lighting has been largely eliminated. Estimation of the relative contributions of non-street lighting sources has received only limited attention in the literature to date, however, and deserves further investigation.

Ultimately, cities should proceed through their street lighting design and selection process with as much knowledge as possible of the benefits and trade-offs of the different options available in order to have realistic expectations of the results. This recommendation holds whether the topic of interest is energy use, lighting quality, associated issues like sky glow, or achieving the best balance among all of the above.

<sup>40</sup> See the related *Light Post* newsletter: [http://energy.gov/sites/prod/files/2016/07/f33/msslc\\_enews\\_jul2016.pdf](http://energy.gov/sites/prod/files/2016/07/f33/msslc_enews_jul2016.pdf).

**Table 6** Selected blue light characteristics of various outdoor lighting sources at equivalent light output.

| Row | Light source          | Luminous  |                   | % Blue*   | Relative Scotopic | Relative Melanopic |
|-----|-----------------------|-----------|-------------------|-----------|-------------------|--------------------|
|     |                       | Flux (lm) | CCT (K)           |           | Content           | Content**          |
| A   | PC White LED          | 1000      | 2700              | 17% - 20% | 1.77 - 2.20       | 1.90 - 2.68        |
| B   | PC White LED          | 1000      | 3000              | 18% - 25% | 1.89 - 2.39       | 2.10 - 2.99        |
| C   | PC White LED          | 1000      | 3500              | 22% - 27% | 2.04 - 2.73       | 2.34 - 3.57        |
| D   | PC White LED          | 1000      | 4000              | 27% - 32% | 2.10 - 2.65       | 2.35 - 3.40        |
| E   | PC White LED          | 1000      | 4500              | 31% - 35% | 2.35 - 2.85       | 2.75 - 3.81        |
| F   | PC White LED          | 1000      | 5000              | 34% - 39% | 2.60 - 2.89       | 3.18 - 3.74        |
| G   | PC White LED          | 1000      | 5700              | 39% - 43% | 2.77 - 3.31       | 3.44 - 4.52        |
| H   | PC White LED          | 1000      | 6500              | 43% - 48% | 3.27 - 3.96       | 4.38 - 5.84        |
| I   | Narrowband Amber LED  | 1000      | 1606              | 0%        | 0.36              | 0.12               |
| J   | Low Pressure Sodium   | 1000      | 1718              | 0%        | 0.34              | 0.10               |
| K   | PC Amber LED          | 1000      | 1872              | 1%        | 0.70              | 0.42               |
| L   | High Pressure Sodium  | 1000      | 1959              | 9%        | 0.89              | 0.86               |
| M   | High Pressure Sodium  | 1000      | 2041              | 10%       | 1.00              | 1.00               |
| N   | Mercury Vapor         | 1000      | 6924              | 36%       | 2.33              | 2.47               |
| O   | Mercury Vapor         | 1000      | 4037              | 35%       | 2.13              | 2.51               |
| P   | Metal Halide          | 1000      | 3145              | 24%       | 2.16              | 2.56               |
| Q   | Metal Halide          | 1000      | 4002              | 33%       | 2.53              | 3.16               |
| R   | Metal Halide          | 1000      | 4041              | 35%       | 2.84              | 3.75               |
| S   | Moonlight             | 1000      | 4681 <sup>†</sup> | 29%       | 3.33              | 4.56               |
| T   | Incandescent          | 1010      | 2836              | 12%       | 2.23              | 2.73               |
| U   | Halogen               | 1000      | 2934              | 13%       | 2.28              | 2.81               |
| V   | F32T8/830 Fluorescent | 1000      | 2940              | 20%       | 2.02              | 2.29               |
| W   | F32T8/835 Fluorescent | 1000      | 3480              | 26%       | 2.37              | 2.87               |
| X   | F32T8/841 Fluorescent | 1000      | 3969              | 30%       | 2.58              | 3.18               |

\* Percent blue calculated according to LSPDD: Light Spectral Power Distribution Database, <http://galileo.graphyics.cegepsheerbrooke.qc.ca/app/en/home>. The specific calculation, developed for evaluating the potential for affecting sky glow, divides the radiant power contained in the wavelengths between 405 and 530 nm by the total radiant power contained from 380 to 730 nm, for each light source.

\*\* Melanopic content calculated according to CIE Irradiance Toolbox, [http://files.cie.co.at/784\\_TN003\\_Toolbox.xls](http://files.cie.co.at/784_TN003_Toolbox.xls), 2015 as derived from [Lucas et al., 2014](#).

**Key:** PC -- phosphor converted

LED -- light emitting diode

<sup>†</sup> Moonlight CCT measured and provided by Teelumen, LLC.

## 10 Conclusions

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Multiple factors contribute to the level of sky glow produced in any location, and the level likely changes with the combination of those factors (and sometimes dynamically as factors such as weather vary over time). A related consideration is that street lighting is only one of many sources of light at night in urban areas. The findings in this study consequently represent only the estimated contributions to sky glow from the street lighting system under the conditions considered, and may not even address the primary sources of sky glow contribution in locations like large urban areas.

The short wavelength content of broad-spectrum sources like LEDs is only one element within the street lighting system. Other characteristics of modern street lighting luminaires can reduce or, in some cases, even eliminate the effects of wavelength content on sky glow. The three main characteristics of luminaires that influence sky glow are SPD, total light output, and light distribution (and, most importantly, the amount emitted as uplight above the horizontal plane). Each of these characteristics can be varied during at least the initial selection of products and should therefore be carefully evaluated as part of the system design.

External factors also influence the relative amount of sky glow that a given observer receives, such as the observer's location relative to the source of the light (especially their distance from it), the size of the source (i.e., city size), and the atmospheric conditions at the time. These points are of interest but may or may not be of value to someone planning an installation since they are largely outside of the range of influence of those plans.

This investigation looked at relative sky glow values produced by varying one factor at a time, so that the effect of SPD, for example, can be compared between sources with all other factors being equal. This investigation also looked at relative sky glow for a typical LED streetlight retrofit in the U.S., where lumen output is reduced by half, and uplight from a glass refractor HPS cobra head is replaced with a luminaire directing light downward only. The results of this common scenario show that, for residents near the city, the visible contribution to sky glow from a typical LED street light conversion in the U.S.<sup>41</sup> should be no worse than before, and may possibly improve, relative to the system being replaced. In terms of impact specific to astronomical observation, the overall contribution to sky glow from the street light system should be considerably reduced (by perhaps more than half) for any observatories near the city. Within some relatively short distance outside the city, the sky glow contribution from this typical street light system conversion appears to substantially diminish at all SPDs (and CCTs), for all observers.

Compared to the 4000 K street lighting systems that much of the country has installed to date, additional reductions in the contribution to sky glow can be pursued through approaches such as adding a dimming system, eliminating unneeded street lights, or moving to a 3000 K (or lower CCT) standard. However, in this latter case, the specific SPDs of the products under consideration must be examined to confirm that a reduction is being achieved. The merits of doing so should be evaluated case by case, carefully comparing the additional collective benefits with any tradeoffs.

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<sup>41</sup> A typical street lighting conversion is here defined to mean the replacement of HPS fixtures with 2% uplight with LED products at half the light output and 0% uplight.

## Appendix A: Sky Glow Models Reviewed

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The modeling of proposed changes in ground-based light sources could be very helpful in designing optimum parameters of outdoor lighting for a given location, if the model's use is straightforward enough for members of the general lighting community. Numerous models exist to estimate sky glow by approximating the distribution of scattered light, but they vary in complexity and transparency of operation.<sup>1</sup> The selection of a model depends on the accuracy required as well as the size of the input data and sensitivity to physical parameters.

This section briefly compares three sky glow models developed to date.

### The Garstang model

Originally developed in the 1980s and designed to execute on an Apple II computer of that era, the methodology used in this model has become a standard reference for subsequent models.<sup>2</sup> Garstang's approach is typically used to predict the effects of outdoor lighting on sky brightness for an observer some distance from the city center. Along a given path through the atmosphere, the model estimates the amount of light scattered, as well as the amount removed by extinction (i.e., attenuation via both scattering and absorption). Garstang's model assumes all light is emitted at 550 nm. A two-component atmosphere is modeled, consisting of molecules and aerosols, with the amount of aerosol defined through a parameter K, which sets the ratio of total molecular (Rayleigh) to aerosol (Mie) scattering. It has been used to predict and evaluate the effects of outdoor lighting on sky glow at astronomical observatories.

The Garstang model was developed using measures of sky brightness to deduce unknown characteristics of on-the-ground lighting—a sky-down approach. It predicts sky glow based on assumed ground lighting characteristics, including total lumen output based on population estimates and assumed lumens per capita, the fraction of light emitted above horizontal (10% uplight), and the average ground albedo. The model assumes the uplight is emitted close to horizontal plane and the reflected component from the ground is reflected in a Lambertian distribution. Together, they form a composite street lighting distribution. The model addresses the radiative transfer portion of the problem through molecular and aerosol scattering and absorption, has provisions for absorptive (haze) layers, and has differing altitudes between light sources (e.g., cities) and corresponding observation points.

### Luginbuhl's modifications to Garstang's model

Luginbuhl reported that "[t]he standard Garstang model...clearly predicts a much brighter sky than that measured."<sup>3</sup> Several factors likely contribute to this observation. Garstang assumed there is no atmosphere between light fixtures and the ground; thus, all downward-directed lighting is undiminished by atmospheric

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<sup>1</sup> For example, a number of examples can be found by searching the internet on the phrase "sky glow model" plus the following additions: Garstang 1991, Cinzano et al. 2000, Gillet et al. 2001, Aube et al. 2005, Baddiley 2007, Kocifaj 2007, Luginbuhl et al. 2009, Kocifaj 2010, Kocifaj et al. 2010, Cinzano and Falchi 2012, Kocifaj et al. 2014, Luginbuhl et al. 2014, Aube 2015, Kollath et al. 2016.

<sup>2</sup> R. H. Garstang. 'Model for Artificial Night-Sky Illumination.' *Publications of the Astronomical Society of the Pacific*, vol. 98, no. 601, 1986, pp. 364-375.

<sup>3</sup> C. Luginbuhl et al. 'From the Ground Up II: Sky Glow and Near-Ground Artificial Light Propagation in Flagstaff, Arizona.' *Publications of the Astronomical Society of the Pacific*, vol. 121, 2009, pp. 204-212.

scattering or absorption. Also, all ground near the sources is assumed flat and horizontal.<sup>4</sup> The model furthermore assumes a fixed fraction of the flux is emitted upward, which is increasingly out of date with the expanded use of modern U0 rated luminaires.<sup>5</sup> All rays reflected from the ground or emitted from fixtures directly upward propagate into the atmosphere, unimpeded by further interaction with surfaces. Thus, the upward intensity distribution function assumed by Garstang (Figure A.1, left) and similar functions, heavily weighted toward the horizon, are unlikely to represent the actual upward light distribution in most cities.

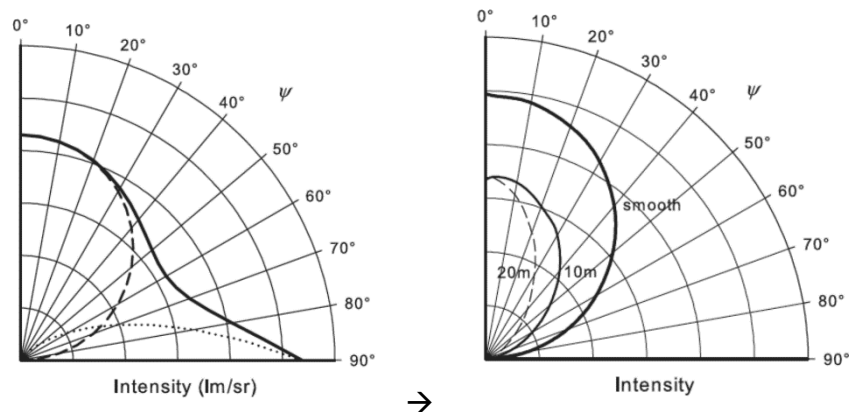


**Figure A.1 Mapped upward intensity distribution of Garstang's model (left) compared with Luginbuhl's modifications (right).** Left: reflected component (15%) of the downward-emitted light (dashed line) along with the direct upward component (10%) (dotted line) together yield upward intensity angular distribution (solid line). Right: smooth earth simulation (solid line) compared with intensity distribution when light fixture is immersed in an array of buildings (inner curves).

Luginbuhl investigated the effects of the near-ground environment by developing specific built environments that accounted for light distribution from specific fixtures, and then studied the resulting impact on the propagation of light (Figure A.1, right). Near-ground extinction is also incorporated through a combination of the direct blocking of some fraction of the near-ground light so the emitted light never reaches the ground and subsequent blocking of reflected rays that consequently never reach the atmosphere. Luginbuhl's follow-up work looked at the effect of light source spectral power distribution (SPD) on sky brightness so as to no longer assume monochromatic radiation.<sup>6</sup>

## ILLUMINA<sup>7</sup>

The difficulty of predicting atmospheric behavior with acceptable precision is well recognized in the field of weather forecasting. Similarly, although a simple sky glow model may provide a cursory estimate of light scatter and propagation in the atmosphere, a supercomputer is usually required to process large amounts of data to help increase confidence in the predictions. For the scope of this paper, Garstang's model is considered "simple" and ILLUMINA the opposite.

<sup>4</sup> In reality, if a portion of the light exiting the fixture strikes a surface oriented perpendicular to ground (e.g., the side of a building), no more than 50% of reflected light will be directed upward, which most heavily affects rays directed close to horizontal.

<sup>5</sup> Illuminating Engineering Society Technical Memorandum 15-2011, Luminaire classification system for outdoor luminaires.

<sup>6</sup> C. Luginbuhl, P. Boley, and D. Davis. 'The impact of light source spectral power distribution on sky glow.' *Journal of Quantitative Spectroscopy & Radiative Transfer*, vol. 139, 2014, pp. 21-26.

<sup>7</sup> Wiki de Martin Aube – ILLUMINA project: Heterogeneous modeling of artificial sky radiance.

Project page: <http://cegepsheerbrooke.qc.ca/~aubema/index.php/Prof/IllumEn>

Read me: <https://bitbucket.org/aubema/illumina>

User's guide: <http://cegepsheerbrooke.qc.ca/~aubema/index.php/Prof/IlluminaGuide2016>

ILLUMINA (developed by Martin Aubé) is an open-source, voxel-based, radiative flux transfer program that can require weeks to run on a supercomputer with several thousand CPUs and terabytes of RAM.<sup>8,9</sup> The model is currently housed at Cégep de Sherbrooke in Canada. Although Garstang's model includes an *ad hoc* term for double scattering, it is not possible to determine whether it correctly models the atmospheric optics. Instead of an *ad hoc* term, ILLUMINA considers diffuse reflections from the ground and in-scattering of scattered light from volumes *m* into the volumes *n* visible to the observer (see Figure A.2).

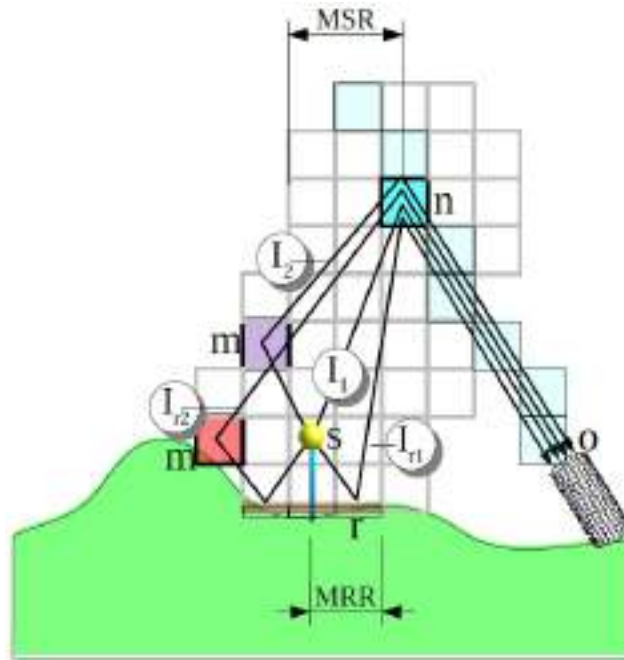


**Figure A.2** ILLUMINA considers diffuse reflections from the ground and in-scattering of scattered light from volumes *m* into the volumes *n* visible to the observer. This graphic shows the contribution of the received flux by a spectrometer in position *o*. The animation in the following link shows the 3D calculation of single and double scattering with or without reflection on the ground: <http://cegepshebrooke.qc.ca/~aubema/index.php/Prof/IllumEn?action=download&upname=illum-anim.gif>.

Aubé decided to implement a heterogeneous sky glow model that allows the simulation of real situations (e.g., a city of any shape, geographical distribution of light, spectral luminosity and angular emission patterns, ground spectral reflectance variability, and topography). Remotely sensed satellite data is used to determine the terrestrial information, such as luminosity data, ground albedo, and topography instead of assuming a population density to light intensity relationship as is the case in most models. ILLUMINA was designed to simulate light scattered back to a spectrometer. The approach is similar to ray-tracing software: essentially a set of photons emitted from luminaires in combination with respective interactions with the ground, molecules, and aerosols. These interactions are computed along light-paths toward a simulated observer for a given voxel intersecting a viewing angle (composed of zenith and azimuth angles). A spectrometer was subsequently designed so it could be used to validate model results or simply monitor sky glow for specific sites. The model can also be used independently to simulate the fraction of sky glow due to the molecules and atmospheric aerosols, based on the assumption that the composition and vertical profile of aerosols are horizontally uniform over the modeling domain.

<sup>8</sup> M. Aubé et al. 'Light Pollution Modelling and Detection in a Heterogeneous Environment: Toward a Night Time Aerosol Optical Depth Retrieval Method.' *Proceedings of SPIE*, vol. 5890, no. 248, 2005.

<sup>9</sup> M. Aubé. 'Light Pollution Modeling and Detection in a Heterogeneous Environment.' *STARLIGHT Proceedings*, 2007, pp. 119-126.



ILLUMINA also gives two maps as standard output: 1) a radiance contribution map (RCM) that provides the contribution of each squared kilometer sea-level footprint of the domain to the sky radiance and 2) a radiance per lumen sensitivity map (RSM) that provides the contribution of each squared kilometer sea-level footprint of the domain to the sky radiance per lumen installed. RCM allows for the identification of the origin of the radiance whereas RSM gives a map of the most critical zones in terms of possible increases or decreases of radiance with any change in light-fixture inventory.

## Appendix B: Graphs

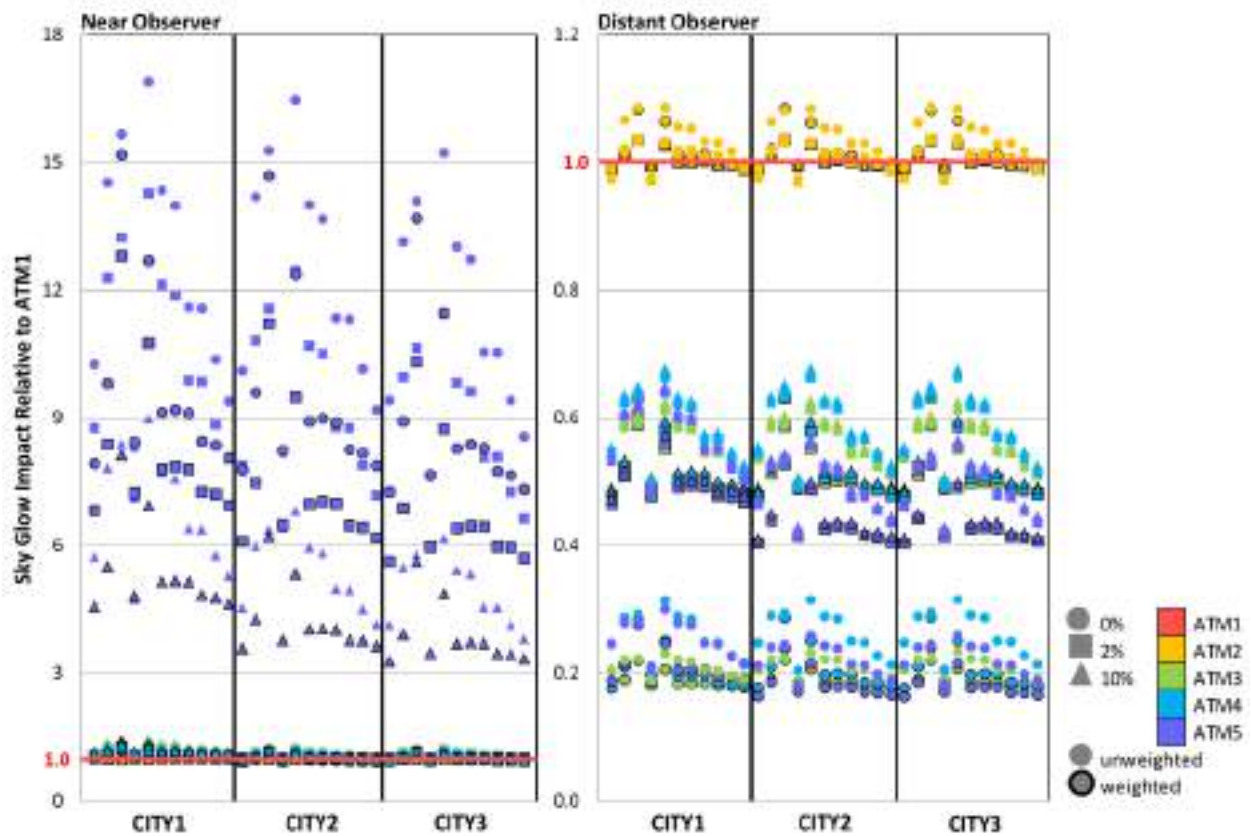


**Figure B.1 Relative impacts of the atmospheric conditions for the near and distant observer positions.** The relative impacts of all atmospheric conditions compared to ATM1 are graphed for each city and all SPDs based on their percent uplight (0%, 2%, 10%). Both the unweighted and scotopically weighted results are graphed. The graph on the left, for the near observer, shows the significant increase in sky glow due to clouds, including the increase in sky glow that comes from decreasing uplight (for the cloudy condition only). The graph on the right, for the distant observer, shows the influence more turbulent and cloudy atmospheres have to decrease sky glow. Unlike the graph for the near observer, decreasing the percent uplight decreases sky glow, also denoted by the arrows.



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## Towards a comprehensive city emission function (CCEF)

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## ABSTRACT

The comprehensive city emission function (CCEF) is developed for a heterogeneous light-emitting or blocking urban environments, embracing any combination of input parameters that characterize linear dimensions in the system (size and distances between buildings or luminaires), properties of light-emitting elements (such as luminous building façades and street lighting), ground reflectance and total uplight-fraction, all of these defined for an arbitrarily sized 2D area. The analytical formula obtained is not restricted to a single model class as it can capture any specific light-emission feature for wide range of cities. The CCEF method is numerically fast in contrast to what can be expected of other probabilistic approaches that rely on repeated random sampling. Hence the present solution has great potential in light-pollution modeling and can be included in larger numerical models. Our theoretical findings promise great progress in light-pollution modeling as this is the first time an analytical solution to city emission function (CEF) has been developed that depends on statistical mean size and height of city buildings, inter-building separation, prevailing heights of light fixtures, lighting density, and other factors such as e.g. luminaire light output and light distribution, including the amount of uplight, and representative city size. The model is validated for sensitivity and specificity pertinent to combinations of input parameters in order to test its behavior under various conditions, including those that can occur in complex urban environments. It is demonstrated that the solution model succeeds in reproducing a light emission peak at some elevated zenith angles and is consistent with reduced rather than enhanced emission in directions nearly parallel to the ground.

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## 1. Introduction

Currently, there is no doubt that over-illumination of nocturnal environments is constantly growing and is already a multi-faceted global issue of concern for at least imposing an unacceptable burden on nature [7]. Artificial lighting at night significantly reduces the quality of astronomical data or even precludes or degrades traditional astronomical observations. We need to deal urgently with the fundamental principles of light propagation and control in a nighttime atmosphere, particularly atmospheric optics and interactions between electromagnetic fields and environments. Theoretically founded formulation of light propagation in nighttime atmospheres can yield a sound understanding of light pollution phenomena. Atmospheric optics [9] and lighting technology [3, 14] are among the primary sources of uncertainty in predicting the collec-

tive optical effects that all city lights can have on the diffuse light of a night sky.

Technology characteristics can usually be determined in laboratories. However, the cumulative light emission from all structures in a heterogeneous light-emitting and blocking urban environment is difficult to obtain, and still remains inadequately quantified.

We use the term city emission function (CEF) throughout this paper to characterize cumulative radiant intensity function (otherwise called upward intensity angular distribution function) of ground-based light sources [15]. In some cases CEF is also interpreted in terms of luminous intensity distribution [10].

One of the first serious works on radiant intensity function of all city light dates back to Garstang, who developed an empirical formula for CEF based on observations in Denver, Colorado [6]. His model is constructed on a principle of weighted contributions of diffuse ground reflection and direct emission upwards and can predict the sky brightness arising from artificial light sources successfully when extended to account for blocking of light rays by objects in the near-ground environment [13]. Despite being a simple and easy use concept of Garstang's CEF (G-CEF), currently it is

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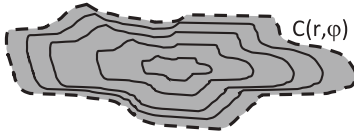


Fig. 1. Light-emitting city-area bounded by a closed curve  $C(r, \varphi)$ .

uncertain whether G-CEF is quantitatively reliable for many cities because it most probably overestimates the amount of light beams directed at low elevation angles (see e.g. [11]). In addition, G-CEF is not related to parameters such as, e.g. characteristic size/height of buildings, prevailing height of light fixtures, inter-building distance, etc., which may be decisive in forming the CEF.

Currently, we are not aware of any model that embraces all topography, luminous building façades, street lighting, or other luminous or blocking constructs. Basically, a universal model that takes all urban elements into account is almost impossible to construct because of extremely large multi-relational data sets. For instance, the light beams emitted from  $M$  lamps can, in principle, interact with  $N$  obstacles, thus resulting in many-to-many ( $M:N$ ) relations that are difficult to treat even if  $M$  and  $N$  are as low as, e.g. 100. It is not only the number of possible combinations ( $100 \times 100$ ), but also the complexity of the input data configuration that make such a CPU-intensive modeling unattractive. Note that, e.g. buildings are 3D objects, so the number of runs needed to characterize the system numerically will exceed the value of 10,000 significantly. Therefore an analytic-statistical approach is preferred to solve the problem of cumulative light emissions from a city or town.

In this paper, we present a new model of CEF that is a function of physical sizes of buildings and light fixtures including statistically averaged distances between these system elements. We will use the term CCEF wherever it is needed. Such emission function is of great importance in estimating night sky brightness from many electrical light sources randomly distributed in a heterogeneous urban environment. Note that the angular distribution of light intensity emitted upwards from cities is also important to predict brightness maps at satellite level [4, 5]. In our paper we present a completely new, previously unpublished, solution to the CEF that accounts for statistical variations in all structures in urban environments. The numerical model is validated for consistency with experimental experiences and basic physical principles. In fact, it is the first time such a model of CCEF is introduced to the scientific community, so we expect it can prove useful especially to light pollution modelers, city planners, lighting engineers, and also many other groups including astronomers, biologists or environmentalists who can use it in many practical situations.

## 2. Buildings as light-emitting and blocking urban elements

Given the heterogeneous distribution of sizes, positions, and orientations of residential, commercial and other buildings in the urban environment the statistical approach appears to be the only reasonable option in the mass modeling of cumulative light emission from all structures, while hoping the underlying mathematics can be easily absorbed by light-pollution researchers.

Hence, let us assume that a radial distance  $r = R(\varphi)$  of any point at the outer edge of a city or town is measured from the center of the coordinate system (usually the center of a city), while the azimuth angle  $\varphi$  ranges from 0 to  $2\pi$ . Then one can draw a closed curve  $C(r, \varphi)$  which bounds a light-emitting city-area at any distance  $r = r(\varphi)$  (see Fig. 1), including  $C(R, \varphi)$  at  $r = R(\varphi)$ .

Light emissions from an elementary city-area  $dS$  due to buildings (subscript  $B$ ) is

$$dE_B^\uparrow(z) = \rho_B \cdot \underbrace{r(\varphi) d\varphi dr}_{dS} \cdot \varepsilon_B(z) P_B(r, \varphi, z, H), \quad (1)$$

provided that  $\rho_B$  is the building density (number of buildings per unit area of a city or town), and  $P_B$  is the probability that the photons emitted from a building are not removed by city structures and reach the atmosphere. The total light emission  $\varepsilon_B(z)$ , i.e. the radiant or luminous intensity function, is averaged azimuthally because buildings typically have various azimuthal orientations. In Eq. (1)  $H$  is a statistical average of building heights.

Consider a building with an average vertical dimension  $H$  is situated at the position  $r(\varphi)$  and emits the light towards zenith angle  $z$ . If the distance to the nearest building is  $r'$ , then the probability  $P_B$  is a sum of two functions

$$P_{B,1}(r, \varphi, z, H) = H_e^m\left(\frac{r'}{H \tan z}\right) + \left[1 - H_e^m\left(\frac{r'}{H \tan z}\right)\right] \left(\frac{D - \ell}{D}\right). \quad (2)$$

The first term at right-hand-side (RHS) of Eq. (2) is to characterize the fraction of light beams that do not interact with the nearest building. Here  $H_e^m$  is the modified Heaviside function satisfying the following conditions

$$\begin{aligned} H_e^m(x) &= x & ; & \quad x \in \langle 0, 1 \rangle \\ H_e^m(x) &= 0 & ; & \quad x < 0 \\ H_e^m(x) &= 1 & ; & \quad x > 1. \end{aligned} \quad (3)$$

The remaining fraction of light  $(1 - H_e^m)$  would be completely removed only if the nearest buildings form a compact barrier which prevents photons directed towards the angle  $z$  to escape from a local building. In real situations the probability that these beams will not be extinguished by an array of buildings is proportional to  $(D - \ell)/D$ , where  $D$  is inter-building separation and  $\ell$  is the characteristic horizontal dimension of a building (see Fig. 2).

Assuming  $\ell = 0$  the probability that light beams illuminate the atmosphere is unity for any values of  $r'$ ,  $H, z$ :

$$P_{B,1}(r, \varphi, z, H)_{\ell=0} = H_e^m\left(\frac{r'}{H \tan z}\right) + \left[1 - H_e^m\left(\frac{r'}{H \tan z}\right)\right] \equiv 1. \quad (4)$$

Eq. (4) models a single light-emitting building in a non-blocking environment. In contrast, a continuous compact array of buildings can be simulated by placing  $\ell = D$ , thus resulting in

$$P_{B,1}(r, \varphi, z, H)_{\ell=D} = H_e^m\left(\frac{r'}{H \tan z}\right). \quad (5)$$

The spaces between buildings permit a part of light beams to propagate even at low elevation angles, however, this light can potentially interact with distant buildings, so the second-order approximation to Eq. (2) is as follows

$$\begin{aligned} P_{B,2}(r, \varphi, z, H) &= H_e^m\left(\frac{r'}{H \tan z}\right) \\ &+ \left[1 - H_e^m\left(\frac{r'}{H \tan z}\right)\right] \left(\frac{D - \ell}{D}\right) \cdot \left\{ H_e^m\left(\frac{r' + D}{H \tan z}\right) \right. \\ &+ \left. \left[1 - H_e^m\left(\frac{r' + D}{H \tan z}\right)\right] \left(\frac{D - \ell}{D}\right) \right\}. \end{aligned} \quad (6)$$

The above concept is applicable in derivation of a higher accuracy iterative formula for the probability function  $P_{B,N}(r, \varphi, z, H)$  that models an interaction of light beams with  $N$  arrays of buildings. The model proposed assumes that the lattice spacing is  $D$ , so the estimated distance to  $i$ th obstacle is  $r' + iD$  and the cumulative probability  $P_B$  for all light-blocking constructs is obtained in the form

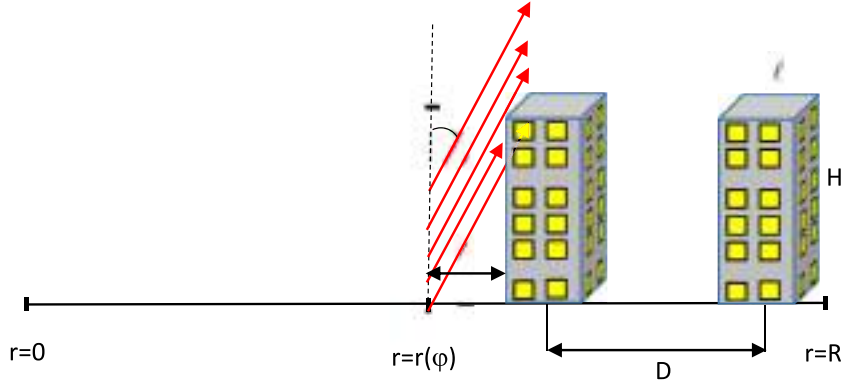


Fig. 2. Buildings as light-emitting and/or blocking urban elements.

$$P_{B,N}(r, \varphi, z, H) = \sum_{n=1}^N \left\{ \left( \prod_{i=0}^{n-2} \left[ 1 - H_e^m \left( \frac{r' + iD}{H \tan z} \right) \right] \right) \left( \frac{D - \ell}{D} \right)^{n-1} \times H_e^m \left( \frac{r' + nD - D}{H \tan z} \right) \right\} + \left( \prod_{i=0}^{N-1} \left[ 1 - H_e^m \left( \frac{r' + iD}{H \tan z} \right) \right] \right) \left( \frac{D - \ell}{D} \right)^N \quad (7)$$

The first few terms in the above series are as follows:

$$n - 1 = 0 : H_e^m(i = 0)$$

$$n - 1 = 1 : [1 - H_e^m(i = 0)] \left( \frac{D - \ell}{D} \right) H_e^m(i = 1)$$

$$n - 1 = 2 : [1 - H_e^m(i = 0)] [1 - H_e^m(i = 1)] \left( \frac{D - \ell}{D} \right)^2 H_e^m(i = 2)$$

...

$$k = n - 1 : \left( \prod_{i=0}^{k-1} [1 - H_e^m(i)] \right) \left( \frac{D - \ell}{D} \right)^k H_e^m(k) + \text{last term}, \quad (8)$$

where  $H_e^m(i)$  is a symbolic notation for the function  $H_e^m \left( \frac{r' + iD}{H \tan z} \right)$ , while 'last term' reads  $\left( \prod_{i=0}^k [1 - H_e^m(i)] \right) \left( \frac{D - \ell}{D} \right)^{k+1}$ . For a city with the surface density distribution of buildings as given earlier, a cursory estimate of  $N$  at the position  $r$  is

$$N = \text{floor} \left( \frac{R(\varphi) - r(\varphi) - \ell}{D} \right) \equiv \text{int} \left( \frac{R(\varphi) - r(\varphi) - \ell}{D} \right), \quad (9)$$

meaning that  $N$  is (integer) remainder after dividing  $R(\varphi) - r(\varphi) - \ell$  by  $D$ . Normally, a city or town is a large collection of houses, buildings and streets, so the value of  $N$  is expected to be large enough. Then the differential form  $dE_B^\uparrow(z)$  is formulated

$$dE_B^\uparrow(z) = \rho_B \cdot C(r(\varphi)) \cdot dr \cdot \varepsilon_B(z) P_B(r, \varphi, z, H), \quad (10)$$

where  $C(r(\varphi))$  is a strip length for a closed curve  $r(\varphi)$  and  $D$  is a strip width. Given that the characteristic dimension of a city exceeds the value of  $D$  by a factor of 10 or even more, and because  $P_B(r, \varphi, z, H)$  is a function of  $r'$  rather than  $r$ , we can transform Eq. (10) for a given strip into a more suitable form

$$\Delta E_B^\uparrow(z, r) = \rho_B \cdot C(r) \cdot \varepsilon_B(z) \int_{r^*=r}^{r^*=r+D} P_B(r^*, \varphi, z, H) dr^*. \quad (11)$$

Substituting the  $r^*$  with  $r' = r^* - r$  we obtain

$$\Delta E_B^\uparrow(z, r) = \rho_B \cdot C(r) \cdot \varepsilon_B(z) \int_0^D P_B(r', \varphi, z, H) dr'. \quad (12)$$

Note that the integral at RHS of Eq. (12) is independent of  $r$  for large values of  $N$ , so the total light emission from all buildings can be approximated by an algebraic representation

$$E_B^\uparrow(z) = \rho_B \cdot \left( \sum_i C_i \right) \cdot \varepsilon_B(z) \int_0^D P_B(r', \varphi, z, H) dr', \quad (13)$$

where the following recurrence relation is roughly applicable to a closed curve  $C(r, \varphi)$

$$C_{i+1} = \int_0^{2\pi} r_{i+1}(\varphi) d\varphi \cong \int_0^{2\pi} [r_i(\varphi) + D] d\varphi = C_i + k 2\pi D. \quad (14)$$

The coefficient of proportionality  $k = 1$  is only for circular strips, otherwise  $k > 1$ . For instance, an ellipse with a surface area equivalent to that of the circle with radius of  $r$  has

$$k_{\text{ellipse}} \cong \frac{1}{\sqrt{1 - \varepsilon^2}} \left[ 1 - \left( \frac{1}{2} \right)^2 \varepsilon^2 - \left( \frac{1 \cdot 3}{2 \cdot 4} \right)^2 \frac{\varepsilon^4}{3} - \left( \frac{1 \cdot 3 \cdot 5}{2 \cdot 4 \cdot 6} \right)^2 \frac{\varepsilon^6}{5} - \dots \right], \quad (15)$$

Considering Eq. (14), the sum of a finite sequence of  $C_i$  in Eq. (13) is

$$\begin{aligned} \left( \sum_i C_i \right) &= C_0 + C_1 + C_2 + \dots + C_N \cong \\ &= C_0 + (C_0 + k 2\pi \cdot D) + (C_0 + k 2\pi \cdot 2D) + \dots + (C_0 + k 2\pi \cdot ND) = \\ &= NC_0 + k 2\pi D(1 + 2 + \dots + N) = N[C_0 + k \pi D(N + 1)], \end{aligned} \quad (16)$$

while the following simplification

$$\left( \sum_i C_i \right) \cong N[C_0 + k \pi D(N + 1)] \cong k \pi D N^2 \quad (17)$$

can be adopted because the inequality  $C_0 < \pi D(N + 1)$  is valid for sufficiently large values of  $N$ . Replacing the light-emitting surface area  $S$

$$S = \int_{\varphi=0}^{2\pi} d\varphi \int_{r=0}^{R(\varphi)} r dr \cong D \sum_i C_i \quad (18)$$

with the area-equivalent circle  $\pi \tilde{R}^2$  we can express Eq. (17) as follows

$$\left( \sum_i C_i \right) \cong \frac{\pi \tilde{R}^2}{D}, \quad (19)$$

so the cumulative radiant intensity of all city buildings is

$$E_B^\uparrow(z) = \frac{\pi \tilde{R}^2}{D^3} \cdot \varepsilon_B(z) \int_0^D P_B(r', \varphi, z, H) dr', \quad (20)$$

where  $\rho_B = D^{-2}$  was adopted. This formula is easy to obtain. Let us consider  $N_x$  buildings separated along the x-axis and  $N_y$  buildings along y-axis. For the surface grid in the x–y plane we have  $N = N_x N_y$  buildings distributed over the area of  $N_x D \cdot N_y D$ , because the inter-building separation is  $D$ . The surface density is then  $\rho_B = N_x N_y / (N_x D \cdot N_y D) = 1/D^2$ .

### 3. A role of light fixtures in cumulative light emissions

In analogy with Eq. (1) we model light emissions from public lighting as follows

$$dE_L^\uparrow(z) = \rho_L \cdot \underbrace{r(\varphi) d\varphi}_{ds} \cdot \varepsilon_L(z) P_L(r, \varphi, z, \hbar), \quad (21)$$

where  $\hbar$  is a statistical average of light fixture vertical dimensions,  $\rho_L$  is the lighting density (number of lamps per unit area), and  $P_L$  is the probability that the public light escapes the city at angle  $z$ , i.e. the light emissions  $\varepsilon_L(z)$  are neither attenuated nor eliminated by any means. The probability function  $P_L$  has the same form as  $P_B$  except for  $H_e^m$  which should be replaced by a regular Heaviside function  $H_e$

$$H_e\left(\frac{r' + nD}{H - \hbar} - \tan z\right). \quad (22)$$

It has to be emphasized that Heaviside step function  $H_e(x)$  is discontinuous at  $x=0$

$$\begin{aligned} H_e(x) &= 0 & ; & & x < 0 \\ H_e(x) &= 1 & ; & & x \geq 0. \end{aligned} \quad (23)$$

Total light emissions from all city light fixtures is computed analogously to Eq. (20)

$$E_L^\uparrow(z) = \rho_L \frac{\pi \tilde{R}^2}{D} \cdot \varepsilon_L(z) \int_0^D P_L(r', \varphi, z, \hbar) dr'. \quad (24)$$

Eq. (24) benefits from a simple relation between  $E_L^\uparrow(z)$  and  $\varepsilon_L(z)$ . The latter is interpreted as an average radiant intensity function of many randomly oriented light fixtures. However,  $E_L^\uparrow(z)$  needs to be integrated over the upper hemisphere in order to obtain the total amount of luminous energy directed upwards. This procedure might appear time-consuming if  $\int P_L dr'$  has to be computed numerically every time the input data-sets change. For instance, it is often necessary to repeat the entire set of calculations with an aim to simulate the light emissions under various conditions – e.g. for prevalingly low or tall buildings or light fixtures. The emission function is core-property in all light pollution models because the sky radiance at any point is due to an amalgamation of all of the beams emitted from different areas under different zenith angles. The signal recorded by a measuring device at any distance is then due to the non-trivial superposition of all light beams travelling along different optical paths. Normally, it represents the integration over all elementary signals  $E_L^\uparrow(z)$  and this is the reason why  $\int P_L dr'$  is so important.

The normalized probability functions  $D^{-1} \int_0^D P_B dr'$  and  $D^{-1} \int_0^D P_L dr'$  computed for a set of discrete values of  $N$  and  $z$  are displayed in Fig. 3. It is illustrated in Fig. 3a that the emissions from light fixtures are blocked more efficiently than those from buildings. That does not mean that public lights are less important than buildings in forming the total CEF. The contributions of luminous building façades and street lighting to all-city light emissions

are weighted by  $\rho_B$  and  $\rho_L$ , while other parameters such as the average vertical dimensions of buildings or light fixtures can change the nature of these weighted contributions partially.

The computations for model parameters have shown that the first and second-order interactions with light blocking structures are largely dominant in forming the light field, while higher-order interactions ( $N > 3$ ) are only important for photons travelling nearly horizontally. The photons escaping from light fixtures at large zenith angles would all interact with buildings except for a small fraction that is transported through inter-building spaces. This fraction remains constant, and for the configuration setup as in Fig. 3 the  $P_{L,1}$  approaches its asymptotic behavior at  $z \approx 75^\circ$ . The corresponding blocking limits for second- and third-order interactions are  $z \approx 82^\circ$ , and  $z \approx 85^\circ$ , respectively. In other words, the light fixtures situated anywhere between buildings (i.e. at any position  $r'$  ranging 0 from to  $D$ ) can only contribute to CEF with a constant radiance when emission angles are below the threshold introduced above.

### 4. Total emission upwards including ground-reflected light

In analogy with Eq. (20) we adopted  $\rho_L = d^{-2}$  for the surface density of light fixtures and reformulate Eq. (24) as below

$$E_L^\uparrow(z) = \frac{\pi \tilde{R}^2}{d^2 D} \cdot \varepsilon_L(z) \int_0^D P_L(r', \varphi, z, \hbar) dr'. \quad (25)$$

Taking into account the direct total emission upwards both due to light fixtures (Eq. (25)) and luminous building façades (Eq. (20)) the total emission function acquires a simple form

$$\begin{aligned} E^\uparrow(z) &= \frac{\pi \tilde{R}^2}{D} \cdot \left[ \frac{\varepsilon_B(z)}{D^2} \int_0^D P_B(r', \varphi, z, H) dr \right. \\ &\quad \left. + \frac{\varepsilon_L(z)}{d^2} \int_0^D P_L(r', \varphi, z, \hbar) dr' \right], \end{aligned} \quad (26)$$

and can be further simplified if the near-ground blocking is absent:

$$E_{free}^\uparrow(z) = \pi \tilde{R}^2 \left[ \frac{\varepsilon_B(z)}{D^2} + \frac{\varepsilon_L(z)}{d^2} \right]. \quad (27)$$

However, part of the light emitted downwards is reflected by the underlying surface and can also contribute to CEF. This amount of light is strongly correlated with ground albedo which in general can depend on wavelength or angle of incidence [16], or type of surface (see e.g. reflection models for soil and vegetation surfaces from multiple-viewing angle photopolarimetric measurements, [12]). Consider the  $\varepsilon_L(z)$  model light emissions to all zenith angles (downward emissions are characterized by zenith angles ranging from  $\pi/2$  to  $\pi$ ). The total radiant flux from a lamp is

$$\Phi_L = \int_{4\pi} \varepsilon_L(z) d\Omega, \quad (28)$$

and can be obtained as linear sum of two components, one for upward flux

$$\Phi_L^\uparrow = 2\pi \int_0^{\pi/2} \varepsilon_L(z) \sin z dz \quad (29)$$

and one for downward flux

$$\Phi_L^\downarrow = 2\pi \int_{\pi/2}^{\pi} \varepsilon_L(z) \sin z dz. \quad (30)$$



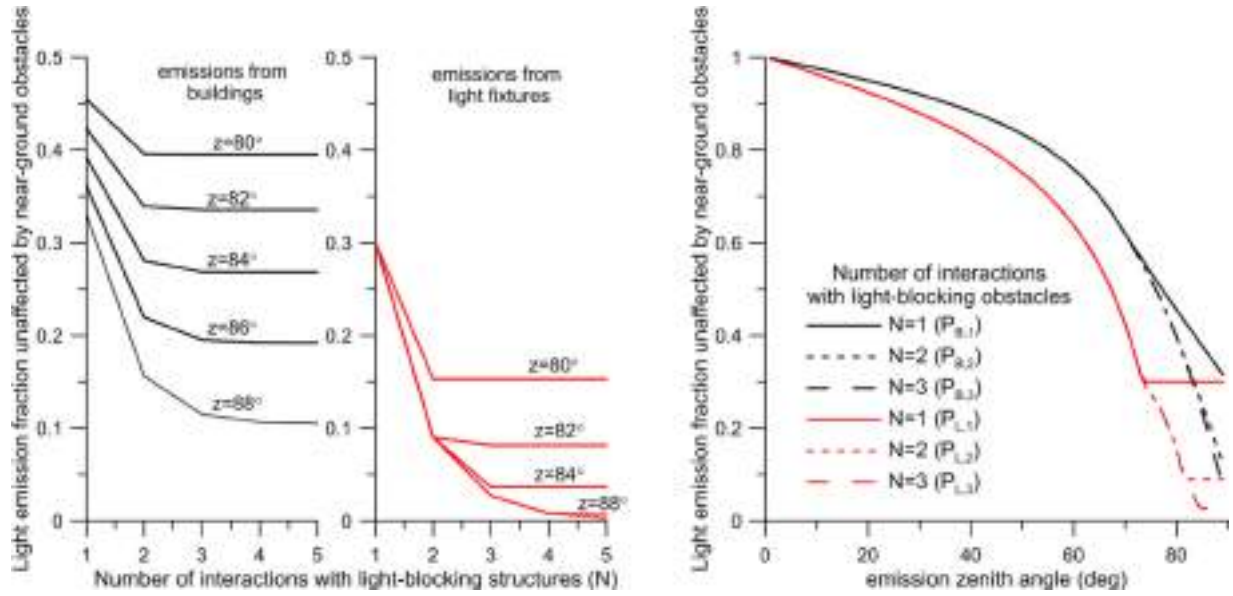


**Fig. 3.** Normalized probabilities  $D^{-1} \int_0^D P_{B,N} dr'$  (black lines) and  $D^{-1} \int_0^D P_{L,N} dr'$  (red lines) as functions of  $N$  (left plot) and  $z$  (right plot) computed for  $H=20$  m,  $D=50$  m,  $\ell=35$  m, and  $\hbar=5$  m. Here  $N$  is the number of building arrays, while  $z$  is the zenith angle of light emissions.

Assigning  $F_L = \Phi_L^\uparrow / \Phi_L$  is the fraction of light emitted from a light fixture directly upwards, then  $(1 - F_L) = \Phi_L^\downarrow / \Phi_L$  is the complementary fraction which is directed downwards and part reflected back into the atmosphere. This process satisfies a formula for Lambert-type ground reflection (we refer readers to the theory of light interaction with inhomogeneous structures in random multiple scattering media). Then

$$-\frac{\varepsilon_L(z) \cos z}{r^2} \frac{G}{\pi} ds = \frac{G}{\pi} \frac{\varepsilon_L(z) \hbar}{r^3} ds, \quad (31)$$

where  $G$  characterizes the fraction of light which is isotropically reflected from the ground. The negative sign at the left-hand-side (LHS) of Eq. (31) follows from the fact that zenith angles are from  $\pi/2$  to  $\pi$  for downwelling radiation. The contribution of reflected light to the upward emissions is determined by integrating Eq. (31) over all elementary surfaces and so within limits case we have

$$\frac{G}{\pi} \hbar \int_{r=\hbar}^{\infty} \int_{\alpha=0}^{2\pi} \frac{\varepsilon_L(z)}{r^3} r dr d\alpha \cong 2G\hbar \int_{r=\hbar}^{\infty} \frac{\varepsilon_L(z)}{r^2} dr. \quad (32)$$

In a special case of isotropically emitting light-source the simple expression for the reflected light can be employed

$$\begin{aligned} E_{refl,L}^\uparrow(z) &\cong 2G\hbar \cos z \int_{r=\hbar}^{\infty} \frac{\varepsilon_L(z)}{r^2} dr = \frac{\Phi_L^\downarrow}{\pi} G \cos z \\ &= \Phi_L^\uparrow \frac{(1 - F_L)}{\pi F_L} G \cos z, \end{aligned} \quad (33)$$

which is equally well suited for a wide range of emission functions if light fixtures are randomly distributed over a city-territory. The contribution of luminous building façades to the reflected light is expressed correspondingly as

$$E_{refl,B}^\uparrow(z) \cong \frac{\Phi_B^\downarrow}{\pi} G \cos z, \quad (34)$$

while a cumulative effect of both these components is

$$E_{refl}^\uparrow(z) = \pi \tilde{R}^2 \left[ \frac{E_{refl,B}^\uparrow(z)}{D^2} + \frac{E_{refl,L}^\uparrow(z)}{d^2} \right]. \quad (35)$$

Eqs. (26) and (35) form a basis for the development of an advanced model for CCEF accepting near-ground blocking effects as naturally observed in many situations. The model we have developed can explain the light amplitude distribution for the urban environment as a whole, except for boundary effects. Two terms are therefore added to the RHS of Eq. (36)

$$\begin{aligned} E_{total}^\uparrow(z) &= \frac{\pi \tilde{R}^2}{D^2} \left[ E_{refl,B}^\uparrow(z) + \frac{\varepsilon_B(z)}{D} \int_0^D P_B(r', \varphi, z, H) dr \right] \\ &+ \frac{2\pi \tilde{R}}{D} \cdot \left[ E_{refl,B}^\uparrow(z) + \varepsilon_B(z) \right] \\ &+ \frac{\pi \tilde{R}^2}{d^2} \left[ E_{refl,L}^\uparrow(z) + \frac{\varepsilon_L(z)}{D} \int_0^D P_L(r', \varphi, z, \hbar) dr \right] \\ &+ \frac{2\pi \tilde{R}}{d} \cdot \left[ E_{refl,L}^\uparrow(z) + \varepsilon_L(z) \right], \end{aligned} \quad (36)$$

aiming to simulate the cumulative emission from all dominant sources, including those located at the city edges. In some cases it is convenient to formulate  $E_{total}^\uparrow(z)$  as a function of radiant fluxes that might appear easier to understand, quantify, and manipulate

$$\begin{aligned} E_{total}^\uparrow(z) &= \frac{\pi \tilde{R}^2}{D^2} \left[ \frac{(1 - F_B)}{\pi} \Phi_B G \cos z + \frac{d\Phi_B^\uparrow(z)}{d\Omega} \frac{1}{D} \int_0^D P_B(r', \varphi, z, H) dr \right] \\ &+ \frac{2\pi \tilde{R}}{D} \left[ \frac{(1 - F_B)}{\pi} \Phi_B G \cos z + \frac{d\Phi_B^\uparrow(z)}{d\Omega} \right] \\ &+ \frac{\pi \tilde{R}^2}{d^2} \left[ \frac{(1 - F_L)}{\pi} \Phi_L G \cos z \right. \\ &+ \left. \frac{d\Phi_L^\uparrow(z)}{d\Omega} \frac{1}{D} \int_0^D P_L(r', \varphi, z, \hbar) dr \right] \\ &+ \frac{2\pi \tilde{R}}{d} \left[ \frac{(1 - F_L)}{\pi} \Phi_L G \cos z + \frac{d\Phi_L^\uparrow(z)}{d\Omega} \right]. \end{aligned} \quad (37)$$

Here  $\Phi_L$  and  $\Phi_B$  are average radiant fluxes from a single lamp and building, respectively. In Eq. (37) we have used two functions  $d\Phi_L^\uparrow/d\Omega$  and  $d\Phi_B^\uparrow/d\Omega$  that represent differential fluxes (radiant in-

tensity functions) upwards. Alternatively, the above quantities can be replaced by their spectral or broadband counterparts (including e.g. those for photopic vision). For practical applications, the above model would be more attractive if analytical solutions for probability functions would exist. After a bit of mathematical manipulations we have found

$$\begin{aligned}\tilde{P}_{B,2}(z) &= \frac{1}{D} \int_0^D P_{B,2}(r', \varphi, z, H) dr' \\ &= \left(\frac{D-\ell}{D}\right)^2 + \frac{\ell}{D} \frac{1}{q} \left\{ \left(\frac{D-\ell}{D}\right) [M_1(2q) - M_2(q)] + M_1(q) \right\} \\ \tilde{P}_{L,2}(z) &= \frac{1}{D} \int_0^D P_{L,2}(r', \varphi, z, \hbar) dr' \\ &= \left(\frac{D-\ell}{D}\right)^2 + \frac{\ell}{D} \left[ f(Q^{-1}) + \left(\frac{D-\ell}{D}\right) f(Q^{-1} - 1) \right], \quad (38)\end{aligned}$$

that both appeared useful for treating  $P_B(z)$  and  $P_L(z)$ . The analytical functions  $M_1, M_2$  that determine the probability  $\tilde{P}_{B,2}(z)$  are very simple

$$\begin{aligned}M_1(q) &= \begin{cases} \frac{1}{2}q^2, & q < 1 \\ q - \frac{1}{2}, & q \geq 1 \end{cases} \\ M_2(q) &= \begin{cases} \frac{5}{6}q^3, & q \leq \frac{1}{2} \\ \frac{1}{3}(1-q)^3 + \frac{1}{2}q(1-q)^2 + \left[q - \frac{1}{2}\right] \cdot \frac{1}{2}, & \frac{1}{2} < q < 1 \\ q - \frac{1}{2}, & q \geq 1 \end{cases}, \quad (39)\end{aligned}$$

and both depend on a dimensionless parameter  $q$

$$q = q(H, D, z) = \frac{D}{H \tan z}. \quad (40)$$

The function  $f$  modeling the probability  $\tilde{P}_{L,2}(z)$  can be expressed for any parameter  $x$  as follows

$$f(x) = g(x) H_e[g(x)], \quad (41)$$

where

$$g(x) = 1 - x H_e(x) \quad (42)$$

and  $H_e(x)$  is the Heaviside step function defined in Eq. (23). The scaling parameter  $Q$  has a direct relation with  $q$

$$Q = Q(H, \hbar, D, z) = q(H - \hbar, D, z) = \frac{D}{(H - \hbar) \tan z}. \quad (43)$$

The theoretical solution we have derived is appropriate for rapidly modeling the city emission function because the integral representation introduced in Eq. (37) reduces to a function defined by a simple formula

$$\begin{aligned}E_{total}^\uparrow(z) &= \frac{\pi \tilde{R}^2}{D^2} \left[ \frac{(1-F_B)}{\pi} \Phi_B G \cos z + \frac{d\Phi_B^\uparrow(z)}{d\Omega} \tilde{P}_{B,2}(z) \right] \\ &+ \frac{2\pi \tilde{R}}{D} \left[ \frac{(1-F_B)}{\pi} \Phi_B G \cos z + \frac{d\Phi_B^\uparrow(z)}{d\Omega} \right] \\ &+ \frac{\pi \tilde{R}^2}{d^2} \left[ \frac{(1-F_L)}{\pi} \Phi_L G \cos z + \frac{d\Phi_L^\uparrow(z)}{d\Omega} \tilde{P}_{L,2}(z) \right] \\ &+ \frac{2\pi \tilde{R}}{d} \left[ \frac{(1-F_L)}{\pi} \Phi_L G \cos z + \frac{d\Phi_L^\uparrow(z)}{d\Omega} \right], \quad (44)\end{aligned}$$

Eq. (44) is well designed for routine use in modeling light emissions from a city or town and only requires the information on

average emission functions for a light fixture  $d\Phi_L^\uparrow(z)/d\Omega$  and a building  $d\Phi_B^\uparrow(z)/d\Omega$ . The latter can be determined quite easily when modeling the buildings as 3D objects with vertical sides. This native attempt may be useful as a zero-order approximation that estimates the maximum emissions towards the horizon, while the intensity of light decreases with  $\cos(\theta)$ . Here  $\theta$  is the angle between the beam direction and the normal to a vertical façade. It is important to note that evaluation of  $\varepsilon_B = d\Phi_B^\uparrow/d\Omega$  involves averaging over azimuthal directions, thus

$$\varepsilon_B(z) = \frac{d\Phi_B(z)}{d\Omega} = \Phi_{0B} \sin z \quad (45)$$

meaning that the total light flux through the entire surface which encloses a building is

$$\Phi_B = \int_{4\pi} \varepsilon_B(z) d\Omega = \pi^2 \Phi_{0B}, \quad (46)$$

Eq. (45) is complete except for a normalization constant that can be determined from Eq. (46) in the form  $\Phi_{0B} = \pi^{-2} \Phi_B$ , so the radiant (or luminous) flux upwards is

$$\Phi_B^\uparrow = 2\pi \int_0^{\pi/2} \varepsilon_B(z) \sin z dz = \Phi_{0B} \frac{\pi^2}{2} = \frac{1}{2} \Phi_B = F_B \Phi_B \quad (47)$$

and a corresponding flux downwards is

$$\Phi_B^\downarrow = 2\pi \int_{\pi/2}^\pi \varepsilon_B(z) \sin z dz = \Phi_{0B} \frac{\pi^2}{2} = \frac{1}{2} \Phi_B = (1 - F_B) \Phi_B. \quad (48)$$

The light escaping a building is therefore linearly proportional to the sine of zenith angle

$$\varepsilon_B(z) = \frac{d\Phi_B(z)}{d\Omega} = \frac{\Phi_B}{\pi^2} \sin z, \quad (49)$$

where  $\Phi_B$  is an average radiative (luminous) flux produced by an average building at night. The emission function  $\varepsilon_L = d\Phi_L^\uparrow/d\Omega$  is usually difficult to obtain in analytical form as the angular light-output pattern strongly depends on a light source. However,  $\varepsilon_L$  considered in this paper is to model an average radiant intensity for an “average” light-fixture, meaning that we are searching for an appropriate parametrized function that can mimic a nominal cumulative directional emission rather than an exact emission function for a specific lighting technology. This is because public lighting is a mixture of different electric lights with various angular emission patterns. By the nominal cumulative emission we understand a function that allows for modeling of many different light sources, from pure diffuse radiators, through sources that combine the properties of both unshielded and shielded lights, to the unshielded lamps that are projecting upwards and illuminating the sky uselessly so causing needless energy loss.

There are many functions which satisfy the above criteria, but only a few belong to a class of elementary functions. We require the function to be as simple as possible in order to permit non-intensive CPU computations, while keeping in mind that the model should describe the full range of capabilities. The exponential function

$$\varepsilon_{La}(z) = \frac{d\Phi_L(z)}{d\Omega} = \Phi_{0L} e^{-a \cos z} \quad (50)$$

is one example which does lead to an easy solution for the normalization constant  $\Phi_{0L}$  and thus for  $\varepsilon_L(z)$ . Eq. (50) guarantees that a certain small number of light sources can emit upwards (e.g. badly shielded luminaires), while the amount of energy emitted can be controlled and adjusted by the parameter  $a$ . This parameter also predetermines the ratio  $e^a$  between the light intensity towards the

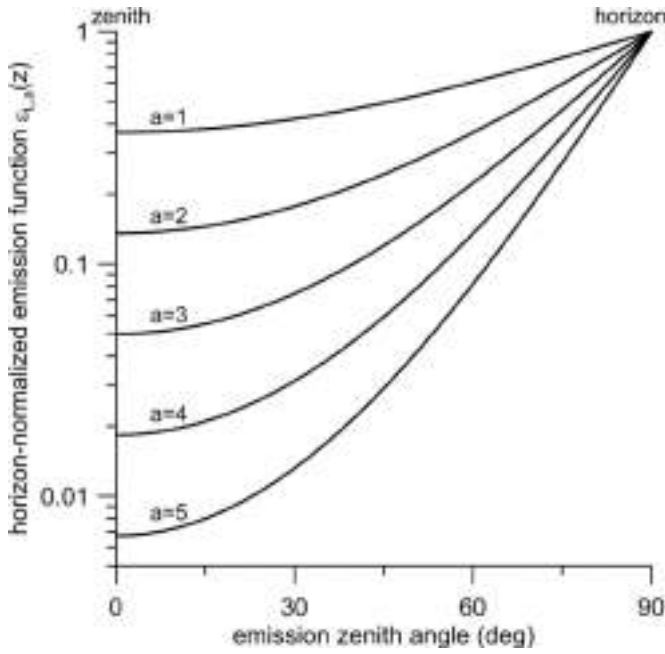


**Fig. 4.** Horizon-normalized light emissions upwards computed for a model light fixture. Relation between  $\varepsilon_{La}(z)$  and the scaling parameter  $a$  is controlled by Eq. (53).

horizon and the zenith. The formula (50) allows for analytical integration over the upper hemisphere, thus providing the total light flux upwards in the form

$$\Phi_{La}^{\uparrow} = 2\pi \int_0^{\pi/2} \varepsilon_{La}(z) \sin z \, dz = 2\pi \Phi_{0L} \frac{1 - e^{-a}}{a} = \Phi_{La} F_{La} \quad (51)$$

while the downwelling radiant flux is to be computed as  $\Phi_{La}^{\downarrow} = \Phi_{La}(1 - F_{La})$ . The flux  $\Phi_{La}^{\uparrow}$  is complementary to  $\Phi_{La}^{\downarrow}$  as superposition of both equals to a constant value,  $\Phi_{La}^{\uparrow} + \Phi_{La}^{\downarrow} = \Phi_{La}$ . The normalization coefficient  $\Phi_{0L}$  is linearly proportional to  $\Phi_{La}$

$$\Phi_{0L} = \Phi_{La} \frac{F_{La}}{2\pi} \frac{a}{1 - e^{-a}} \quad (52)$$

so

$$\varepsilon_{La}(z) = \frac{d\Phi_{La}(z)}{d\Omega} = \Phi_{La} \frac{F_{La}}{2\pi} \frac{a}{1 - e^{-a}} e^{-a \cos z}. \quad (53)$$

A steep radiant intensity gradation from zenith towards horizon can be achieved when increasing the value of the parameter  $a$  (see Fig. 4). On the other hand, a light source is of uniform (same) radiance if the parameter  $a$  approaches zero.

## 5. The model and its asymptotic behavior

With Eq. (44) we have completed the theoretical model for the total emission upwards, where both of components  $\varepsilon_B(z)$  and  $\varepsilon_L(z)$  are assumed to be known *a-priori*. It has been shown earlier that  $\varepsilon_B(z)$  is easy to estimate, but  $\varepsilon_L(z)$  requires more detailed information on the lighting technology installed in a city or town. Nevertheless, an accurate and reliable inventory of all city lights is rarely available, so  $\varepsilon_L(z)$  is always obtained within the combined error bounds of statistical theory and methods of data processing. Experimental uncertainty due to (partially) missing or low-resolution information on light source properties should also be taken into account.

The approach we have introduced in the previous section is to attempt to circumvent this situation by deriving an equation that

can model wide range of situations while satisfying basic theoretical principles. Placing Eqs. (49) and (53) into Eq. (44) we finally obtain the formula (54)

$$E_{total,a}^{\uparrow}(z) = \Phi_B \frac{\tilde{R}}{D} \left\{ G \cos z \left( 1 + \frac{\tilde{R}}{2D} \right) + 2 \frac{\sin z}{\pi} \left[ 1 + \tilde{B}_{B,2}(z) \frac{\tilde{R}}{2D} \right] \right\} + \Phi_{La} \frac{\tilde{R}}{d} \left\{ 2(1 - F_{La}) G \cos z \left( 1 + \frac{\tilde{R}}{2d} \right) + \frac{a e^{-a \cos z}}{1 - e^{-a}} F_{La} \left[ 1 + \frac{\tilde{R}}{2d} \tilde{B}_{L,2}(z) \right] \right\}, \quad (54)$$

that is well designed for a routine use as the values of the model parameters are either known or can be determined experimentally or inferred from indirect measurements (it deals with e.g.  $\Phi_B$  or  $\Phi_{La}$ ). The substitution of average values for the parameters ( $H, D, \ell, h, \dots$ ) of the model, in Eq. (54), is contingent on the assumption of no-correlation between them. The complete list of input parameters is below:

$2\tilde{R}$ : a characteristic size of a city or town with  $\tilde{R} = \sqrt{S/\pi}$  measured in meters. Here  $S$  is the surface area of all light-emitting pixels in a city-territory.

$D$ : a statistically averaged inter-building separation measured in meters. Note that surface density is defined as  $\rho_B = D^{-2}$ .

$H$ : an averaged vertical dimension of all buildings (it is measured in meters).

$\ell$ : a mean (statistically averaged) horizontal dimension of a building measured in meters.

$\tilde{h}$

: a mean vertical dimension of a light fixture measured in meters.

$d$ : an average horizontal distance between light fixtures (measured in meters). The lighting density is  $\rho_L = d^{-2}$ .

$F_{La}$ : an uplight fraction for streetlights. It is a dimensionless parameter ranging from 0 to 1.

$a$ : a dimensionless scale parameter that controls angular behavior of  $\varepsilon_L(z)$ .

$\Phi_L$ : a mean amount of Watts or lumens emitted from “an average” light fixture.

$\Phi_B$ : a mean amount of Watts or lumens emitted from “an average” building.

It is worthwhile mentioning that “an average” building mentioned above is a construct that emits the same amount of Watts or lumens as all buildings in a city, while this cumulative emission is normalized to the number of buildings. The same principle applies to “an average” light fixture.

Typically  $\tilde{R} \gg D$  and  $\tilde{R} \gg d$ , thus the following approximation to Eq. (54) might appear useful for many cities or towns

$$E_{total,a}^{\uparrow}(z) \cong \Phi_B \left( \frac{\tilde{R}}{D} \right)^2 \left\{ \frac{G \cos z}{2} + \frac{\sin z}{\pi} \tilde{B}_{B,2}(z) \right\} + \Phi_{La} \left( \frac{\tilde{R}}{d} \right)^2 \left\{ (1 - F_{La}) G \cos z + \frac{F_{La}}{2} \left( \frac{a e^{-a \cos z}}{1 - e^{-a}} \right) \tilde{B}_{L,2}(z) \right\}, \quad (55)$$

The emissions towards zenith are rarely attenuated by obstacles except for perfectly shielded light sources, so the theoretical maximum for zenith emission is

$$E_{total}^{\uparrow}(0) = \frac{\pi \tilde{R}^2}{D^2} \left[ \frac{(1 - F_B)}{\pi} \Phi_B G + \frac{d\Phi_B^{\uparrow}(z)}{d\Omega} \right] + \frac{\pi \tilde{R}^2}{d^2} \left[ \frac{(1 - F_L)}{\pi} \Phi_L G + \frac{d\Phi_L^{\uparrow}(z)}{d\Omega} \right]. \quad (56)$$

An approximation to Eq. (56) is below

$$E_{total,a}^{\uparrow}(0) \cong \Phi_B \left( \frac{\tilde{R}}{D} \right)^2 \frac{G}{2} + \Phi_{La} \left( \frac{\tilde{R}}{d} \right)^2 \left\{ (1 - F_{La}) G + \frac{F_{La}}{2} \left( \frac{a e^{-a}}{1 - e^{-a}} \right) \right\}. \quad (57)$$

The above formula is advantageous as it allows for rapid prediction of zenith emissions from dominant light sources and can be interrelated with satellite data, for instance that provided by Visible Infrared Imaging Radiometer Suite (VIIRS). The urban environment is usually a complex system of various luminous and blocking constructs, where  $\Phi_B D^{-2}$  and/or  $\Phi_{La} d^{-2}$  are known relative to other cities/towns. In other words, the value of  $E_{total,a}^{\uparrow}$  is known except for the linear constant – a coefficient of proportionality. In this light, Eqs. (55) and (57), or more generally Eqs. (44) and (56), are of great practical interest because both pairs of the equations allow us to work with the zenith-normalized emission function. That way the normalization constant is canceled out.

It follows from Eq. (57) that light fixtures contribute to the zenith emissions proportionally to  $(1 - F_{La}) G + 0.5 F_{La} a e^{-a} / (1 - e^{-a})$ , where the first term coincides with that proposed by Cinzano [2] except that the calibration constant in Eq. (57) strongly depends on the total amount of Watts or lumens installed in city area. In contrast to Lambertian component of ground-emitted radiation which is present in all models including those by Garstang [6], Cinzano [2], and Falchi et al. [5], the new formula given above also accounts for a small amount of direct uplight from light fixtures as well as for the contribution of luminous building façades. Lambertian distribution function dictates the emissions approach zero at horizon, while Garstang and Cinzano predict the intensity near horizon is linearly proportional to  $F$  (the scaling factor is as large as 3.4). Eq. (55) is more general, showing the amount of photons emitted from light fixtures is also proportional to  $F_{La}$ , but the scaling factor is a function of a mean building size, inter-building separation, a statistically averaged vertical dimension of light fixtures and, a dimensionless scale parameter that controls angular behavior of  $\varepsilon_L(z)$ . In extreme case with no near-ground blocking of light the scaling factor for light fixtures equals to  $0.5a / (1 - e^{-a})$ . The value of  $a \approx 6.7$  would fit the Garstang's scaling factor well, however, looking to the Fig. 4 one can quickly recognize that  $\varepsilon_{La}(z)$  with  $a > 5$  overestimates the emissions to low elevation angles. This is why Garstang's model is not appropriate to model most of the heterogeneous light-emitting and blocking urban environments. In addition, Garstang's model ignores direct horizontal emissions from buildings, i.e. the term  $(\sin z) \pi^{-1} \tilde{P}_{B,2}(z)$  in Eq. (55). Assuming  $\tilde{P}_{B,2}(z)$  is unity (no blocking effects), the model introduced here predicts a constant addition of  $\pi^{-1}$  to the horizontal emission due to vertically oriented building façades.

For the purpose of theoretical validation it is useful to analyze the model behavior under extreme conditions. Assuming the reflectance of a dark underlying surface is zero, the mathematical formula for zenith emission reduces to

$$E_{total,a}^{\uparrow}(0) \Big|_{G=0} = \frac{\pi \tilde{R}^2}{D^2} \frac{d\Phi_B^{\uparrow}(z)}{d\Omega} + \frac{\pi \tilde{R}^2}{d^2} \frac{d\Phi_L^{\uparrow}(z)}{d\Omega} \cong \frac{\pi \tilde{R}^2}{d^2} \frac{d\Phi_L^{\uparrow}(z)}{d\Omega} \quad (58)$$

or

$$E_{total,a}^{\uparrow}(0) \Big|_{G=0} \cong \Phi_{La} \left( \frac{\tilde{R}}{d} \right)^2 \frac{F_{La}}{2} \left( \frac{a e^{-a}}{1 - e^{-a}} \right) \quad (59)$$

for  $\varepsilon_L(z)$  estimated in accordance with Eq. (53). The formula (59) suggests that the zenith emission increases proportionally to the lighting density ( $\rho_L = d^{-2}$ ) or city-area ( $S$ ). This is not unexpected, because the number of emitted photons normally increases

with the size of a city. On the other hand, the collective effect of both components  $\Phi_B D^{-2}$  and  $\Phi_{La} d^{-2}$  can be inferred from satellite data if full cut-off fixtures dominate a municipal territory. Then

$$E_{total,a}^{\uparrow}(0) \cong G \tilde{R}^2 \left\{ \frac{\Phi_B}{2 D^2} + \frac{\Phi_{La}}{d^2} \right\}. \quad (60)$$

The contribution of light fixtures to the zenith emissions also retains its form for extremely large values of  $F_{La}$ ; compare second term at RHS of Eq. (61) with that of Eq. (59) and find

$$E_{total,a}^{\uparrow}(0) \Big|_{F_{La} \rightarrow 1} \cong \Phi_B \left( \frac{\tilde{R}}{D} \right)^2 \frac{G}{2} + \Phi_{La} \left( \frac{\tilde{R}}{d} \right)^2 \frac{F_{La}}{2} \left( \frac{a e^{-a}}{1 - e^{-a}} \right). \quad (61)$$

Most roadway and other lights are dimmed to a certain percentage of maximum wattage at midnight, thus reducing power consumption during off-peak hours and saving energy in many cities worldwide. On-off logic is very often based on astronomical time for a particular location. For instance, Canary Sky Law prescribes a lighting reduction after midnight [1]. The operation modes are generally known, thus allowing for targeted characterization of  $\Phi_B D^{-2}$  and  $\Phi_{La} d^{-2}$  from VIIRS data taken for a given locality before and after midnight. Let the  $E_{total}^{\uparrow BM}(0)$  be the zenith radiance of a city-pixel measured at the satellite level before midnight, while  $E_{total}^{\uparrow AM}(0)$  is the corresponding data gathered after midnight. Then the relation between  $\Phi_B D^{-2}$  and  $\Phi_{La} d^{-2}$  can be roughly estimated from the data retrieved

$$\begin{aligned} \left( \frac{\Phi_B}{D^2} \right) &\cong \left( \frac{\Phi_{La}}{d^2} \right) \xi_{AM}^{BM}(0) \\ \xi_{AM}^{BM}(0) &= \frac{c E_{total}^{\uparrow BM}(0) - E_{total}^{\uparrow AM}(0)}{2(1 - F_{La}) E_{total}^{\uparrow AM}(0)}. \end{aligned} \quad (62)$$

We have assumed in Eq. (62) that  $a > 2$ , i.e. the radiant intensity  $\varepsilon_L(z)$  is a steep function of zenith angle. The parameter  $c$  in Eq. (62) is a percentage of full power light output. For instance, decreasing the light output through dimming to about 60% ( $c=0.6$ ) is implemented in the city of Tucson for LED lamps [8]. However, the city-area averaged value of  $c$  surely exceeds that of 0.6 as LED sources represent only a small (though increasing) fraction of all city lights. Using the satellite data, the problem of two unknown weighting coefficients is eliminated by removing the functional dependency of Eq. (55) on  $\Phi_B D^{-2}$

$$E_{total,a}^{\uparrow}(z) \cong \Phi_{La} \left( \frac{\tilde{R}}{d} \right)^2 \left\{ (1 - F_{La}) G \cos z + \frac{F_{La}}{2} \left( \frac{a e^{-a \cos z}}{1 - e^{-a}} \right) \tilde{P}_{L,2}(z) + \left[ \frac{G \cos z}{2} + \frac{\sin z}{\pi} \tilde{P}_{B,2}(z) \right] \xi_{AM}^{BM}(0) \right\}. \quad (63)$$

As the emission angle approaches the horizontal direction both  $\tilde{P}_{B,2}(z)$  and especially  $\tilde{P}_{L,2}(z)$  decay rapidly, so all terms originally introduced in Eq. (54) have to be taken into account

$$E_{total,a}^{\uparrow}(z) \cong \Phi_{La} \left( \frac{\tilde{R}}{d} \right)^2 \left\{ (1 - F_{La}) G \cos z + \frac{F_{La}}{2} \left( \frac{a e^{-a \cos z}}{1 - e^{-a}} \right) \left[ 2 \frac{d}{\tilde{R}} + \tilde{P}_{L,2}(z) \right] + \left( \frac{G \cos z}{2} + \frac{\sin z}{\pi} \left[ 2 \frac{D}{\tilde{R}} + \tilde{P}_{B,2}(z) \right] \right) \xi_{AM}^{BM}(0) \right\}. \quad (64)$$

resulting in an approximate formula for near-horizon emission

$$E_{total,a}^{\uparrow} \left( \frac{\pi}{2} \right) \cong \Phi_{La} \left( \frac{\tilde{R}}{d} \right)^2 \left\{ a F_{La} \frac{d}{\tilde{R}} + \frac{\xi_{AM}^{BM}(0)}{\pi} \left[ 2 \frac{D}{\tilde{R}} + \tilde{P}_{B,2} \left( \frac{\pi}{2} \right) \right] \right\}. \quad (65)$$



The intensity  $E_{total,a}^{\uparrow}(\pi/2)$  corrected by the effect of scattering and absorption along the horizontal line-of-sight complemented by the satellite data  $E_{total}^{\uparrow BM}(0)$  and  $E_{total}^{\uparrow AM}(0)$  can be potentially used as a basis for a concurrent retrieval of  $\Phi_B D^{-2}$  and  $\Phi_{La} d^{-2}$ . If one or both of these parameters are known, then the other two unknowns in Eq. (65) can be inferred from the satellite and ground-based measurements.

## 6. Numerical demonstrations

The analytical formula (54) or its general form (37) represent completely new, previously undisclosed, solutions to the CEF which can simulate a wide range of emission functions for many cities or towns. The model is applicable to many luminous or blocking system elements such as houses and buildings with interior lights escaping from exterior windows (but also residential porch lights), streetlights including arbitrarily angled fixtures or architectural lighting, etc. The positions of individual system elements can be arranged randomly as typically occurs in human settlements with complex infrastructure of built environment. In such case it is difficult or rather impossible to characterize each of these elements separately. Therefore, the statistical approach to the problem is necessary in practice, while the mean values of the model parameters are used instead of huge data sets for 3D topography.

The numerical experiments here are to demonstrate the ways in which the input parameters introduced in Sect. 5 govern the model behavior. This investigation looked at CCEF values produced by varying one factor at a time, so that the effect of  $F_{La}$ , for example, can be compared between sources with all other factors being equal. The cumulative radiant intensity functions (CCEF) are normalized to the total lumen output (TLO), so the displayed data are for:

$$CCEF_{norm}(z) = E_{total,a}^{\uparrow}(z) \left[ \frac{\pi \tilde{R}^2}{D^2} \Phi_B + \frac{\pi \tilde{R}^2}{d^2} \Phi_{La} \right]^{-1}. \quad (66)$$

where the term in square brackets at RHS of Eq. (66) is obtained by integrating Eq. (27) over the whole space, assuming near-ground blocking of light is absent, i.e.  $\Phi_L = \int_{4\pi} \varepsilon_L(z) d\Omega$  (see Eq. (28)) and  $\Phi_B = \int_{4\pi} \varepsilon_B(z) d\Omega$  (see Eq. (46)). Here the TLO-normalized CCEF, i.e.  $CCEF_{norm}(z)$ , is measured in  $\text{sr}^{-1}$  unlike  $CCEF(z) \equiv E_{total,a}^{\uparrow}(z)$  that is in  $\text{lm} \cdot \text{sr}^{-1}$ .

### 6.1. The effects of emission gradation function and uplight fraction for a light fixture

The dimensionless parameter  $a$  has been introduced in Eqs. (50)–(53) to control angular behavior of  $\varepsilon_L(z)$ . The light fixtures with small or even constant unity gradation of upwardly emitted beams can be characterized by small values of  $a$ , while large values of  $a$  are for lights with steep decay of the intensity from horizon to zenith. The values of  $a$  ranging from 0.4 to 4 all exemplify situations which can be of interest in modeling of various light sources. We allow  $a$  to vary within its defined ranges, while holding all other model factors constant assuming their baseline values are:  $H=20\text{ m}$ ,  $\ell=40\text{ m}$ ,  $D=100\text{ m}$ ,  $\tilde{h}=9\text{ m}$ ,  $d=25\text{ m}$ ,  $F_{La}=0.07$ ,  $G=0.1$ ,  $\Phi_{La}/\Phi_B \approx 2.2$ ,  $\tilde{R}=5000\text{ m}$ . The parameter  $a$  is varied in Fig. 5, otherwise it is fixed at 1.5 in all other plots.

The TLO-normalized radiant intensity function reported in Fig. 5 shows the  $CCEF_{norm}(z)$  sharply decreases towards the horizon if  $a$  approaches zero. That is because the light sources with low values of  $a$  emit less energy towards the horizon in favor of increased upwards radiative flux. In the extreme case ( $a=0$ ),  $\varepsilon_{La}(z)$  approaches unity for all zenith angles (see Eq. 53). Such sources

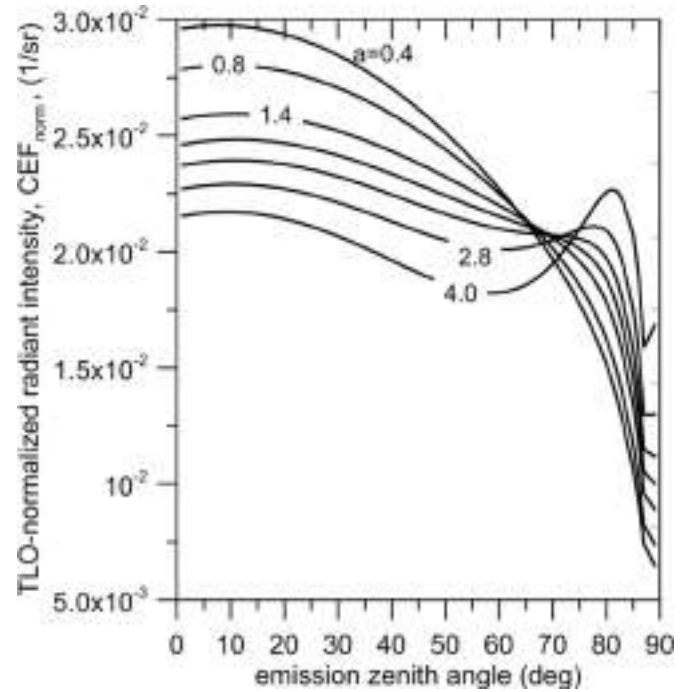


Fig. 5. TLO-normalized city emission function computed from Eq. (66) for the parameter  $a$  ranging from 0.4 to 4. All other parameters are specified in the text.

emit equally to all directions. Note, however, that although this is a well-known feature of isotropic radiance, here we are dealing with CCEF, which is a cosine-projected radiance. The modern fixtures are designed to prevent upward directional light, so a collective effect of all city streetlights from unshielded to fully-shielded is assumed to be characterized by  $\varepsilon_{La}(z)$  with  $a$  exceeding the value of 2. In a hypothetical case, the large values of  $a$  should be employed to simulate (full) cutoff lights. It can be inferred from Eq. (53) that radiant intensity  $\varepsilon_{La}(z)$  tends to decay exponentially with decreasing zenith angle, so the intensity ratio of horizontally and vertically directed beams is approximately  $e^a$  for  $a > 4$ . The emission function for these types of light sources shows progressive development of a subsidiary peak at about 10–20° above horizontal (see Fig. 5) and approaches a non-zero value as the direction of rays escaping the surface becomes parallel to the ground. It coincides with what we know from observations and it also conforms to what we would normally expect. A small increase of  $\varepsilon_{La}(z)$  at  $z \rightarrow \pi/2$  is most probably due to light sources located at the city edges because the photons escaping from these fixtures do not interfere with obstacles and thus can be transported over long distances. The contribution of these beams relative to others is small, but may increase if increasing the slope of  $\varepsilon_{La}(z)$ , i.e. if increasing  $a$ . The light fixtures characterized by small values of  $a$  distribute the photons more-or-less uniformly, thus causing an inefficient horizontal energy transfer and continuous decrease of  $CCEF_{norm}(z)$  with increasing zenith angle (Fig. 5).

The parameter  $F_{La}$  is to model the fraction of light radiated directly upward from fixtures and is defined as  $F_L = \Phi_L^{\uparrow} / \Phi_L$  (see the text below Eq. (30)). The function  $\varepsilon_{La}(z)$  restricted to the upper hemisphere (i.e. to the bounded interval of zenith angles  $z \in [0, \pi/2]$ ) and the parameter  $F_L$  are complements of each other as both together determine the direct upward emissions from light fixtures. Varying  $F_L$  from 0 to 0.5, while keeping  $\varepsilon_{La}(z)$  fixed indicates the light output pattern for the upper hemisphere remains unchanged, but the ratio of luminous energy escaping into the upper hemisphere and that escaping downwards increases. Such lamps use luminous energy inefficiently, because instead of illu-

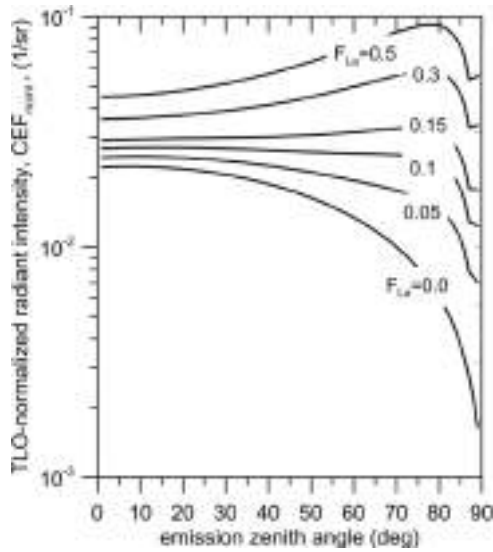


**Fig. 6.** The same as in Fig. 5 except for uplight fraction  $F_{La}$  ranging from 0 to 0.5.  $F_{La}$  characterizes light emissions from fixtures. The input parameters used in the computations are the same as in Fig. 5 and are specified in the text.

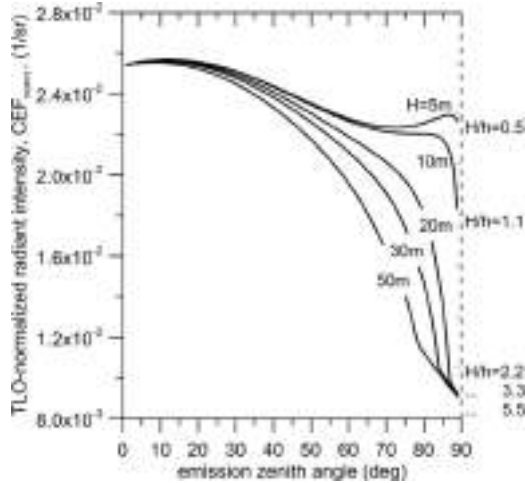


**Fig. 7.** The same as in Fig. 5 except for building vertical dimension  $H$  ranging from 5 m to 50 m. The input parameters are specified in the first paragraph of the Sect. 6.1.

minating roads and adjacent urban areas, much energy is wasted due to poor upward light control. The zenith-angle distribution of upward emissions is controlled by  $\varepsilon_{La}(z)$  which does not necessarily correlate with  $F_L$ . The total emission  $CCEF_{norm}(z)$  computed for  $\alpha=1.5$  is plotted in Fig. 6 as a function of zenith angle. Fig. 6 shows the transition from  $F_L=0$  to 0.5 to make the original cosine-shaped  $CCEF_{norm}(z)$  smoothly increasing or even non-monotonic with a peak located somewhere between  $z=70^\circ$ – $80^\circ$ . Just a small deviation from  $F_L=0$  results in a substantial increase of light emissions near the horizon. A constantly decreasing function of  $z$  reverses to slightly increasing function of  $z$  if  $F_L>0.1$  and observations are primarily made at zenith angles below  $70^\circ$ – $80^\circ$ . An increase of  $F_L$  from 0.05 (that is representative for e.g. drop-lens cobra head street lights) to  $F_L=0.1$  (which is a good example for optical quality acorn post-top light) has only a negligible effect on zenith emissions. However, it can increase the contribution to the total emission from all city street lights about 80% relative to what we have obtained for  $F_L=0.05$ . Because of the linearity of the system studied, the values of  $CCEF_{norm}(z)$  also increase linearly with  $F_L$ , but only for large values of  $z$ . For these zenith angles the con-

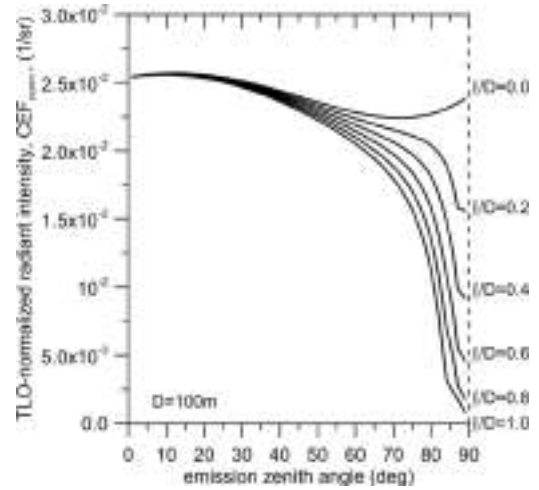


**Fig. 8.** The same as in Fig. 5 except for the ratio of  $\ell/D$  which ranges from 0 to 1. The input parameters are specified in the first paragraph of the Section 6.1.

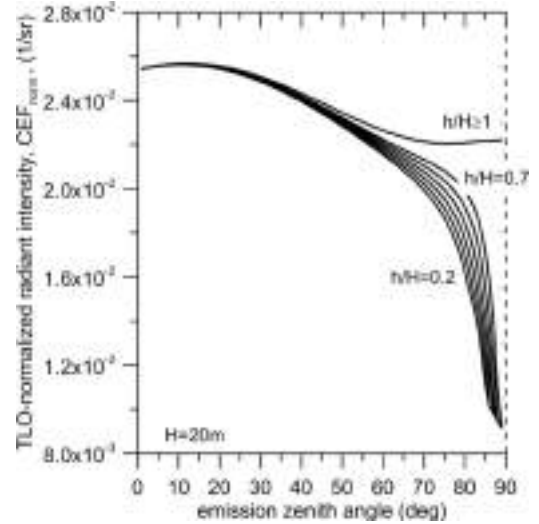


**Fig. 9.** The same as in Fig. 5 except for the ratio of  $h/H$  above 0.2. The input parameters are specified in the first paragraph of the Section 6.1.

tribution to  $CCEF_{norm}(z)$  from light fixtures is dominant if taking into account  $\Phi_{La}/\Phi_B$  used in our model computations.

## 6.2. The effect of building and fixture dimensions

Light emitted from building interiors reaches the atmosphere except when being obstructed due to other buildings or vegetation. A large fraction of the light beams not extinguished by trees and other vegetation would be removed by building façades that cover huge square meter areas and block emissions to low elevation angles. Light absorption or blocking effects of buildings is clearly manifested in Fig. 7, where the light emissions to low and intermediate elevation angles are influenced by the vertical dimension of a building ( $H$ ), but high-angle lighting is almost independent of  $H$ .

The range in which  $CCEF_{norm}$  vary with  $H$  strongly depends on inter-building separation,  $D$ , and partly also on the characteristic horizontal dimension of a building,  $\ell$ . The latter is studied in Fig. 8, where  $\ell$  is identified to have a great effect on the photons transported at low elevation angles. The probability that near-ground artificial light in a built urban environment penetrates the barrier of buildings decays rapidly as  $\ell/D$  approaches unity. Such proba-



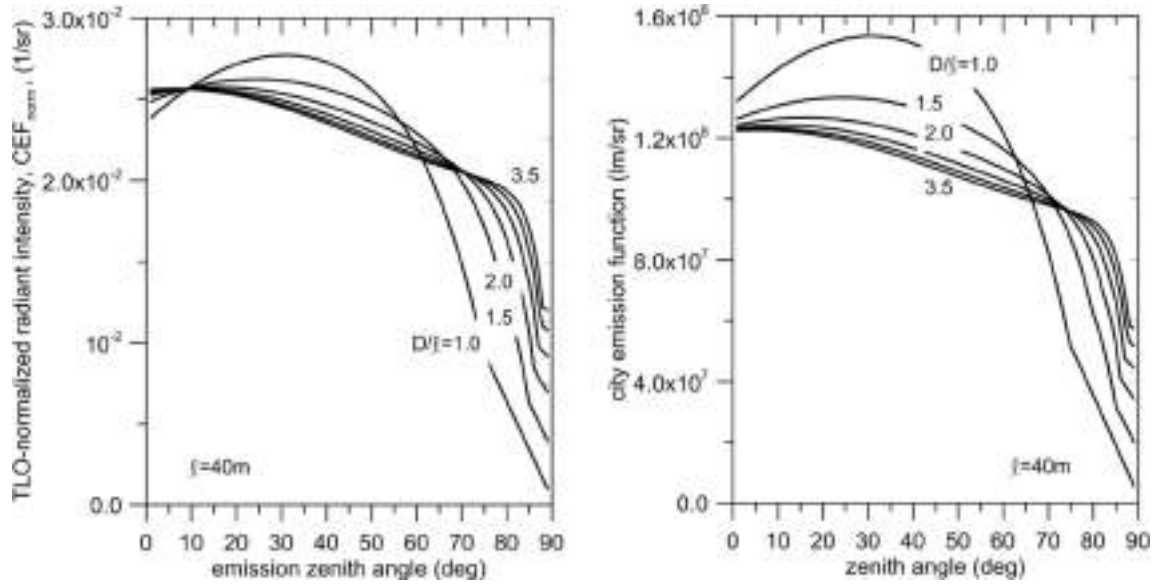


**Fig. 10.** a) TLO-normalized city emission function (left panel) and b) raw data for city emission function (right panel) for  $D/\ell$  ranging from 1 to 3.5. The characteristic size of a building  $\ell$  is fixed at 40 m. All other parameters used are specified in the text (see the first paragraph in Section 6.1).

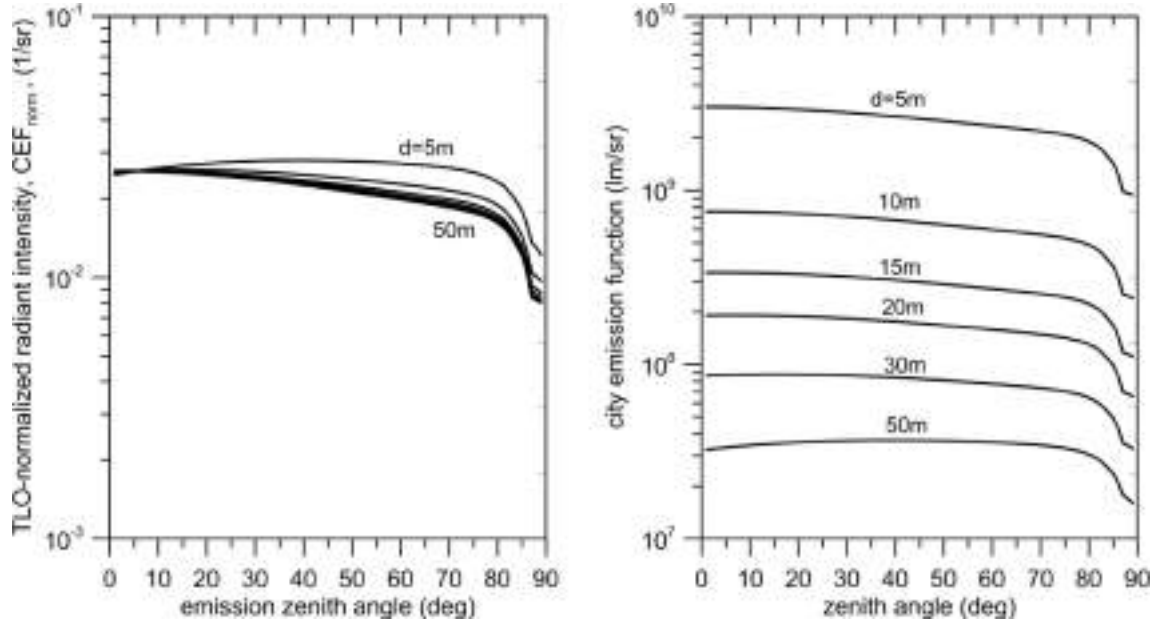


**Fig. 11.** The same as in Fig. 10, but for the parameter of  $d$  ranging from 5 m to 50 m. All other parameters used are specified in the text (see the first paragraph in Section 6.1).

bility is a non-linear function of  $\ell/D$  although at first sight one would expect linearity. However, it is easy to accept this result if we remember that linearity is only a reasonable approximation for a single-barrier case. Urban environment is an organized, but heterogeneous collection of isolated buildings which all interact with highly inclined light beams, i.e. those transported along highly slanted paths. For this reason the probability falls very quickly with increasing  $\ell/D$ , basically, if the value of  $\ell/D$  is above 0.2.

A light fixture is approximated by a point source with a vertical distance from the ground surface which coincides with the vertical dimension of the fixture,  $\tilde{h}$ . Any horizontal dimension of a fixture is assumed to be small to block any light on its skyward path. Given that streetlights represent no obstruction to light beams, the intensity distribution when a light fixture is immersed in an array of buildings is due only to  $\varepsilon_{La}(z)$  combined with the blocking effect of buildings. By increasing the value of  $\tilde{h}$  the chance of light beams

reaching the atmosphere improves. It is demonstrated in Fig. 9 that  $CCEF_{norm}$  decreases at high zenith angles because many light beams exiting the fixture strike the side of a building except for those with  $\tilde{h} \geq H$ .

### 6.3. The effects of city size and building and lighting densities

Among the streetlight factors and building lighting found to affect CCEF there are also external factors such as city size and building and lighting densities that can impact total upwards emission. The lighting density  $\rho_L = 1/d^2$  actually simplifies the problem and introduces the lattice spacing  $d$  as an average horizontal distance between lamps. The same approach has been applied to building density  $\rho_B = 1/D^2$  (see last paragraph in Sect. 2). In this paper, the lighting (or building) density is interpreted as the number of light

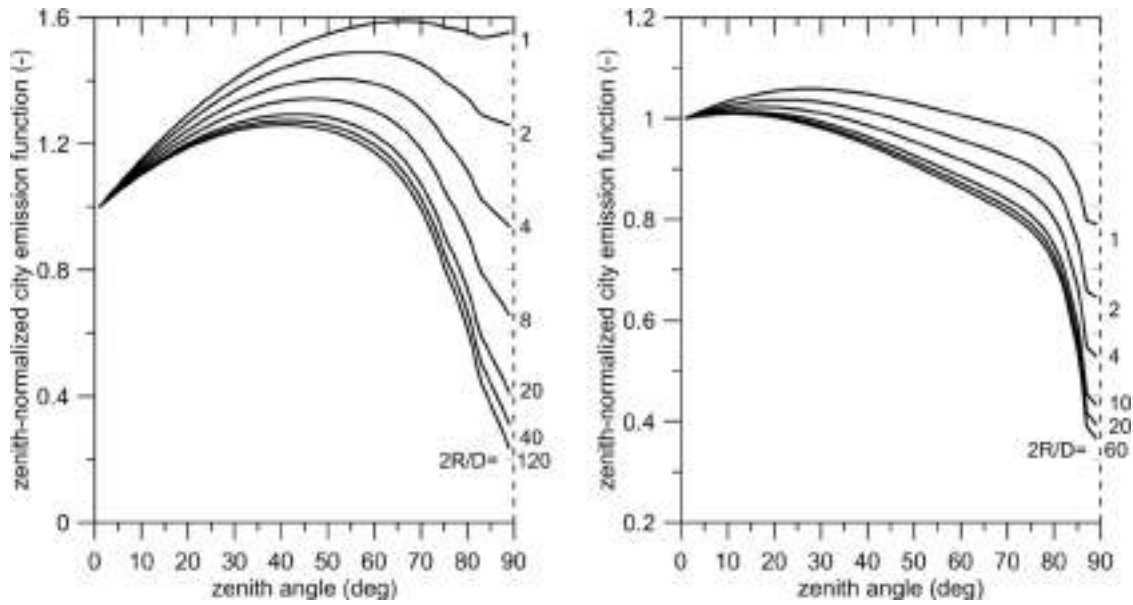


**Fig. 12.** Zenith-normalized CCEF for: a) (left panel)  $H=20$  m,  $\ell=35$  m,  $D=50$  m,  $\tilde{h}=7$  m,  $d=30$  m,  $a=2.2$ ,  $F_{La}=0.1$ ,  $G=0.1$ ,  $\Phi_{La}/\Phi_B \approx 1.3$ , and, b) (right panel)  $H=20$  m,  $\ell=40$  m,  $D=100$  m,  $\tilde{h}=9$  m,  $d=25$  m,  $a=1.5$ ,  $F_{La}=0.07$ ,  $G=0.1$ ,  $\Phi_{La}/\Phi_B \approx 2.2$ .

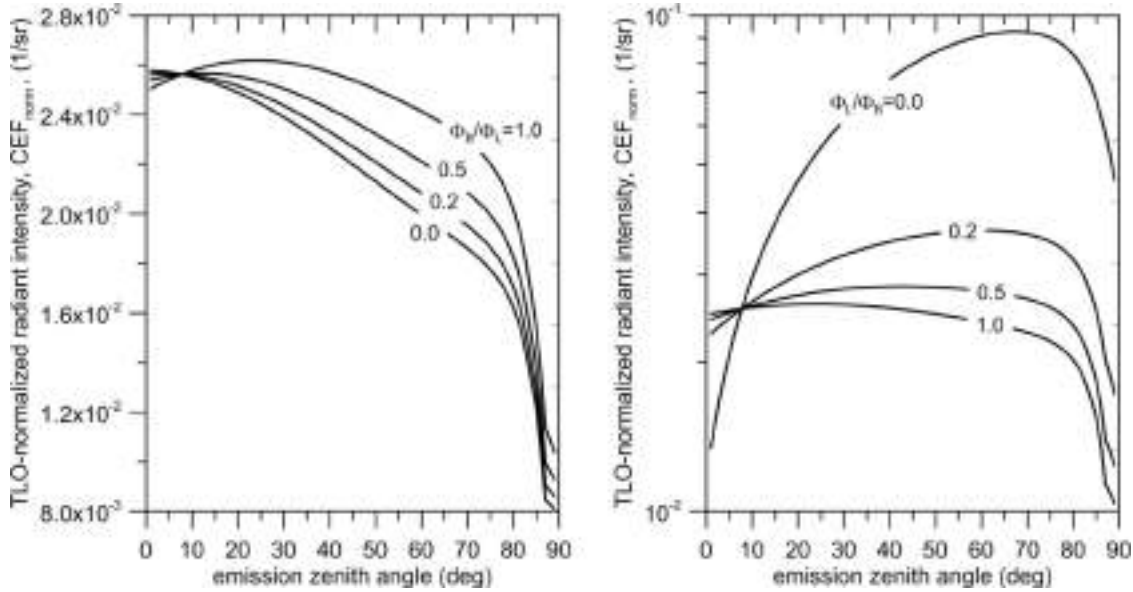


**Fig. 13.** TLO-normalized city emission function computed from Eq. (66) for  $\Phi_{La}/\Phi_B$  and  $\Phi_B/\Phi_{La}$  both ranging from 0 to 1. All other parameters used are specified in the text (see the first paragraph in Section 6.1).

sources per unit area, e.g. the number of fixtures (or buildings) per square kilometer.

By decreasing the inter-building separation  $D$  the total light output to low zenith angles increases, because luminous building façades oriented perpendicular to ground emit a considerable amount of photons to angles high above the horizontal plane. Even though buildings are assumed to have a peak emission towards the horizon, no further increase of CCEF due to lowering of  $D$  is observed at high zenith angles (consult Fig. 10). This is because all  $\rho_B$  considered in our model computations exceed  $\rho_L$  at least by a factor of 2.5 and also because  $\Phi_{La}/\Phi_B > 2$  (see the first paragraph in Sect. 6.1). Therefore the building lighting is scarcely a key element, although it may control some CCEF features at high and/or intermediate elevation angles (compare total-lumen-output-normalized radiant intensity in Fig. 10a with raw CCEF in Fig. 10b).

The raw data are especially useful in analyzing the role of  $d$  in forming CCEF. Note that  $d$  preferentially shapes the radiant intensity function because  $\Phi_{La}\rho_L$  to  $\Phi_B\rho_B$  ratio is as large as 5 or even larger (depending on the model studied). We have varied the horizontal distance between light fixtures over a wide interval, from 5 m to 50 m. The value of  $d=5$  m is totally unrealistic, but can document the model behavior under extreme conditions. The effect of  $d$  is not as apparent in Fig. 11a, where  $CCEF_{norm}(z)$  is depicted, but is visible in Fig. 11b, where no normalization is used. Altering  $d$  over one or more orders of magnitude is meaningful because urbanized zones or even cities differ in design, and thus in amount of upwardly directed light. The computations have proven that absolute values of cumulative uplight are controlled by  $\rho_L$  rather than showing an inverse linear relationship between CCEF and  $d$  (see Fig. 11b, where zenith emissions are roughly proportional to  $1/d^2$ ).

Simplified models consider that the total luminous flux per unit solid angle is proportional to city area independent of zenith angle. The light emission pattern for all city-lights is conserved and only the total light output increases with increasing  $\tilde{R}$ . Such an assumption is expected to be appropriate for large cities, but might appear inaccurate for small villages or towns. The built environment with a small population density might only encompass a few clustered buildings including residential buildings or groups of houses that all occupy a small area (up to some tens of square kilometers). Many villages in Slovakia have sizes below 5 km. Therefore, the numerical modeling performed here for  $2\tilde{R} \leq 6$  km is to uncover the role of city size in shaping the light emission as well as to verify the asymptotic behavior of the model at  $\tilde{R}$  approaching its upper limit (3 km) we have used for Slovakian villages. The theoretical model also allows for extremely small values of  $2\tilde{R} = D$ , implying that a human settlement is only a single-array of buildings. In Fig. 12a and b two situations are analyzed that differ in  $\varepsilon_{La}(z)$ ,  $\Phi_{La}$  to  $\Phi_B$  ratio, uplight fraction, building density, lighting density and some other parameters (see the figure caption). The effect of light emissions from buildings is strengthened by increasing  $\rho_B$  and lowering  $\Phi_{La}/\Phi_B$ , concurrently. The near-ground emissions are blocked inefficiently if  $2\tilde{R}/D$  is low, thus CCEF obtained in Fig. 12a is higher than that found in Fig. 12b. It has to be noted that light fixtures also contribute to the near-ground emission through an elevated value of  $a$  and due to a slightly enhanced uplight fraction  $F_{La}$ . In addition, the numerical experiment performed in Fig. 12 has demonstrated that CCEF converges to its asymptotic limit if  $2\tilde{R}$  is maximized.

#### 6.4. The effect of total light outputs ratio

Total luminous flux is one of the factors that are inherent to the lighting system and predetermine the CCEF as a whole. Buildings are known to strengthen the horizontal radiation transport as the building sides are oriented vertically. This is why the light beams escaping from windows are preferably directed towards the horizon as evidenced in right panel in Fig. 13 (see the CCEF computed for  $\Phi_{La}/\Phi_B = 0$ ). The emissions to low elevation angles are suppressed when increasing  $\Phi_{La}/\Phi_B$  while keeping the total lumen output fixed. This is the opposite of what we observe at high elevation angles. The reverse ratio of  $\Phi_B/\Phi_{La}$  is used in the left plot of Fig. 13 to demonstrate the model behavior when street lighting emissions dominate the far-field amplitude of CCEF. The data for  $\Phi_B/\Phi_{La} = 0$  are to model a lit urban environment with interior lighting totally absent. Although beyond the usual range it falls into a class of situations after midnight with many indoor lights turned off. Most typically  $\Phi_B/\Phi_{La} > 0$  has to be taken into account when modeling after-midnight city lights.

## 7. Conclusions

Although city design can fundamentally differ one from each other and we expect that certain properties of the light output patterns are fundamentally different for the cities, we are currently unable to differentiate the specific urban structures from the total radiant flux directed upwards. We are unable even to predict the cumulative light emission from all structures in a heterogeneous light-emitting or blocking urban environment, embracing all topography, luminous building façades, street lighting, advertising displays and other luminous or blocking constructs. Part of the problem is that appropriate theories and computational codes to calculate the collective emissions from many urban elements have been missing so far and those available (if any) would be extremely computationally expensive (because of large multi-relational data). Since the field is very much in its infancy, the necessary initial studies have yet to be conducted.

The approach we present here attempts to fill this gap by introducing an analytic-statistical formulation of the problem for the light output pattern. We have developed new comprehensive formulae Eqs. (54) and ((66)) in which the cumulative city emission function results from interaction between many urban elements, specifically light fixtures and buildings taking into account blocking effects near the ground. The model allows for arbitrary combination of light-emitting and blocking elements and can predict the statistically relevant radiant (or luminous) intensity distributions for many cities worldwide. The solution function for zenith emissions can be interrelated with optical data taken by satellites in nighttime aiming to estimate separate contributions to uplight from street lights and vertically oriented light-emitting surfaces (such as luminous building façades). It makes it possible to either minimize the number of unknowns in the model through an increase of the information content of ground-based data or to improve the usability of data from e.g. the VIIRS database.

The numerical simulations we have performed for a set of input parameters document the correct model behavior under various conditions, including extreme conditions. Despite the complexity of the derived equations, the numerical computations can be accomplished rapidly using an inexpensive CPU. Due to their single integral forms and the analytical representations of Eq. (38), only a few milliseconds is needed using a modest PC and CPU to compute the complete emission function using Eq. (54). The main strengths of the model presented here are its easy parameterization and ability to predict more realistic angular luminous or radiant intensity distributions (CCEF) for more-or-less arbitrary city design. For instance, the mathematical formulae we have developed here are applicable to both compact and diffuse cities, while the primary differences between these two city models would be the input parameters (particularly the density functions). The theoretical foundation of the documented solution implies its applicability to a wide range of situations, hence, it can be incorporated into larger numerical tools that simulate the propagation of artificial light at night. This is also a sound motivation for increasing modeling activities, which in turn encourage experimentalists to measure CCEF patterns in order to verify existing models and this new model, to ascertain how the theoretically-derived solution compares with that physically observed in complex urban environments.

Local city topography could be taken into account in future versions of this model. E.g. for a town on a hill, the effective exterior perimeter that emits unblocked beams of light at high zenithal angles is not formed by the most exterior array of buildings only: a substantial part of the town, depending on topography, may give rise to emissions not blocked by the immediate outer building array located at a lower place. However, that requires some effort to develop a generalized solution based on an analytical-statistical approach to modeling of surface topography, taking into account its wavy structure. It is a great challenge to develop a parametrizable, rather than single-purpose surface model.

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# Life-Cycle Assessment of Energy and Environmental Impacts of LED Lighting Products

Part 2: LED Manufacturing and Performance

May 2012

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## COMMENTS

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## Acronyms and Abbreviations

|                                |                                        |                    |                                       |
|--------------------------------|----------------------------------------|--------------------|---------------------------------------|
| Ag                             | silver                                 | N <sub>2</sub>     | nitrogen                              |
| Al                             | aluminum                               | nm                 | nanometers (m <sup>-9</sup> )         |
| AlN                            | aluminum nitride                       | NH <sub>3</sub>    | ammonia                               |
| Al <sub>2</sub> O <sub>3</sub> | aluminum oxide (alumina)               | NH <sub>4</sub> OH | ammonium hydroxide                    |
| Au                             | gold                                   | Ni                 | nickel                                |
| CCT                            | correlated color temperature           | NO <sub>x</sub>    | oxide of nitrogen                     |
| Ce                             | cerium                                 | O <sub>2</sub>     | oxygen                                |
| CH <sub>4</sub>                | methane                                | pcLED              | phosphor converting LED               |
| CO <sub>2</sub>                | carbon dioxide                         | PNNL               | Pacific Northwest National Laboratory |
| CVD                            | chemical vapor deposition              | PVD                | physical vapor deposition             |
| DOE                            | Department of Energy                   | R&D                | research and development              |
| ECD                            | electrochemical deposition             | SF <sub>6</sub>    | sulfur hexafluoride                   |
| ESD                            | electrostatic discharge                | SiC                | silicon carbide                       |
| GaN                            | gallium nitride                        | SiH <sub>4</sub>   | silicon tetrahydride (silane)         |
| g                              | grams                                  | Sn                 | tin                                   |
| H <sub>2</sub>                 | hydrogen                               | SO <sub>2</sub>    | sulfur dioxide                        |
| H <sub>2</sub> O <sub>2</sub>  | hydrogen peroxide                      | SSL                | solid state lighting                  |
| HCl                            | hydrochloric acid                      | Ti                 | titanium                              |
| HF                             | hydrofluoric acid                      | TMAI               | trimethylaluminum                     |
| ISO                            | International Standards Organisation   | TMGa               | trimethylgallium                      |
| kWh                            | kilowatt-hour                          | TMIn               | trimethylindium                       |
| LCA                            | life cycle assessment                  | UK                 | United Kingdom                        |
| LCD                            | liquid crystal display                 | μm                 | micrometer (m <sup>-6</sup> )         |
| LCI                            | life cycle inventory                   | UPW                | ultra-pure water                      |
| LCIA                           | life cycle impact assessment           | U.S.               | United States                         |
| LED                            | light emitting diode                   | UV                 | ultraviolet                           |
| LLO                            | laser lift off                         | V                  | volts                                 |
| lm                             | lumen                                  | W                  | watts                                 |
| mA                             | milliampere                            | W                  | tungsten                              |
| mm                             | millimeter (m <sup>-3</sup> )          | YAG                | yttrium aluminum garnet               |
| MOCVD                          | metalorganic chemical vapor deposition | ZnSe               | zinc selenide                         |

## 1 Executive Summary

The report *LED Manufacturing and Performance* covers the second part of a larger U.S. Department of Energy (DOE) project to assess the life-cycle environmental and resource costs in the manufacturing, transport, use, and disposal of light-emitting diode (LED) lighting products in relation to comparable traditional lighting technologies. The assessment comprises three parts:

- *Part 1: Review of the Lifecycle Energy Consumption of Incandescent, Compact Fluorescent and LED Lamps.* Comparison of the total life-cycle energy consumed by LED and other lamp types based on existing life-cycle assessment (LCA) literature. This report was published in February 2012 and is available on U.S. DOE website:  
[http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2012\\_LED\\_Lifecycle\\_Report.pdf](http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2012_LED_Lifecycle_Report.pdf)
- *Part 2: LED Manufacturing and Performance.* This study develops a conservative LCA method for considering both the direct and indirect material and process inputs to fabricate, ship, operate and dispose of LED products in 2012 and estimated for 2017. An LCA comparison to an incandescent lamp and a compact fluorescent lamp (CFL) is provided.
- *Part 3: LED Environmental Testing.* The purchase, disassembly and chemical testing of LED and conventional lighting products to study whether potentially hazardous materials are present in concentrations that exceed hazardous waste regulatory thresholds.

Part 1 of the overall effort reviewed existing LCA literature to determine the range of energy consumption and downstream energy savings. The report compared existing life-cycle energy consumption of an LED lamp product to incandescent lamp and CFL technologies based on 10 literature studies. Part 1 of the work provided the following results:

1. A detailed literature review of more than 25 existing LCA studies in this field.
2. A summary of the LCA process and methodology.
3. A meta-analysis based on a functional unit of 20 million lumen-hours for incandescent, halogen, CFL and LED lamps.

The Part 1 report concluded that the life cycle energy consumption of LED lamps and CFLs are similar at approximately 3,900 MJ per 20 million lumen-hours. Incandescent lamps consume significantly more energy (approximately 15,100 MJ per 20 million lumen-hours). The authors also concluded that the use phase is the most important contributor to the energy consumption, followed by manufacturing of the lamps and finally transportation (less than 1% of energy consumption). One key issue identified in the report is the high uncertainty in energy consumption associated with the manufacturing process estimates in surveyed literature range from 0.1% to 27% of the total life-cycle energy consumption.

Part 2 of the project (this report) uses the conclusions from Part 1 as a point of departure to focus on two objectives: producing a more detailed and conservative assessment of the manufacturing process and providing a comparative LCA with other lighting products based on the improved manufacturing analysis and taking into consideration a wider range of environmental impacts. In this study, we first analyzed the manufacturing process for a white-light LED lamp (based on a sapphire-substrate, blue-light, gallium-nitride LED package pumping a yellow phosphor applied to the lamp envelope), to understand the impacts of the manufacturing process. We then conducted a comparative LCA, looking at the impacts associated with the Philips EnduraLED and comparing those to a CFL and an incandescent lamp. The comparison took into account the Philips EnduraLED as it is now in 2012 and then projected forward



what it might be in 2017, accounting for some of the anticipated improvements in LED manufacturing, performance and driver electronics.

Overall, this study confirmed that energy-in-use is the dominant environmental impact, with the 15-watt CFL and 12.5-watt LED lamps performing better than the 60-watt incandescent lamp. These three lamps all produce approximately the same light output (~850 lumens), but the environmental impacts associated with the incandescent are markedly more significant than the CFL and LED lamps because of the energy-in-use phase of the life-cycle.

In order to evaluate the fifteen impact measures of interest across the four lamp types considered, “spider” graphs were prepared. Each of the fifteen impacts is represented (and labeled) by a spoke in the web, and the relative impacts of each lamp type are plotted on the graph. The lamp type having the greatest impact of the set analyzed (incandescent, in this case) defines the scale represented by the outer circle at the greatest distance from the center of the web. The other products are then normalized to that impact, so the distance from the center denotes the severity of the impact relative to the incandescent lamp. In other words, those sources with the least impact will have their circle close to the center and those with the greatest impact would be on the outer perimeter of the web. The data plotted in this graph are normalized for the quantity of lighting service, measured in lumen-hours.



Figure 1-1. Life-Cycle Assessment Impacts of the Lamps Analyzed Relative to Incandescent

As shown in Figure 1-1, the plots representing LED and CFL technology fall well within the outer circle, illustrating clearly that the incandescent lamp has the highest impact per unit lighting service of all the lamps considered. This finding is not a function of the material content of a single lamp, as the incandescent lamp has the lowest mass and is least complex lighting system. Rather, it represents the low efficacy of this light source, and the resulting large quantities of energy required to produce light and many replacements are required to span the (longer) rated life of an LED lamp or CFL. Generating the higher amount of electric energy consumed per unit of light output causes substantial environmental impacts and results in the incandescent lamp being the most environmentally harmful across all fifteen impact measures.

While it has substantially lower impacts than incandescent, the compact fluorescent lamp is slightly more harmful than the 2012 integrally ballasted LED lamp against all but one criterion – hazardous waste landfill – where the large aluminum heat sink causes the impacts to be slightly greater for the LED lamp than for the CFL. The best performing light source is the projected LED lamp in 2017, which takes into account several prospective improvements in LED manufacturing, performance, and driver electronics.

Figure 1-2 presents the same findings shown in Figure 1-1, but the graph has been adjusted to remove the incandescent lamp and provide the impacts relative (primarily) to the CFL.

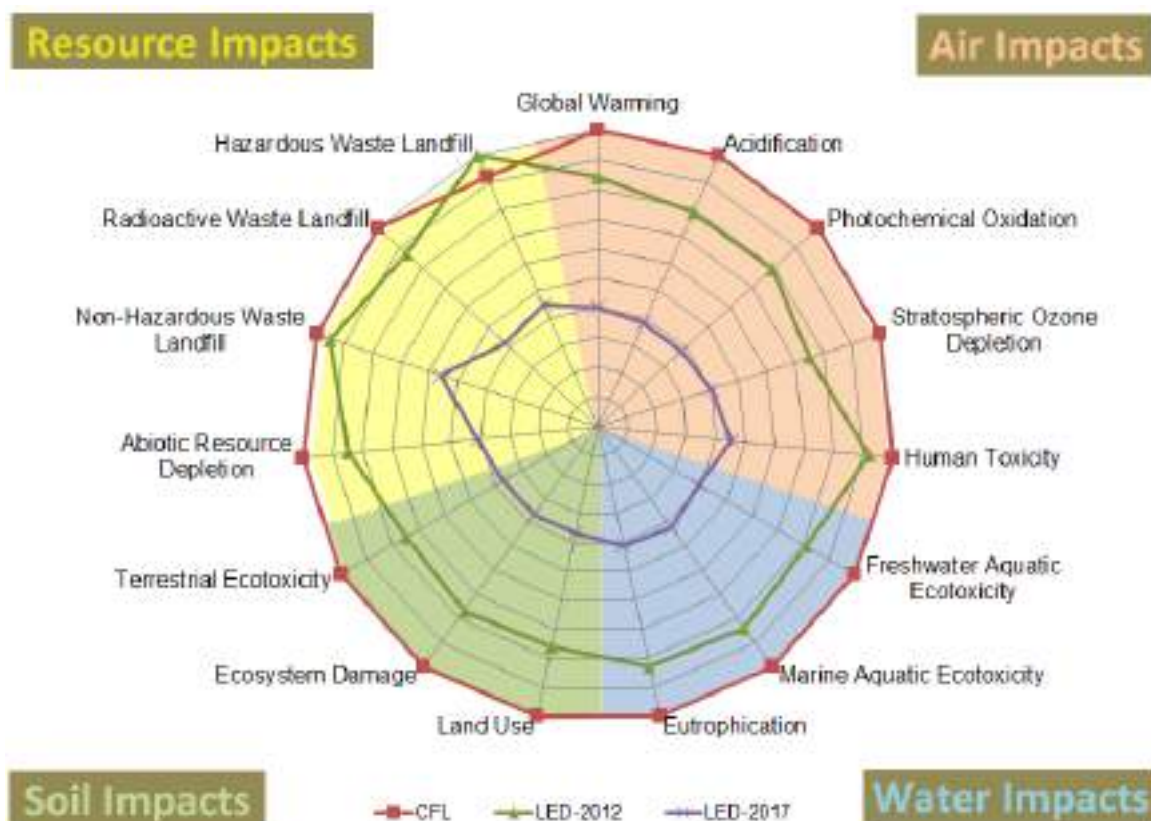


**Figure 1-2. Life-Cycle Assessment Impacts of the Lamps Analyzed Relative to CFL**

Overall, the prospective impacts of the improved LED lamp in 2017 are, like the others, significantly less than the incandescent, and about 70% lower than the CFL and approximately 50% lower than the 2012 LED lamp, which reflects the best available technology today. The important finding from these graphs is not necessarily the minor relative differences between the LED lamp and the CFL, but instead the very significant reduction in environmental impacts that will result from replacing an incandescent lamp with a more efficient product. Environmental impact reductions on the order of 3 to 10 times are possible across the indicators through transitioning the market to these new, more efficacious light sources. Because of the dominant role of energy consumption in driving the impacts, continued focus on efficacy targets, cost reduction and market acceptance is appropriate. Furthermore, the greatest environmental impact after energy in-use for the LED sources is the aluminum heat sink, which would be reduced in size as the efficacy increases, and more of the input wattage is converted to useful lumens of light (instead of waste heat). The heat sink is the main reason that the LED currently exceeds the CFL in the category of hazardous waste to landfill, which is driven by the upstream energy and environment impacts from the manufacturing of the aluminum from raw materials. Although end-of-life was evaluated in a conservative way for this report, recycling efforts could also reduce the adverse impact of manufacturing the aluminum heat sink. The potential to alleviate impacts through good design and end of life recovery was evaluated in a letter published by Carnegie Mellon University (Hendrickson, 2010).

### **Underlying LED Technology Assumptions**

In the literature reviewed for Part 1 of this study, one of the researchers had used the Ecoinvent database entry for the LED when characterizing the packaged LEDs from a general illumination lamp. This entry is for an indicator LED, and it is based on LED manufacturing technology from 2007, rather than the equipment being used today. For the purposes of understanding how much LED technology has improved or otherwise differs from the LED characterization in the present Ecoinvent database version 2.2, the authors prepared a comparison of the environmental impacts associated with two representative LEDs, one assumed by Ecoinvent, and the other reflecting newer technology. Due to the fact that the former LED is a 5 millimeter indicator lamp and the latter a high-brightness LED used in general illumination applications, the impacts need to be normalized for lighting service (i.e., lumen-hours) from each device. The indicator lamp was found to have a light output of 4 lumens, while the high-brightness LED was found to have a light output of 100 lumens (Radio-Electronics, 2012; Philips, 2012). The results show a significant reduction in the environmental impacts on a per-lumen basis that have been achieved between the 2007 Ecoinvent assessment and the 2011 technology that was assumed in this study. Overall, the average reduction in impact is 94.5%. Thus, on a lumen output basis, it would appear that high-brightness LEDs manufactured in 2011 are significantly less harmful for the environment than the 5mm indicator LEDs that were produced in 2007.

This report represents the first publicly available LCA that includes a unit process for the LED manufacturing specific to illumination applications. This process can be used for future investigations of other lighting products based on LEDs and can be refined by the lighting community to represent new processes as they become available. As one of the first public assessments of this type, the authors have made several conservative assumptions:

- Recovery and recycling of materials – there is a lack of information in the public domain about the extent to which materials used in the manufacturing of LEDs are reused and recycled. If these materials are recovered, processed and then reused, this would reduce the per unit production environmental impacts. However, this version of the study assumes new materials are used at all stages of the LCA process, thus providing a conservative estimate of the impacts. In other words,

to the extent that materials are recovered and recycled, the environmental impacts will be less than those reported in this study.

- Transport and end-of-life – Information was limited on the transport and end-of-life phases of LED, CFL and incandescent lamps. Working estimates were developed based on available data and supplemented with stakeholder input to try and address all aspects of the life cycle.
- Wafer size – This report assumes a three-inch sapphire wafer substrate, although industry sources indicate that larger wafers are rapidly being adopted. This assumption is also conservative to the extent that improvements in this area also reduce the impact of LEDs in the next 5 years.

## 2 Introduction

The U.S. Department of Energy (DOE) supports the market introduction of new energy efficient products through several programs. The research described in this report falls within DOE's Solid-State Lighting (SSL) program and seeks to apply the internationally-recognized environmental assessment method called Life Cycle Assessment (LCA) to the environmental impact of light emitting diodes (LEDs). LED-based general illumination products have the potential to surpass many conventional lighting technologies in terms of energy efficiency, lifetime, versatility, and color quality. According to a recent forecast, LED lighting will represent 74 percent of U.S. general illumination lumen-hour sales by 2030, resulting in an annual primary energy savings of 3.4 quads (DOE, 2012d).

An LCA is a scientific methodology that enables researchers to quantify the environmental and sustainability impacts of a product across a range of categories for a product over its entire life cycle. An LCA study can take on many forms, including, for example, analysis of different products to determine their comparative impacts. LCA studies are publicly available on a wide range of products, including supermarket shopping bags (EAUK, 2011), automobile tires (Continental, 1999), lithium-ion batteries (Gaines, 2010) and lamps and luminaires (OSRAM, 2009).

Published earlier in 2012, Part 1 of this study identified gaps in the public literature associated with LED manufacturing and use (DOE, 2012a). The authors reviewed existing LCA literature, focusing on the energy consumed in manufacturing and use of the lamps studied. The report compares the life-cycle energy consumption of an LED lamp to those of an incandescent lamp and a CFL based on the findings of ten independent studies. The Part 1 report provides the following results:

1. A literature review of more than 25 LCA studies in this field.
2. A summary of the LCA process and methodology.
3. A meta-analysis based on findings of the ten most relevant studies and a functional unit of 20 million lumen-hours for incandescent, halogen, CFL and LED lamps.

Table 2-1 shows the ten studies that were used for the Part 1 analysis.

**Table 2-1. Key Publications Reviewed in DOE's Part 1 Report (DOE, 2012a)**

| Publication Title                                                                                                                  | Author                                          | Year | Lamp Types |     |                |
|------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------|------|------------|-----|----------------|
|                                                                                                                                    |                                                 |      | GLS        | CFL | LED            |
| 1. Life-cycle Analyses of Integral Compact Fluorescent Lamps Versus Incandescent Lamps                                             | Technical University of Denmark                 | 1991 | X          | X   |                |
| 2. Comparison Between Filament Lamps and Compact Fluorescent Lamps                                                                 | Rolf P. Pfeifer                                 | 1996 | X          | X   |                |
| 3. The Environmental Impact of Compact Fluorescent Lamps and Incandescent Lamps for Australian Conditions                          | University of Southern Queensland               | 2006 | X          | X   |                |
| 4. Comparison of Life-Cycle Analyses of Compact Fluorescent and Incandescent Lamps Based on Rated Life of Compact Fluorescent Lamp | Rocky Mountain Institute                        | 2008 | X          | X   |                |
| 5. Energy Consumption in the Production of High-Brightness Light-Emitting Diodes                                                   | Carnegie Mellon University                      | 2009 |            |     | X <sup>1</sup> |
| 6. Life-Cycle Assessment and Policy Implications of Energy Efficient Lighting Technologies                                         | Ian Quirk                                       | 2009 | X          | X   | X              |
| 7. Life-cycle Assessment of Illuminants - A Comparison of Light Bulbs, Compact Fluorescent Lamps and LED Lamps                     | OSRAM, Siemens Corporate Technology             | 2009 | X          | X   | X              |
| 8. Life-cycle Assessment of Ultra-Efficient Lamps                                                                                  | Navigant Consulting Europe, Ltd.                | 2009 | X          | X   | X              |
| 9. Reducing Environmental Burdens of Solid-State Lighting through End-of-Life Design                                               | Carnegie Mellon University                      | 2010 |            |     | X <sup>2</sup> |
| 10. Life-cycle Energy Consumption of Solid-State Lighting                                                                          | Carnegie Mellon University, Booz Allen Hamilton | 2010 |            |     | X <sup>3</sup> |

1. The Carnegie Mellon (2009) study only provides energy estimates for an LED package.

2. The Carnegie Mellon (2010) study only provides data on the bulk lamp materials of an LED lamp.

3. Data from this publication was provided from a poster presentation at the 2011 DOE SSL R&D Workshop.

The Part 1 report concluded that the life cycle energy consumption of LED lamps and CFLs are similar at approximately 3,900 MJ per 20 million lumen-hours of lighting service as shown in Figure 2-1. Incandescent lamps consume approximately four times more energy (approximately 15,100 MJ per 20 million lumen-hours). The authors also conclude that the use phase is the largest contributor to the energy consumption, followed by manufacturing of the lamps and finally transportation (the last representing less than 1% of total energy consumption). One key issue identified in the report is the high uncertainty associated with the manufacturing process reflecting differences among studies in literature, which span a range of 0.1% to 27% of the total energy consumption from manufacturing.



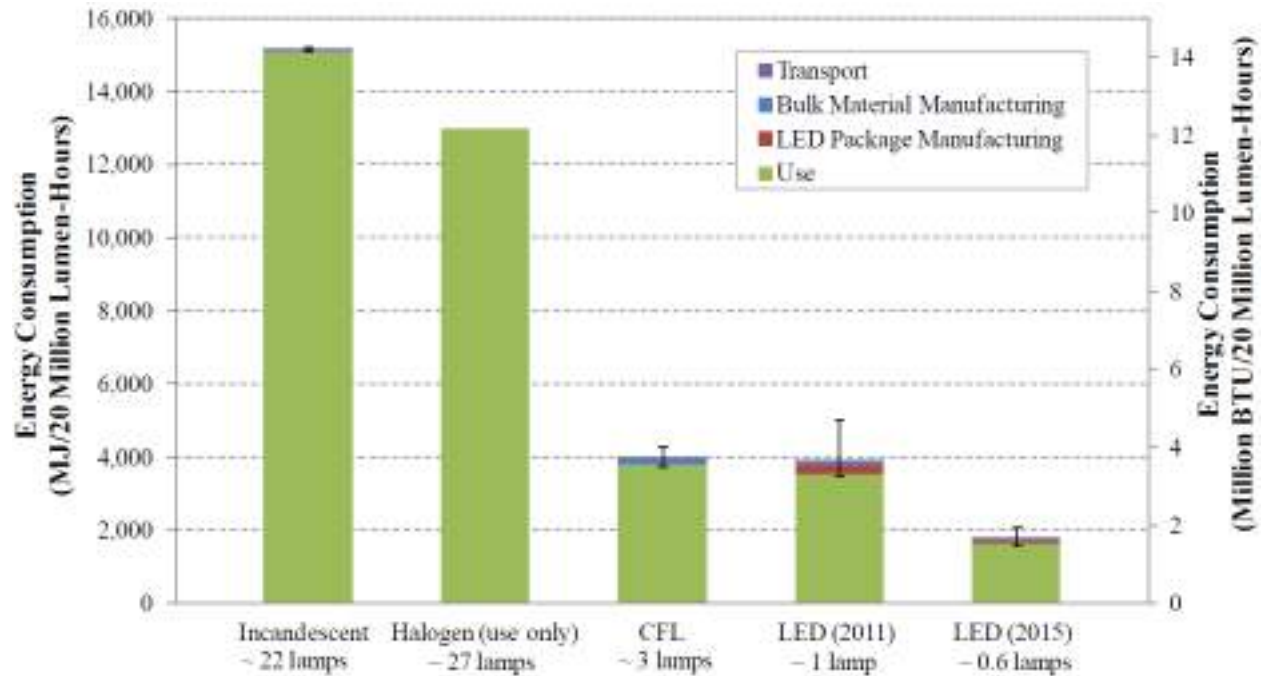


**Figure 2-1. Life-Cycle Energy of Incandescent Lamps, CFLs, and LED Lamps (DOE, 2012a)**

The manufacturing process for packaged LEDs has only been analyzed in two sources of literature. The first involves a simple unit process for LED's used by the electronic industry for indicator lights developed in 2007 (Ecoinvent 2012) and the second is an independent LCA performed by a manufacturer, OSRAM (OSRAM 2009). Since each of these studies has its respective limitations, the focus of Part 2 is exploring the LED manufacturing process in an attempt to address the high uncertainty in the literature.

This Part 2 report seeks also to evaluate the materials and processes that are hazardous to human health and the environment involved in the manufacturing of LED based products. The results of this analysis were then incorporated into a study of the wider life-cycle impacts of LED lamps and luminaires (addressing residential and commercial products), relative to conventional light sources.

### 3 Life-Cycle Assessment Methodology

An LCA is a scientific methodology that enables researchers to quantify the environmental and sustainability impacts across a range of categories for a product over its entire life cycle. An LCA characterizes and quantifies the inputs, outputs, and environmental impacts of a specific product or system at each life-cycle stage (ISO, 2006). The general procedure for conducting a life-cycle analysis is defined by the International Organization for Standards (ISO) 14000 series. The main phases of an LCA according to ISO guidelines are goal, scope, and boundary definition; life-cycle inventory (LCI) analysis; life-cycle impact assessment; and interpretation. The LCA is discussed in more detail in the Part 1 report (DOE, 2012a).

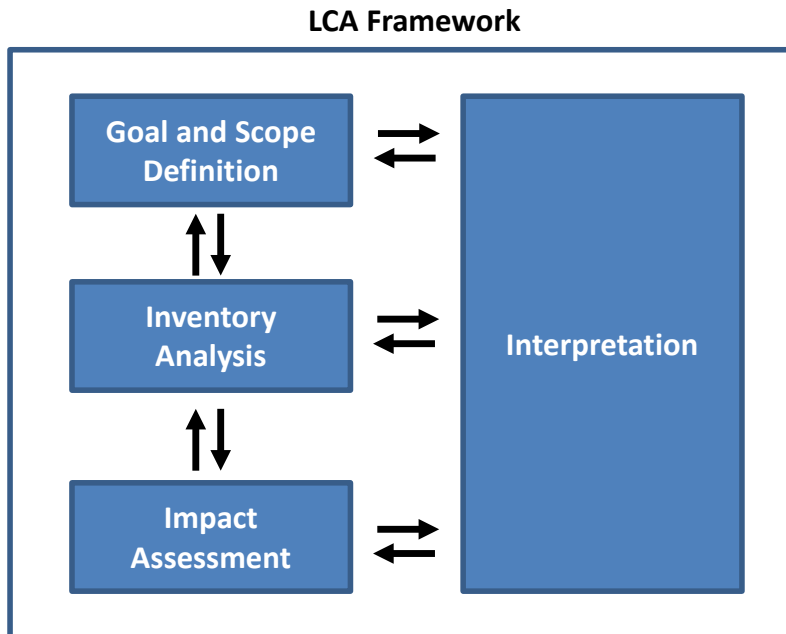
#### 3.1 International LCA Standards

LCA methods are scientifically grounded in a series of standards and technical specifications issued by the ISO. A list of the current standards and reports included in this series is provided below, along with the ISO's brief descriptions of each document (note: some of the ISO descriptions make reference to ISO standards that have subsequently been superseded by other standards). The DOE research project conducting an LCA of LED lamps and luminaires compared to traditional light sources conforms to the methodology and requirements of the current ISO standards and technical specifications.

- **ISO 14040:2006.** Environmental management – Life cycle assessment – Principles and framework. ISO 14040:2006 describes the principles and framework for a LCA including: definition of the goal and scope of the LCA, the LCI phase, the life cycle impact assessment (LCIA) phase, the life cycle interpretation phase, reporting and critical review of the LCA, limitations of the LCA, the relationship between the LCA phases, and conditions for use of value choices and optional elements. ISO 14040:2006 covers LCA studies and LCI studies. It does not describe the LCA technique in detail, nor does it specify methodologies for the individual phases of the LCA.
- **ISO 14044:2006.** Environmental management – Life cycle assessment – Requirements and Guidelines. ISO 14044:2006 specifies requirements and provides guidelines for LCA including: definition of the goal and scope of the LCA, the LCI phase, the LCIA phase, the life cycle interpretation phase, reporting and critical review of the LCA, limitations of the LCA, relationship between the LCA phases, and conditions for use of value choices and optional elements. ISO 14044:2006 covers both LCA and LCI studies. This standard supersedes and replaces ISO 14041:1998, ISO 14042:2000 and ISO 14043:2000.

#### 3.2 Brief Overview of an LCA

The four primary phases of an LCA process involve iterations of interpretation and revision. The diagram below illustrates these key aspects of the process, and a brief description on each is presented below the diagram. Each aspect of the process is discussed in more detail in the Part 1 report (DOE, 2012a).



Source: ISO 14044:2006

**Figure 3-1. Key Aspects of an LCA Study (ISO 2006)**

1. **Goal & Scope Definition: section 4.2 ISO 14044:2006.** The first phase of an LCA is to specify the goal and scope of the study. The goal has four key aspects, including: (1) the intended application of the study (e.g., marketing, product development, strategic planning); (2) the purpose of the study (e.g., to be published or used internally); (3) the intended audience, including shareholders, executives, consumers; and (4) use as a comparative analysis, whereby the LCA results are used to compare with other products or materials.
2. **Inventory Analysis: section 4.3 ISO 14044:2006.** The second phase is characterized by the compilation and quantification of inputs and outputs for a given product system through its life cycle. The data collected and used in this phase includes all environmental and technical quantities for all relevant unit processes within the system boundaries.

The final part of this phase is a data quality and processing stage, which requires the following three actions to be completed: (1) data validation (an on-going process); (2) relating data to unit processes and (3) relating data to the functional unit. This stage is necessary in order to complete the next phase, calculating the impact for each unit process and the overall system.

3. **Impact Assessment: section 4.4 ISO 14044:2006.** This third phase identifies and evaluates the magnitudes and relative importance of the environmental impacts arising from the inventory analysis. The inputs and outputs are assigned to impact categories and their potential impacts are quantified according to the characterization factors. Examples of the impact categories include: resource depletion (energy, water, fossil fuels, chemicals, etc.), land use, greenhouse gas emissions, and water pollution. According to ISO 14044, certain mandatory elements must be included when conducting an LCA – such as the selection of relevant impact categories,

classification and characterization. Other elements are optional, such as normalizing the findings, grouping them and/or applying a weighting of any sort.

Impact categories are chosen as the outputs from the study, for which environmental effects of the analyzed system will be quantified. This selection of categories is driven at least in part by the goal of the study, ensuring that the metrics for comparison are relevant to the objective.

4. **Interpretation:** In this final phase, the results are checked and evaluated to confirm that they are consistent with the goal of the study. As shown in the diagram, the three other phases are all connected to Interpretation, illustrating the point that this phase is a pivotal part of the process and can lead to revisions in any point of the process.

The evaluation step is focused on enhancing the reliability of the study. This includes for example a sensitivity check on the uncertainties around the data, assumptions, allocation methods and calculations. It also includes a gap analysis or completeness check, to ensure there aren't any missing or incomplete areas that need to be analyzed in order to meet the goal and the scope of the study. If no missing information is identified, then this should be noted in the report. Finally, the evaluation step includes a consistency check to ensure that the methods and the goal are met, including for example, data quality, system boundaries, data symmetry or time period, and so on.

## 4 Goal and Scope

During the scope phase, the product or process under study is fully described, all assumptions are defined and the methodology that will be used to assess the product system is presented. There are many factors that must be taken into consideration in the scope phase, including the function of the product, the functional unit, the system boundaries, the impact categories and assessment method, the data requirements and assumptions, and the limitations of the analysis.

### 4.1 Goal Statement

The DOE is conducting a broad study to assess and compare the environmental impacts of general illumination LED lamps and luminaires with conventional lamps and luminaires. Table 1 provides an overview of the goal of the study consistent with the ISO standard (ISO, 2006).

**Table 4-1. Summary of the Life-Cycle Assessment Goal for this Report**

| LCA Element           | Summary for this Work                                                                                                                                                                                                                              |
|-----------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Intended Application  | To compare the energy and environmental impact of LED lamps used in general illumination applications with traditional lighting products.                                                                                                          |
| Reasons for the Study | <ul style="list-style-type: none"> <li>To quantify the energy and environment impacts of LEDs.</li> <li>To address uncertainty in the existing body of literature and LCA reports concerning LED manufacturing methods and assumptions.</li> </ul> |
| Audience              | Lighting designers, policy makers, researchers and technical experts considering LED technology in general illumination applications.                                                                                                              |
| Public Results        | Results of this study will be freely available, published on the U.S. DOE Solid State Lighting website: <a href="http://www1.eere.energy.gov/buildings/ssl/">http://www1.eere.energy.gov/buildings/ssl/</a>                                        |

### 4.2 Scope

The scope of this study is a comparison between the energy and environmental impacts of LED technology used in general illumination applications and traditional light sources, namely incandescent lamps and CFLs. For consistency with Part 1 of the work the functional unit has been established as 20 million lumen-hours of lighting service, which is approximately representative of total light output of a Philips EnduraLED 12.5W lamp over its lifetime.

The diagram in Figure 4-1 depicts the system boundary and the five stages (Inputs, Manufacturing, Transport, Use and End of Life) of the LCA analysis. All of these stages will be discussed and analyzed for an integrated LED lamp in the context of this (Part 2) study. The red box highlights three unit processes for the LCA that focus specifically on the manufacturing of LEDs. In general, the authors found that this has not been reported in adequate detail in prior literature and thus represents an important area for study and analysis.

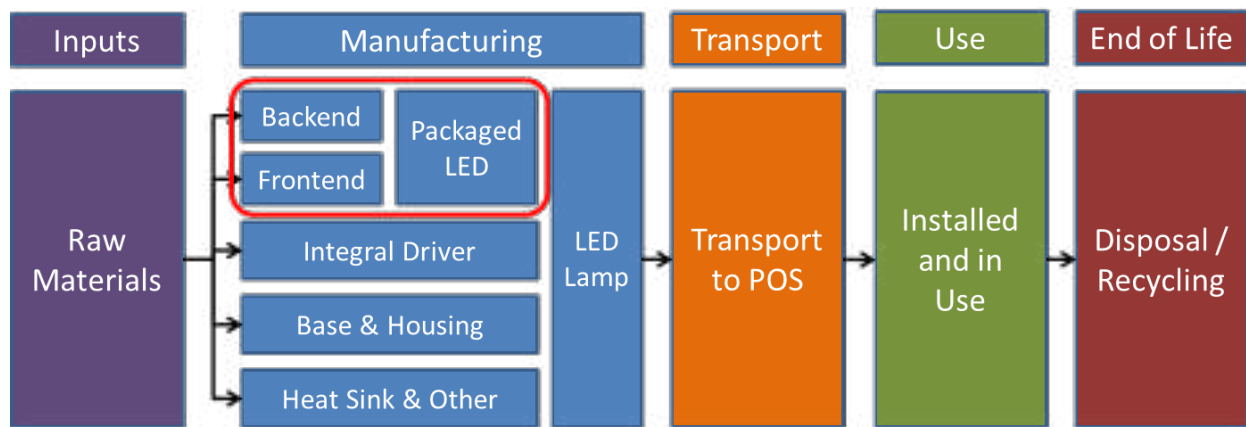


**Figure 4-1. System boundary of the Life Cycle Assessment of this Study (Part 2)**

As shown in the figure above, the impact inventories are broken down into the five life cycle stages, which include (1) inputs / raw materials, (2) manufacturing, (3) transportation to point of sale, (4) use of the product and (5) end-of-life disposal / recycling. These five stages of an LCA are briefly described below.

1. Raw Material Production - many products are made up of multiple components, and lamps are no exception. This first stage of the life cycle accounts for the emissions and resource usage associated with the production and transport of the various raw materials and intermediate products that are inputs to the final product. Estimating impacts of producing and transporting material inputs prior to their reaching the final manufacturer relies on Ecoinvent (version 2.2), an extensive database developed and maintained by the Swiss Center for Life Cycle Inventories.<sup>1</sup>
2. Manufacturing - the manufacturing phase takes all of the raw materials defined above, as delivered to the point of production, and accounts for the energies used and emissions associated with fabricating the lamp. In this analysis all of the major component parts are depicted in the figure to highlight these component parts.
3. Distribution - the distribution phase covers the transportation of the product from its point of manufacture to its point of installation and use. There might be a tendency when thinking about an LCA to believe that a detailed transport model will be required. However, for many products, transport and distribution form a small part of the overall environmental footprint. Impacts from distribution tend to be much more significant if the product needs to be refrigerated during the distribution stage of the process, which isn't the case for lighting products.
4. Use/Consumption - the use/consumption phase of a product is usually straightforward to describe, though it is important that a consistent basis is chosen to enable fair comparisons between different products. In order to be consistent with the Part 1 study, the use phase is based around the lighting service associated with each lamp type.

<sup>1</sup> Swiss Center for Life Cycle Inventories, <http://www.ecoinvent.org/>



5. End-of-Life - the final stage of a life cycle is the end-of-life stage which reflects what happens to the lighting products when they have stopped working and are no longer required. The end-of-life phase takes into account any other integral parts of a product's life-cycle, most notably the box and packaging. There is also the question of whether to give a process credit for any end-of-life recycling which could, for example, reduce reliance on raw materials. However, if a particular process assumes a reduced impact due to the incorporation of recycled materials, this might constitute double-counting. For this study therefore, any benefits associated with recycling packaging have been excluded from the system boundary.

### 4.3 Bounding the Scope of the Study

Due to the fact that there are many different materials, methods and technologies available for producing packaged white light LEDs, some analytical decisions were made to ensure the scope of this LCA is manageable and representative of LEDs used for general illumination. These decisions were taken with the objective of ensuring that the material and/or the process selected is common practice in the market or is representative of the methods that will be adopted in the future. In this way, the findings from this LCA study are intended to be representative of the LEDs commonly used in general illumination. Future innovations such as improved yield rates and larger wafer sizes will reduce the waste and environmental impact associated with manufacturing each packaged LED. In this way, the conclusions from this analysis represent a conservative estimate of the impacts.

Given the many different approaches and technologies for creating white-light LEDs, several decisions are needed in order to create a manageable scope for this LCA study. These decisions relate to (1) the substrate used in manufacturing, (2) the type of LED produced and (3) the methodology used to create white light.

#### 4.3.1 Substrate

Gallium nitride (GaN) LEDs, which are commonly used as the light source for white light LEDs, can be grown on a range of different substrates, including sapphire, silicon carbide (SiC), bulk GaN, silicon, germanium, borosilicate glass, poly-crystal aluminum nitride (AlN), zinc oxide and diamond.<sup>2</sup> Of these, the one most commonly used for growing GaN LEDs is sapphire. In fact, it is estimated that more than 80 percent of LEDs are built on a sapphire substrate (Compound Semiconductor, 2011). Indicative of this majority share in the market, the recent surge in demand for LEDs as the television industry converted liquid crystal display (LCD) flat-screen back-lighting technology from cold-cathode fluorescent to white-light LED, the market experienced an acute shortage in sapphire wafers (Yole, 2011).

Within the substrate technologies, the general trend is toward larger wafer size in LED manufacturing. It is understood, from years of experience working with semiconductors that moving to larger wafer sizes will not only reduce manufacturing costs but will also improve yield. In moving to the larger substrate wafers, manufacturers get better results through more efficient use of the epitaxy reactor and fewer edge-related defects. However, due to deposition stresses experienced by the wafers, larger diameter wafers have to be thicker than smaller diameter wafers. The typical thickness of a 2" (51 mm) wafer is 425  $\mu\text{m}$  compared to a 6" (150 mm) wafer which is typically 625  $\mu\text{m}$  thick (Dadgar, 2006) – an increase of 47%.

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<sup>2</sup> Yole Développement, personal communication, November 2011.

However, the process improvements in the reactor more than off-set the higher substrate cost, so the overall effect is a net reduction in per unit cost (LED Magazine, 2010).

The manufacturing shift to larger wafers will reduce the unusable edge area on each wafer that has to be excluded from further processing, and it enables more effective (and less wasteful) use of metal organics and hydrides in the metalorganic chemical vapor deposition (MOCVD) process. Consider the output data from the Aixtron 2800G4 HT, one of the popular MOCVD reactors used by the LED industry. The comparison is illustrated in the figure below, which shows one of the wafer trays, loaded with 42 two inch wafers on the left and 6 six inch wafers on the right.

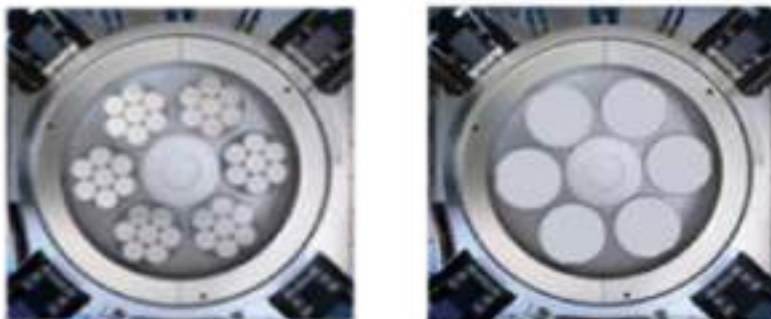


**Figure 4-2. Comparison of MOCVD Reactor Tray, 2" versus 6" wafers**

The table below provides the data behind the rationale for this gradual shift toward larger wafer sizes. In this table, the total wafer area that can be loaded into the machine is calculated, and then in a second calculation, the un-usable rim area is deducted from the usable area, giving the anticipated number of LED chips that would result from using the larger wafer size. For example, the surface area of a six inch wafer is nine times that of a two inch wafer, but it can yield between ten and twelve times as many chips as a two inch. Thus, industry experience with wafers for LED production has shown the yield multiplier is greater than the surface area multiplier.

**Table 4-2. Wafer Sizes and the Corresponding Surface Area and Yield of LED Chips**

| Wafer Size      | Surface Area Multiplier | Yield Multiplier<br>(i.e., Number of LED Chips) |
|-----------------|-------------------------|-------------------------------------------------|
| 2 inch (51 mm)  | S                       | N                                               |
| 4 inch (100 mm) | 4·S                     | 4.5·N to 5·N                                    |
| 6 inch (150 mm) | 9·S                     | 10·N to 12·N                                    |
| 8 inch (200 mm) | 16·S                    | 20·N to 22·N                                    |
| 12 inch (300mm) | 36·S                    | 45·N to 50·N                                    |

Source: Compound Semiconductor, 5 December 2011.

According to a study by Aixtron, a German manufacturer who produces MOCVD reactors, the overall result is a 52% increase in the usable wafer area that can be gained simply by moving from two inch diameter to the larger six inch wafers. These significant gains in LED manufacturing reflect the same savings that the silicon industry experienced as it scaled microchip production to larger and larger wafer diameters. In addition, the cost associated with retooling the MOCVD reactors to move from two inch to

four or six inch, as shown by the illustration above, is not a high – the equipment has been designed to be flexible and thereby accommodate the anticipated transition to larger substrate diameters.

The following diagram prepared by Yole Développement depicts the forecasted trend in sapphire substrate diameters for the coming years (Compound Semiconductor, 2011). Small two inch (51 mm) diameter wafers are expected to be 1% by 2015, while six inch wafers (150 mm) are projected to be more than half the market in that year.

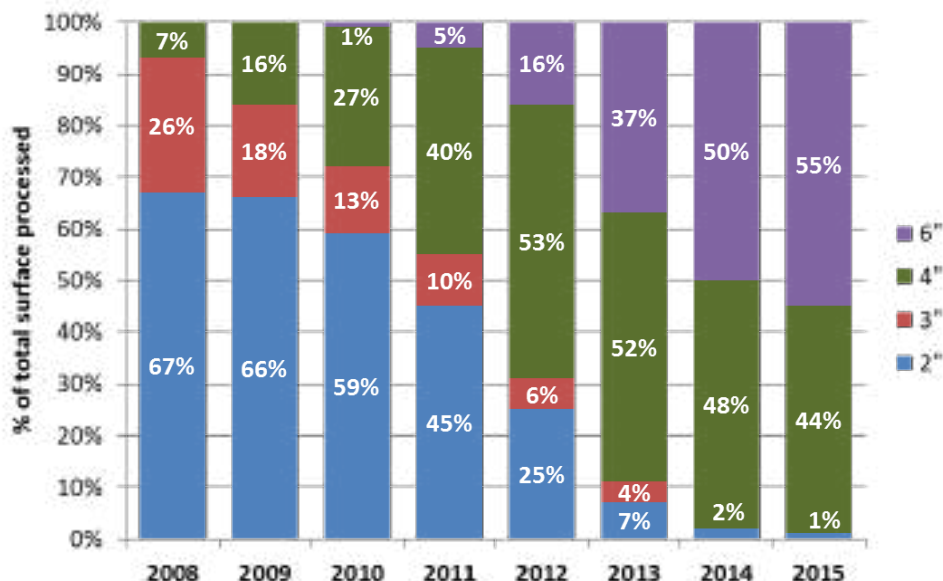


**Figure 4-3. Trends in Diameter of Sapphire Substrates for LED Manufacturing**

Source: Yole Développement, 2011 as published in Compound Semiconductor, December 2011.

Although Yole Développement projects a trend in the market toward larger wafer sizes, for the purposes of this study, we focused on three inch sapphire wafers for two main reasons. First, LED manufacturing with smaller diameter wafers is better known and more widespread in 2012, thus it is easier to gather data and input from experts familiar with the common practice. Second, the environmental impact per unit of LED produced (i.e., LED yield) at a smaller diameter will be greater than the impact experienced at the larger wafer sizes, which will be more prevalent in the future. Thus, by quantifying the LCA impacts of a three inch wafer in 2012, we know that these impacts represent an upper limit of environmental impacts now, and future impacts will be less than those in 2012 as the industry migrates to larger wafer sizes.

#### 4.3.2 LED Type

Numerous chemistries have been developed for commercially available LEDs based around phosphides and nitrides. The light emission from an LED depends on the p-n junction and the chemicals (e.g., gallium, arsenic) that are doped into the layers of the LED and used to construct the active layer. These different materials emit light at discrete wavelengths in the electromagnetic spectrum, spanning from the infrared through to the ultraviolet, and including visible light. The exact choice of the semiconductor material used in the LED helps to determine the color of the light emission.

The following table presents some of the common chemistries used today in producing the colored LEDs listed in the first column.

**Table 4-3. Summary of LED Colors and Common Chemistries**

| Color       | Wavelength | Materials                                                                         |
|-------------|------------|-----------------------------------------------------------------------------------|
| Infra-Red   | 850-940 nm | Gallium arsenide, Aluminum gallium arsenide                                       |
| Red         | 630-660 nm | Aluminum gallium arsenide, Gallium arsenide phosphide, Gallium phosphide          |
| Amber       | 605-620 nm | Gallium arsenide phosphide, Aluminum gallium indium phosphide                     |
| Yellow      | 585-595 nm | Aluminum gallium phosphide, Gallium arsenide phosphide, Gallium phosphide         |
| Green       | 550-570 nm | Aluminum gallium phosphide, Gallium nitride                                       |
| Blue        | 430-505 nm | Indium gallium nitride, Gallium nitride, Silicon carbide, Sapphire, Zinc selenide |
| Ultraviolet | 370-400 nm | Indium gallium nitride, Aluminum gallium nitride                                  |

LEDs are discrete wavelength emitters, meaning they produce light in a narrow bandwidth based on the chemistry of their underlying p-n junction. White light, on the other hand, consists of many different wavelengths (colors) of light which, when blended together, are perceived by the human eye as being “white”. As discussed in the next section of this report, there are several different methods for producing white light from LEDs, however it is recognized that the vast majority of white light LEDs manufactured today are based on the combination of a blue-emitting gallium nitride (GaN) or indium gallium nitride (InGaN) LED source used in combination with a yellow-emitting cerium-doped yttrium aluminum garnet (Ce<sup>3+</sup> YAG) phosphor (LFW, 2011).

For general illumination applications, lamp and luminaire manufacturers have some flexibility when designing the light producing portion of their equipment. This can include, for example, a cluster of many low-power LEDs which have a low light output individually, but when grouped together produce light levels sufficient for general illumination applications. This may also include devices that incorporate a small number of jumbo LEDs or multi-chip arrays, each emitting thousands of lumens. Although there is potential to use any of these approaches in general illumination applications, it is expected that the high power and jumbo LEDs will ultimately dominate the lighting market as these configurations can benefit from better optics, optimized thermal control and fewer components. The following table presents some of the electrical characteristics and applications for the different classes of white light LEDs.

**Table 4-4. White Light LED Package Segmentation**

| Item                 | Low Power LED                                                                      | Mid Power LED                                                                  | High Power LED                                          | Jumbo LEDs & Multichip Arrays                           |
|----------------------|------------------------------------------------------------------------------------|--------------------------------------------------------------------------------|---------------------------------------------------------|---------------------------------------------------------|
| Driving current      | 5 to 20 mA                                                                         | 50 to 150 mA                                                                   | $\geq 350$ mA                                           | $\geq 350$ mA (up to 6.5)                               |
| Bias voltage         | 2.9 to 3.5 V                                                                       | 2.9 to 3.5 V                                                                   | 2.9 to 3.5 V                                            | 3 to 3.5 V                                              |
| Power                | <100 mW                                                                            | <500 mW                                                                        | 1 to 3 W                                                | 1 to 3 W                                                |
| Die size             | 200 to 360 $\mu\text{m}$                                                           | 380 to 600 $\mu\text{m}$                                                       | 500 to 1500 $\mu\text{m}$                               | >4 mm <sup>2</sup> (up to 36 mm <sup>2</sup> )          |
| Package flux         | 4 to 15 lm                                                                         | 12 to 65 lm                                                                    | 70 to 120 lm                                            | up to 6000 lm                                           |
| Packaging            | Encapsulated LED, SMD top & side                                                   | SMD top & side                                                                 | Power package                                           | Power package; arrays                                   |
| Typical Applications | Mobile phones – keypad and display<br>Small LCD backlight<br>Signs, large displays | TV backlighting<br>Automobile headlights<br>Large displays<br>General lighting | Automobile headlights<br>Projection<br>General lighting | General lighting<br>Projection<br>Automobile headlights |

Although it is possible to have general illumination devices developed from low power LEDs, devices in 2012 are more commonly designed around mid-power, high-power and jumbo-LEDs. For the purposes of this study, we will therefore focus our LCA assessment on the 1-watt LED devices which can be commonly found in multiple-LED configurations in lamps and luminaires for general illumination applications.

#### 4.3.3 White Light

As discussed, LEDs are discrete semiconductors that produce a narrow-band emission which, depending on the chemistry, can emit energy in the ultraviolet (UV), visible, or infrared regions of the electromagnetic wavelength spectrum. To produce white light for general illumination applications, either the narrow spectral emission from LEDs must be converted into white light or two (or more) discrete LED light outputs must be mixed together.

White light LED devices are generally based on one of three approaches for producing a distribution of visible wavelengths that are perceived as “white light”. These are: (a) phosphor-conversion LEDs (pc-LEDs); (b) discrete color-mixing; or (c) a hybrid method, as shown in the figure below (DOE, 2012b). Phosphor-conversion LEDs create white light by blending a portion of the blue light emitted directly from the chip with light emission down-converted by a phosphor from the blue part of the spectrum to other colors. Discrete color-mixing, on the other hand, starts with discrete colored sources and uses color mixing optics to blend together the light output to create white light emission. The hybrid method uses a combination of pcLEDs and discrete-colored LEDs to create the desired light output. Two other methods of producing white light emission that are not discussed here include (1) an approach based on homoepitaxially grown zinc selenide (ZnSe) on a ZnSe substrate that emits blue light from the active region and yellow light from the substrate (Chang, 2007) and (2) quantum dots that achieve the light wavelength down shift within the visible spectrum (Salisbury, 2005).

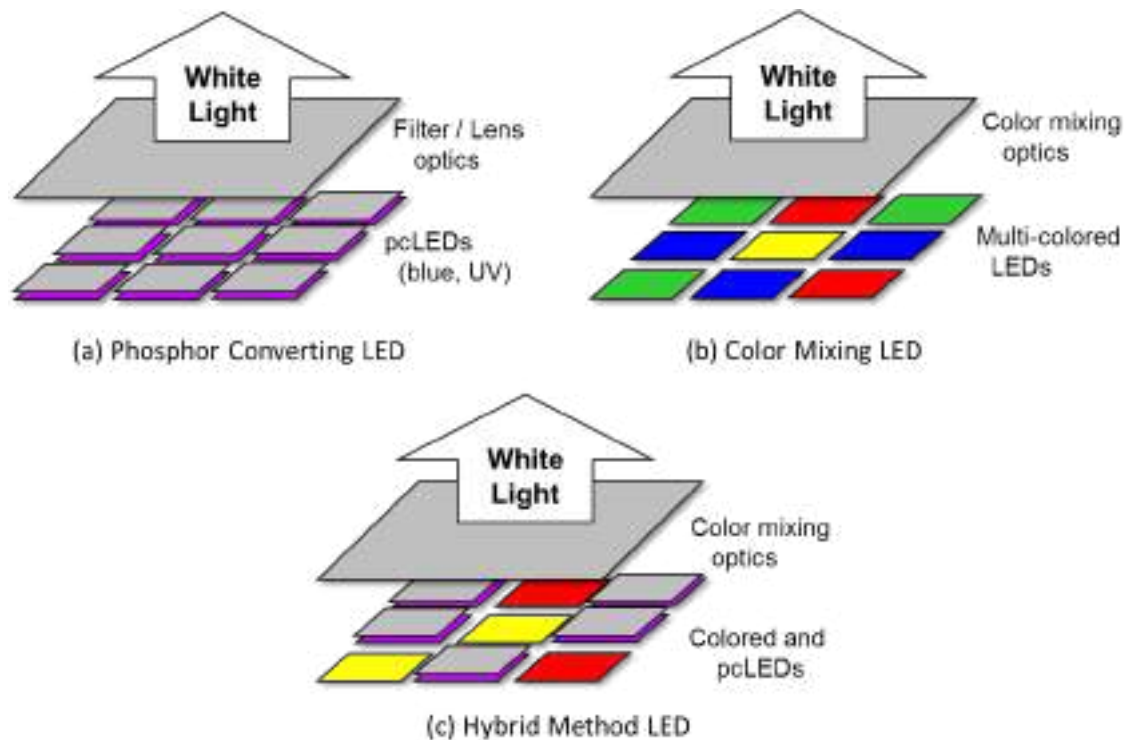


**Figure 4-4. General Types of White Light Emitting Diode (LED) Devices**

Source: DOE, 2012b. Solid-State Lighting Research and Development: Multi-Year Program Plan.

The majority of white light LEDs in production today are phosphor converting LEDs based on gallium-nitride, emitting blue light between 450-470 nm (DOE, 2011). This blue light excites a yellow phosphor, usually made of  $\text{Ce}^{3+}:\text{YAG}$  crystals that have been converted into a powder. As the LED chip emits blue light, some is emitted directly through the phosphor and some is converted by the phosphor to a broad spectrum centered around 580 nm (yellow) by the  $\text{Ce}^{3+}:\text{YAG}$ . This yellow light stimulates the red and green receptors in the human eye, resulting in a mix that gives the appearance of white light.

The pcLED approach, developed by Nichia, was first marketed by them in 1996 as a white-light LED. This approach has since been adopted by numerous other manufacturers as a method for producing white light, and constitutes the most common approach today. Depending on the phosphors used, and whether those phosphors are mounted in the LED package or located remotely (e.g., such as you find with the Philips EnduraLED lamp), there can be improvements made in the light quality and efficiency of the phosphor. While improvements in phosphor technology will yield benefits to the performance overall, the losses associated with absorbing blue light and down-converting it to other wavelengths such as green, yellow and red, establish a limit to the ultimate efficiency of the LED system. These losses are called “Stoke’s loss” and are associated with any phosphor-based down-conversion of light, including the process by which fluorescent tubes emit white light.

Discrete color-mixing of LED light emissions avoids the need for phosphors, and therefore promises to offer the highest efficacy LED device. In color-mixing, LED devices mix discrete light emissions from two or more LED chips which are blended together to produce white light. The principal advantage of the color-mixing method is that it does not involve phosphors, thereby eliminating phosphor conversion losses in the production of white light. This approach is not without its challenges however, such as multi-



chip mounting and potentially sophisticated optics and electronics for blending and maintaining the balance of colored light emissions.

The third method shown in the figure is a hybrid approach that combines pc-LEDs and colored-light emission LEDs into the same luminaire, producing the desired white light output. For example, some manufacturers are combining pc-LEDs with high (cool-white) correlated color temperature<sup>3</sup> (CCT) emission with several yellow and red-light emitting LEDs to create a lower (warm-white) CCT. In this example, the discrete color-emitting LEDs are used to change cool-white CCT to a warm-white CCT. The efficacy of this hybrid system will be higher than a pc-LED system, but lower than a color-mixing system, and will be proportional to the relative share of light output of the LEDs used in the hybrid system.

The most common approach used in white light LEDs today for general illumination applications are the blue-light emitting phosphor converting LEDs. These LEDs can have a range of resultant CCT values, depending on the types and amounts of phosphor used. For lamps that use remote phosphors, the LEDs will emit a deep blue light which is then converted by the remote phosphor into white light. For the purposes of this study, we are focusing on this system – namely blue light LEDs that are pumping a remote phosphor and creating a warm white light emission.

#### **4.3.4 The Representative LED for the Manufacturing Unit Processes**

Taking into account the discussion in this chapter, the conclusion reached is that this LCA study will focus on the following archetype general illumination LED lamp system:

- Three-inch sapphire wafer substrate
- Indium-Gallium Nitride grown on sapphire substrate
- High brightness LED packages (i.e., greater than 0.5 watt / package)
- Deep-blue LEDs (which are pumping a remote phosphor)

Overall, the type of LED which is meant to be characterized by this study then would be something akin to the following commercially available high brightness products such as: Cree's XLamp; Osram's Dragon; Philips' Luxeon Rebel or Seoul Semiconductor's P4. The decision to use a three-inch wafer is intended to make the LCA conservative in assessing the technology, although it is known that the larger wafers are being adopted quickly as shown in Figure 4-3.

#### **4.4 Limitations of the Study**

The content of the literature and technical information assessed for this study was focused as much as possible on LED manufacturing and lamp parts / assembly. As discussed in the next section, matches between the material and the process in the Ecoinvent database were imperfect in some instances. The

---

<sup>3</sup> The CCT is the temperature of a blackbody that best matches the color of a given light source. It describes the color appearance of the source, measured on the Kelvin (K) scale. Lamps with a CCT below 3500 K appear more yellowish-white (i.e., warm) in color. Lamps at or above 4000 K appear bluish-white (i.e., cool) in color. For additional information, see the DOE fact sheet "LED Color Characteristics" ([www.ssl.energy.gov/factsheets.html](http://www.ssl.energy.gov/factsheets.html)).

study investigators chose the best appropriate match, and in one instance adjusted one of the key impact parameters to account for a more energy intensive version of a similar material.

There are some gaps in relation to the life cycle assessment which have been identified:

- Emissions during LED manufacturing stage - it should be noted that direct emissions from the manufacturing process were not included in this analysis, due to lack of available data. The facilities where LEDs are manufactured operate in 'clean room' environments and use reactors to create the LED die. These reactors have some recovery systems that are able to reuse materials and others that allow harmless gases like nitrogen to vent into the atmosphere.
- Recovery and recycling of materials – there is a lack of information in the public domain about the extent to which materials used in the manufacturing of LEDs are reused and recycled. If these materials are recovered, processed and then reused, this would reduce the per unit production environmental impacts. However, in this version of the study, we are assuming new materials are used at all stages of the LCA process, thus providing a conservative estimate of the impacts. In other words, to the extent that materials are recovered and recycled, the environmental impacts will be less than those reported in this study.
- Transport and end of life – information on the transport and end of life phases of LED, CFL and incandescent lamps was limited. Working estimates were developed based on available data and supplemented with stakeholder input in an attempt to address all aspects of the life cycle.

## 4.5 Critical Review

In order to ensure the results of this work are accurate, a formal review process for the manufacturing unit process was initiated early in the study. In the expert interviews stage, manufacturers and researchers were invited to review the draft flow diagram for the manufacture of LEDs, and to comment on the various inputs and steps in that process. These comments provided corrections as well as new data to improve the accuracy of the process description. The final study has been reviewed in a similar way by a group of reviewers broader than the initial review team, but inclusive of the same group of manufacturers and researchers.

The diagram in Figure 4-5 depicts the analytical process that was followed for the manufacturing unit process part of the study, and identifies the two steps in the process where external expertise was requested. These occurred at the "Expert Interviews" stage where the draft process flow diagram was circulated with experts for review and at the "Expert Review" stage where the findings of this study compiled in a report form were again circulated for review and comment.

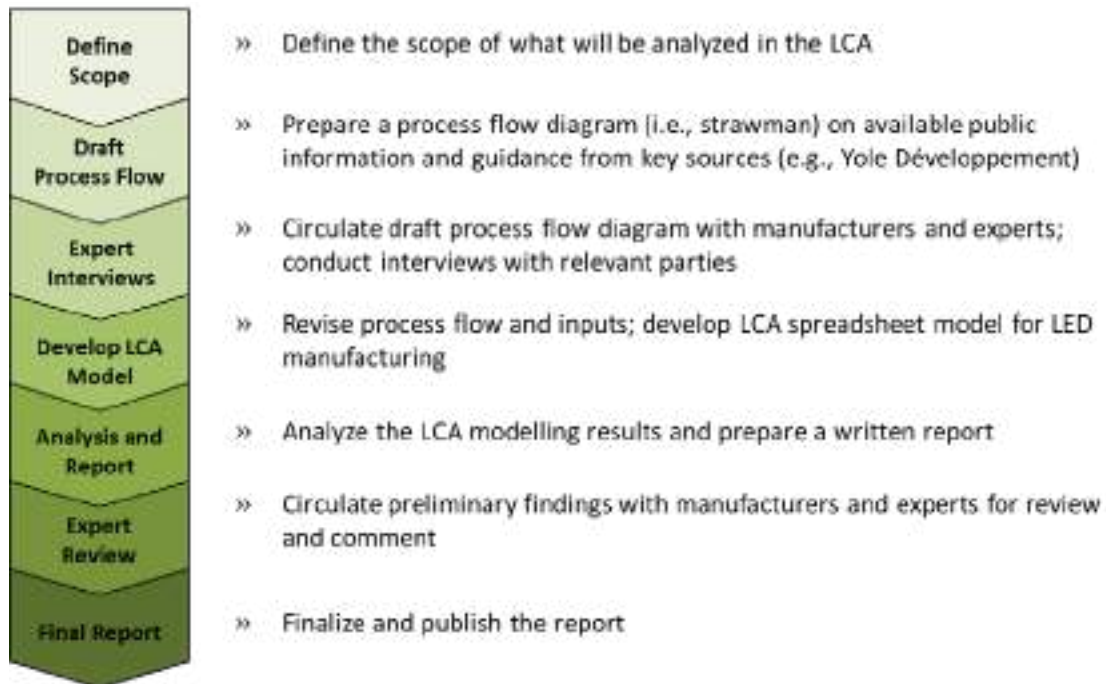


**Figure 4-5. Flow of Data Gathering and Analysis for this Research Project**

## 5 Life Cycle Inventory Analysis

This inventory of materials and processes developed for LED, CFL and incandescent lamps is drawn from the work shared by Yole Développement and System Plus Consulting, Navigant Consulting Europe's report on a life-cycle assessment of ultra-efficient lamps, summary data from Osram Optoelectronic's 2009 life-cycle assessment of an LED lamp, and various industry experts and researchers who provided comment and input on the draft analysis. The quantification of the life-cycle impacts is based on the Ecoinvent database (version 2.2). To address the large error bars associated with LED manufacturing which was identified in DOE's literature summary (DOE, 2012a), the focus of this life cycle inventory will include this specific area.

### 5.1 Inputs

To quantify the environmental impacts of the incandescent, CFL and LED lamps, the authors used the Ecoinvent life cycle impact assessment database version 2.2, from the Swiss Centre for Life Cycle Inventories (<http://www.ecoinvent.org>). This database contains environmental impact data on over 4000 manufacturing or related processes, such as the impacts associated with the production of a kilogram of cast aluminum from bauxite or the transportation by truck of one ton of material for one kilometer. For each material and process in the database, there are estimates of the environmental impact for over 250 standard environmental indicators. For example, the database estimates that the global warming potential impact associated with one kilogram of cast aluminum is 3.0614 kilograms of carbon dioxide equivalents.

In this chapter, there are a series of tables presented which provide detail on the inventories of materials and processes associated with LED manufacturing and then with each of the mains-voltage general illumination lamps studied. These tables give detail on the materials and processes that were selected from Ecoinvent and used to model those materials and processes. Some of the Ecoinvent materials and processes are very close matches to the ones used in the lamps while others are approximations. The relative significance of these approximations becomes clear when the results are reviewed in Chapter 6, and the more critical materials and processes are investigated in the sensitivity analysis presented in Appendix A of this report.

Each of the three finished lamps analyzed in this study is different, having different levels of power consumption and operating life. In order to make a fair comparison between the lamp technologies, it becomes necessary to compare their relative performance over a comparable time period and using a common metric. To achieve this, all of the impacts calculated for the three lamps are compared on a normalized basis of lighting service delivered during the analytical time period. The quantity of light produced over that time period is reported in lumen-hours of lighting service and then used to normalize the estimated impacts.

Although the three lamps were chosen because they have approximately equal instantaneous light output, it should be noted that over the lifetime of each lamp, the total lighting service is different. For instance, due to the large disparity between the incandescent lamp and the LED lamp, the incandescent lamp must take into account multiple lamp changes (and thus multiples of lamp-related impacts are compounded in the analysis). Ultimately, all of the analysis culminates in a measurement of impacts in megalumen-hours (Mlm-hr) over the full "use" stage of the LCA. For example, the final results for global warming potential will be presented in units of kilograms of CO<sub>2</sub>-equivalent per Mlm-hr.

In addition to considering the impacts associated with an LED lamp in 2012, this study also projects the impacts of the LED lamp in 2017. The impacts of the future LED lamp are expected to be lower due to

the fact that LED performance and drivers will continue to improve and materials and components used in the lamp can be reduced over time. Details relating to the assumptions behind the LED lamp in 2017 are provided in this chapter.

The following table provides the performance parameters used as inputs to the three lamps analyzed and the projected performance of an LED lamp in 2017. The second row from the bottom of the table calculates the “total lifetime light output”. This parameter represents the cumulative light output measured over the entire service life of the lamp, and is measured in megalumen-hours of light. The total light output for the 2012 LED lamp, 20.3 Mlm-hr represents the functional unit from DOE’s Part 1 study and is used in this analysis as a normalizing factor to adjust the impacts for equivalency. The scalar shown in the bottom row of the table is calculated from the ratios of the lighting service output relative to the 2012 LED lamp.

**Table 5-1. Performance Parameters for Lamps Considered in this Analysis**

| Characteristics             | Incandescent | CFL        | LED lamp – 2012 | LED lamp – 2017 |
|-----------------------------|--------------|------------|-----------------|-----------------|
| Power Consumption           | 60 watts     | 15 watts   | 12.5 watts      | 6.1 watts       |
| Lumen Output                | 900 lumens   | 825 lumens | 812 lumens      | 824 lumens      |
| Efficacy                    | 15 lm/W      | 55 lm/W    | 65 lm/W         | 134 lm/W        |
| Lamp Lifetime               | 1500 hours   | 8000 hours | 25,000 hours    | 40,000 hours    |
| Total Lifetime Light Output | 1.35 Mlm-hr  | 6.6 Mlm-hr | 20.3 Mlm-hr*    | 33.0 Mlm-hr     |
| Impacts Scalar              | 15.04        | 3.08       | 1.00            | 0.61            |

\* In Part 1 of DOE’s study (*Review of the Lifecycle Energy Consumption of Incandescent, Compact Fluorescent and LED Lamps*), 20 megalumen-hours was selected as the functional unit for comparison of the energy use. In this study (Part 2), we use the same functional unit as a normalizing scalar to ensure the impacts are comparable.

## 5.2 LED Manufacturing

LED manufacturing is a very complex and highly technical process and very few companies in the world operate across all segments of the value chain. In an effort to simplify the process for producing a packaged LED and to better align with the areas of specialization and expertise that exist in the industry, we have broken down the value chain for LED manufacturing into three large segments – (1) substrate production, (2) LED die fabrication and (3) packaged LED assembly. The flow diagram in Figure 5-1 summarizes these stages and the major steps contained within each stage. It should be noted that direct emissions from the manufacturing process were not included in this analysis, due to lack of available data.

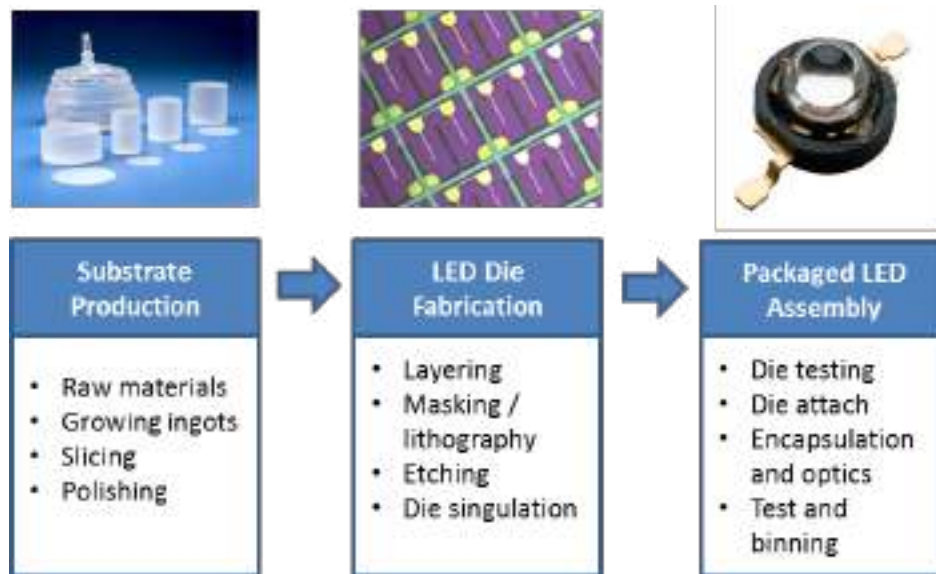


**Figure 5-1. Three Major Stages of Packaged LED Manufacturing**

Following this structure, this chapter is divided into three sections, each discussing and describing these stages of LED manufacturing.

### 5.2.1 Substrate Production

This stage is focused on preparing polished, cleaned sapphire wafers to use in an MOCVD reactor for LED die fabrication. Wafer manufacturing starts with the growth of large sapphire crystal boules. To produce these boules, a large amount of aluminum oxide is melted down and a seed crystal is introduced to the molten solution. This seed crystal is then pulled slowly out of the solution, and because crystal growth occurs uniformly in all directions, the cross section of the resulting crystal is circular. The diameter of the crystal is a function of the melt temperature, the speed of rotation and the speed at which the seed holder is pulled from the melt. The resulting boule must then be ground down to obtain the desired diameter before it is sliced into wafers, polished and cleaned for LED fabrication.

The table on the following page provides the main processing steps involved in the production of sapphire wafers, starting with the growth of sapphire boules and ending with finished, cleaned wafers. A brief description of each step is provided in the table, along with an indication of the resources consumed in the process, including both energy and material. The estimates provided in this table were kindly provided by Yole Développement and System Plus Consulting for the purposes of assisting with this LCA study.



**Table 5-2. Steps Associated with Sapphire Wafer Substrate Manufacture**

| Processing Step                                 | Picture                                                                             | Description                                                                                                                                                                                                                                              | Inputs                                                                         |
|-------------------------------------------------|-------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------|
| Boule growth in reactor                         |    | Using the Czochralski method to melt aluminum oxide ( $\text{Al}_2\text{O}_3$ ) and grow a large sapphire crystal boule                                                                                                                                  | Energy: 15.51 kWh/wafer<br>Alumina: 16.61 gm/wafer<br>Water: 100 liters/wafer  |
| Core fabrication                                |    | Using diamond tooling, drill the sapphire boule to create the sapphire cores in the appropriate diameters                                                                                                                                                | Energy: 1.35 kWh/wafer                                                         |
| Wafer slicing                                   |    | Slicing the cores into thin wafers using a diamond internal diameter saw with deionized cooling water                                                                                                                                                    | Energy: 1.24 kWh/wafer<br>Water: 2 liters/wafer                                |
| Lapping and beveling                            |    | Rough-cut wafers are treated to remove saw marks and other defects on both sides; also thins the wafer and relieves stresses accumulated from slicing; uses a diamond slurry, $6\mu\text{m}$                                                             | Energy: 0.09 kWh/wafer<br>Slurry: 430 gm/wafer<br>Water: 0.67 liters/wafer     |
| Polishing and Chemical-mechanical planarization |   | Wafers are subjected to 2-3 polishing treatments using progressively finer slurry of polycrystalline diamond ( $3\mu\text{m}$ - $1\mu\text{m}$ ); removes irregularities making wafer flat (i.e., planar)                                                | Energy: 0.06 kWh/wafer<br>Slurry: 400 gm/wafer<br>Water: 0.67 liters/wafer     |
| Geometry and optical inspection                 |  | Inspection to identify geometric or optical defects that may limit yield (e.g., surface pits or micro-cracks)                                                                                                                                            | N/A                                                                            |
| Final cleaning                                  |  | Cleaning to remove trace metals, residues and particles. Uses $\text{NH}_4\text{OH}$ , followed by dilute HF acid, followed by a deionized water rinse. The second clean consists of HCl and $\text{H}_2\text{O}_2$ followed by a deionized water rinse. | Energy: 0.001 kWh/wafer<br>Cleaner: 3.50 liters/wafer<br>Water: 2 liters/wafer |

Source: Yole Développement and System Plus Consulting for quantities of process inputs.

As a quality assurance check on the mass of Alumina consumed to produce one wafer, a simple mass calculation can be performed that takes into account the finished product and quantities of material lost through processing from the raw crystal. Given that a three inch wafer diameter is 7.62 cm (radius  $[r] = \text{diameter}/2 = 3.81 \text{ cm}$ ), the thickness ( $t$ ) of the wafer is 0.033 cm and the density ( $\rho$ ) of sapphire is

$3.98 \text{ g/cm}^3$ , the mass of the finished three inch wafer is  $m=r^2 \cdot \pi \cdot t \cdot \rho = 6.0$  grams. Taking into account sawing and polishing losses per wafer which are approximately 85% of the finished wafer, the mass of sapphire core necessary to produce one finished 6.0 gram wafer would be 11.1 grams. A further 40% of the original boule is lost when the sapphire cores are cut and approximately 5% of the Alumina remains in the crystal-growing chamber. Taking these further adjustments into account, the 11.1 grams of sapphire core scales to a raw material consumption to 16.3 grams per finished 6.0 gram wafer. The estimated consumption of Alumina ( $\text{Al}_2\text{O}_3$ ) per finished three-inch wafer was given in Yole Développement's data as 16.6 grams, therefore this estimate seems accurate.

Combining all of the materials and impacts quantified in the table above, the quantity of materials used in producing cleaned, polished sapphire wafers for GaN LED fabrication are shown in the table below. This table provides both the quantity consumed per wafer both in terms of volume and in terms of mass. The right two columns provide the unique ID and description of the Ecoinvent database record to which it is matched.

**Table 5-3. Energy and Material Consumption for Three-Inch Sapphire Wafer Manufacturing**

| Stage      | Material Used                        | Amount             |                | Eco-ID | Ecoinvent Description                                              |
|------------|--------------------------------------|--------------------|----------------|--------|--------------------------------------------------------------------|
|            |                                      | Volume per wafer   | Mass per wafer |        |                                                                    |
| Material   | Alumina ( $\text{Al}_2\text{O}_3$ )  | 16.6 g/wafer       | 16.6 g/wafer   | 244    | aluminum oxide, at plant                                           |
| Material   | Cleaning Chemical (alkali detergent) | 3.5 liters/wafer   | 3.5 kg/wafer   | 5902   | ethoxylated alcohols (AE7), petrochemical, at plant                |
| Production | Energy Consumption                   | 18.3 kWh/wafer     | 18.3 kWh/wafer | 6693   | electricity mix in China                                           |
| Material   | Diamond Slurry                       | 830.0 g/wafer      | 0.83 kg/wafer  | 1997   | zeolite, slurry, 50% in $\text{H}_2\text{O}$ , at plant (adjusted) |
| Material   | Water                                | 105.3 liters/wafer | 105.3 kg/wafer | 7237   | water, ultrapure, at plant                                         |

To represent the diamond slurry used in manufacturing, the closest match in the Ecoinvent database is zeolite slurry, however there are two important differences. First, the embodied energy in diamonds is greater than that of zeolite, and second the concentration of diamond abrasive in the slurry is lower than the 50% level associated with the zeolite slurry. Due to these differences, and to make sure that this stage of the LCA did not underestimate impacts, the authors increased the zeolite slurry energy impacts by a factor of ten to represent the higher energy consumed manufacturing the diamonds. Overall, this adjustment resulted in a 15% increase in the GHG emissions associated with the manufacturing of a packaged LED, but constituted less than one-tenth of one percent of GHG emissions over the life cycle of the 2012 LED lamp (i.e., including the balance of system (i.e., driver, housing, heat sink) as well as other stages of the LCA including energy in use, transport and disposal).

### 5.2.2 LED Die Fabrication

In this section, the steps associated with fabricating LED die are described, with estimates of the associated energy and materials consumed in these manufacturing steps. The LED die fabrication process is subdivided into epitaxial growth and other front-end processes.

In the epitaxial growth phase, the substrate is mounted in an metal organic chemical vapor deposition (MOCVD) reactor and experiences a heating stage, followed by the deposition of the nucleation layer, the n-type layer, the active layers (multi-quantum well) and finally the p-type layer. At the end of this phase, the wafer is referred to as an LED epitaxial wafer.

The nucleation layer is critical because crystalline or contaminate defects will have a detrimental effect on the yield from the wafer, so it is imperative that the sapphire layer is ultra-pure. This is a layer of sapphire that is grown on the raw sapphire wafer through an epitaxial growth process. The layer is very thin, just 3% or less of the wafer thickness, but it is a critical step in the fabrication process.

**Table 5-4. Steps Associated with Gallium Nitride Epitaxy**

| Processing Step           | Description                                                                                                                                                                                                                                                                                                                                                                                                                                    | Inputs                                                                                                                                                                                                                   |
|---------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Bake out                  | Nitridation of the sapphire substrate at high temperature in a hydrogen and ammonia atmosphere.                                                                                                                                                                                                                                                                                                                                                | 8.75 kWh/wafer<br>0.06 m <sup>3</sup> H <sub>2</sub> / wafer<br>0.02 kg NH <sub>3</sub> / wafer                                                                                                                          |
| Nucleation layer          | The wafer is then lowered in temperature to 550°C to grow the nucleation layer.                                                                                                                                                                                                                                                                                                                                                                | 4.74 kWh/wafer                                                                                                                                                                                                           |
| Temperature ramp          | The reactor chamber is heated to a very high temperature (1200°C) under reduced ammonia pressure to stabilize the nucleation layer.                                                                                                                                                                                                                                                                                                            | 1.46 kWh/wafer<br>0.02 kg NH <sub>3</sub> / wafer                                                                                                                                                                        |
| Buffer + N layer (3.84µm) | The temperature is dropped to approximately 550°C to grow the buffer layer. This is a thin amorphous film of gallium, just 50 to 100 atoms thick grown directly on the wafer. The wafer is then heated up until the gallium forms a smooth, mirror-like layer of gallium nitride. Next, a layer of negatively doped gallium nitride is deposited, with silane (i.e., silicon tetrahydride, SiH <sub>4</sub> ) as the electron-donating dopant. | 9.77 kWh/wafer<br>1.38 grams TMGa <sup>4</sup> / wafer<br>0.42 kg NH <sub>3</sub> / wafer<br>1.54 m <sup>3</sup> H <sub>2</sub> / wafer<br>1.54 m <sup>3</sup> N <sub>2</sub> / wafer<br>0.06 g SiH <sub>4</sub> / wafer |
| Active layer MQW (60nm)   | The temperature is dropped from 1,200°C to 750-850°C to grow an indium gallium nitride quantum well. This will include approximately 20 angstroms of InGaN and 100 angstroms of GaN. This process is repeated to grow several wells.                                                                                                                                                                                                           | 4.74 kWh/wafer<br>0.03 grams TMGa / wafer<br>0.01 kg NH <sub>3</sub> / wafer<br>0.01 m <sup>3</sup> H <sub>2</sub> / wafer<br>0.01 m <sup>3</sup> N <sub>2</sub> / wafer<br>0.01 g TMI <sup>5</sup> n / wafer            |

<sup>4</sup> TMGa = trimethylgallium

<sup>5</sup> TMI<sup>n</sup> = trimethylindium

| Processing Step | Description                                                                                                                                                                                                                                        | Inputs                                                                                                                                                                                                       |
|-----------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| P layer (170nm) | After growing the last combination of InGaN+GaN, the wafer is heated back up and a confining layer of positively doped aluminum gallium nitride (AlGaN) is deposited. The positively doped layer confines the charge carriers in the active layer. | 3.28 kWh/wafer<br>0.06 grams TMGa / wafer<br>0.02 kg NH <sub>3</sub> / wafer<br>0.06 m <sup>3</sup> H <sub>2</sub> / wafer<br>0.06 m <sup>3</sup> N <sub>2</sub> / wafer<br>0.00 g TMAI <sup>6</sup> / wafer |

Source: Yole Développement and System Plus Consulting for quantities of process inputs.

Taking the LED epitaxial wafer, a series of steps are followed which are working toward making the device and preparing it for packaging. Following inspection, the wafer is subjected to masking / lithography, followed by etching and then establishing metallization / contacts on the LED. These process steps create the LED mesa-structure, and results in visible LED dies on the wafer. Once these are developed, the substrate is separated from the LED dies, and they are then cut (i.e., die singulation) and tested/ binned according to their performance. At the end of this stage, the LED dies are ready to be packaged.

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<sup>6</sup> TMAI = trimethylaluminum

**Table 5-5. Post-Epitaxy Steps Associated with LED Die Fabrication**

| Processing Step   | Process Sub-Steps                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | Inputs                                                                                                                                                                                                                                                             |
|-------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Wafer Inspection  | Detailed inspection of the wafer to determine if there are any cracks or defects that might otherwise make the wafer unsuitable.                                                                                                                                                                                                                                                                                                                                                                                                                                                 | Energy: 0.03 kWh/wafer                                                                                                                                                                                                                                             |
| P contact         | <ul style="list-style-type: none"> <li>• Cleaning</li> <li>• Silver (Ag) Deposition (PVD - 0.097µm)</li> <li>• Ti Deposition (PVD : 0.103µm)</li> <li>• W Deposition (PVD : 0.681µm)</li> <li>• Measurement</li> <li>• Cleaning</li> </ul>                                                                                                                                                                                                                                                                                                                                       | Target Ag 0.44 mm <sup>3</sup> /wafer<br>Target Ti 0.47 mm <sup>3</sup> /wafer<br>Target W 3.09 mm <sup>3</sup> /wafer<br>UPW <sup>7</sup> 60.00 l/wafer<br>N <sub>2</sub> 0.70 m <sup>3</sup> /wafer<br>Energy: 1.19 kWh/wafer                                    |
| N contact Opening | <ul style="list-style-type: none"> <li>• Litho 1 - Coatings</li> <li>• Litho 1 - Baking</li> <li>• Litho 1 - Stepper</li> <li>• Litho 1 - Development</li> <li>• Measurement</li> <li>• Wet Etching Ti + W</li> <li>• Wet Etching Ag</li> <li>• Photoresist Removal</li> <li>• Measurement</li> <li>• Cleaning</li> <li>• Litho 2 - Coating</li> <li>• Litho 2 - Baking</li> <li>• Litho 2 - Stepper</li> <li>• Litho 2 - Development</li> <li>• Measurement</li> <li>• GaN Etching (1.5µm)</li> <li>• Photoresist Removal</li> <li>• Measurement</li> <li>• Cleaning</li> </ul> | Acetone 0.20 l/wafer<br>Developer 50.00 ml/wafer<br>Etchant Ag 30.00 ml/wafer<br>Etchant Metal 60.00 ml/wafer<br>GaN Etchant 0.19 l/wafer<br>Photoresist 8.00 ml/wafer<br>UPW 60.00 l/wafer<br>N <sub>2</sub> 0.70 m <sup>3</sup> /wafer<br>Energy: 2.30 kWh/wafer |

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<sup>7</sup> UPW is an abbreviation for Ultra Pure Water

| Processing Step | Process Sub-Steps                                                                                                                                                                                                                                                                                                                                                                                              | Inputs                                                                                                                                                                                                                                                                                          |
|-----------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| GaN Pattern     | <ul style="list-style-type: none"> <li>• Dielectric (CVD : 400nm)</li> <li>• Measurement</li> <li>• Cleaning</li> <li>• Litho 3 - Coating</li> <li>• Litho 3 - Baking</li> <li>• Litho 3 - Stepper</li> <li>• Litho 3 - Development</li> <li>• Measurement</li> <li>• Dielectric Etching</li> <li>• Photoresist Removal</li> <li>• Measurement</li> <li>• Cleaning</li> </ul>                                  | Acetone 0.10 l/wafer<br>Developer 25.00 ml/wafer<br>Photoresist 4.00 ml/wafer<br>SF <sub>6</sub> 0.10 l/wafer<br>SiH <sub>4</sub> 0.18 g/wafer<br>UPW 60.00 l/wafer<br>N <sub>2</sub> 0.70 m <sup>3</sup> /wafer<br>O <sub>2</sub> 2.00 m <sup>3</sup> /wafer<br>Energy 2.71 kWh/wafer          |
| N Contact       | <ul style="list-style-type: none"> <li>• Litho 4 - 2 Coating</li> <li>• Litho 4 - Baking</li> <li>• Litho 4 - Stepper</li> <li>• Litho 4 - Development</li> <li>• Measurement</li> <li>• Cleaning</li> <li>• Al Deposition (PVD : 0.284µm)</li> <li>• Ni Deposition (PVD : 0.069µm)</li> <li>• Gold-Tin (ECD : 3.256µm)</li> <li>• N Contact- PR Removal</li> <li>• Measurement</li> <li>• Cleaning</li> </ul> | Acetone 0.10 l/wafer<br>AuSn 14.77 mm <sup>3</sup> /wafer<br>Developer 40.00 ml/wafer<br>Photoresist 7.00 ml/wafer<br>Target Al 1.27 mm <sup>3</sup> /wafer<br>Target Ni 0.42 mm <sup>3</sup> /wafer<br>UPW 60.00 l/wafer<br>N <sub>2</sub> 0.70 m <sup>3</sup> /wafer<br>Energy 1.13 kWh/wafer |
| Other           | <ul style="list-style-type: none"> <li>• Back Grinding Sapphire</li> <li>• Fine grinding Sapphire - 75µm</li> <li>• Scribe laser</li> <li>• Break substrate</li> </ul>                                                                                                                                                                                                                                         | Energy 2.47 kWh/wafer                                                                                                                                                                                                                                                                           |

Source: Yole Développement and System Plus Consulting.

The following table summarizes all the materials and energy consumed in this second stage of LED manufacturing, the LED die fabrication stage. This table combines the material and energy consumption of both the epitaxy and P-N junction deposition stage and post-epitaxy steps associated with contacts, patterning, substrate removal and preparing finished LED die. The second and third columns of the table specify the quantity of material used (presented with the units), and the right two columns provide the unique ID and description of the Ecoinvent database record to which it is matched.



**Table 5-6. Energy and Material Consumption for LED Die Fabrication**

| Material         | Quantity Consumed            |                 | Eco-ID | Ecoinvent Description                                     |
|------------------|------------------------------|-----------------|--------|-----------------------------------------------------------|
|                  | Volume / Wafer               | Mass / Wafer    |        |                                                           |
| Acetone          | 0.59 l/wafer                 | 467 g/wafer     | 363    | acetone, liquid, at plant                                 |
| AuSn solder      | 14.8 mm <sup>3</sup> /wafer  | 0.29 g/wafer    | 10107  | gold, from combined metal production, at refinery         |
| Developer        | 115 ml/wafer                 | 115 g/wafer     | 264    | chemicals inorganic, at plant                             |
| Etchant Ag       | 30 ml/wafer                  | 30 g/wafer      | 283    | hydrogen fluoride, at plant                               |
| Etchant Metal    | 60 ml/wafer                  | 60 g/wafer      | 283    | hydrogen fluoride, at plant                               |
| GaN Etchant      | 0.192 l/wafer                | 192 g/wafer     | 283    | hydrogen fluoride, at plant                               |
| H <sub>2</sub>   | 1.62 m <sup>3</sup> /wafer   | 136 g/wafer     | 286    | hydrogen, liquid, at plant                                |
| N <sub>2</sub>   | 4.42 m <sup>3</sup> /wafer   | 5527 g/wafer    | 300    | nitrogen, liquid, at plant                                |
| NH <sub>3</sub>  | 0.447 kg/wafer               | 447 g/wafer     | 246    | ammonia, liquid, at regional storehouse                   |
| O <sub>2</sub>   | 2 l/wafer                    | 2.3 kg/wafer    | 301    | oxygen, liquid, at plant                                  |
| Photoresist      | 19 ml/wafer                  | 19 g/wafer      | 382    | chemicals organic, at plant                               |
| Energy           | 42.57 kWh/wafer              | 42.57 kWh/wafer | 6694   | electricity mix                                           |
| SF <sub>6</sub>  | 0.1 l/wafer                  | 13 g/wafer      | 348    | sulfur hexafluoride, liquid, at plant                     |
| SiH <sub>4</sub> | 0.242 g/wafer                | 0.242 g/wafer   | 321    | silicon carbide, at plant                                 |
| Slurry           | 2.3 l/wafer                  | 2.3 kg/wafer    | 1997   | zeolite, slurry, 50% in H <sub>2</sub> O, at plant        |
| Target Ag        | 0.44 mm <sup>3</sup> /wafer  | 0.005 g/wafer   | 10122  | silver, from combined gold-silver production, at refinery |
| Target Al        | 1.27 mm <sup>3</sup> /wafer  | 0.003 g/wafer   | 1056   | aluminum, production mix, at plant                        |
| Target Ni        | 0.417 mm <sup>3</sup> /wafer | 0.004 g/wafer   | 1121   | nickel, 99.5%, at plant                                   |
| Target Ti        | 0.467 mm <sup>3</sup> /wafer | 0.002 g/wafer   | 355    | titanium dioxide, production mix, at plant                |
| Target W         | 3.089 mm <sup>3</sup> /wafer | 0.06 g/wafer    | 8143   | palladium, secondary, at precious metal refinery          |
| TMAI             | 0.003 g/wafer                | 0.003 g/wafer   | 1056   | aluminum, production mix, at plant                        |
| TMGa             | 1.47 g/wafer                 | 1.47 g/wafer    | 6908   | gallium, semiconductor-grade, at plant                    |
| TMIn             | 0.01 g/wafer                 | 0.01 g/wafer    | 7164   | indium, at regional storage                               |
| UPW              | 240 l/wafer                  | 240 kg/wafer    | 7237   | water, ultrapure, at plant                                |

### 5.2.3 Packaged LED Assembly

This third phase of LED manufacturing is referred to as the “packaging” of the device. It involves taking the LED die, mounting it in housing, making electrical connections, applying phosphor, encapsulant and optics. It also involves testing and binning the LED into the correctly classified product.

**Table 5-7. Steps Associated with LED Packaging and Assembly**

| Processing Step             | Description                                                                                                                                                                                                                | Inputs                                                             |
|-----------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------|
| Package Element Building    | The ceramic substrate (2-layers of alumina) are prepared for mounting the LED chip.                                                                                                                                        | 0.01 kWh / LED<br>13.5 mm <sup>2</sup> Alumina / LED               |
| Stud Bumping                | Wire bonding process, where gold is bonded to the die pad.                                                                                                                                                                 | 0.001 kWh / LED<br>0.004 mm <sup>3</sup> gold / LED                |
| Reflow                      | The LED is heated to a temperature above the melting point of the solder, but below the temperature that may damage other parts of the LED package.                                                                        | 0.003 kWh / LED                                                    |
| LED & Protective die attach | The LED is attached to the package element, incorporating protection against electrostatic discharge (ESD).                                                                                                                | 0.003 kWh / LED<br>0.220 mm <sup>2</sup> ESD diode (silicon) / LED |
| Reflow                      | The LED is heated again to the melting point of solder.                                                                                                                                                                    | 0.003 kWh / LED                                                    |
| Under filling               | Underfill (i.e., an organic polymer and inorganic filler) is added to the package that provides support to the solder ball interconnect.                                                                                   | 0.003 kWh / LED<br>0.05 mm <sup>3</sup> underfill / LED            |
| Phosphor                    | Application of a Ce <sup>3+</sup> :YAG phosphor coating that will convert a portion of the blue light emission from the LED die to longer wavelengths which gives the packaged LED emission the appearance of white light. | 0.000 kWh / LED<br>0.192 mm <sup>3</sup> phosphor / LED            |
| Lens                        | An optical lens that gathers and directs the light in the appropriate beam angle for the desired application.                                                                                                              | 0.003 kWh / LED<br>8.400 mm <sup>3</sup> silicon / LED             |
| Annealing                   | The package is heated to anneal together the polymer, phosphor and lens into one cohesive unit.                                                                                                                            | 0.003 kWh / LED                                                    |
| Substrate Dicing            | The substrate is cut into the individual packaged LEDs for use.                                                                                                                                                            | 0.001 kWh / LED                                                    |

Source: Yole Développement and System Plus Consulting for quantities of process inputs.

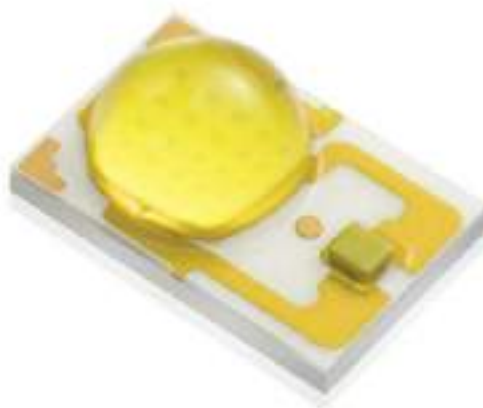


**Figure 5-2. Example of the Finished Packaged LED, the Philips Luxeon Rebel**

Taking into account all the inputs for LED packaging and assembly presented in Table 5-7, the following table presents the aggregate consumption per LED produced. The middle columns of the table specifies the quantity of material used (presented with the units), and the right two columns provide the unique ID and description of the Ecoinvent database record to which it is matched.

**Table 5-8. Energy and Material Consumption for LED Packaging Assembly**

| Stage      | Material Used                       | Amount                     |               | Eco-ID | Ecoinvent Description                             |
|------------|-------------------------------------|----------------------------|---------------|--------|---------------------------------------------------|
|            |                                     | Volume per LED             | Mass per LED  |        |                                                   |
| Material   | Ceramic Substrate (2-layer Alumina) | 13.5 mm <sup>2</sup> /LED  | 0.0135 g/LED  | 244    | aluminum oxide, at plant                          |
| Production | Energy (kWh)                        | 0.03 kWh/LED               | 0.03 kWh/LED  | 6693   | electricity mix for China                         |
| Material   | ESD diode (Silicon)                 | 0.22 mm <sup>2</sup> /LED  | 0.055 g/LED   | 7111   | diode, unspecified, at plant                      |
| Material   | Gold                                | 0.004 mm <sup>3</sup> /LED | 0.00006 g/LED | 10107  | gold, from combined metal production, at refinery |
| Material   | Underfill                           | 0.05 mm <sup>3</sup> / LED | 0.0196 g/LED  | 324    | silicone product, at plant                        |
| Material   | Silicone                            | 8.4 mm <sup>3</sup> /LED   | 0.00006 g/LED | 1802   | epoxy resin, liquid, at plant                     |

### 5.3 LED Lamp Analysis

After preparing an Ecoinvent inventory of the materials and processes that contribute to the production of a packaged LED, the next step in the analysis is to consider installing several of these packaged LEDs into a self-ballasted LED lamp that can be inserted into a mains voltage socket. For the purposes of this study (and not as an endorsement of the product) we selected the Philips EnduraLED lamp that was introduced in 2011 and was commonly available in the U.S. market in 2012. There is a picture of this lamp on the right.



The table below presents the materials used in manufacturing the LED lamp and accounts for the energy involved in the assembly and manufacturing steps. The finished LED lamp weighs 178 grams and the card-stock packaging was measured at 37 grams, taken together the lamp inside the box totals approximately 215 grams.

The table estimates the transport of the lamp from China to the U.S. by sea and then a further 1000 kilometers distribution within the U.S. The table presents the energy consumed by the lamp over its lifetime – specifically, 12.5 watts times 25000 hours, or 312.5 kilowatt-hours. Finally, in the end of life stage, the table presents some estimates of the rates of recycling, with the LED lamp being recycled 20% of the time and the packaging 30% of the time. The middle column of the table specifies the quantity of material used (presented with the units), and the right two columns provide the unique ID and description of the Ecoinvent database record to which it is matched.

**Table 5-9. LCA Inventory for the 12.5 Watt LED Lamp in 2012**

| Stage    | Material Used          | Amount   | Eco-ID | Ecoinvent Description                                                                 |
|----------|------------------------|----------|--------|---------------------------------------------------------------------------------------|
| Material | LEDs (blue light)      | 12 units |        | LED impacts taken from the above section                                              |
| Material | Remote phosphor        | 1.0g     | 6954   | rare earth concentrate, 70% rare earth oxide (REO), from bastnasite, at beneficiation |
| Material | Plastic phosphor host  | 11.1g    | 6954   | rare earth concentrate, 70% REO, from bastnasite, at beneficiation                    |
| Material | Aluminum heat sink     | 68.2g    | 1057   | aluminum, production mix, cast alloy, at plant                                        |
| Material | Copper                 | 5.0g     | 1084   | copper, primary, at refinery                                                          |
| Material | Nickel                 | 0.003g   | 1121   | nickel, 99.5%, at plant                                                               |
| Material | Brass                  | 1.65g    | 1066   | brass, at plant                                                                       |
| Material | Cast iron              | 4.0g     | 1069   | cast iron, at plant                                                                   |
| Material | Chromium               | 0.0002g  | 1072   | chromium steel 18/8, at plant                                                         |
| Material | Inductor               | 5 pcs.   | 1074   | copper, at regional storage                                                           |
| Material | IC chip                | 2.0g     | 7016   | integrated circuit, IC, logic type, at plant                                          |
| Material | Capacitor SMD          | 8 pcs.   | 7010   | capacitor, SMD type, surface-mounting, at plant                                       |
| Material | Electrolytic Capacitor | 6 pcs.   | 7011   | capacitor, electrolyte type, < 2cm height, at plant                                   |

| Stage       | Material Used        | Amount    | Eco-ID | Ecoinvent Description                                                  |
|-------------|----------------------|-----------|--------|------------------------------------------------------------------------|
| Material    | Diode                | 6 pcs.    | 7075   | diode, glass-, SMD type, surface mounting, at plant                    |
| Material    | Printed Wiring Board | 15.0g     | 10995  | printed wiring board, surface mount, lead-free surface, at plant       |
| Material    | Resistor SMD         | 35 pcs.   | 7068   | resistor, SMD type, surface mounting, at plant                         |
| Material    | Resistor             | 3 pcs.    | 7109   | resistor, wirewound, through-hole mounting, at plant                   |
| Material    | Transistor           | 6 pcs.    | 7113   | transistor, wired, big size, through-hole mounting, at plant           |
| Material    | Resin Glue           | 4.5g      | 1802   | epoxy resin, liquid, at plant                                          |
| Material    | Solder paste         | 0.3g      | 10800  | flux, wave soldering, at plant                                         |
| Production  | Power                | 5.0 MJ    | 6693   | electricity mix for China                                              |
| Production  | Manufacturing        | 178g      | 10169  | assembly, LCD screen                                                   |
| Material    | Packaging            | 37g       | 1698   | packaging, corrugated board, mixed fiber, single wall, at plant        |
| Transport   | Sea - 215g           | 10000 km  | 1968   | transport, transoceanic freight ship                                   |
| Transport   | Road - 215g          | 1000 km   | 1943   | transport, truck >16t, fleet average                                   |
| Use         | Energy in use        | 312.5 kWh | 6694   | electricity mix for the U.S.                                           |
| End of Life | Lamp, Recycling      | 20%       | 10977  | disposal, treatment of CRT glass                                       |
| End of Life | Lamp, Landfill       | 80%       | 2071   | disposal, glass, 0% water, to inert material landfill                  |
| End of Life | Package, Recycling   | 30%       | 1693   | corrugated board, recycling fiber, single wall, at plant               |
| End of Life | Package, Landfill    | 70%       | 2077   | disposal, packaging cardboard, 19.6% water, to inert material landfill |

Compared with the LED fabrication step of the manufacturing process, this stage (i.e., lamp assembly, transport, use and disposal) of the LCA study had some very good matches between the material used in the lamp and the options in the Ecoinvent database. It should be noted that there are two different electricity values used in the analysis – a mix of electricity for China which is used at the manufacturing stage and a mix of electricity for the U.S. which is used for the energy in use stage. It is important that the energy in use stage reflect the mix where the lamp is being used because the magnitude of the impact associated with the electricity consumed during the use phase is later found to be very important. The recycling levels are meant to represent levels that would be commonly found in the U.S. for the different materials – the lamp and its packaging.

As discussed earlier, in addition to considering the LCA impacts of the incandescent, CFL and LED lamps in 2012, the authors also examined the impacts of the projected performance of LED lamps in 2017. This is of particular interest because LEDs are a rapidly evolving technology and expectations are that it will continue to achieve substantial improvements in its performance in the coming years (DOE, 2012b). In order to determine the performance of a 2017 lamp, the 2012 LED lamp analysis was modified as detailed in the list below:

- Efficacy improvement from 65 lm/W (Philips EnduraLED lamp) to 134 lm/W system output – this adjustment is based on the projected performance improvement of warm-white LEDs in Figure 5.5 and Table 5.6 of the U.S. DOE 2012 Multiyear Program Plan (DOE, 2012b).
- Reduce wattage for the lamp in order to hold lumen output at approximately the equivalent of a 60 watt incandescent lamp. Wattage is reduced from 12.5W to 6.1W while lumen output is adjusted from 812 to 824 lumens.
- Lamp lifetime will increase, benefitting from less heat generated in the lamp itself and improvements in the LEDs and the drive electronics. The lifetime is adjusted from 25,000 to 40,000 hours.
- LED manufacturing improvements in the MOCVD reactors and migration to larger wafer sizes will result in LED die yield improvements. Presently, the model is running on the assumption of a 69% yield on a 3-inch wafer, producing 2438 units. By 2017, the wafer sizes will have increased and yield will have increased such that the expected yield relative to a 3-inch wafer would be approximately 92% (3250 units). The model is therefore adjusted to reflect this yield rate, which is equivalent to a 52% yield on a 4-inch wafer, a very conservative estimate.
- Fewer LEDs in the lamp – given expected improvements in efficacy and package power handling capability, luminous flux output is projected to increase, and thus fewer LEDs will be needed in the finished product to achieve the equivalent light output. For the 2017 lamp, it is assumed that only 12 LEDs will be used (whereas the 2012 lamp uses 18).
- Smaller heat sink – given that the power consumption of the lamp will be decreasing (from 12.5 W to 6.1 W, the heat sink mass necessary to conduct and disperse the heat will be smaller. It is assumed that the mass of the heat sink will be reduced proportionally with power reduction (i.e., 6.1/12.5).
- Fewer input chemicals needed for epitaxy – it is assumed that manufacturing processes will continue to advance, and chemicals required in the epitaxy and growth of LED die will decrease by 20%. Thus the input chemicals necessary for the creating the LED die are reduced by 20%. This adjustment does not, however, apply to the wafer preparation stage or the packaging of the LED, these are both assumed to remain constant.
- Redesign of the LED driver – it is expected that the LED driver component count will decrease as more sophisticated drivers are developed that reduce size and increase reliability of the driver. For 2017, the model assumes that there will be a 50% increase in the Integrated Circuit (IC) chips used in the LED driver and a 33% reduction in the number of individual components such as resistor, capacitors and diodes.
- Improvement in waste management – the model also considers the end-of-life stage, and for 2017, it is assumed that there will be slightly higher proportions of lamp and packaging recycling. Thus, the model assumes an improvement from 20% recycling of the LED lamp in 2012 to 30% in 2017. The model also assumes the packaging recycling rate increases from 30% in 2012 to 50% in 2017.

To provide more detail on these changes to the underpinning LED technology and lamp design, the table below provides an entry for each of the input variables that was changed from the 2012 to the 2017 lamp. The Ecoinvent records to which each of the materials and processes were matched in 2012 remained the same in 2017.



**Table 5-10. Changes to LCA Inputs for LED Lamp Manufacturing in 2017**

| Material for Manufacturing | Quantity in 2012 | Quantity in 2017 | Units         | Percentage Reduction / Increase |
|----------------------------|------------------|------------------|---------------|---------------------------------|
| Acetone                    | 0.59             | 0.472            | l/wafer       | 20%                             |
| AuSn solder                | 14.8             | 11.817           | mm3/wafer     | 20%                             |
| Developer                  | 115              | 92               | ml/wafer      | 20%                             |
| Etchant Ag                 | 30               | 24               | ml/wafer      | 20%                             |
| Etchant Metal              | 60               | 48               | ml/wafer      | 20%                             |
| GaN Etchant                | 0.192            | 0.154            | l/wafer       | 20%                             |
| H <sub>2</sub> gas         | 1.62             | 1.296            | m3/wafer      | 20%                             |
| N <sub>2</sub> gas         | 4.42             | 3.536            | m3/wafer      | 20%                             |
| NH <sub>3</sub> gas        | 0.447            | 0.358            | kg/wafer      | 20%                             |
| O <sub>2</sub> gas         | 2                | 1.6              | l/wafer       | 20%                             |
| Photoresist                | 19               | 15.2             | ml/wafer      | 20%                             |
| Power                      | 42.57            | 34.06            | kWh/wafer     | 20%                             |
| SF <sub>6</sub>            | 0.1              | 0.08             | l/wafer       | 20%                             |
| SiH <sub>4</sub>           | 0.242            | 0.194            | g/wafer       | 20%                             |
| Slurry                     | 2.3              | 1.84             | l/wafer       | 20%                             |
| Target Ag                  | 0.44             | 0.352            | mm3/wafer     | 20%                             |
| Target Al                  | 1.27             | 1.016            | mm3/wafer     | 20%                             |
| Target Ni                  | 0.417            | 0.334            | mm3/wafer     | 20%                             |
| Target Ti                  | 0.467            | 0.374            | mm3/wafer     | 20%                             |
| Target W                   | 3.089            | 2.471            | mm3/wafer     | 20%                             |
| TMAI                       | 0.003            | 0.002            | g/wafer       | 33%                             |
| TMGa                       | 1.47             | 1.176            | g/wafer       | 20%                             |
| TMin                       | 0.01             | 0.008            | g/wafer       | 20%                             |
| UPW                        | 240              | 192              | l/wafer       | 20%                             |
| LEDs (blue light)          | 18               | 12               | packaged LEDs | 33%                             |
| Aluminum heat sink         | 0.0682           | 0.032736         | kg            | 49%                             |
| IC chip                    | 0.002            | 0.003            | kg            | -50% (increase)                 |
| Electrolytic Capacitor     | 6                | 4                | pieces        | 33%                             |
| Diode                      | 6                | 4                | pieces        | 33%                             |
| Resistor SMD               | 35               | 23               | pieces        | 34%                             |
| Resistor                   | 3                | 2                | pieces        | 33%                             |
| Transistor                 | 6                | 4                | pieces        | 33%                             |
| Lamp Weight                | 0.178            | 0.143            | kg            | 20%                             |
| Total Lamp+Pack Weight     | 0.215            | 0.18             | kg            | 16%                             |
| Manufacturing              | 0.178            | 0.143            | kg            | 20%                             |
| Energy in Use              | 312              | 240              | kWh           | 23%                             |
| End of Life - lamp         | 20%              | 30%              | Recycling     | -50% (increase)                 |
| End of Life - lamp         | 80%              | 70%              | Landfill      | 13%                             |
| End of Life - packaging    | 30%              | 50%              | Recycling     | -67% (increase)                 |

| Material for Manufacturing | Quantity in 2012 | Quantity in 2017 | Units    | Percentage Reduction / Increase |
|----------------------------|------------------|------------------|----------|---------------------------------|
| End of Life - packaging    | 70%              | 50%              | Landfill | 29%                             |

Comparing our findings to those presented in the Part 1 report, there is very good alignment for the energy in use phase for the LED lamp where we estimate that this phase represents on average 81% of the impacts associated with this lamp. In Part 1, it was reported that the primary energy in use 3,540 MJ per 20 megalumen-hours of lighting service. In Part 2, we calculate 3,527 MJ for the same lighting service (converted using an average power plant heat rate of 10,633 BTU/kWh for 2011 (DOE, 2012c). This shows that for the most important stage of the LCA, there is very good alignment between the two studies.

## 5.4 Incandescent Lamp Analysis

In order to benchmark the environmental impact of the LED lamp against a familiar light source, an inventory of materials and processes was developed for a 60 watt A-19 general lighting service incandescent lamp. The table below presents the materials used in manufacturing the lamp, and accounts for the energy involved in the glasswork and other manufacturing steps. The lamp itself weighs 38.2 grams and the card-stock packaging was measured at 40 grams, taken together the lamp inside the box totals approximately 78.2 grams.



The table estimates the transport of the lamp from China to the U.S. by sea and then a further 1000 kilometers distribution within the U.S. The table presents the energy consumed by the lamp over its lifetime – specifically, 60 watts times 1500 hours, or 90 kilowatt-hours. Finally in the end of life stage, the table presents some estimates of the rates of recycling, with the lamp being recycled 10% of the time and the packaging 30% of the time. The middle column of the table specifies the quantity of material used (presented with the units), and finally, the material or process in the Ecoinvent database to which it was matched is provided. The table shows both the unique Ecoinvent ID for each matched material or process and the database description.

**Table 5-11. LCA Inventory for the 60 Watt Incandescent Lamp**

| Stage    | Material Used | Amount | Eco-ID | Ecoinvent Description                   |
|----------|---------------|--------|--------|-----------------------------------------|
| Material | Argon gas     | 0.137g | 252    | argon, liquid, at plant                 |
| Material | Nitrogen gas  | 0.845g | 300    | nitrogen, liquid, at plant              |
| Material | Oxygen gas    | 7.290g | 301    | oxygen, liquid, at plant                |
| Material | Hydrogen gas  | 0.001g | 286    | hydrogen, liquid, at plant              |
| Material | Ammonia       | 0.085g | 246    | ammonia, liquid, at regional storehouse |
| Material | Aluminum      | 1.150g | 1056   | aluminum, production mix, at plant      |
| Material | Brass         | 0.050g | 1066   | brass, at plant                         |
| Material | Resin Glue    | 1.550g | 1802   | epoxy resin, liquid, at plant           |
| Material | Solder paste  | 0.150g | 10800  | flux, wave soldering, at plant          |

| Stage       | Material Used           | Amount    | Eco-ID | Ecoinvent Description                                                  |
|-------------|-------------------------|-----------|--------|------------------------------------------------------------------------|
| Material    | Glass Bulb              | 22.54g    | 810    | glass tube, borosilicate, at plant                                     |
| Material    | Getter                  | 0.002g    | 311    | phosphoric acid, industrial grade, 85% in H <sub>2</sub> O             |
| Material    | Glass Flare             | 2.097g    | 810    | glass tube, borosilicate, at plant                                     |
| Material    | Exhaust Tube            | 2.165g    | 810    | glass tube, borosilicate, at plant                                     |
| Material    | Lead wire               | 0.100g    | 1178   | wire drawing, copper                                                   |
| Material    | Molybdenum support wire | 0.013g    | 1116   | molybdenum, at regional storage                                        |
| Material    | Filament - Tungsten     | 0.010g    | 1142   | rhodium, at regional storage                                           |
| Production  | Power                   | 0.372g    | 6693   | electricity mix for China                                              |
| Production  | Manufacturing           | 38.2g     | 10169  | assembly, LCD screen                                                   |
| Material    | Packaging               | 40.0g     | 1698   | packaging, corrugated board, mixed fiber, single wall, at plant        |
| Transport   | Sea – 78.2g             | 10,000 km | 1968   | transport, transoceanic freight ship                                   |
| Transport   | Road – 78.2g            | 1000 km   | 1943   | transport, truck >16t, fleet average                                   |
| Use         | Energy in use           | 90.0 kWh  | 6694   | electricity mix for the U.S.                                           |
| End of Life | Lamp, Recycling         | 10%       | 10977  | disposal, treatment of CRT glass                                       |
| End of Life | Lamp, Landfill          | 90%       | 2071   | disposal, glass, 0% water, to inert material landfill                  |
| End of Life | Package, Recycling      | 30%       | 1693   | corrugated board, recycling fiber, single wall, at plant               |
| End of Life | Package, Landfill       | 70%       | 2077   | disposal, packaging cardboard, 19.6% water, to inert material landfill |

Overall, there were very good matches between the material used in the incandescent lamp and the options available in the Ecoinvent database. All of the gases used in the manufacturing and filling of the lamp were available, the metals and the glass were prepared. It should be noted that there are two different electricity values used in the analysis – there is a mix of electricity for China which is used at the manufacturing stage and a mix of electricity for the U.S. which is used for the energy in use stage. It is important that the energy in use stage reflect the mix where the lamp is being used because the magnitude of the impact associated with the electricity consumed during the use phase is later found to be the dominant factor in the environmental impact associated with this lamp. The recycling levels are meant to represent levels that would be commonly found in the U.S. for the different materials – the lamp and its packaging.

Comparing our findings to those presented in the Part 1 report, there is very good alignment for the energy-in use phase of the incandescent lamp which represents on average 93% of the impacts associated with this lamp. In Part 1, it was reported that the primary energy in use 15,100 MJ per 20 megalumen-hours of lighting service. In Part 2, we calculate 14,960 MJ for the same lighting service (converted using an average power plant heat rate of 10,633 BTU/kWh for 2011 (DOE, 2012c)). This shows that for the most important stage of the LCA, there is very good alignment between the two studies.

## 5.5 Compact Fluorescent Lamp Analysis

In addition to comparing the LED lamp against an incandescent lamp, it is also important to compare the LED lamp with the most common energy-efficient light source used in the U.S. today, a CFL. The CFL is a miniaturized version of the large linear tube fluorescent systems commonly found in commercial office buildings. The linear tube has been bent and twisted to conform to a smaller form-factor and the electronic ballast is contained in the base of the lamp, rather than being a separate component wired to sockets. The glass tube is permanently attached to the lamp base / ballast, and the system is designed to operate for approximately 8,000 hours, after which the entire lamp is either recycled or disposed.



The inventory of materials and processes presented in the table below were developed for a 15 watt integrally-ballasted CFL. The table below presents the materials used in manufacturing the lamp and ballast. The lamp itself weighs 153 grams and the card-stock packaging was measured at 81 grams, taken together the lamp inside the box totals approximately 234 grams.

The table estimates the transport of the lamp from China to the U.S. by sea and then a further 1000 kilometers distribution within the U.S. The table presents the energy consumed by the lamp over its lifetime – specifically, 15 watts times 8000 hours, or 120 kilowatt-hours. Finally, in the end of life stage, the table presents some estimates of the rates of recycling, with the CFL being recycled 20% of the time and the packaging 30% of the time. The middle column of the table specifies the quantity of material used (presented with the units), and finally, the material or process in the Ecoinvent database to which it was matched is provided. The table shows both the unique Ecoinvent ID for each matched material or process and the database description.

**Table 5-12. LCA Inventory for the 15 Watt Integrally Ballasted Compact Fluorescent Lamp**

| Stage    | Material Used  | Amount  | Eco-ID | Ecoinvent Description                                              |
|----------|----------------|---------|--------|--------------------------------------------------------------------|
| Material | Argon gas      | 0.004g  | 252    | argon, liquid, at plant                                            |
| Material | Nitrogen gas   | 0.119g  | 300    | nitrogen, liquid, at plant                                         |
| Material | Oxygen gas     | 0.159g  | 301    | oxygen, liquid, at plant                                           |
| Material | Hydrogen gas   | 0.002g  | 286    | hydrogen, liquid, at plant                                         |
| Material | Neon gas       | 0.0004g | 294    | krypton, gaseous, at plant                                         |
| Material | Noble Earths   | 0.001g  | 6954   | rare earth concentrate, 70% REO, from bastnasite, at beneficiation |
| Material | Yttrium Oxide  | 1.37g   | 6954   | rare earth concentrate, 70% REO, from bastnasite, at beneficiation |
| Material | Ammonia        | 0.13g   | 246    | ammonia, liquid, at regional storehouse                            |
| Material | Nitric acid    | 7.9g    | 299    | nitric acid, 50% in H <sub>2</sub> O, at plant                     |
| Material | Sulfuric acid  | 1.67g   | 350    | sulfuric acid, liquid, at plant                                    |
| Material | Aluminum Oxide | 0.008g  | 244    | aluminum oxide, at plant                                           |
| Material | Lead           | 0.19g   | 1103   | lead, at regional storage                                          |

| Stage       | Material Used               | Amount  | Eco-ID | Ecoinvent Description                                                  |
|-------------|-----------------------------|---------|--------|------------------------------------------------------------------------|
| Material    | Copper                      | 0.402g  | 1084   | copper, primary, at refinery                                           |
| Material    | Nickel                      | 0.003g  | 1121   | nickel, 99.5%, at plant                                                |
| Material    | Brass                       | 1.65g   | 1066   | brass, at plant                                                        |
| Material    | Cast iron                   | 0.029g  | 1069   | cast iron, at plant                                                    |
| Material    | Chromium                    | 0.0002g | 1072   | chromium steel 18/8, at plant                                          |
| Material    | Mercury                     | 0.004g  | 1111   | mercury, liquid, at plant                                              |
| Material    | Capacitor                   | 40 pcs. | 7010   | capacitor, SMD type, surface-mounting, at plant                        |
| Material    | Coil miniature              | 3 pcs.  | 10155  | inductor, miniature RF chip type, MRFI, at plant                       |
| Material    | Diode SMD                   | 40 pcs. | 7075   | diode, glass-, SMD type, surface mounting, at plant                    |
| Material    | PWB                         | 3.7g    | 10995  | printed wiring board, surface mount, lead-free surface, at plant       |
| Material    | Resistor SMD                | 40 pcs. | 7068   | resistor, SMD type, surface mounting, at plant                         |
| Material    | Thermistor, NTC             | 0.19g   | 7068   | resistor, SMD type, surface mounting, at plant                         |
| Material    | Transistor power large      | 3.70g   | 7113   | transistor, wired, big size, through-hole mounting, at plant           |
| Material    | Resin Glue                  | 4.5g    | 1802   | epoxy resin, liquid, at plant                                          |
| Material    | Solder paste                | 0.3g    | 10800  | flux, wave soldering, at plant                                         |
| Material    | Glass Tube                  | 1.20g   | 810    | glass tube, borosilicate, at plant                                     |
| Material    | Housing top & bottom (PBTP) | 2.39g   | 1827   | polyethylene terephthalate, granulate, amorphous, at plant             |
| Production  | Natural Gas                 | 10.7kg  | 8338   | metal working factory operation, heat energy from natural gas          |
| Production  | Power                       | 3.13MJ  | 6693   | electricity mix for China                                              |
| Production  | Manufacturing               | 153g    | 10169  | assembly, LCD screen                                                   |
| Material    | Packaging                   | 81g     | 1698   | packaging, corrugated board, mixed fiber, single wall, at plant        |
| Transport   | Sea - 234g                  | 10000km | 1968   | transport, transoceanic freight ship                                   |
| Transport   | Road - 234g                 | 1000km  | 1943   | transport, truck >16t, fleet average                                   |
| Use         | Energy in use               | 120 kWh | 6694   | electricity mix for the U.S.                                           |
| End of Life | Lamp, Recycling             | 20%     | 10977  | disposal, treatment of CRT glass                                       |
| End of Life | Lamp, Landfill              | 80%     | 2071   | disposal, glass, 0% water, to inert material landfill                  |
| End of Life | Package, Recycling          | 30%     | 1693   | corrugated board, recycling fiber, single wall, at plant               |
| End of Life | Package, Landfill           | 70%     | 2077   | disposal, packaging cardboard, 19.6% water, to inert material landfill |

Overall, the CFL is a complex system which includes the lamp, cathodes, a ballast, housing and a socket. Across the list of materials and processes identified in manufacturing a CFL, there were good matches in

the Ecoinvent database. For example, the components in the ballast were able to be matched one-for-one with exactly the same component selected from the Ecoinvent database. As with the previous lamps discussed, this table shows two different electricity values used in the analysis – there is a mix of electricity for China which is used at the manufacturing stage and a mix of electricity for the United States which is used for the energy in use stage. This differentiation is important because the magnitude of the impact associated with the electricity consumed during the use phase is later shown to be a significant factor in the environmental impact associated with this lamp. Finally, the recycling levels are meant to represent levels that would be commonly found in the U.S. Compared with incandescent, it was assumed that there is a slightly higher recycling rate of the lamp (20%) because of the mercury in the glass tube.

Comparing our findings for this lamp to those presented in the Part 1 report, there is very good alignment for the energy-in use phase of the incandescent lamp which represents on average 78% of the impacts. In Part 1, it was reported that the primary energy in use 3,780 MJ per 20 megalumen-hours of lighting service. In Part 2, we calculate 4,079 MJ for the same lighting service (converted using an average power plant heat rate of 10,633 BTU/kWh for 2011 (DOE, 2012c)). This shows that for the most important stage of the LCA, we are estimating approximately 8% higher energy consumption for the energy in use stage of the LCA.



## 6 Life Cycle Impact Assessment Indicators

This section of the report discusses the indicators that were selected from the Ecoinvent database for this study. The inventories presented in Chapter 5 are combined with impact data from the Ecoinvent database to determine the levels of environmental impact. For this study, DOE wanted to make sure the assessment quantified impacts associated with air/climate, water, soil and resources. There were fifteen indicators chosen for this study, as shown in Table 6-1. After the table, a brief description of each of these indicators is provided.

**Table 6-1. LCA Environmental Indicators Selected for this Analysis**

|               | Abbr. | Name                                     | Indicator                    | Ecoinvent Indicator                              | Units                    |
|---------------|-------|------------------------------------------|------------------------------|--------------------------------------------------|--------------------------|
| Air / Climate | GWP   | Global Warming Potential                 | greenhouse gas emissions     | global warming potential (GWP100a) [CML2001]     | kg CO <sub>2</sub> -eq   |
|               | AP    | Acidification Potential                  | air pollution                | acidification potential [CML2001]                | kg SO <sub>2</sub> -eq   |
|               | POCP  | Photochemical Ozone Creation Potential   | air pollution                | photochemical oxidation [CML2001]                | kg O <sub>3</sub> formed |
|               | ODP   | Ozone Depleting Potential                | air pollution                | stratospheric ozone depletion (ODP10a)           | kg CFC11-eq              |
|               | HTP   | Human Toxicity Potential                 | toxicity                     | human toxicity (HTP100a) [CML2001]               | kg 1,4-DCB-eq            |
| Water         | FAETP | Freshwater Aquatic Ecotoxicity Potential | water pollution              | freshwater aquatic ecotoxicity (FAETP100a)       | kg 1,4-DCB-eq            |
|               | MAETP | Marine Aquatic Ecotoxicity Potential     | water pollution              | marine aquatic ecotoxicity (MAETP100a) [CML2001] | kg 1,4-DCB-eq            |
|               | EP    | Eutrophication Potential                 | water pollution              | eutrophication potential [CML2001]               | kg PO <sub>4</sub> -eq   |
| Soil          | LU    | Land Use                                 | land use                     | land use [CML2001]                               | m <sup>2</sup> a         |
|               | EDP   | Ecosystem Damage Potential               | biodiversity impacts         | ecosystem damage potential [EDP]                 | points                   |
|               | TAETP | Terrestrial Ecotoxicity Potential        | soil degrad. & contamination | terrestrial ecotoxicity (TAETP100a) [CML2001]    | kg 1,4-DCB-eq            |
| Resources     | ARD   | Abiotic Resource Depletion               | resource depletion           | depletion of abiotic resources [CML2001]         | kg Sb-eq                 |
|               | NHWL  | Non-Hazardous Waste Landfilled           | non-hazardous waste          | landfilling of bulk waste [EDIP2003]             | kg waste                 |
|               | RWL   | Radioactive Waste Landfilled             | hazardous waste              | landfilling of hazardous waste [EDIP2003]        | kg waste                 |
|               | HWL   | Hazardous Waste Landfilled               | hazardous waste              | landfilling of radioactive waste [EDIP2003]      | kg waste                 |

In the above table, the far-right column identifies the units in which each of these environmental indicators are measured. The abbreviation “eq” stands for equivalents which will often be used when more than one pollutant can cause a particular impact. For example, global warming is attributed to a number of gases, including carbon dioxide (CO<sub>2</sub>) and methane (CH<sub>4</sub>); however emissions are reported for this indicator simply in units of “kg of CO<sub>2</sub> equivalents.” On that basis, CO<sub>2</sub> is said to have a global

warming potential (GWP) of one because one kg of CO<sub>2</sub> has the warming potential of itself, but methane has a GWP of 25 (one kg of CH<sub>4</sub> has the warming potential of 25 kg of CO<sub>2</sub>). By using equivalent values, it simplifies the outputs of the LCA and facilitates comparisons between studies. Several other criteria are reported in a similar way, notably the toxicity criteria, which are assessed relative to the toxicity of 1,4-DiChloroBenzene (1,4-DCB), a known carcinogenic substance.

The following material provides a brief overview of each of the 15 environmental criteria against which the incandescent, CFL and LED lamps are assessed.

**Indicator: Global Warming Potential (GWP)**

*Measurement Units: kilograms of carbon dioxide (CO<sub>2</sub>) equivalents*

Description: This indicator is a measurement of activities associated with the life cycle of the product that alter the chemical composition of the atmosphere through the build-up of greenhouse gases, primarily carbon dioxide, methane, and nitrous oxide. As these and other heat-trapping gases increase their concentration, the heat-trapping capability of the earth's atmosphere will also increase, triggering global climate change and associated environmental impacts.

**Indicator: Acidification Potential (AP)**

*Measurement Units: kilograms of sulfur dioxide (SO<sub>2</sub>) equivalents*

Description: This indicator is a measure of the air pollution (mainly ammonia, sulfur dioxide and nitrogen oxides) caused by the product's life cycle which contributes to the deposition of acidic substances. The resultant 'acid rain' is best known for the damage it causes to forests and lakes. However, less well known impacts are the ways acidification affects freshwater and coastal ecosystems, soils and even ancient historical monuments. Acid deposition can also increase the environmental mobility of metals, resulting in the pollution of water sources and increased uptake of metals (e.g., mercury) by biota.

**Indicator: Photochemical Ozone Creation Potential (POCP)**

*Measurement Units: kilograms of ozone (O<sub>3</sub>) formed*

Description: This indicator is a measure of the photochemical smog generated during the product's life cycle. Common sources include automobile internal combustion engines, as well as the increased use of fossil fuels for heating, industry, and transportation. These activities lead to emissions of two major primary pollutants, volatile organic compounds (VOCs) and nitrogen oxides. Interacting with sunlight, these primary pollutants convert into various hazardous chemicals known as secondary pollutants – namely peroxyacetyl nitrates (PAN) and ground-level (tropospheric) ozone. These secondary pollutants cause what is commonly referred to as "urban smog."

**Indicator: Ozone Depleting Potential (ODP)**

*Measurement Units: kilograms of CFC-11 equivalents*

Description: This metric quantifies the ozone depleting potential of the product during its life cycle. Although ground-level ozone is a pollutant, stratospheric ozone is beneficial, protecting the earth from excessive amounts of ultraviolet light. The stratospheric ozone layer is attacked by free radical catalysts, some of which are produced by many man-made chemicals such as chlorofluorocarbons (CFCs) which were used as a blowing agent in aerosols and insulation and as a working fluid in refrigerator compressors. This indicator adjusts all ozone depleting chemicals associated with the UEL to the equivalent level of emissions of these harmful chemicals.

**Indicator: Human Toxicity Potential (HTP)**

*Measurement Units: kilograms of 1,4-dichlorobenzene (DCB) equivalents*

Description: This indicator attempts to quantify the air, water and soil emissions associated with the product's life cycle that may be detrimental to human health. The toxicological factors are calculated using scientific estimates for the acceptable daily intake or tolerable daily intake of the toxic substances, but are still at an early stage of development, so can only be taken as an indication and not as an absolute measure of the toxicity potential. The measurement units are in equivalents of 1,4-dichlorobenzene, a known carcinogen.

**Indicator: Freshwater Aquatic Ecotoxicity Potential (FAETP)**

*Measurement Units: kilograms of 1,4-dichlorobenzene (DCB) equivalents*

Description: This indicator is very similar to human toxicity potential, but combines factors associated with the maximum tolerable concentrations of different toxic substances in water by freshwater aquatic organisms.

**Indicator: Marine Aquatic Ecotoxicity Potential (MAETP)**

*Measurement Units: kilograms of 1,4-dichlorobenzene (DCB) equivalents*

Description: This indicator is analogous to FAETP, combining factors associated with the maximum tolerable concentrations of different toxic substances in water, but refers to marine aquatic organisms.

**Indicator: Eutrophication Potential (EP)**

*Measurement Units: kilograms of phosphate (PO<sub>4</sub>) equivalents*

Description: Nitrates and phosphates are essential for life, but increased concentrations in water can encourage excessive growth of algae, reducing the oxygen within the water and damaging ecosystems – a phenomenon known as eutrophication.

**Indicator: Land Use (LU)**

*Measurement Units: square meters per year (m<sup>2</sup>a), the product of m<sup>2</sup> area and years*

Description: Land use is an economic activity that generates large benefits for human society, but it also has negative impacts on the environment. The occupation of a location by an industrial facility precludes the return of that site to a more natural environment, including availability for wildlife. The indicator captures the impact on both the area involved and the number of years over which that occurs.

**Indicator: Ecosystem Damage Potential (EDP)**

*Measurement Units: points*

Description: Biodiversity has been negatively influenced by intensive agriculture, forestry and the increase in urban areas and infrastructure. This indicator attempts to provide some measure of that impact. It combines land-use and land transformation (both to and from industrial uses), and assigns characterization factors to account for the relative impact of the land usage.

**Indicator: Terrestrial Ecotoxicity Potential (TAETP)**

*Measurement Units: kilograms of 1,4-dichlorobenzene (DCB) equivalents*

Description: This indicator is very similar to the previous toxicity potentials, but refers to the maximum tolerable concentrations of different toxic substances by terrestrial organisms.

**Indicator: Abiotic Resource Depletion (ARD)**

*Measurement Units: Equivalent kilograms of the scarce element, antimony (Sb)*

Description: The current levels of global resource consumption are widely acknowledged to be unsustainable. Abiotic resources are natural, and essentially limited, resources, such as iron ore, crude oil and natural gas, as opposed to renewable, biotic sources such as biomass. ARD impacts are reported against the remaining global inventory of antimony (Sb), a relatively scarce element.

**Indicators: Non-Hazardous Waste Landfilled (NHWL), Radioactive Waste Landfilled (RWL), and Hazardous Waste Landfilled (HWL)**

*Measurement Units: Kilograms of each of these three land-fill processes*

Description: For the products being considered in this LCA, these indicators all seek to quantify the amount of materials sent to landfill, split between three categories – non-hazardous waste, radioactive waste and hazardous waste.

## 7 Life Cycle Assessment Results

Having identified the materials and processes being consumed for each of the lamp types in Chapter 5 and selecting the fifteen environmental indicators in Chapter 6, this chapter presents the results of the analysis. The first review is to determine which stages of the life-cycle assessment are significant and which ones are negligible from an environmental impacts point of view. This analysis is important to inform the sensitivity analysis, which will investigate significant assumptions and test whether conclusions drawn are robust to plausible variations in the underlying data.

For each lamp type, the LCA impacts are calculated separately for the raw materials, the manufacturing, the transport (by sea and by road), the power consumed during the lamp's operating life and finally the end of life. The following series of tables and bar charts present the LCA results for each lamp type, broken down by these LCA stages. The values shown are in the units presented in Chapter 6 (and repeated below), but normalized to represent the impact associated with 20 megalumen-hours of light. This quantity of lighting service was used in DOE's Part 1 study and is equal to the light output of the 12.5 Watt LED lamp (2012) over its rated lifetime.

|       |                                          |                          |
|-------|------------------------------------------|--------------------------|
| GWP   | Global Warming Potential                 | kg CO <sub>2</sub> -eq   |
| AP    | Acidification Potential                  | kg SO <sub>2</sub> -eq   |
| POCP  | Photochemical Ozone Creation Potential   | kg O <sub>3</sub> formed |
| ODP   | Ozone Depleting Potential                | kg CFC11-eq              |
| HTP   | Human Toxicity Potential                 | kg 1,4-DCB-eq            |
| FAETP | Freshwater Aquatic Ecotoxicity Potential | kg 1,4-DCB-eq            |
| MAETP | Marine Aquatic Ecotoxicity Potential     | kg 1,4-DCB-eq            |
| EP    | Eutrophication Potential                 | kg PO <sub>4</sub> -eq   |
| LU    | Land Use                                 | m <sup>2</sup> a         |
| EDP   | Ecosystem Damage Potential               | points                   |
| TAETP | Terrestrial Ecotoxicity Potential        | kg 1,4-DCB-eq            |
| ARD   | Abiotic Resource Depletion               | kg Sb-eq                 |
| NHWL  | Non-Hazardous Waste Landfilled           | kg waste                 |
| RWL   | Radioactive Waste Landfilled             | kg waste                 |
| HWL   | Hazardous Waste Landfilled               | kg waste                 |

Table 7-1. Life Cycle Impacts of the 60W Incandescent Lamp

| Incandescent<br>LCA Stage | GWP     | AP      | Air<br>POCP | ODP        | HTP     | FAETP   | Water<br>MAETP | EP      |
|---------------------------|---------|---------|-------------|------------|---------|---------|----------------|---------|
| Raw Materials             | 6.28    | 0.90049 | 0.000604    | 0.00000069 | 3.224   | 2.9873  | 11.026         | 0.05847 |
| Manufacturing             | 7.77    | 0.06905 | 0.000796    | 0.00000030 | 4.373   | 0.0405  | 0.901          | 0.02756 |
| Transport                 | 0.28    | 0.00387 | 0.000043    | 0.00000004 | 0.098   | 0.0017  | 0.107          | 0.00053 |
| Energy in Use             | 1017.12 | 6.93390 | 0.044379    | 0.00001008 | 197.746 | 18.5601 | 99.647         | 1.85966 |
| Disposal                  | 0.19    | 0.00059 | 0.000035    | 0.00000003 | 0.045   | 0.0011  | 0.017          | 0.00031 |
| TOTAL                     | 1031.64 | 7.90790 | 0.045857    | 0.00001114 | 205.486 | 21.5907 | 111.698        | 1.94653 |

| Incandescent<br>LCA Stage | LU      | Soil<br>EDP | TAETP    | ARD    | NHWL   | RWL       | HWL       |
|---------------------------|---------|-------------|----------|--------|--------|-----------|-----------|
| Raw Materials             | 1.7476  | 1.1385      | 0.002262 | 0.0499 | 2.060  | 0.0003923 | 0.0007504 |
| Manufacturing             | 0.7402  | 0.5534      | 0.001446 | 0.0447 | 2.321  | 0.0000822 | 0.0002103 |
| Transport                 | 0.0033  | 0.0026      | 0.000051 | 0.0020 | 0.019  | 0.0000044 | 0.0000038 |
| Energy in Use             | 20.2769 | 15.2903     | 0.120488 | 7.5409 | 30.601 | 0.0421082 | 0.0224757 |
| Disposal                  | 0.0198  | 0.0122      | 0.000134 | 0.0014 | 0.949  | 0.0000024 | 0.0000032 |
| TOTAL                     | 22.7878 | 16.9970     | 0.124381 | 7.6389 | 35.950 | 0.0425895 | 0.0234434 |

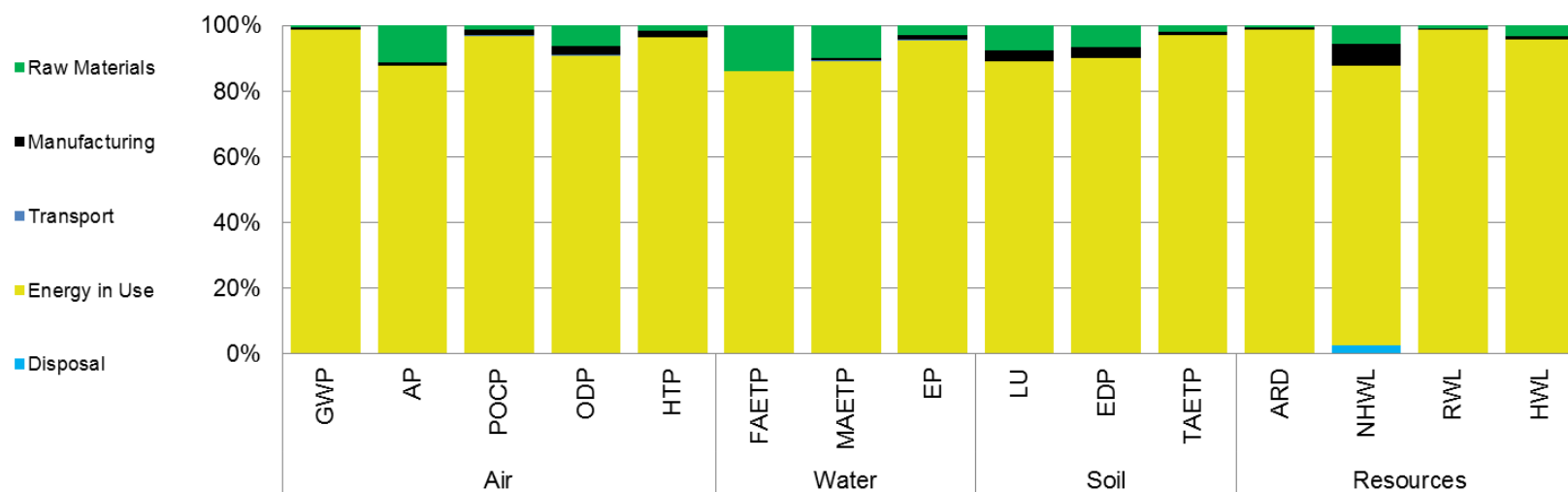


Figure 7-1. Proportions of the Life Cycle Impacts for the 60W Incandescent Lamp



Table 7-2. Life Cycle Impacts of the Compact Fluorescent Lamp

| CFL LCA Stage | Air     |         |          |            |        | Water  |         |         |
|---------------|---------|---------|----------|------------|--------|--------|---------|---------|
|               | GWP     | AP      | POCP     | ODP        | HTP    | FAETP  | MAETP   | EP      |
| Raw Materials | 10.680  | 0.29225 | 0.002879 | 0.00000117 | 9.007  | 0.5182 | 6.9088  | 0.10631 |
| Manufacturing | 16.560  | 0.08449 | 0.001215 | 0.00000120 | 4.677  | 0.3486 | 2.2256  | 0.03657 |
| Transport     | 0.173   | 0.00237 | 0.000026 | 0.00000002 | 0.060  | 0.0010 | 0.0654  | 0.00032 |
| Energy in Use | 277.380 | 1.89095 | 0.012103 | 0.00000275 | 53.928 | 5.0615 | 27.1750 | 0.50715 |
| Disposal      | 0.086   | 0.00029 | 0.000016 | 0.00000001 | 0.020  | 0.0005 | 0.0077  | 0.00014 |
| TOTAL         | 304.879 | 2.27035 | 0.016239 | 0.00000515 | 67.692 | 5.9298 | 36.3825 | 0.65049 |

| CFL LCA Stage | Soil   |        |          | Resources |        |          |          |
|---------------|--------|--------|----------|-----------|--------|----------|----------|
|               | LU     | EDP    | TAETP    | ARD       | NHWL   | RWL      | HWL      |
| Raw Materials | 1.0292 | 0.7001 | 0.013140 | 0.08395   | 1.382  | 0.000801 | 0.001169 |
| Manufacturing | 0.7215 | 0.5433 | 0.002536 | 0.08566   | 2.995  | 0.000239 | 0.000350 |
| Transport     | 0.0020 | 0.0016 | 0.000031 | 0.00121   | 0.012  | 0.000003 | 0.000002 |
| Energy in Use | 5.5297 | 4.1698 | 0.032858 | 2.05648   | 8.345  | 0.011483 | 0.006129 |
| Disposal      | 0.0085 | 0.0052 | 0.000057 | 0.00063   | 0.555  | 0.000001 | 0.000001 |
| TOTAL         | 7.2909 | 5.4200 | 0.048622 | 2.22793   | 13.289 | 0.012527 | 0.007651 |

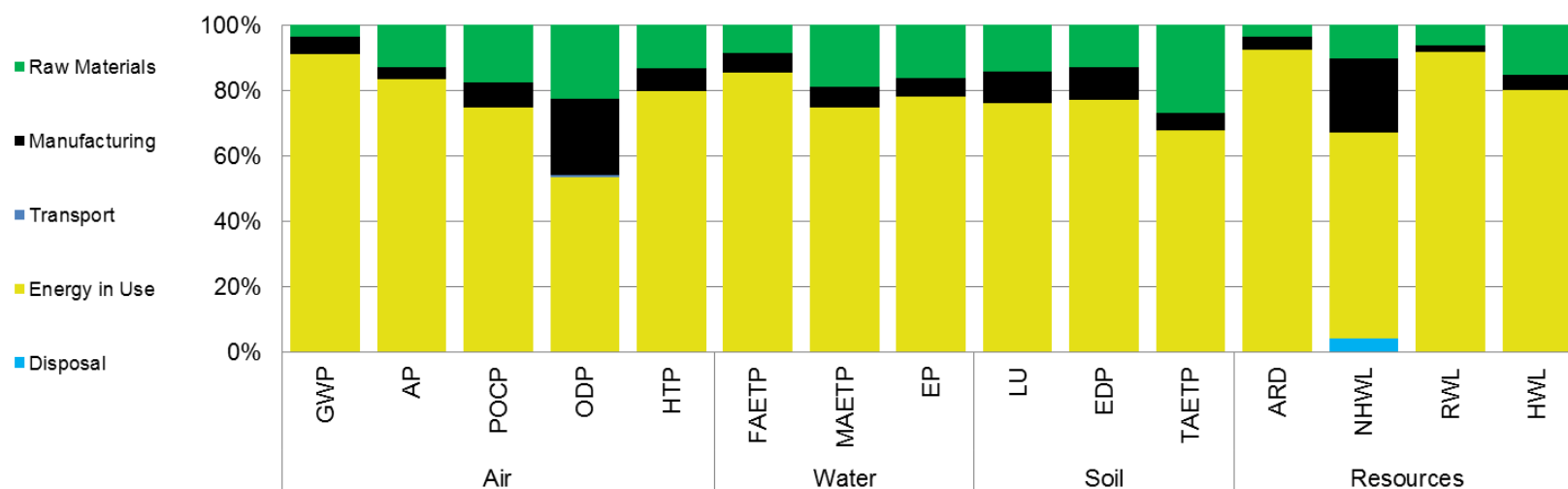


Figure 7-2. Proportions of the Life Cycle Impacts for the Compact Fluorescent Lamp

Table 7-3. Life Cycle Impacts of the 2012 LED Lamp

| LED-2012<br>LCA Stage | Air     |          |           |              |         | Water    |         |         |
|-----------------------|---------|----------|-----------|--------------|---------|----------|---------|---------|
|                       | GWP     | AP       | POCP      | ODP          | HTP     | FAETP    | MAETP   | EP      |
| Raw Materials         | 12.752  | 0.118812 | 0.0020015 | 0.0000013575 | 13.2821 | 0.376537 | 6.4255  | 0.09046 |
| Manufacturing         | 3.450   | 0.031194 | 0.0003134 | 0.0000000989 | 1.4660  | 0.015090 | 0.3198  | 0.00939 |
| Transport             | 0.052   | 0.000708 | 0.0000078 | 0.0000000064 | 0.0180  | 0.000310 | 0.0196  | 0.00010 |
| Energy in Use         | 234.756 | 1.600375 | 0.0102428 | 0.0000023255 | 45.6406 | 4.283750 | 22.9991 | 0.42922 |
| Disposal              | 0.015   | 0.000059 | 0.0000027 | 0.0000000025 | 0.0035  | 0.000091 | 0.0014  | 0.00002 |
| TOTAL                 | 251.025 | 1.751148 | 0.0125682 | 0.0000037908 | 60.4102 | 4.675778 | 29.7654 | 0.52919 |

| LED-2012<br>LCA Stage | Soil    |         |           | Resources |         |           |           |
|-----------------------|---------|---------|-----------|-----------|---------|-----------|-----------|
|                       | LU      | EDP     | TAETP     | ARD       | NHWL    | RWL       | HWL       |
| Raw Materials         | 0.45011 | 0.33650 | 0.0069973 | 0.08918   | 4.3440  | 0.0008670 | 0.0028337 |
| Manufacturing         | 0.26894 | 0.20316 | 0.0005715 | 0.02003   | 0.7873  | 0.0000281 | 0.0000658 |
| Transport             | 0.00060 | 0.00048 | 0.0000093 | 0.00036   | 0.0035  | 0.0000008 | 0.0000007 |
| Energy in Use         | 4.68000 | 3.52906 | 0.0278091 | 1.74047   | 7.0628  | 0.0097188 | 0.0051875 |
| Disposal              | 0.00140 | 0.00085 | 0.0000089 | 0.00011   | 0.1692  | 0.0000002 | 0.0000003 |
| TOTAL                 | 5.40105 | 4.07005 | 0.0353961 | 1.85015   | 12.3668 | 0.0106149 | 0.0080880 |

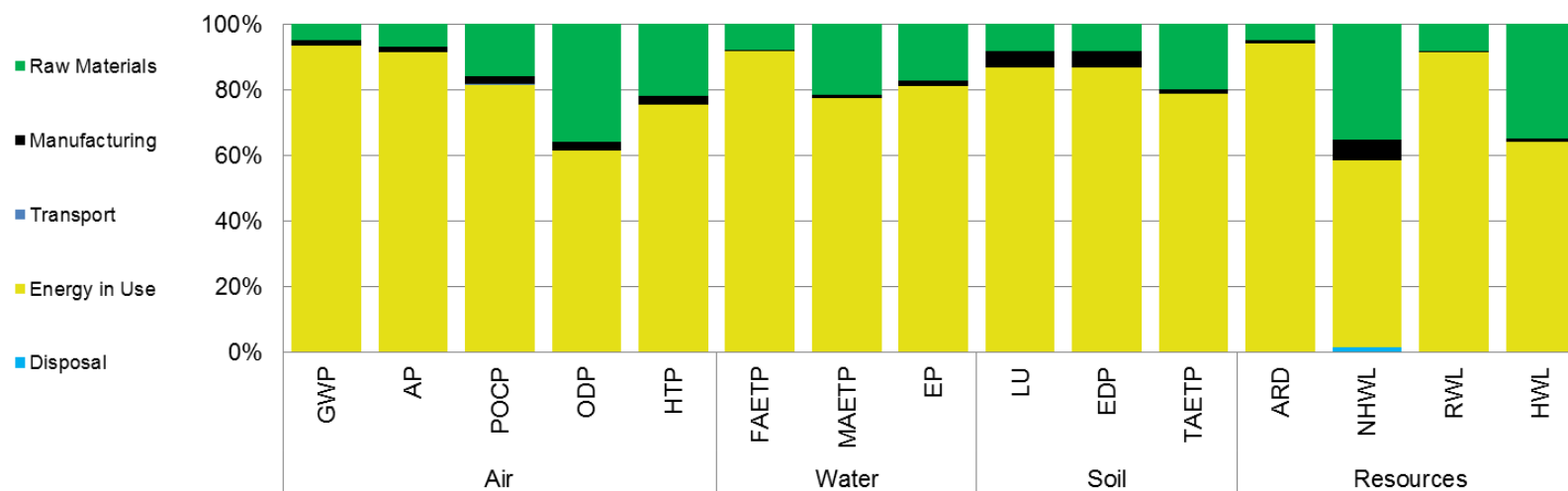


Figure 7-3. Proportions of the Life Cycle Impacts for the 2012 LED Lamp

Table 7-4. Life Cycle Impacts of the 2017 LED Lamp

| LED-2017<br>LCA Stage | Air     |          |          |             |         | Water   |         |          |
|-----------------------|---------|----------|----------|-------------|---------|---------|---------|----------|
|                       | GWP     | AP       | POCP     | ODP         | HTP     | FAETP   | MAETP   | EP       |
| Raw Materials         | 6.995   | 0.059638 | 0.000980 | 0.00000856  | 7.5722  | 0.24578 | 4.0410  | 0.056569 |
| Manufacturing         | 1.900   | 0.017255 | 0.000167 | 0.00000050  | 0.7461  | 0.00794 | 0.1658  | 0.004804 |
| Transport             | 0.027   | 0.000365 | 0.000004 | 0.000000003 | 0.0093  | 0.00016 | 0.0101  | 0.000050 |
| Energy in Use         | 113.837 | 0.776046 | 0.004967 | 0.000001128 | 22.1318 | 2.07726 | 11.1526 | 0.208135 |
| Disposal              | 0.013   | 0.000046 | 0.000002 | 0.000000002 | 0.0031  | 0.00008 | 0.0012  | 0.000022 |
| TOTAL                 | 122.772 | 0.853350 | 0.006120 | 0.000002039 | 30.4625 | 2.33122 | 15.3707 | 0.269580 |

| LED-2017<br>LCA Stage | Soil   |         |          | Resources |        |           |           |
|-----------------------|--------|---------|----------|-----------|--------|-----------|-----------|
|                       | LU     | EDP     | TAETP    | ARD       | NHWL   | RWL       | HWL       |
| Raw Materials         | 0.2547 | 0.18857 | 0.004386 | 0.04949   | 3.5353 | 0.0004879 | 0.0011664 |
| Manufacturing         | 0.1404 | 0.10642 | 0.000306 | 0.01106   | 0.4023 | 0.0000144 | 0.0000327 |
| Transport             | 0.0003 | 0.00025 | 0.000005 | 0.00019   | 0.0018 | 0.0000004 | 0.0000004 |
| Energy in Use         | 2.2694 | 1.71130 | 0.013485 | 0.84398   | 3.4249 | 0.0047128 | 0.0025155 |
| Disposal              | 0.0013 | 0.00080 | 0.000009 | 0.00010   | 0.0826 | 0.0000002 | 0.0000002 |
| TOTAL                 | 2.6661 | 2.00734 | 0.018191 | 0.90482   | 7.4469 | 0.0052157 | 0.0037152 |

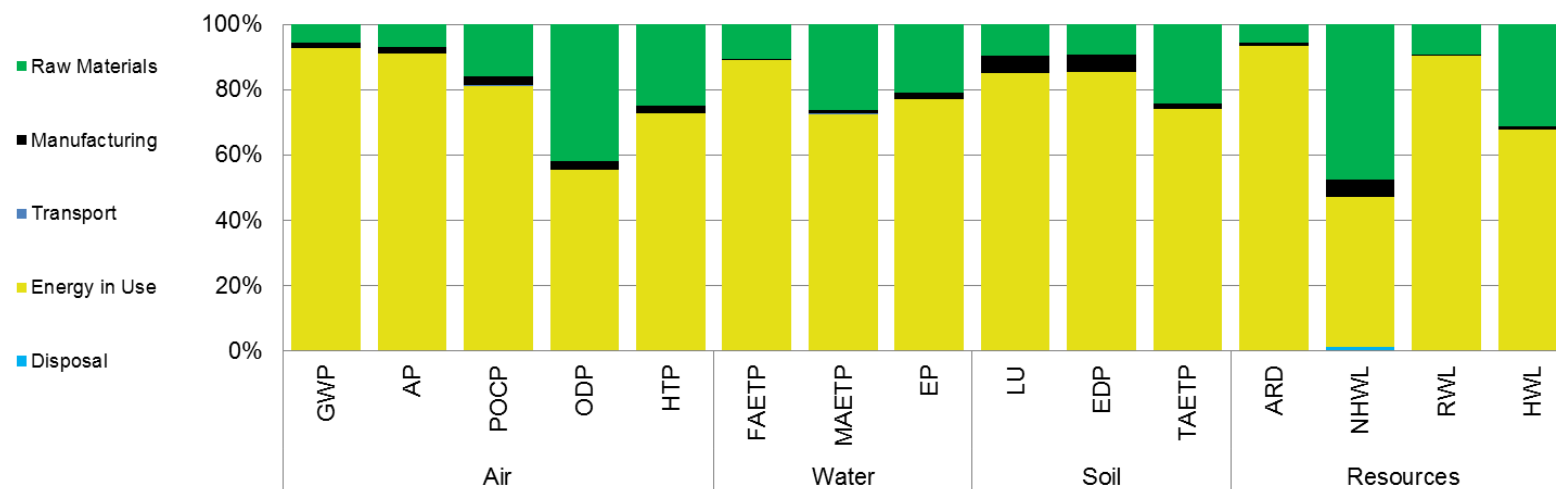


Figure 7-4. Proportions of the Life Cycle Impacts for the 2017 LED Lamp

## 7.1 Discussion of Life Cycle Assessment Results

The four sets of results clearly show that the factor that dominates the majority of the environmental indicators considered is 'energy in use' which is depicted in each figure with yellow shading. The proportion of impact attributable to energy in use is particularly high for the 60 watt incandescent lamp, where energy in use constitutes an average 93% of the fifteen impacts over the lifetime of the lamp. The next most significant stage of the assessment is the raw materials which constitute on average about 5% of the total impact, ranging from 13.8% for freshwater aquatic ecotoxicity potential to 0.6% for abiotic resource depletion. Manufacturing is the third most significant step in the LCA, with an average impact over the fifteen indicators of approximately 1.8%. The remaining two LCA steps – disposal and transport – constitute 0.2% and 0.1% respectively, although the majority of the disposal impact is in non-hazardous waste landfilled, where it represents 2.6% of that impact. Transportation was found to be virtually negligible, even though the lamps in their packaging have traveled over 11,000 kilometers from factory to home.

For the CFL, the largest contributor to environmental impacts is energy, which represents at most 92.3% of the impact (for abiotic resource depletion) and at least 53.4% (for ozone depleting potential). On average, energy in use represents about 78% of the impact of a CFL. The next most significant stage of the LCA is the raw materials, representing on average 13.6% of the impacts, with terrestrial ecotoxicity potential being the most impacted with 23.3% overall. Manufacturing is the third most impactful step in the LCA, with an average impact of approximately 8.2% overall. The remaining two LCA steps – disposal and transport – constitute 0.3% and 0.1% respectively, although the majority of the disposal impact is in non-hazardous waste landfilled, where it represents 4.2% of that impact. As with the incandescent lamp, the impact associated with transport was found to be virtually negligible, even though the packaged CFLs travel over 11,000 kilometers from factory to home.

For the LED lamp in 2012, the largest contributor to environmental impact is energy in use, which represents an average of 81% across the fifteen indicators. The proportion of impact varies from a high of 94.1% for abiotic resource depletion to a low of 57.1% for non-hazardous waste landfill. The second most significant impact is the raw materials used in manufacturing the LED lamp. These include a range of components, the LEDs and the large heat sink. On average the impact from the raw materials is 16.8%, with a high of 35.8% (for ozone depleting potential) and a low of 4.8% (for abiotic resource depletion). Manufacturing is the third most impactful step in the LCA, with just 2.3% and the disposal and transport impacts are extremely low, both less than 0.1%. As with the incandescent lamp and CFL, the packaged LED Lamp is assumed to be transported over 11,000 kilometers by sea and road, but the impacts are virtually negligible.

For the LED lamp in 2017, the profile is similar to that of the 2012 lamp, however the significance of energy is diminished due to the fact that this lamp is considerably more efficacious. For this reason, the other impacts are able to gain a slightly higher proportion of the relative impact for each of the fifteen categories considered. In this analysis, energy in use represents an average of 78.2% of the impact, followed by raw materials at 19.3% and manufacturing at 2.3%. The transportation and disposal of the lamp are negligible, at less than 0.2% each.

## 7.2 Comparative Results Between the Lamps

As well as understanding which parts of the life cycle are the main contributors to the overall environmental impacts of each lamp analyzed, it is also important to compare the lamps themselves to determine which have the smallest overall impact. The results of that analysis are presented in this subsection of the report.

The table below presents the environmental impacts associated with air and climate for each of the lamp types. Within each of the impact indicators, the values presented are comparable between the different lamp types because the lighting service has been normalized to represent 20 Mlm-hr of light output.

**Table 7-5. Air-Related Environmental Impacts of the Lamps for 20 Mlm-hr of Lighting Service**

| Lamp Type    | Global Warming Potential (GWP) | Acidification Potential (AP) | Photochemical Oxidation (POCP) | Stratospheric O <sub>3</sub> depletion (ODP) | Human Toxicity Potential (HTP) |
|--------------|--------------------------------|------------------------------|--------------------------------|----------------------------------------------|--------------------------------|
|              | <i>kg CO<sub>2</sub>-Eq</i>    | <i>kg SO<sub>2</sub>-Eq</i>  | <i>kg formed O<sub>3</sub></i> | <i>kg CFC-11-Eq</i>                          | <i>kg 1,4-DCB-Eq</i>           |
| Incandescent | 1031.640                       | 7.90790                      | 0.0458570                      | 0.0000111                                    | 205.4860                       |
| CFL          | 304.879                        | 2.27035                      | 0.0162390                      | 0.0000052                                    | 67.6920                        |
| LED-2012     | 251.025                        | 1.75115                      | 0.0125682                      | 0.0000038                                    | 60.4102                        |
| LED-2017     | 122.772                        | 0.85335                      | 0.0061200                      | 0.0000020                                    | 30.4625                        |

For global warming potential, the incandescent lamp has the largest CO<sub>2</sub>-equivalent emissions, with over one tonne of emissions associated with the functional unit of 20 million lumen-hours of light. The CFL lamp represents a 70% reduction over the incandescent lamp for equivalent lighting service. The LED lamps are even better, offering a 76% reduction with the 2012 lamp and an 88% savings with the 2017 lamp.

For acidification potential, the trend is similar. The incandescent lamp causes the greatest impact, with 7.9 kilograms of sulfur dioxide equivalent emissions for 20 megalumen-hours of light. The CFL offers a reduction of 71% over the incandescent and the two LED lamps offer a 78% and 89% reduction respectively, greatly reducing the acidification potential.

Photochemical oxidation leads to urban smog, and the emissions of this air pollutant are the most severe with the incandescent lamp. That lamp will emit approximately 46 grams of ozone for the functional unit of light output. The CFL and both LED lamps offer savings over that baseline of 65%, 73% and 87% respectively.

Stratospheric ozone depletion potential is highest with the incandescent baseline lamp. The other, more efficacious lamps, offer savings potentials of between 53% and 82% when compared with the incandescent baseline.

For human toxicity potential, the lamp with the highest impact for the functional unit of light output is the incandescent lamp. The CFL offers a 67% reduction over incandescent and the two LED lamps offer a 71% and 85% savings potential in 2012 and 2017 respectively.

The following table presents the environmental impacts associated with water-related indicators for each of the lamp types, normalized for 20 Mlm-hr of light output.

**Table 7-6. Water-Related Environmental Impacts of the Lamps for 20 Mlm-hr of Lighting Service**

| Lamp Type    | Freshwater Aquatic Ecotoxicity Potential (FAETP) | Marine Aquatic Ecotoxicity Potential (MAETP) | Eutrophication Potential (EP) |
|--------------|--------------------------------------------------|----------------------------------------------|-------------------------------|
|              | <i>kg 1,4-DCB-Eq</i>                             | <i>kg 1,4-DCB-Eq</i>                         | <i>kg PO4-Eq</i>              |
| Incandescent | 21.5907                                          | 111.6980                                     | 1.9465                        |
| CFL          | 5.9298                                           | 36.3825                                      | 0.6505                        |
| LED-2012     | 4.6758                                           | 29.7654                                      | 0.5292                        |
| LED-2017     | 2.3312                                           | 15.3707                                      | 0.2696                        |

For freshwater aquatic ecotoxicity potential, the incandescent lamp has the largest impact, with over three times the impact of the CFL and ten times the impact of the LED in 2017. The units for this environmental indicator are reported in equivalent kilograms of “1,4-DCB” which is 1,4-DiChloroBenzene, a known carcinogen. The LED lamp in 2012 offers a 78% reduction in this impact compared to the incandescent lamp.

For marine aquatic ecotoxicity potential, the trend is similar. The incandescent lamp causes the greatest impact, with 112 kilograms of 1,4-DiChloroBenzene equivalent emissions for 20 megalumen-hours of light. The CFL offers a reduction of 67% over the incandescent and the two LED lamps offer a 73% and 86% reduction respectively, greatly reducing this environmental damage potential.

Eutrophication potential is the last indicator of water-related impacts, measuring the impact in terms of kilograms of phosphate equivalents that could cause excessive algal growth in waterways reducing oxygen in the water and damaging the ecosystem. The incandescent lamp will emit approximately 2 kilograms of phosphate equivalents over the 20 megalumen-hour lighting service functional unit. The CFL is approximately 67% less than that with 0.65 kg, and the two LED lamps are even lower at 0.53 kg and 0.27 kg in 2012 and 2017 respectively. The 2017 LED lamp represents an 8-fold reduction in the damages measured by this environmental indicator.

The following table presents the environmental impacts associated with soil-related indicators for each of the three lamp types, normalized for 20 Mlm-hr of light output.



**Table 7-7. Soil-Related Environmental Impacts of the Lamps for 20 Mlm-hr of Lighting Service**

| Lamp Type    | Land Use (LU)         | Ecosystem Damage Potential (EDP) | Terrestrial Ecotoxicity (TAETP) |
|--------------|-----------------------|----------------------------------|---------------------------------|
|              | <i>m<sup>2</sup>a</i> | <i>points</i>                    | <i>kg 1,4-DCB-Eq</i>            |
| Incandescent | 22.7878               | 16.9970                          | 0.1244                          |
| CFL          | 7.2909                | 5.4200                           | 0.0486                          |
| LED-2012     | 5.4011                | 4.0701                           | 0.0354                          |
| LED-2017     | 2.6661                | 2.0073                           | 0.0182                          |

Land use is a measure of impact on both the area involved and the number of years over which that impact occurs. Of the lamps considered, the incandescent lamp has the largest impact, with a value three times higher than the CFL and four times higher than the LED in 2012. The land use equivalent for an incandescent lamp providing 20 megalumen-hours of lighting service is 22.8 square meters per year. For the same lighting service, a CFL reduces that impact by 68%. The LED lamps reduce it further still, to only 5.4 square meters with the 2012 lamp and 2.5 square meters in 2017. These levels represent a 76% and 88% reduction respectively when compared to the incandescent lamp.

For ecosystem damage potential, the trend is similar. The incandescent lamp causes the greatest impact, with 17 points of ecosystem damage potential over the functional unit. The CFL offers a 68% reduction over the incandescent and the two LED lamps offer a 76% and 88% reduction respectively, greatly reducing the ecosystem damage potential.

Terrestrial ecotoxicity is measured in the 1,4-dichlorobenzene equivalents. The incandescent lamp was found to cause the release of 0.12 kilogram equivalents of this carcinogen. Compared to that impact, the CFL offers a reduction of 61%, lessening the impact to only 0.05 kilogram equivalents. The two LED lamps are even lower at 0.035 kg and 0.018 kg in 2012 and 2017 respectively. The 2017 LED lamp represents an 85% reduction over the incandescent lamp benchmark for the damages measured by this environmental indicator.

The following table presents the four resource-related environmental indicators that were assessed for each of the three lamp types, normalized for 20 Mlm-hr of light output.

**Table 7-8. Resource-Related Environmental Impacts of the Lamps for 20 Mlm-hr of Lighting Service**

| Lamp Type    | Abiotic Resource Depletion (ARD) | Non-Hazardous Waste Landfill (NHWL) | Radioactive Waste Landfill (RWL) | Hazardous Waste Landfill (HWL) |
|--------------|----------------------------------|-------------------------------------|----------------------------------|--------------------------------|
|              | <i>kg antimony-Eq</i>            | <i>kg waste</i>                     | <i>kg waste</i>                  | <i>kg waste</i>                |
| Incandescent | 7.6389                           | 35.9500                             | 0.0426                           | 0.0234                         |
| CFL          | 2.2279                           | 13.2890                             | 0.0125                           | 0.0077                         |
| LED-2012     | 1.8502                           | 12.3668                             | 0.0106                           | 0.0081                         |
| LED-2017     | 0.9048                           | 7.4469                              | 0.0052                           | 0.0037                         |

For the first of the resource-related environmental impacts, abiotic resource depletion potential has the largest depletion of the metric used for this environmental indicator, kilograms of antimony equivalents depleted. The incandescent lamp's impact is approximately 7.6 kilograms, while the more efficient lamp types offer a 71% (CFL) to 88% (LED in 2017) reduction over that baseline.

For non-hazardous waste landfill, the trend is similar. The incandescent lamp causes the greatest impact, with 36 kilograms of non-hazardous waste equivalents for the functional unit of 20 megalumen-hours of light. The CFL offers a reduction of 63% over the incandescent and the two LED lamps offer a 66% and 79% reduction respectively, greatly reducing the impact for this metric.

For radioactive waste landfill, the proportions of the reduction are nearly identical to that of the abiotic resource depletion potential. The incandescent lamp generates 43 grams of radioactive waste landfill equivalents, where the CFL and both LED lamps case the generation of substantially less waste. The CFL offers a reduction of 71%, to just 12 grams per 20 megalumen-hours of lighting service. The LED lamp in 2012 offers a 75% savings at 11 grams and the 2017 lamp offers a substantial savings of 88% savings at just 5 grams of radioactive waste landfill generated for the same light output.

For hazardous waste landfill, the trend is similar but not exactly the same. The incandescent lamp still has the largest impact, with 23 grams of hazardous waste landfill generated. The LED in 2012 has the next lower impact, with 8.1 grams, a 65% reduction. The CFL lamp is slightly lower than the LED with 7.7 grams, which represents a reduction of 67% over the baseline. And finally, the LED in 2017 has the lowest impact overall, with only 3.7 grams of hazardous waste landfill, a reduction of 84%. The reason that the LED lamp in 2012 has a slightly higher impact than the CFL is due to the large aluminum heat sink, which represents 20% of the total impact measured for this metric. While these are the mean values reported, the difference between the two is within the error margin for this study. Please see Annex A for a sensitivity analysis on this particular environmental indicator (i.e., Hazardous Waste Landfill).

Setting the other stages of an LCA to one side, if a comparison is performed simply between the raw material inputs of the lamp types studied in this analysis, the distribution of environmental impacts tends to be greater for the more efficient lamps because they are more complex systems. The CFL and LED lamps both make use of technology in order to reduce the watts of power consumed when producing light. Since the energy-in-use is the dominant LCA stage in terms of impacts (see Figures 7-1 through 7-4), the greater raw material impacts are justified on a life-cycle basis because these lamps reduce the overall environmental impacts associated with the same lighting service. In the future, improvements in LED manufacturing technology will improve efficacy and reduce costs facilitating the added benefit of lower impacts in almost all respects than any of the competing products on a life-cycle basis, even before accounting for the energy consumed in use.

### 7.3 Summary of the Environmental Impacts

To facilitate simpler interpretation of the results across the four lamps and the fifteen environmental indicators, the results are also presented in two 'spider graphs' shown in Figure 7-5 and Figure 7-6. Each radial line on the chart represents a different environmental impact, and the impacts are grouped into four categories – air (orange), water (blue), soil (green) and resources (yellow). For each impact, whichever lamp has the largest impact is plotted at the outer circumference, and the other products are then normalized to that impact. Therefore, the distance from the center of the spider graph represents the severity of the impact relative to that worst performer. The relative position of the points for the other lamps demonstrates their relative environmental impact to that maximum. Therefore, the closer each point is to the center of the graph, the smaller that particular impact. Those lamps with most of their plotted

impacts close to the center of the web are generally the best performers from an environmental perspective.

It is clear from Figure 7-5 that the incandescent lamp has the highest impact per unit lighting service of all the sources considered (it occupies all of the outermost points on the chart). This result is intuitive because this lamp has the lowest efficacy of all the lamps considered and energy in use was already identified as the most significant indicator of environmental impact.

In all but one environmental indicator category (i.e., hazardous waste landfill), the next worst performer is the CFL, followed by the LED lamp in 2012 and then the LED lamp in 2017. The actual difference between the CFL and the LED for the hazardous waste to landfill category is 0.4 grams. The reason that the LED lamp in 2012 has a slightly higher impact than the CFL is due to the large aluminum heat sink, which represents 20% of the total impact measured for this metric.



**Figure 7-5. Life-Cycle Assessment Impacts of the Lamps Analyzed Relative to Incandescent**

The incandescent lamp has the highest impact per unit lighting service of all the lamps considered. This finding is not a function of the material content, as the incandescent lamp has the lowest mass and is least complex lighting system. Rather, it represents the very low efficacy of this light source, where large quantities of energy are required to produce light. The high energy consumption per unit light output

causes substantial environmental impact and results in the incandescent lamp being the most environmentally harmful across all fifteen impact measures.

The next worst performer is the compact fluorescent lamp, which has substantially lower impacts than incandescent, but is slightly more harmful than the 2012 integrally ballasted LED lamp. This is true in all but one category – hazardous waste landfill – where the large aluminum heat sink causes the impacts to be slightly greater for the LED lamp than for the CFL. The best performing light source is the projected LED lamp in 2017, which takes into account several projected improvements in LED manufacturing, LED performance and driver electronics.

Figure 7-6 presents the same findings shown in Figure 1-1, but the graph has been adjusted to remove the incandescent lamp and provide the impacts relative (primarily) to the CFL.

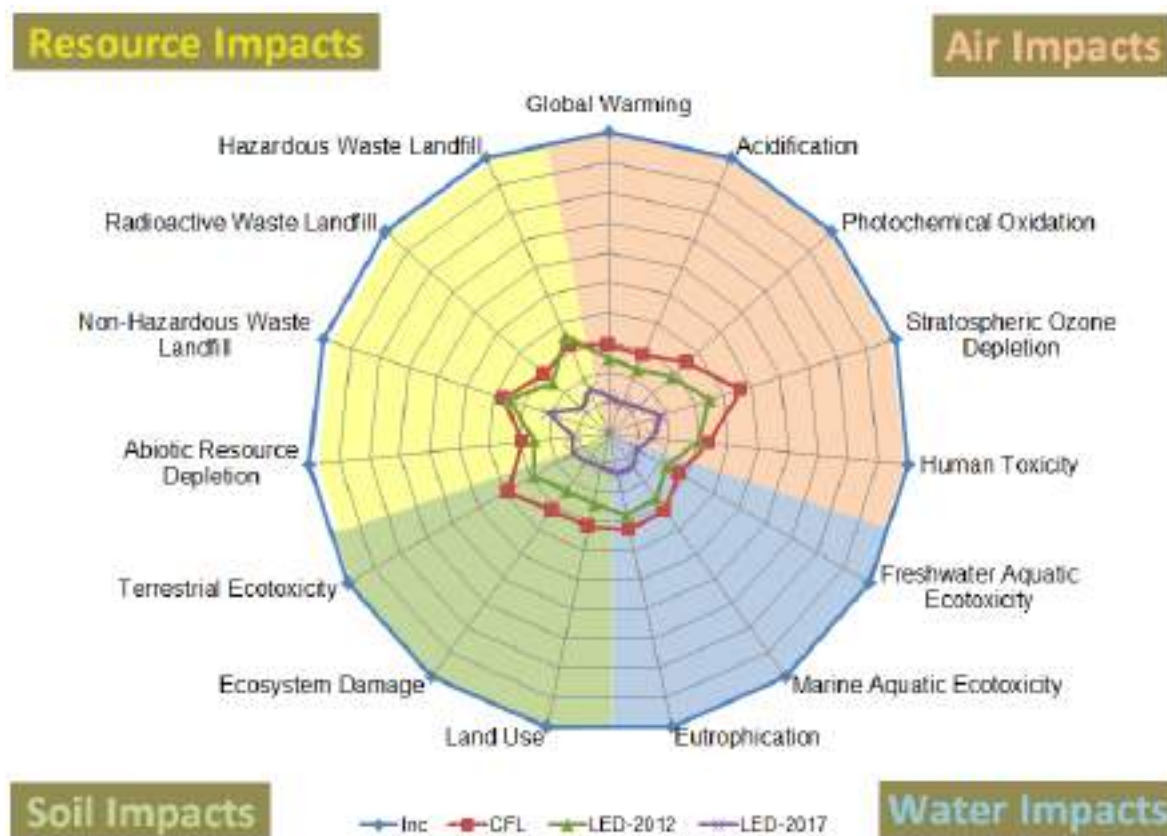


**Figure 7-6. Life-Cycle Assessment Impacts of the CFL and LED Lamps Analyzed (Detail)**

Overall, the impacts of the LED lamp in 2017 are significantly less than the incandescent, and about 70% lower than the CFL and approximately 50% lower than the LED lamp in 2012, which itself is the best available technology in 2012. The important finding from these graphs is not necessarily the minor relative differences between the CFL and LED lamps, but instead the very significant reduction in environmental impacts that will result from replacing an incandescent lamp. Environmental impact reductions on the order of 3 to 10 times are possible across the indicators through transitioning the market to these more efficacious light sources. These reductions are largely due to the reduction in energy consumption per unit light delivered in 2017. Thus, due to the dominant role of energy consumption in

driving the impacts, continued focus on efficacy targets and incentives is appropriate. Furthermore, the greatest environmental impact after energy in-use for the LED sources is the aluminum heat sink, which would be reduced as the efficacy increases, and more of the input wattage is converted to useful lumens of light (instead of waste heat).

### 7.3.1 Comparison with DOE Part 1 Study Findings

As discussed in Chapter 2 of this report, DOE published Part 1 of this LCA study earlier in 2012 (DOE, 2012a). The Part 1 study reviewed existing LCA literature, focusing on the energy consumed in manufacturing and use of the lamps studied. The report compared existing life-cycle energy consumption of an LED lamp to that of an incandescent lamp and a CFL based on ten key published studies.

As shown in Figure 2-1 of this report, the Part 1 report found that the life cycle energy consumption of LED lamps and CFLs to be similar at approximately 3,900 MJ per 20 million lumen-hours of lighting service. Incandescent lamps were found to consume approximately four times more energy (approximately 15,100 MJ per 20 million lumen-hours).

In Figure 7-7, the equivalent findings of the Part 2 study are presented. In general, these findings largely corroborated the Part 1 study results with only very slight differences. For incandescent lamps, the power consumption in Part 2 was less than 1% lower than the Part 1 result. For CFLs, the Part 1 finding was 4.3% lower than the Part 2. For LED lamps, the Part 2 study was found to be lower than Part 1, however this is to be expected as the Part 2 study is the first of its kind considering this relatively new lamp and the Part 1 study is considering lamps that were analyzed in LCA studies already published.

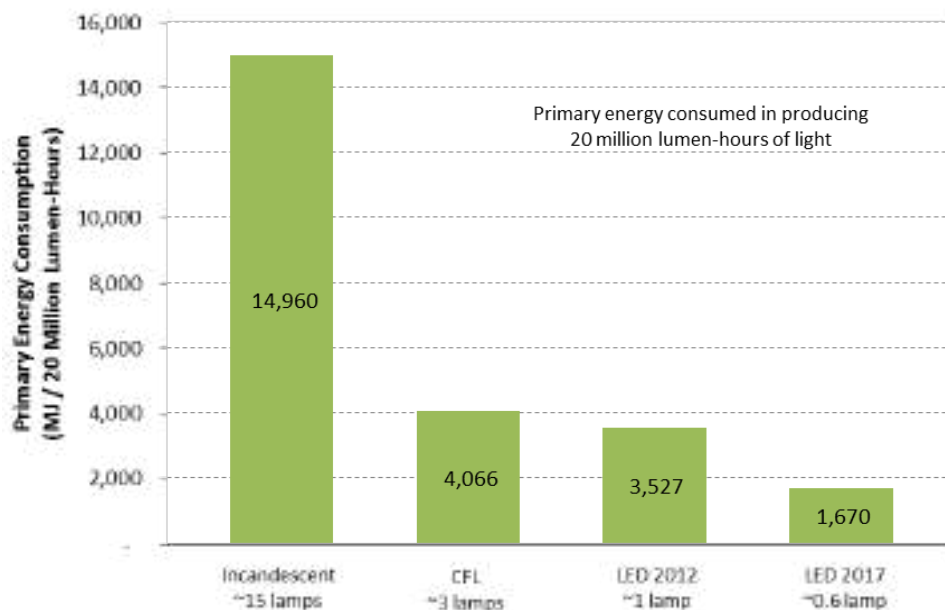


**Figure 7-7. Life Cycle Assessment Primary Energy for Lamps in Part 2 Study**

## 7.4 Data Quality Assessment

This section of the report considers the quality of the data underpinning the analysis. To document the quality of the data collected in this life cycle inventory, the table below was prepared to rate each data source based on key data quality criteria.

**Table 7-9. Data Quality Ranking Based on Highest Value for this Goal and Scope (5 high, 1 low)**

| Reference     | Time Related Coverage | Geographical Coverage | Technology Coverage | Precision of the Data | Completeness of the Data |
|---------------|-----------------------|-----------------------|---------------------|-----------------------|--------------------------|
| Yole Develop. | 4                     | 5                     | 4                   | 5                     | 5                        |
| OSRAM input   | 2                     | 5                     | 3                   | 5                     | 5                        |
| DEFRA LCA     | 2                     | 4                     | 3                   | 5                     | 4                        |

In terms of the time-related coverage, the OSRAM life-cycle assessment (OSRAM, 2009) and the DEFRA study (DEFRA, 2009) were both published in 2009 and therefore represent LED technology from 2008 and 2009. These two studies are given a relatively low ranking on a time-scale due to the very rapid evolution of LED technology, which is experiencing significant change in both the manufacturing processes and the performance of the technology itself. The Yole research that was shared with this team, on the other hand, represents InGaN white-light LED production from the 2010 – 2011 time period, so it represents technologies and processes that are closer to those used in 2012.

In terms of geographical coverage, all of the studies scored relatively high. Yole's research is modeling the manufacturing processes of one of the major LED manufacturers in the world, therefore this is clearly given the highest score for global coverage. OSRAM retails product in over 150 countries around the world, so their LCA is about a technology that is global in nature, even if it has only been introduced in a few markets initially. The DEFRA study is given a slightly lower score because its focus was the UK market, drawing examples of products – as much as possible – from the UK. Many of these same or similar products are available elsewhere in the world, however the focus is on the UK and so the geographical coverage score is a 4.

In terms of technology coverage, the scores reflect the age of each of the data sources as well as the content contained therein. The Yole research is reflective of a recent manufacturing process for a high-volume, globally available LED technology. However it only characterizes the process and performance of this one manufacturer, and therefore isn't representative of all the technologies and approaches followed in the market. For this reason, the study is given a 4. For the OSRAM and DEFRA studies, these are both slightly dated, so the technologies being discussed and characterized in these reports are slightly out of date on a technological basis, resulting in a score of 3 for both.

In terms of the precision of the data, each study is given a 5 because they are all considered to be thoroughly researched, documented and peer-reviewed. The presentation in each case is clear and concise, and is easy to analyze and adapt to this work. Hence they are all given the top score for this data quality criterion.

Finally, on completeness of the data, the Yole research is given top marks again because the study offers a highly detailed and rigorous process analysis. The research team at Yole Développement includes several process engineers, solid-state scientists and researchers with industry experience. Given that level of



technical expertise in-house, we find that the product of their research institute to be complete for the purposes of this study. Similarly, the OSRAM study is given top marks because it is the first LCA that we are aware of that was published by one of the global manufacturers of LEDs. In preparing their work, OSRAM drew upon a wide range of expertise from within their company, and ensured that the detail included in their resulting report was highly rigorous and accurate. OSRAM confirms this fact by demonstrating that this study was peer-reviewed by three independent experts who are familiar with LCA science. The DEFRA report is given 4 out of 5 because it relies on secondary sources of information for some of the lamps analyzed which are not complete. This became clear, for example, studying the baseline incandescent lamp and CFL which are cross-referenced to other studies.

#### **7.4.1 Comparison of Ecoinvent LED with DOE LED Impact Estimates**

As discussed earlier in this report, the Ecoinvent database version 2.2 already contains an entry for an LED. The Ecoinvent LED record covers raw material input and production of 5 millimeter LEDs for hole-through mounting technology. The LEDs modeled in the Ecoinvent database are commonly used in the information and communication technology industries and have a typical weight of 0.35 grams per unit. The impact assessment takes into account average diode production technology, including the diode wafer production (i.e., cleaning, masking, etching, doping, oxidizing, and metal deposition) and the final assembly of the diode (wafer sawing, die bonding, molding, trimming and forming). While this is a very good record for an indicator LED, it does not represent a high-brightness LED and also is based on LED manufacturing technology from 2007 and 2008, rather than the equipment being used today.

In Chapter 5 of this report, the authors present their characterization of the LED manufacturing process. LED manufacturing is an interim step in the production of an LED lamp which is ultimately what this study is investigating. However, for the purposes of understanding how much LED technology has improved and/or is different relative to the Ecoinvent LED that already exists in database version 2.2, the authors prepared a comparison of the environmental impacts associated with these two LEDs. Due to the fact that one LED is a 5 millimeter indicator lamp and the other is a high-brightness LED used in general illumination applications, the impacts need to be normalized for light output from the device. The indicator lamp was found to have a light output of 4 lumens, whereas the high-brightness LED was found to have a light output of 70 lumens (Philips, 2012).

The following table presents the comparison between the Ecoinvent LED and the InGaN LED manufactured for use in the Philips EnduraLED lamp. The table shows the significant reduction in the environmental impacts on a per-lumen basis that have been achieved between the 2007 Ecoinvent assessment and the 2011 technology that was assessed in this model. Overall, the average reduction in impact is 94.5%.

**Table 7-10. Comparison of Ecoinvent LED and this Study's LED Manufacturing Impacts**

| <b>Ecoinvent Indicator</b>                  | <b>Units</b>    | <b>Ecoinvent LED*<br/>(2007)</b> | <b>DOE LED<br/>(2011)</b> | <b>Reduced<br/>Impact %</b> |
|---------------------------------------------|-----------------|----------------------------------|---------------------------|-----------------------------|
| Global Warming Potential                    | kg CO2-Eq       | 0.0268                           | 0.00155                   | 92.3%                       |
| Acidification Potential                     | kg SO2-Eq       | 0.000131                         | 0.0000105                 | 89.3%                       |
| Photochemical Ozone<br>Creation Potential   | kg formed ozone | 0.00000318                       | 0.000000105               | 95.6%                       |
| Ozone Depleting Potential                   | kg CFC-11-Eq    | 2.33E-09                         | 2.86E-11                  | 98.4%                       |
| Human Toxicity Potential                    | kg 1,4-DCB-Eq   | 0.00613                          | 0.000192                  | 95.8%                       |
| Freshwater Aquatic<br>Ecotoxicity Potential | kg 1,4-DCB-Eq   | 0.000129                         | 0.00000402                | 95.9%                       |
| Marine Aquatic Ecotoxicity<br>Potential     | kg 1,4-DCB-Eq   | 0.00317                          | 0.0000829                 | 96.5%                       |
| Eutrophication Potential                    | kg PO4-Eq       | 0.0000841                        | 0.00000193                | 96.9%                       |
| Land Use                                    | m2a             | 0.000571                         | 0.0000446                 | 89.6%                       |
| Ecosystem Damage Potential                  | points          | 0.000444                         | 0.0000352                 | 89.4%                       |
| Terrestrial Ecotoxicity<br>Potential        | kg 1,4-DCB-Eq   | 0.00000535                       | 0.000000213               | 94.7%                       |
| Abiotic Resource Depletion                  | kg antimony-Eq  | 0.000199                         | 0.0000084                 | 94.4%                       |
| Non-Hazardous Waste<br>Landfilled           | kg waste        | 0.00139                          | 0.0000863                 | 91.7%                       |
| Radioactive Waste Landfilled                | kg waste        | 0.00000233                       | 2.64E-08                  | 98.5%                       |
| Hazardous Waste Landfilled                  | kg waste        | 0.00000065                       | 9.14E-09                  | 98.1%                       |
|                                             |                 |                                  | Average:                  | 94.5%                       |

\* The Ecoinvent database unique ID for the “light emitting diode, LED”, at plant is 7077.

Thus, on a lumen output basis, it would appear that high-brightness LEDs manufactured in 2011 are significantly less harmful for the environment than the 5mm indicator LEDs that were produced in 2007.

## 8 Critical Review

Input solicited from several lighting experts and manufacturers during the course of the project has provided the critical peer review section of the LCA. This report will be circulated in draft form to allow additional comments from industry prior to finalizing the study results.

Early review by manufacturers confirmed that the assumptions in this report are realistic, and they indicated that many of the manufacturing processes are already more efficient than those documented in this report. Other reviewers indicated that the chemical and energy use documented in this report for the MOCVD process appears to be reasonable.

## 9 Recommendations

This report and the Part 1 study (DOE 2012a) together provide a full summary of LED LCA work to date. This analysis documents the manufacturing process in a publicly-accessible medium for external review and comment, which will enable the LCA and lighting research communities to continue refining the research.

Several recommendations for future work have been highlighted by the study:

1. Work with manufacturers to reduce the size of aluminum heat sinks and/or find alternative materials and configurations to reduce the mass. The aluminum heat sinks contribute significantly to upstream waste and energy consumption. Manufacturers are testing a variety of new techniques to improve heat transfer, which may result in more environmentally friendly products with smaller heat sinks.
2. Work with manufacturers to meet the DOE targets for efficacy and performance that will make LED lighting solutions dramatically better than CFLs for the full life cycle environmental impacts. This may include, for example, creating the “L-Prize Mark II” to further encourage innovation and improvement in the efficacy of LED lamps, as the energy-in-use phase has proven to have the most significant environmental impact of all those analyzed.
3. Encourage academic and industry studies of and programs for recycling to improve end of life options for LED products. The heat sink represents a significant cost opportunity for recycling programs.
4. Revisit the manufacturing process documented in this report periodically to account for improvements to the process, which may further reduce the environmental impacts of LED systems.
5. Encourage Ecoinvent to establish a new category of ‘high brightness LED’ for the Ecoinvent database which reflects 2012 LED manufacturing technology as opposed to the 2007 indicator light LED that is currently in the database.

The last part of this study (Part 3) will provide additional insight about the disposal of the products by testing LEDs for disposal thresholds. This part of the study will provide a useful “check” on the actual environmental impact of one LED lamp and compare it to the benchmark provided by EPA and other regulatory groups.

## 10 APPENDIX A: Sensitivity Analysis

This section provides an overview of an analysis that was conducted to quantify the sensitivity of the results to possible changes in the assumptions or estimates underpinning the model. One option for dealing with this uncertainty is simply to make an estimate of the unknown parameters. This is a pragmatic approach to arriving at an answer, but creates uncertainty about the reliability of the results. A sensitivity analysis aims to explore the sensitivity of the results and conclusions to these underlying assumptions, and thereby provide comment on the confidence in the results.

A Monte Carlo analysis is a useful tool for checking confidence in estimates and assumed values. With this tool, the user stipulates which parameters will be variables, and specifies the distribution for each of those parameters. The Monte Carlo analysis then performs multiple calculations, each time randomly generating a value from within the defined range and using it to generate results from a run of the model. The final output of a Monte Carlo analysis is a distribution of results instead of a single point result. By plotting histograms of the distributions for the different lamp types analyzed, it is possible to determine, by the amount of overlap, a level of confidence in the results.

A Monte Carlo sensitivity analysis was run on the LCA model varying the lifetime of each of the lamps, the efficacy and the percentage recycling at end of life. The calculations were performed in the Microsoft Excel workbook that had been created, using the Oracle Crystal Ball software plug-in. Table A-1 presents the parameters chosen for the simulation. All were modeled using a normal distribution, and the means and standard deviations (SD) of the distributions are also shown. A total of 10,000 runs of the model were conducted for this sensitivity analysis.

**Table A-1. Parameters of Normal Distributions Used in the Monte Carlo Sensitivity Analysis**

| <b>Incandescent</b>              | <b>Mean</b> | <b>Standard Deviation</b> | <b>Units</b>     |
|----------------------------------|-------------|---------------------------|------------------|
| Efficacy                         | 15          | 1                         | lumens/watt      |
| Lifetime                         | 1500        | 100                       | hours            |
| Recycling Lamp                   | 0.1         | 0.025                     | percent recycled |
| Recycling Packaging              | 0.3         | 0.05                      | percent recycled |
|                                  |             |                           |                  |
| <b>Compact Fluorescent Lamp</b>  | <b>Mean</b> | <b>Standard Deviation</b> | <b>Units</b>     |
| Efficacy                         | 55          | 5                         | lumens/watt      |
| Lifetime                         | 8000        | 1000                      | hours            |
| Recycling Lamp                   | 0.2         | 0.025                     | percent recycled |
| Recycling Packaging              | 0.3         | 0.05                      | percent recycled |
|                                  |             |                           |                  |
| <b>Light Emitting Diode 2012</b> | <b>Mean</b> | <b>Standard Deviation</b> | <b>Units</b>     |
| Efficacy                         | 65          | 7                         | lumens/watt      |
| Lifetime                         | 25000       | 5000                      | hours            |
| Recycling Lamp                   | 0.2         | 0.025                     | percent recycled |
| Recycling Packaging              | 0.3         | 0.05                      | percent recycled |
|                                  |             |                           |                  |
| <b>Light Emitting Diode 2017</b> | <b>Mean</b> | <b>Standard Deviation</b> | <b>Units</b>     |
| Efficacy                         | 134         | 15                        | lumens/watt      |
| Lifetime                         | 40000       | 5000                      | hours            |
| Recycling Lamp                   | 0.2         | 0.025                     | percent recycled |
| Recycling Packaging              | 0.5         | 0.1                       | percent recycled |

## Results

The general form of the results is depicted in Figure A-1, which shows the predicted future global warming potential of the four lamps analyzed in this report. The plot is based on 10,000 runs of the model varying the input assumptions shown in Table A-1. From this graph, it is clear that the incandescent lamp has the highest impact for global warming potential with a mean at 51 kg CO<sub>2</sub>-equivalents per million lumen hours and a standard deviation of 3.5 kilograms. The CFL has a mean of 15.2 kg CO<sub>2</sub>-equivalents per million lumen hours with a much tighter standard deviation of 1.4 kilograms. The LED 2012 lamp has virtually the same shape as the CFL and the same standard deviation, but its mean has shifted lower to 12.5 kg CO<sub>2</sub>-equivalents. Finally, the LED 2017 lamp has the tightest distribution of results, with a mean of 5.7 kg and a standard deviation of only 0.6 kg.

This finding strengthens the overall outcome of this study, providing more assurance that varying the inputs to the degree they are in Table A-1 does not change the overall finding and prioritization of impacts for this environmental indicator. And, while this graph only presents the impacts in terms of global warming potential, the outcome is similar for the other 14 indicators.

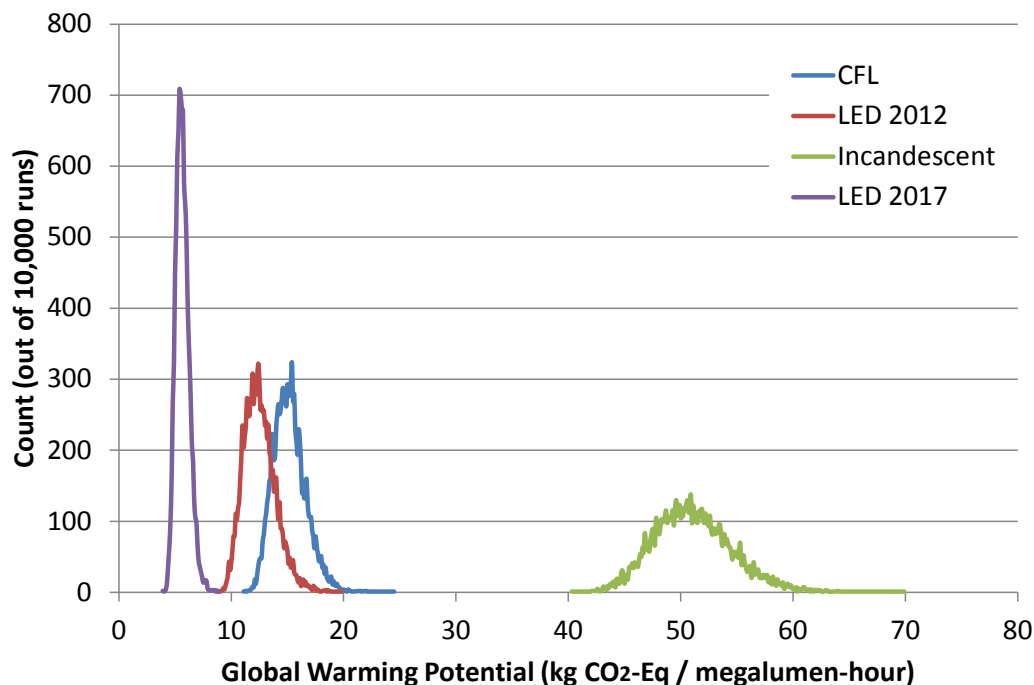


**Figure A-1 Scatter Plot of Results for Monte Carlo Analysis of Global Warming Potential**

Figure A-2 presents the scatter plot of results for the Monte Carlo analysis of Hazardous Waste Landfill. This is the environmental indicator which found that LED lamps in 2012 had slightly more impact than CFLs (see Figure 7-6). Using the same range of input variables given in Table A-1, the following graph was prepared for the Hazardous Waste Landfill indicator.



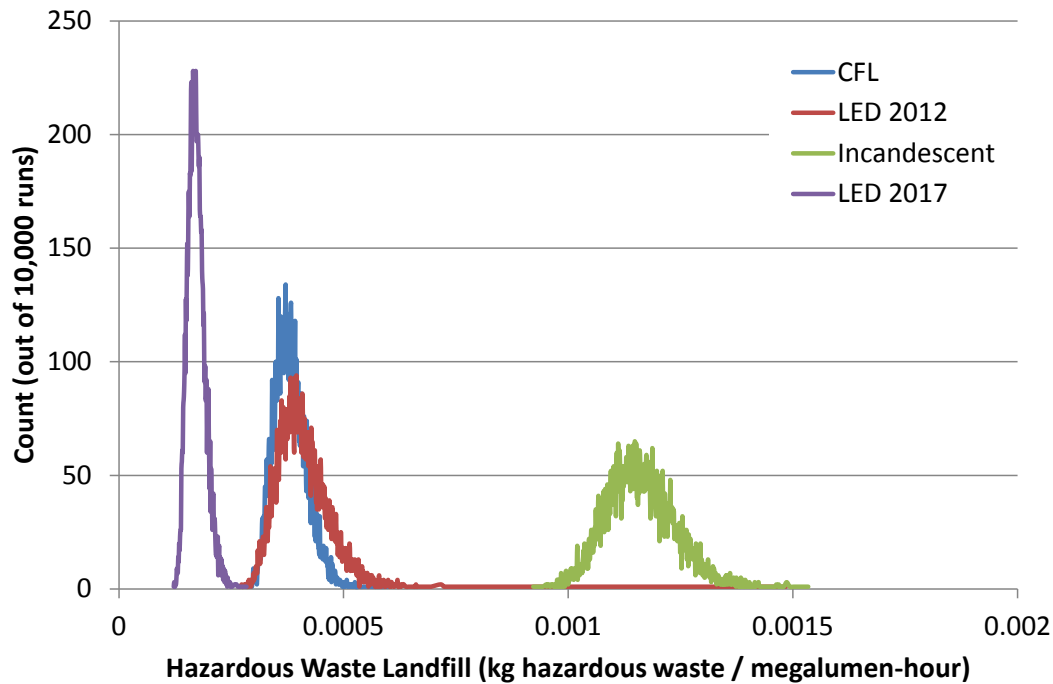


**Figure A-2 Scatter Plot of Results for Monte Carlo Analysis of Hazardous Waste Potential**

The shape and overlapping nature of the two graphs are slightly different. The LED has a mean of 0.41 grams of hazardous waste per megalumen-hour with a standard deviation of 0.06 grams. The CFL has a mean of 0.38 grams of hazardous waste with a standard deviation of just 0.04 grams. The mean values of the two lamp types are extremely close and the area described under the two scatter plots of results is very similar. To get a more detailed view of these two lamps, we remove the incandescent lamp and the LED 2017 lamp, as shown in Figure A-3.

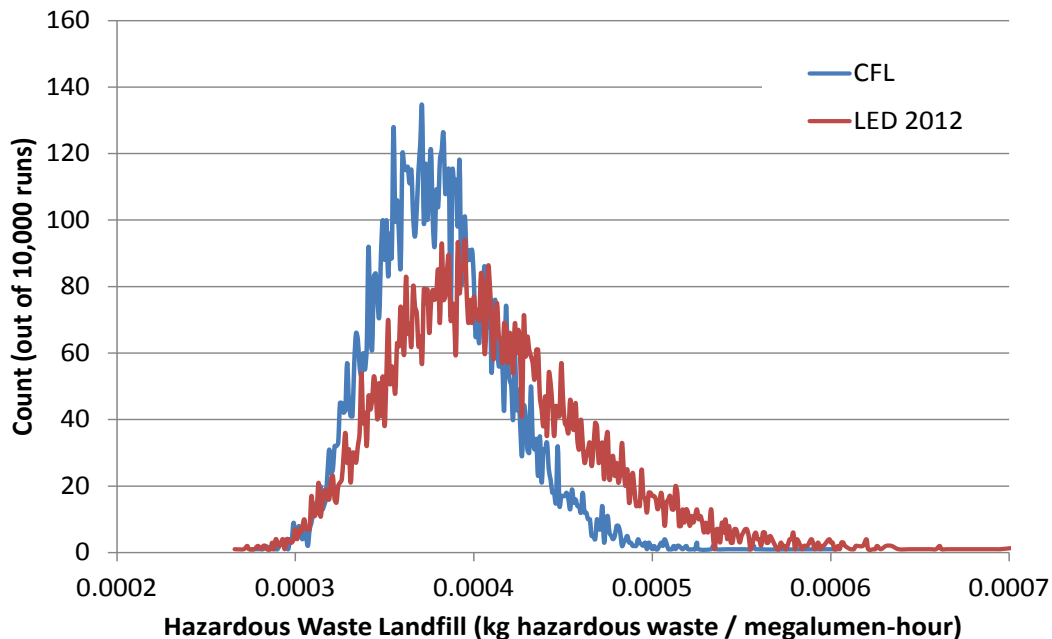


**Figure A-3 Scatter Plot of Results for CFL and LED 2012 of Hazardous Waste Potential**

In Figure A-3, by zooming in on this section of the X-axis and removing the other lamp types from the plot, it becomes easier to focus on a comparison between these two distributions. There is reasonably good overlap to the left of the two plots, which represents those lamps having lower hazardous waste landfill impacts. The mean values for these two scatter plots are different, but the CFL lamp is only 7% lower than the LED 2012. The reason for this difference is because of the right hand part of the two curves, where the LED lamp has a longer tail stretching out to the right. Referring back to Figure A-2, it is important to note that the LED lamp in 2017 has significantly lower hazardous waste landfill impact when compared to CFLs. This is due to the projected improvements in efficacy and the associated reduction in the mass of the aluminum heat sinks used in the 2017 LED lamp design.

In conclusion, the Monte Carlo sensitivity analysis shows that the incandescent lamp has, by a considerable margin, the largest environmental impact and thus represents the least preferred lighting option. Due to the great impact associated with energy-in use, changing to a more efficient lamp will reduce impacts, with LED lamps in 2012 being a better option on a LCA basis than CFLs. LED lamps in 2017 represent a significantly better lighting option, with much lower environmental impacts.

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## Article

# The Reality of Light Pollution: A Field Survey for the Determination of Lighting Environmental Management Zones in South Korea

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**Abstract:** Light pollution has been receiving increased attention worldwide. Scientific research has provided convincing evidence that ties artificial lighting to health-related issues. Consequently, the involved parties are now leaned towards the implementation of regulations to help limit the use of artificial lighting. Many countries, together with international organizations, have embarked on setting standards and regulations aimed at halting the excessive and improper usage of artificial lighting, there-by eradicating light pollution and its effects. In Korea, outdoor lighting at night is a common phenomenon. Moreover, as the economic development grows even further, the use of artificial lighting is expected to increase making Korea vulnerable to the adverse effects of artificial lighting. In this study, we discuss the issue of light pollution based on field measurements conducted in Seoul, South Korea. The measurements were undertaken to broaden the understanding and assessment of light pollution. During the investigation, we noted that the most severe forms of light pollution were found in developed urban and densely commercialized areas. Currently, there are ongoing light pollution measurement projects around the entire Korea. It would be informative to see how the rest of South Korea compares to the Capital, Seoul in terms of light pollution levels.

**Keywords:** light pollution; light trespass; glare; lighting zones

## 1. Introduction

Modern artificial lighting can be considered a key achievement in the technology revolution of the past century. However, even though artificial lighting is hugely beneficial to modern society, it still presents significant disadvantages, in the form of pollution, to human health and the ecological wellbeing of the environment. Light or photo pollution can be simply defined as excessive or misdirected artificial lighting. Scientifically, it has been defined as the changes in outdoor natural light levels as a result of artificial lighting [1]. The IDA (International Dark-Sky Association) defines light pollution as the inappropriate or excessive use of artificial lighting [2]. There are also several legal definitions of light pollution. For instance, the Korean government defines light pollution as “any situation where inappropriate use of artificial lighting may interfere with people’s health and comfort, or harm the ecological system” [3].

Other than the radical issue of sky glow caused by artificial lighting [4,5], light pollution is also the cause of a number of known ecological concerns. Among the known effects, health issues in humans caused by exposure to artificial lighting at night are the most pressing. To understand how light may affect humans, it is ideal to realize first how light is introduced into the body and how it is used by the body. Light is introduced to the body through the eye. Some of the light is then used for vision whereas the rest of the light mediates in other human biological processes, such as the synchronization of the light and dark cycles. In that context, the effects of light pollution in humans

can also be divided into 2 categories; the image forming effects and the non-image forming effects. The image forming problems caused by artificial lighting are mostly associated with discomfort and disability glare. Photometric parameters of light have been indicated to be a contributing force to the occurrence of both types of glare; discomfort and disability glare [6]. The non-image forming effects are mainly due to a disrupted circadian rhythm—an internal clock that regulates most of the physiological systems in mammals [7]. The circadian cycle is a complex system that begins in the eye and ends in the pineal gland where melatonin hormone is secreted—a neuro hormone responsible for the rhythmic functioning of the human internal clock. Melatonin is secreted during the dark hours of the night. The peak secretion of melatonin has been reported to be between midnight and 4 a.m. in the morning [8]. Consequently, exposure to light during this period of the day may inhibit the production of melatonin and thus a disruption of the entire circadian cycle. The desynchronization of the circadian rhythm is believed to be the cause of many clinical conditions in humans. It has been linked to simple discomforts such as fatigue [9], reduced work productivity [10] and so forth. It has also been linked to much more grave conditions including diabetes [11] and many different forms of cancer [12]. Some of the most prevalent studies in this area are those linking breast cancer to artificial lighting exposure, especially during the night. The idea that artificial lighting may indeed be a concern in regards to breast cancer was given even more credit after a number of pioneering studies in this field showed breast cancer cases to be comparatively lower in blind women than in women with functioning eyesight [13,14]. Similarly, a couple of studies [15,16], conducted in the US (United States) have shown correlations between high risk of breast cancer incidents and exposure to artificial lighting. The subjects for both studies were medical nurses who worked a minimum of three night shifts a month. In the first study [15], 78,562 such nurses were investigated in a 10-year follow-up. Based on data obtained from the investigation, statistical analysis showed that women who worked night shifts had a higher risk of developing breast cancer. In addition, the risk of developing breast cancer tended to increase with the number of years spent working night shifts; women who worked night shifts for more than 30 years showed a higher risk of developing breast cancer than women who worked night shifts for less than 29 years. In the second study, Schernhammer et al. [16] studied the relationship between rotating night shift work and the involved risk of developing breast cancer. 115,002 nurses were studied over a period of 12 years. The results revealed that high risk of breast cancer incidents is associated with longer periods of rotating shifts. Additionally, among 115,002 of the subjects who had no breast cancer at the beginning of the 12-year follow up, 1352 developed breast cancer during the time of the follow-up.

As evidenced through the existing literature, there is a potential link between light pollution and certain human health conditions. Concerns associated with light pollution have thus prompted a legal battle. A number of countries including Korea [17,18], France and Italy [19] have begun dictating lighting level limits through regulations in order to reduce the amount of light pollution. In places like Taiwan, light pollution research and policy is also becoming prevalent [20]. Additionally, concerned institutions such as the International Commission on Illumination (CIE) also offer general lighting recommendations for proper and sustainable usage of artificial lighting. In Korea, it has been 29 years since the Seoul municipal government installed outdoor lighting to celebrate the 1988 Seoul Olympic Games. Since then, artificial lighting at night has become common practice in cities all over Korea. Moreover, a recent series of controversies related to light pollution have sparked a number of debates in Korea. For this reason, it has become of vital importance that prior to planning and installing new lighting concepts, all parties involved have a firm understanding of the direct and indirect impact of artificial lighting on the surroundings. Additionally, while solutions are being developed, lighting guidelines and recommendations must be put in place so that light designers can create sustainably lit-environments at night with minimum risk of light pollution.

The aim of this paper is to present recent findings and discussions regarding light pollution and sustainable lighting. The assessment provided in this study is based on data gathered from field measurements conducted in Seoul, South Korea. Furthermore, the authors are of the view that close



collaboration between architects and lighting designers at the conceptual stage of lighting projects is one way to reduce the current impact of excessive artificial lighting on the environment, while at the same time encouraging sustainable lighting.

## 2. Restriction of Light Pollution

The aim of light pollution laws is generally to permit reasonable usage of artificial lighting for safety, utility, and security, while minimizing the degradation of the nighttime visual environment and the night sky. Although countries and communities have different anti-pollution laws, light pollution regulations have three common main sections, namely, the classification of light pollution management zones, the establishment of standards and the provision of regulations.

Drafting laws that prevent excessive usage of artificial lighting and subsequently light pollution is not an easy task. Many questions arise when it comes to regulating light pollution. For instance, how to legally define light pollution or to what extent should artificial lighting be regulated? Without generally agreed upon solutions to such questions it becomes rather difficult to develop proper and effective legislation. The endeavors to develop regulations for light pollution reduction are also usually linked to questions of energy efficiency and or cityscape aesthetics [21]. Moreover, light pollution regulations should be simple and comprehensible to everyone. They should possess the advantage of simplicity, as they should not require in-depth knowledge of lighting. However, this also presents a disadvantage in that the laws are often relaxed, making it difficult to enforce. Morgan discusses the difficulty often faced while drafting light pollution legislation [22]. Below are some examples of the regulations in different nations and communities.

The illuminating engineering society and the International Dark-sky Association (IDA) joined together and established common regulations to be used as guidelines for preventing light pollution, the Model Lighting Ordinance [23]. The regulations recommend that fully shielded outdoor lighting be used at all times. They also advise that outdoor light fixtures have a control device/system that automatically turns off the light when sufficient daylight is available. Furthermore, the IDA regulations encourage the establishment of time limits after which the total lumens coming from outdoor lighting fixtures should be decreased by about 30% or lights turned off completely.

Korea is one of the most recent countries to enact a light pollution related law. The Korean government spent a period of 4 years, from September 2009 when the bill of the light pollution was submitted to the assembly to December 2011 when the bill was passed, debating all possible actions to prevent light pollution caused by excessive ALAN (Artificial Lighting At Night). As a result, the Light Pollution Prevention Act was enacted in February 2013. The prevention act was instated following a number of public complaints about light radiating from advertisement boards, streetlights, etc., trespassing into people's homes at night and disrupting their sleep patterns. The Korean Light Pollution Prevention Act breaks areas down into four environmental zones, which will herein after be referred to as Environmental Management Zones (E zones) [17]. The E zones range from E1, which covers the darkest areas, to E4, the brightest areas. The zones are categorized based on land use under the Korean law on National Land Planning and Use. Table 1a shows Environmental Management Zones presented by the CIE whereas Table 1b shows Environmental Management Zones as established by the Light Pollution Prevention Act of South Korea. The idea behind the creation of Environmental Management Zones is that the levels of artificial lighting are not equally rigorous in all areas, thus the light disturbance diminution measures are not supposed to be equally stringent in all regions.

The Environmental Management Zones are divided into four zones [4] as shown in Table 1a. The zones labeled E1 to E4 describe natural, rural, suburban, and urban surroundings, respectively. Following this, the CIE provides lighting standards that are recommended for each of these four Environmental Management Zones [24]. The Korean government has established lighting regulations identical to those of the CIE. The Environmental Management Zones established by the South Korean Light Pollution Prevention Act are also divided into four zones and lighting recommendations are

presented for each zone [25]. Figure 1 shows the Environmental Management Zones of Seoul City established based on the conducted field survey [26].

**Table 1.** Description of lighting environmental management zones.

| (a) Zones by CIE (Commission Internationale de l’Eclairage), 2003 |                                                                  |                            |                                         |
|-------------------------------------------------------------------|------------------------------------------------------------------|----------------------------|-----------------------------------------|
| Zone                                                              | Surroundings                                                     | Lighting Environment       | Examples                                |
| E1                                                                | Natural                                                          | Intrinsically dark         | National parks or protected sites       |
| E2                                                                | Rural                                                            | Low district brightness    | Agricultural or residential rural areas |
| E3                                                                | Suburban                                                         | Medium district brightness | Industrial or residential suburbs       |
| E4                                                                | Urban                                                            | High district brightness   | Town centers and commercial areas       |
| (b) Zones by Korean Light Pollution Legislation, 2013             |                                                                  |                            |                                         |
| Zone                                                              | Descriptions                                                     |                            |                                         |
| E1                                                                | Green areas used for ecological purposes and wildlife protection |                            |                                         |
| E2                                                                | Green areas used for agricultural activities                     |                            |                                         |
| E3                                                                | Residential and semi-residential areas                           |                            |                                         |
| E4                                                                | Commercial and industrial zones                                  |                            |                                         |

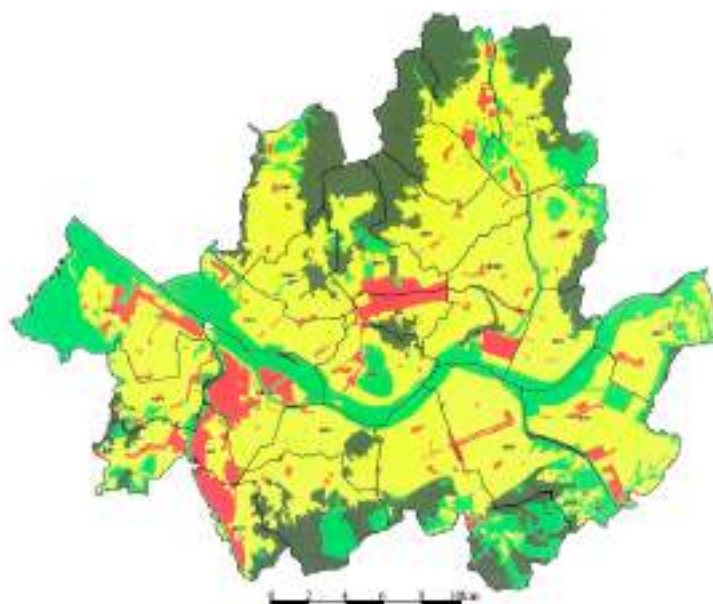


**Figure 1.** Environmental Management Zones of Seoul City, South Korea.

In addition to Environmental Management Zones, lighting standards make up a major part of light pollution prevention laws. Existing light pollution laws have focused on determining both the appropriate illuminance and luminance levels of artificial light that would cause minimum harm to the ecosystem. Standards for the prevention of light pollution give the light parameters values (mostly illuminance and luminance values) allowed in a given lighting Environmental Management Zone. Table 2 shows the lighting standards established by the CIE [4].

The lighting standards by the South Korean Light Pollution Prevention Law are very similar to those of the CIE. The two sets of standards differ only on minor details such as the degree to which light is limited in different environmental zones. Table 3 shows light recommendations by the South Korean Light Pollution Prevention Law.

**Table 2.** Standards for light pollution by the International Commission on Illumination (CIE).

| Light Technical Parameter (lux) | Light Technical Parameter (cd)              | Application Conditions | Lighting Environmental Zones |      |        |        |
|---------------------------------|---------------------------------------------|------------------------|------------------------------|------|--------|--------|
|                                 |                                             |                        | E1                           | E2   | E3     | E4     |
| Vertical illuminance            |                                             | Pre-curfew             | 2                            | 5    | 10     | 25     |
|                                 |                                             | Post-curfew            | 0                            | 1    | 2      | 5      |
|                                 | Luminous intensity                          | Pre-curfew             | 2500                         | 7500 | 10,000 | 25,000 |
|                                 |                                             | Post-curfew            | 0                            | 500  | 1000   | 2500   |
|                                 | Building façade luminance<br>Sign luminance | No curfew              | 0                            | 5    | 10     | 25     |
|                                 |                                             | No curfew              | 50                           | 400  | 800    | 1000   |

**Table 3.** Standards for light pollution in Korea.

| Category                   | Parameter (lux)                 | Parameter (cd/m <sup>2</sup> ) | Time of Application                          | Zones |     |      |      |
|----------------------------|---------------------------------|--------------------------------|----------------------------------------------|-------|-----|------|------|
|                            |                                 |                                |                                              | E1    | E2  | E3   | E4   |
| Roads and street           | Max. vertical plane Illuminance |                                | 60 min after sunset to 60 min before sunrise | 10    | 10  | 10   | 25   |
| Non-flashing advertisement |                                 | Max. luminance                 | 60 min after sunset to 60 min before sunrise | 50    | 400 | 800  | 1000 |
| Screen video and Flashing  | Max. vertical plane             |                                | 60 min after sunset to 60 min before sunrise | 10    | 10  | 10   | 25   |
|                            |                                 | Avg. luminance                 | 60 min after sunset to 24:00                 | 400   | 800 | 1000 | 1500 |
|                            |                                 |                                | 24:00 to 60 min before sunrise               | 50    | 400 | 800  | 1000 |
| Decorative                 |                                 | Avg. luminance                 | 60 min after sunset to 60 min before sunrise | 5     | 5   | 15   | 25   |
|                            |                                 | Max. luminance                 |                                              | 20    | 60  | 180  | 300  |

### 3. Measurement of Light Pollution

The nightscape in the modern environment is hugely made up of lit objects. From building lights that reveal architectural characteristics of high-rise buildings and bright advertisement signboards showcasing economic development, to security lights in residential neighborhoods and parks. As such, attention should be paid to the way lit environments are measured, and regular assessments of the luminous condition of lit areas should be conducted.

Lighting standards require an expert in the field of lighting since they are based on the quantification of light. The methods of measurement and analysis play a significant role in assessing a given environment for possible light pollution. As a visually luminous environment is a complex issue involving various elements such as lighting sources and luminous properties, measurements should be conducted accurately [27].

Generally, luminance measurements can be taken as point luminance measurements using luminance meters; however, this method has been disregarded due to its inaccuracy when measuring surface luminance emitted by light sources. As an alternative, aerial nighttime photography is being used to perform spatial nighttime artificial lighting analyses [21]. Similarly, using data capturing technologies, nighttime satellite images and maps are being utilized to develop spatial GIS database for sensitive suburban areas [28]. In addition, using radiative transfer methods in the propagation of light pollution, studies [29] have been able to review available indicators for quantifying and monitoring light pollution.

There also exist different methods that can be used to determine the quality and amount of light displayed within a given visual environment. Among the existing techniques, high dynamic range (HDR) imaging has been acknowledged by experts as the most efficient [30]. The luminous tone mapping technique has become popular recently as it can be used to simulate an accurate image of any lit environment to match the actual amount of light radiated within it. Moreover, advancements in computer technology have offered new ways of using the tone mapping technique to produce visual

environment images as accurately as the human eye [31]. Figure 2 shows the luminous tone mapping technique that has become popular recently as it can be used to simulate an accurate image of any lit environment to match the actual amount of light radiated within it.

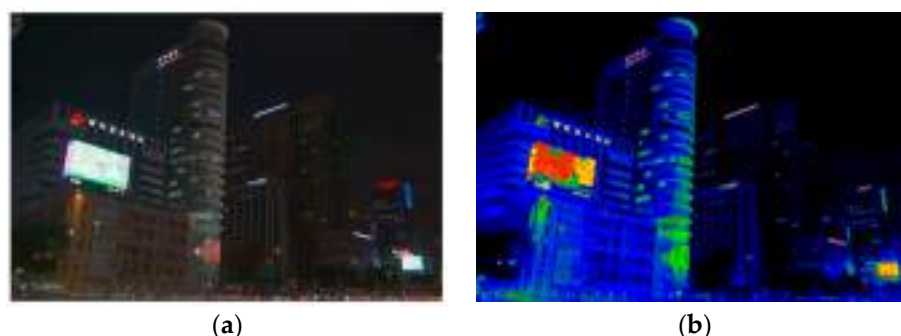


**Figure 2.** Digital image processing for the determination of light pollution: (a) Actual image of a billboard sign; (b) Analysis image using light measuring camera (LMK) lab soft.

Until recently in Korea, there was no scientific method to obtain quantitative light pollution data. A drive towards quantitative measurement accompanied the enactment of the Light Pollution Prevention Act. The National Institute of Environmental Research of Korea (NIERK) has established a prototype measurement method for determining light pollution from a lighting source. This method of lighting evaluation considers possible enhancements of landscapes at night while at the same time facilitating visual safety and reducing light pollution. The method assesses the quantity of light through reducing the measurement target to either an individual point or a target surface. In so doing, it allows the consideration of distance and measuring angle in the evaluation of light pollution [27,30].

For this study, simple hand-held tools such as the Chroma Meter CL-200A and LMK Luminance Meter were utilized. The former for the measurement of vertical plane illuminances and the latter for the measurement of surface luminance levels. The process involved in measuring vertical illuminances on areas adjacent to lighting sources is quite simple and straightforward. The CL-200A meter has to be held in a vertical position onto a surface adjacent to the lamp being assessed for light-trespass such as a window on a building facade. The meter will then read out the number of lumens falling onto a single unit of the surface. The resulting element, lumen per square meter is what is known as illuminance and is mostly presented with “lux” as a unit.

The process involved in obtaining surface or point luminance however is a bit more sophisticated. The Luminance Meter camera uses the High Dynamic Range (HDR) technology. It works in a way that several low dynamic images of an illuminated surface are taken at different exposure times (shutter speeds). These images are then combined into one but richer image referred to as an HDR image. This final image is what is used together with a computer software to extract minimum and maximum luminance levels of the surface being analyzed [27]. The software program also gives an option of extracting luminance of the entire surface or single specific points of interest on the surface, for example a billboard sign mounted on a building facade. In this study, we used a light measuring camera (LMK), developed by Techno Team, for capturing images and LMK lab software to analyze the images.

To improve accuracy in the measurement of luminance levels, a method developed by the National Institute of Environmental Research of Korea was utilized. The method involves subtracting the luminance of the background field from the luminance of the target area and multiplying by a weighting factor of 0.9 to give an accurate luminance value dissipated by target area [32].

In addition, the Korean Light Pollution Prevention Act provides other guidelines for conducting the measurement procedure. For instance, the measurements are to be taken in the absence of severe weather conditions such rain or snow. This is because weather elements might amplify or lessen the effect of lighting parameters measured by simple equipment. Secondly, for the measurement of

luminance values using light-mapping cameras, measurements are to be taken parallel to the light source being assessed. If it is impossible to capture full images due to obstacles, images are to be taken at angles between 0 and 30 degrees. In addition, the camera should be positioned in a manner that the vertical height between the ground and the camera is at least 1.5 m. All these suggestions by the Korean Light Pollution Prevention Act were followed in the assessment of light pollution discussed in the current study.

#### 4. Field Study of Light Pollution in Seoul City

Since the Light Pollution Prevention Act was enacted, robust field studies were conducted in Seoul City regarding the probable effects of light pollution. The principal purpose for conducting light pollution measurements in Seoul, Korea, was to determine the current nature of artificial lighting usage in Seoul City, and thus obtain a starting point for tackling its effects. The measurements primarily considered the main contributors of artificial lighting in modernized urban environments. Specifically, the investigation was to measure the extent to which light radiated from space lighting (i.e., security and street lighting) and advertisement lighting exceeded the lighting levels dictated by the Light Pollution Prevention Act. The investigation was carried out based on the Environmental Management Zones.

Field measurements were conducted in more than 300 locations. The amount of excessive lighting was measured to collect more data on the sources of light pollution. In Seoul, the areas to be investigated were chosen based on the number of public complaints (starting with the highest), high-lit areas, and areas expected to cause the most severe forms of light pollution. These field studies were then used as key guidelines for improving the regulations and standards that had earlier been established into a dedicated law by the Korean government. The Seoul City case project is used as an example of how measurements were conducted to investigate light pollution caused by light trespass, decorative lighting, and advertisement lighting [26].

##### 4.1. Space Lighting and Light Trespass

Space lighting consists of street and security lighting. Light radiating from both these sources was measured in E3, which consists mainly of residential areas. The lighting fixtures that were targeted in the residential areas were those in close proximity with building facades and thus most likely to cause disturbance to building occupants. The light component measured was vertical illuminance, which was measured at a distance between the lamppost and the building façade. For better assessment, measurements were taken at the brightest spots of the first-floor windows, before and after the lights were turned on. For street lighting, measurements were conducted on walkways and city squares in E4, which consists mainly of business district.

The results from the field survey on space lighting in E3 showed that, 67%, 70%, and 86% of the street and security lighting exceeded the recommended vertical luminance values in residential, semi-residential, and industrial areas respectively. The survey on space lighting found in E4 showed that 5% of space lighting in semi-residential areas and 36% of space lighting in industrial areas exceeded the vertical luminance values dictated by the law.

In the target areas investigated for light pollution caused by space lighting 67%, 70%, and 86% of the street and security lighting exceeded the recommended vertical luminance values in residential, semi-residential, and industrial areas located in E3, respectively. Similarly, 5% and 36% of space lighting in semi-residential and industrial areas, respectively, located in E4 exceeded the vertical luminance values dictated by the law. Figure 3 shows the ratio of areas with space lighting exceeding the recommended lighting limits.

In addition, the types of luminaires were also considered in order to determine the light types that were responsible for causing the maximum amount of light pollution. The luminaire types found in the target areas were ceramic metal halide (CMD), Sodium Halide (NH), Metal Halide (MH), and Light Emitting Diodes (LED). The results of the investigation show that 88% of installed CMD,



70% of installed NHs, 47% of MHs, and 13% of LEDs radiated light that exceeded the recommended lighting limits.

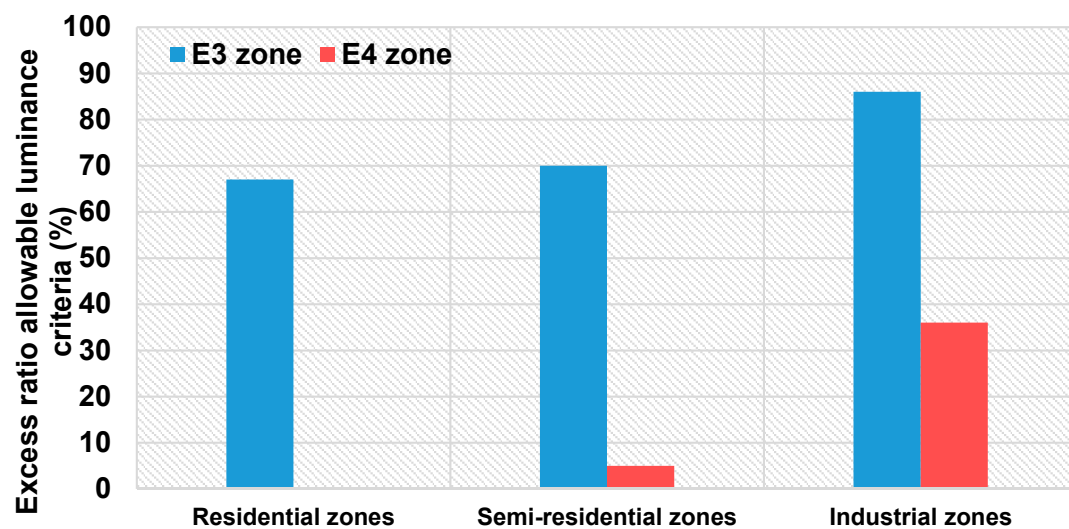


Figure 3. Ratio of areas with space lighting exceeding the recommended lighting limits.

#### 4.2. Advertisement Lighting and Luminance

Lighting belonging to advertisement billboards in commercial districts, as well as decorative lighting, also appeared to play a significant role in light pollution related complaints from people residing in these areas. As such, they were a huge part of the investigation. The obtained values were then compared with the allowed luminance values to gauge the extent to which advertisement companies and individual businesses were exceeding the recommended limit of light luminance. In addition, the types of lighting being used in advertisement lighting, such as the channel letter, flux, neon lights, etc., were considered in order to determine which of the light types were responsible for the largest spread of light pollution. Figure 4 shows the ratio of areas with advertisement lighting exceeding the recommended lighting limits.

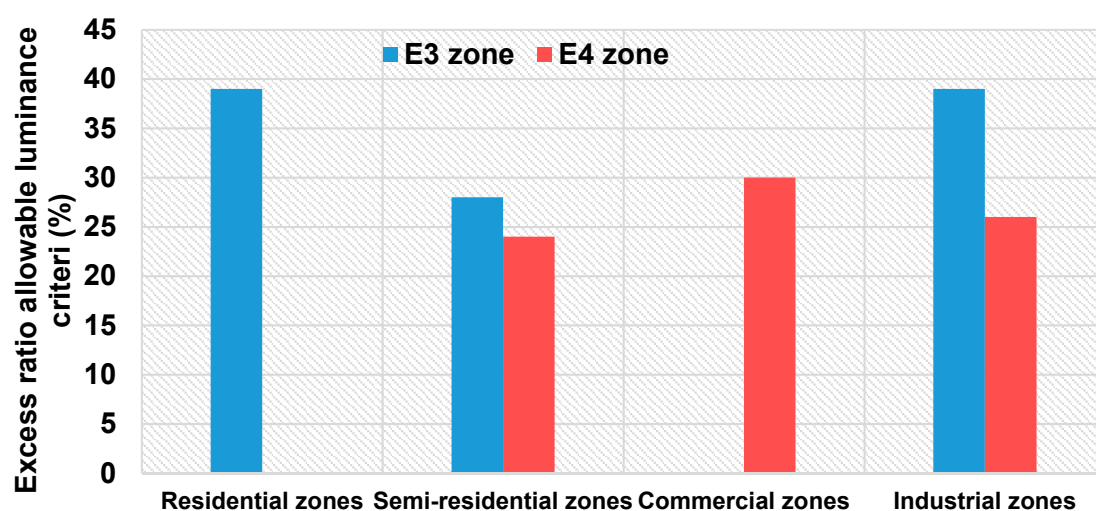


Figure 4. Ratio of areas with advertisement lights exceeding allowed lighting limits.

For advertisement lights, residential, semi-residential, and industrial areas located within E3 had 39%, 28%, and 26%, respectively, of the installed advertisement lights exceeding the limit values.



In addition, 24% of advertisement lights in semi-residential areas, 30% of advertisement lights in commercial areas, and 26% of the advertisement lights in industrial areas located within E4 exceeded the surface luminance values.

#### 4.3. Decorative Lighting and Luminance

Regarding the number of decorative lights with surface luminance exceeding the allowed values in the investigated areas, 86%, 100%, and 56% of the decorative spaces in residential, semi-residential, and industrial areas, respectively, in E3 had higher luminance values than those dictated by the law. Correspondingly, 88% of semi-residential areas, 72% of commercial areas, and 44% of industrial areas located within E4 exceeded the lighting limits allowed. Figure 5 shows the ratio of areas with decorative lighting exceeding the recommended lighting limits.

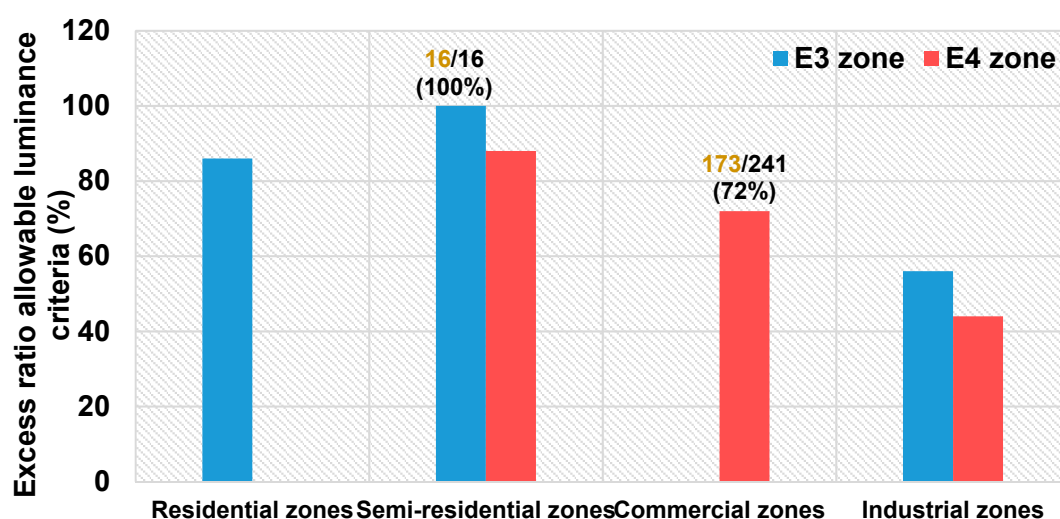


Figure 5. Ratio of areas with decorative lighting exceeding recommended lighting limits.

## 5. Discussion and Conclusions

The continuous increase in nighttime outdoor lighting and its effects on the environment have recently been receiving vast amounts of attention. This has corresponded to an increase in the demand for solutions. This paper has provided an extensive discussion on light pollution, emphasizing the related issues, standards, and legislation. This study also presented assessments of real case studies in urban environments. The findings can be summarized as follows.

As evidenced through the literature, excessive light at night interferes with the production of the melatonin, and has been linked to the increased risk of cancer, diabetes, and obesity. As such, light pollution has become a serious issue facing humanity. Luminaires chosen and the degree to which they distribute light should be considered carefully before the installation of any light fixtures. Additionally, it is also important to point out that, new lighting technologies do not necessarily offer better alternatives in regards to the control of light pollution. A good example of such a technology is the light—emitting diodes (LEDs). Governments and municipalities around the world are readily replacing traditional lamps with LEDs in streets and general industrial usage; this is done largely because of the potential shown by LEDs to save energy. However, as discussed by Pawson and Bader [33], white LEDs are more likely to have negative impacts on natural ecosystems than high-pressure sodium (HPS) vapor lamps.

Light pollution prevention standards and regulations should be given equal weight for the efficient eradication of the effects of artificial lighting at night. The results from real surveys conducted in Seoul, South Korea, show that a large proportion of the investigated areas exceeded the lighting limits dictated by the Korean Light Pollution Prevention Act. In most cases, all chosen sample spots

exceeded the lighting limits allowed in their respective lighting environmental management zones. Moreover, most of the luminaires that were being used in Seoul were found to be outdated, in terms of lighting technology, and were found to be responsible for the spread of light pollution and causing setbacks to sustainable lighting; this however does not mean that newer lighting technologies are not a cause of light pollution. Extensive research in this area seems rather necessary. The assessments conducted also show that there have not been any reductions in light pollution despite the enactment of the law against light pollution. As such, a robust strategy that would reinforce the light pollution law, not only in Seoul but also in other regions of South Korea, is of crucial necessity.

**Author Contributions:** Hong Soo Lim and Jack Ngarambe participated in the process of measuring data, analysis of the luminous environment, and documentation of the study. Jeong Tai Kim conducted the project as the principal investigator and pushed the light pollution issues in parallel with the policy advances to draw conclusion. Gon Kim led the construction of the manuscript and his academic skill on both lighting pollution and assessment provided the knowledge on how to measure the luminous data and evaluate the illuminated environment in the study.

**Conflicts of Interest:** The authors declare no conflict of interest.

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The Society of  
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# Road lighting research for drivers and pedestrians: The basis of luminance and illuminance recommendations

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This article discusses quantitative recommendations for road lighting as given in guidelines and standards, primarily, the amount of light. The discussion is framed according to the type of road user, the driver and the pedestrian, these being the user groups associated with major and minor roads, respectively. Presented first is a brief history of road lighting standards, from early to current versions, and, where known, the basis of these standards. Recommendations for the amount of light do not appear to be well-founded in robust empirical evidence, or at least do not tend to reveal the nature of any evidence. This suggests a need to reconsider recommended light levels, a need reinforced by recent developments in the science and technology of lighting and of lighting research. To enable improved recommendations, there is a need for further evidence of the effects of changes in lighting: This article therefore discusses the findings of investigations, which might be considered when developing new standards.

## 1. Introduction

The Commission Internationale de l'Eclairage (CIE) describes two main purposes of road lighting: (1) to allow all road users, including operators of motor vehicles, motor cycles, pedal cycles and animal drawn vehicles to proceed safely; and (2) to allow pedestrians to see hazards, orientate themselves, recognise other pedestrians and give them a sense of security.<sup>1</sup> A third purpose is also given (to improve the day- and night-time appearance of the environment) but that does not fall within the scope of this paper.

Guidelines and standards for road lighting are provided to help designers achieve these

purposes, and to do so, they provide quantitative recommendations for the appropriate level (luminance or illuminance), colour (or other characteristic derived from the spectral power distribution (SPD)) and spatial distribution of light. Example documents include CIE 115:2010,<sup>1</sup> EN 13201-1:2014,<sup>2</sup> EN 13201-2:2015,<sup>3</sup> IESNA/ANSI RP-8:2014<sup>4</sup> and BS 5489-1:2013.<sup>5</sup> These are consensus documents which means that they are written and reviewed by committees representing a cross-section of the industry – manufacturers, designers, installers and researchers.

This paper discusses the basis of quantitative recommendations for road lighting; the background to current guidance, the need to revise standards to respond to developments in science and technology, and recent and ongoing research being carried out to provide an empirical basis for revised recommendations. The discussion is focussed upon

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research into road lighting for pedestrians and drivers, the categorisation used by the CIE to distinguish between two sets of lighting recommendations.<sup>1</sup> The European standard EN 13201 also presents two sets of recommendations, the M-classes and the P-classes: the M-class is intended for drivers on traffic routes; the P-class for pedestrians and cyclists but also for drivers at low speeds ( $\leq 40$  km/h).<sup>2,3</sup>

Road lighting is an extremely broad topic. To limit the scope, we have not included research of vehicle-mounted lighting, tunnel lighting, conflict areas, the effects of or measurement of glare, sign illumination, traffic signals or parking and dedicated pathway areas.

## 2. The basis of current road lighting recommendations

### 2.1. Early standards

A road lighting standard is required to ensure a good installation and to provide a basis for tender.<sup>6</sup> In 1927, British Standard 307<sup>7,8</sup> identified eight classes of lighting, defined by minimum mounting height and maximum space:height ratio.<sup>6</sup> While minimum illuminances were also defined for each of the eight classes, these ranging from 0.1 lux (0.01 foot candles) to 21.5 lux (2.0 foot candles) at a test point, these minima were not intended to be considered as a figure of merit

for the installation but only as a rating of its size and had no theoretical basis.<sup>6</sup> The 1927 British Standard was suggested by Waldram to be the first milestone in the technical progress of street lighting. The second milestone, Waldram suggested, was the 1928 field study in Sheffield, UK, of 52 experimental installations, the problems observed in that study leading promptly to a revised standard.<sup>6</sup>

Many early standards tended to prescribe lighting system characteristics rather than performance metrics such as illuminance or luminance, this being possible partly because there were only a limited range of lamp types available. For example, the 1974 British Standard gave recommendations for between-post spacing according to road width (Table 1).<sup>9</sup> This remained the primary approach for lighting design until well into the 1980s when the use of computers for lighting design became commonplace.<sup>10</sup> It was not until the 1985 British Standard,<sup>11</sup> based on CIE recommendations,<sup>12</sup> replaced the 1974 Code of Practice<sup>13</sup> that photometric objectives were explicitly stated, this being done to allow the design to a pre-selected level and uniformity of light.<sup>10</sup>

### 2.2. Standards for driving

Two approaches have been used to set lighting standards for traffic routes where drivers are the primary road user: consideration of visual function and consideration of road accidents.

**Table 1** Example of the 'recipe' method for prescribing road lighting criteria. This example is from British Standards Code of Practice 1004:1974 part 2.<sup>9</sup>

| Light distribution class | Height (m) | Minimum lower hemisphere flux (lm) | Design space (m)         |    |    |    |    |    |    |    |    |    |    |
|--------------------------|------------|------------------------------------|--------------------------|----|----|----|----|----|----|----|----|----|----|
|                          |            |                                    | Effective road width (m) |    |    |    |    |    |    |    |    |    |    |
|                          |            |                                    | 11                       | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 20 | 22 | 24 |
| Cut off                  | 10         | 12,000                             | 33                       | 33 | 33 | 31 | 29 | 27 | 26 | 24 | 22 | 29 | 26 |
|                          | 12         | 20,000                             |                          |    |    |    |    |    |    |    |    |    |    |
| Semi cut off             | 10         | 12,000                             |                          |    |    |    | 44 | 44 | 42 | 40 | 36 | 47 | 43 |
|                          | 12         | 20,000                             |                          |    |    |    |    |    |    |    |    |    |    |

In North America, the initial approach for establishing light levels was to consider how changes in lighting affected the frequency of road traffic collisions, and hence the safety of vehicle occupants and the vulnerable road users they hit. This is the basis of the Illuminating Engineering Society of North America (IESNA) road lighting recommendations (originally implanted in 1972 but still the basis of current standards in North America), derived from the work of Box.<sup>14</sup> Box examined the relationship between illuminance and freeway (or motorway) crashes on 203 miles of road. First, he considered the presence versus absence of road lighting: the day/night crash rate ratios for lit and unlit roads were 1.43 and 2.37, respectively. Using this ratio to calculate an expected crash rate, Box concluded that installing road lighting on freeways reduced nighttime crashes by an average of 40%. Consider next the light level (Figure 1): Box concluded that roads with the lower range of illuminances (0.3 to 0.6 horizontal foot candles (HFC), or 3.2lux to 6.4lux) had a lower night/day crash ratio

than roads with a higher range of illuminances (0.8 to 1.1 HFC and 1.3 to 1.5 HFC; 8.6lux to 11.8lux and 14lux to 16.1lux). As a result of these data, Box recommended a level of 0.5 HFC (5.4lux) for freeways. This result seems counter to intuition as a higher lighting level increased the crash rate ratio. It must be remembered that additional lighting can create additional glare and impacts the driver's adaptation level so while this result is not expected, it may be justifiable.

There are limitations in the Box data. First, Box performed only a limited statistical analysis: subsequent study has concluded the data do not exhibit a relationship between light level and crash rate.<sup>15</sup> This can be seen by the regression lines shown in Figure 1; while results for the four-lane roads are well-fitted by a polynomial curve ( $R^2=0.97$ ), those for the six-lane road are not ( $R^2=0.02$  for the linear fit is not improved by a polynomial equation). Second, these values were applied only to freeways; the levels for other roadway categories had no empirical backing. Despite these limitations, the

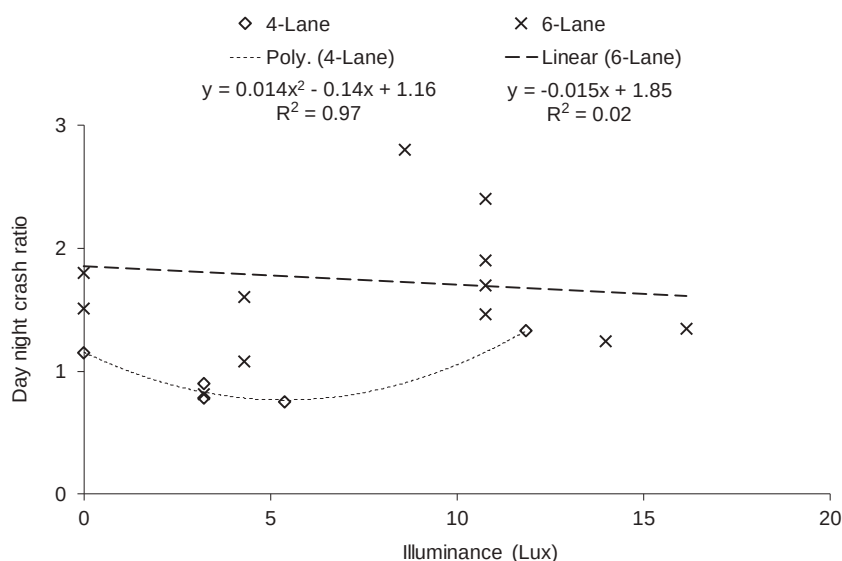


**Figure 1** Day/night crash ratio plotted against illuminance, after Box<sup>14</sup>



0.5 foot candle illuminance determined by Box has been carried through the standards and translated into luminance criterion.

The first step in developing a metric based on human vision was to establish an appropriate photometric quantity. This required the use of luminance, which describes the luminous intensity per unit area in a given direction, specifically that reflected from the road surface towards the driver, and which provides a better measure than illuminance of how well an object can be seen. The luminance method, developed during the 1970s, was documented by the CIE in 1982,<sup>16</sup> and accepted by the IESNA in 1983.<sup>17</sup> In the process of accepting luminance as the criteria, the IESNA converted the existing illuminance values to luminances based on the roadway pavement classification.

The luminance of any point on a road surface is a function of the illuminance on, and the reflection properties of, the pavement material. The luminance method therefore requires knowledge of the road surface properties and the geometry between the light source and the observation position relative to a point on the road surface. The need to make assumptions about the observation point and viewing direction means that luminance-based design is applied only to situations such as motorways where the assumption can be made. In conflict areas, where multiple directions of view are likely, illuminance-based design is retained. Road surfaces are divided into a small number of representative classes according to the type of surface material and texture (in some countries, weather is also a factor), and for each class, there is a representative road surface reflectance table.<sup>18</sup>

Field verification suggests that the targeted design luminance is not always met, with *in-situ* measurement of road surface luminance varying by up to 45% from the design value.<sup>19</sup> One contribution to this difference is uncertainty in the road surface reflectance

data,<sup>20,21</sup> for example, the age and the traffic volumes on the pavement can vary the reflection characteristics. Another limitation is the difficulty in measuring luminance *in-situ* with limitations from both the instrumentation and the logistics of performing the measurements.<sup>22</sup> The luminance method is also limited in adverse weather and wet road surface conditions due to changes of surface reflection.<sup>23</sup>

The second step in developing a vision-based system for lighting design was to consider how changes in luminance (and other road lighting characteristics) affect factors of visual performance such as the ability and time taken to detect and identify objects. Using lighting that increases the likelihood of detecting a potential hazard and reduces the time taken to achieve this detection leads to a more rapid braking response. This in turn can avoid accidents or at least reduce the severity of an accident by reduction in the impact speed. Indeed, studies have shown that road lighting has a greater effect for reducing fatalities and serious injuries than for minor injuries.<sup>15,24–26</sup>

Adrian<sup>27</sup> developed a model of visibility based on the detection of a small object in the roadway. This target was a square of 20% reflectance, observed as a two-dimensional flat object: with a side length 180 mm, it was located at a distance ahead to subtend a visual angle of 10 minutes of arc. The other inputs to the model included a driver age of 63 years and an observation time of 0.2 seconds. The visibility level (VL) of an array of these targets was calculated and a weighting function used to create a single metric that became known as small target visibility (STV).

The definition of ‘small’ in STV is an important factor. For smaller sizes, a slight change in size can have significant effect on visual performance whilst for larger sizes, where performance is already at a plateau,<sup>28</sup> then changes in size may have negligible effect on performance<sup>29</sup> (see also Section 4.1).

**Table 2** STV values in IES-2000 based on roadway type and usage<sup>30</sup>

| Road and pedestrian conflict area |                          | STV criteria         | Luminance criteria                    |                     |                                                      |
|-----------------------------------|--------------------------|----------------------|---------------------------------------|---------------------|------------------------------------------------------|
| Road                              | Pedestrian conflict area | Weighting average VL | L <sub>avg</sub> (cd/m <sup>2</sup> ) |                     | Uniformity ratio                                     |
|                                   |                          |                      | Median strip <7.3 m                   | Median strip >7.3 m | L <sub>max</sub> /L <sub>min</sub> (maximum allowed) |
| Freeway Class A                   |                          | 3.2                  | 0.5                                   | 0.4                 | 6.0                                                  |
| Freeway Class B                   |                          | 2.6                  | 0.4                                   | 0.3                 | 6.0                                                  |
| Expressway                        |                          | 3.8                  | 0.5                                   | 0.4                 | 6.0                                                  |
| Major                             | High                     | 4.9                  | 1.0                                   | 0.8                 | 6.0                                                  |
|                                   | Medium                   | 4.0                  | 0.8                                   | 0.7                 | 6.0                                                  |
|                                   | Low                      | 3.2                  | 0.6                                   | 0.6                 | 6.0                                                  |
| Collector                         | High                     | 3.8                  | 0.6                                   | 0.5                 | 6.0                                                  |
|                                   | Medium                   | 3.2                  | 0.5                                   | 0.4                 | 6.0                                                  |
|                                   | Low                      | 2.7                  | 0.4                                   | 0.4                 | 6.0                                                  |
| Local                             | High                     | 2.7                  | 0.5                                   | 0.4                 | 10.0                                                 |
|                                   | Medium                   | 2.2                  | 0.4                                   | 0.3                 | 10.0                                                 |
|                                   | Low                      | 1.6                  | 0.3                                   | 0.3                 | 10.0                                                 |

STV: small target visibility; VL: visibility level. Median strip: the reserved area (central reservation) separating opposing lanes of traffic on dual carriageways and motorways. The table refers to the width of the strip.

The STV approach was implemented in the US standard IESNA RP-8 in 2000.<sup>30</sup> In this document, the IESNA allowed the use of three methods for calculating lighting levels on roadways; illuminance, luminance and STV. Table 2 shows the recommended values for this STV (VL) values and the associated luminance criteria based on the roadway type and the potential conflict levels. It is interesting that the IESNA 2000 document contradicted itself in using different luminance values for the same roadway criterion if luminance only was used as the design metric (levels shown in Table 3) rather than STV and luminance.

As any of the three criteria of illuminance, luminance or STV could be used to establish lighting designs, local agencies were able to choose which. One of the issues with STV was that it could not be field verified and, as a result, the concept was discussed and reviewed significantly, and in next version of IES RP 8,<sup>4</sup> luminance was established as the only design criteria; illuminance was used for field verification and STV was used as a selection criterion between designs.

STV is stated to be the basis of some road lighting standards for drivers<sup>31</sup> although standards themselves tend to be somewhat vague about the basis of recommendations. While it was hinted in CIE115:1995<sup>32</sup> that visibility was the basis of the luminance recommendations, it was also stated that ‘*These recommendations are based on research on and experience in all aspects of the visual requirements at night*’ and furthermore that ‘*Although prescribed values of the criteria were originally arrived at as a result of experimental work, they have been tempered by experience over this time...*’ Table 4 shows light levels recommended in CIE115:1995 for the M-class roads, where Table 6.1 of that document gives recommendations without clear acknowledgement of the basis and Table A1 of that document gives recommendations based on STV. This suggests that the main recommendations were not based on STV. Note that M-series of lighting classes as shown in Table 4 are ‘*intended for drivers of motorized vehicles on traffic routes, and in some countries also on residential roads, allowing medium to high driving speeds*’;<sup>1</sup> for pedestrian and low

**Table 3** Luminance values in IES-2000 based on roadway type and usage<sup>30</sup>

| Road and pedestrian conflict area |                          | Average luminance<br>(cd/m <sup>2</sup> ) | Uniformity ratio                       |                                        | Veiling luminance ratio<br>$L_{vmax}/L_{avg}$<br>(maximum allowed) |
|-----------------------------------|--------------------------|-------------------------------------------|----------------------------------------|----------------------------------------|--------------------------------------------------------------------|
| Road                              | Pedestrian conflict area |                                           | $L_{ave}/L_{min}$<br>(maximum allowed) | $L_{max}/L_{min}$<br>(maximum allowed) |                                                                    |
| Freeway Class A                   |                          | 0.6                                       | 3.5                                    | 6.0                                    | 0.5                                                                |
| Freeway Class B                   |                          | 0.4                                       | 3.5                                    | 6.0                                    | 0.3                                                                |
| Expressway                        | High                     | 1.0                                       | 3.0                                    | 5.0                                    | 0.3                                                                |
|                                   | Medium                   | 0.8                                       | 3.0                                    | 5.0                                    | 0.3                                                                |
|                                   | Low                      | 0.6                                       | 3.5                                    | 6.0                                    | 0.3                                                                |
| Major                             | High                     | 1.2                                       | 3.0                                    | 5.0                                    | 0.3                                                                |
|                                   | Medium                   | 0.9                                       | 3.0                                    | 5.0                                    | 0.3                                                                |
|                                   | Low                      | 0.6                                       | 3.5                                    | 6.0                                    | 0.3                                                                |
| Collector                         | High                     | 0.8                                       | 3.0                                    | 5.0                                    | 0.4                                                                |
|                                   | Medium                   | 0.6                                       | 3.5                                    | 6.0                                    | 0.4                                                                |
|                                   | Low                      | 0.4                                       | 4.0                                    | 8.0                                    | 0.4                                                                |
| Local                             | High                     | 0.6                                       | 6.0                                    | 10.0                                   | 0.4                                                                |
|                                   | Medium                   | 0.5                                       | 6.0                                    | 10.0                                   | 0.4                                                                |
|                                   | Low                      | 0.3                                       | 6.0                                    | 10.0                                   | 0.4                                                                |

**Table 4** Comparison of average luminances recommended in CIE115:1995 in Table 6.1 and also Appendix A Table A1, which gives lighting requirements 'when the STV concept is used'<sup>32</sup>

| Lighting class | Table 6.1<br>Average luminance<br>(cd/m <sup>2</sup> ) | Table A1         |                                           |
|----------------|--------------------------------------------------------|------------------|-------------------------------------------|
|                |                                                        | Visibility level | Average luminance<br>(cd/m <sup>2</sup> ) |
| M1             | 2.0                                                    | 7.5              | 1.0                                       |
| M2             | 1.5                                                    | 7.0              | 1.0                                       |
| M3             | 1.0                                                    | 6.0              | 0.7                                       |
| M4             | 0.75                                                   | 5.5              | 0.5                                       |
| M5             | 0.50                                                   | 5.0              | 0.5                                       |

speed traffic areas, the P-series of lighting classes is used.<sup>1</sup>

Table 5 shows the light levels recommended in CIE115:2010 for the M-series of lighting classes and Table 6 shows the parameters by which an appropriate class is selected. To establish a lighting class, the appropriate weighting values from Table 6 are summated, and this total subtracted from 6: the resultant value is the M-class (or, if this is not a whole number, the next lower whole number is used). A similar approach is used to establish a class within the P-series

(Tables 7 and 8). Differences between the 2010 and 1995 issues of CIE115 are the extension from five to six classes in the M-series, the main change being the addition in 2010 of class M6. The method of choosing a class also changed, being a narrative description of road type in 1995 and a quasi-objective approach in 2010.

### 2.3. Standards for pedestrians

Lighting in minor roads, often called subsidiary roads, is intended to target the needs of pedestrians. For example, BS5489-1:2013 states that the main purpose of lighting for subsidiary roads and areas associated with those roads is “to enable pedestrians and cyclists to orientate themselves and detect vehicular and other hazards, and to discourage crime against people and property.”<sup>5</sup> The lighting on such roads can provide some guidance for motorists, but is unlikely to be sufficient for revealing objects on the road without the use of headlights”. CIE guidance<sup>1</sup> states that ‘The road lighting should enable pedestrians to discern obstacles or other hazards in their path and be aware of the movements of other

**Table 5** M lighting classes for dry roads from CIE<sup>1</sup>

| Lighting class | Average luminance (cd/m <sup>2</sup> ) | Overall uniformity | Longitudinal uniformity |
|----------------|----------------------------------------|--------------------|-------------------------|
| M1             | 2.0                                    | 0.40               | 0.70                    |
| M2             | 1.5                                    | 0.40               | 0.70                    |
| M3             | 1.0                                    | 0.40               | 0.60                    |
| M4             | 0.75                                   | 0.40               | 0.60                    |
| M5             | 0.50                                   | 0.35               | 0.40                    |
| M6             | 0.30                                   | 0.35               | 0.40                    |

Note: Not shown here are recommendations for wet surface uniformity, threshold increment and surround ratio.

**Table 6** Weighting factors for selecting an M-class of road lighting<sup>1</sup>

| Parameter                       | Option                                      | Weighting value |
|---------------------------------|---------------------------------------------|-----------------|
| Speed                           | Very high                                   | 1               |
|                                 | High                                        | 0.5             |
|                                 | Moderate                                    | 0               |
| Traffic volume                  | Very high                                   | 1               |
|                                 | High                                        | 0.5             |
|                                 | Moderate                                    | 0               |
|                                 | Low                                         | -0.5            |
| Traffic composition             | Very low                                    | -1              |
|                                 | Mixed with high percentage of non-motorised | 2               |
|                                 | Mixed                                       | 1               |
|                                 | Motorised only                              | 0               |
| Separation of carriageways      | No                                          | 1               |
|                                 | Yes                                         | 0               |
| Intersection density            | High                                        | 1               |
|                                 | Moderate                                    | 0               |
| Parked vehicles                 | Present                                     | 0.5             |
|                                 | Not present                                 | 0               |
| Ambient luminance               | High                                        | 1               |
|                                 | Moderate                                    | 0               |
|                                 | Low                                         | -1              |
| Visual guidance/traffic control | Poor                                        | 0.5             |
|                                 | Moderate or good                            | 0               |

**Table 7** P lighting classes from CIE<sup>1</sup>

| Lighting class | Average horizontal illuminance (lux) | Minimum horizontal illuminance (lux) | Additional requirement if facial recognition is necessary |     |
|----------------|--------------------------------------|--------------------------------------|-----------------------------------------------------------|-----|
|                |                                      |                                      | A                                                         | B   |
| P1             | 15                                   | 3.0                                  | 5.0                                                       | 3.0 |
| P2             | 10                                   | 2.0                                  | 3.0                                                       | 2.0 |
| P3             | 7.5                                  | 1.5                                  | 2.5                                                       | 1.5 |
| P4             | 5.0                                  | 1.0                                  | 1.5                                                       | 1.0 |
| P5             | 3.0                                  | 0.6                                  | 1.0                                                       | 0.6 |
| P6             | 2.0                                  | 0.4                                  | 0.6                                                       | 0.4 |

A. Minimum vertical illuminance (lux).

B. Minimum semicylindrical illuminance (lux).

**Table 8** Weighting factors for selecting a P-class of road lighting<sup>1</sup>

| Parameter           | Option                                      | Weighting value            |
|---------------------|---------------------------------------------|----------------------------|
| Travel speed        | Low                                         | 1                          |
|                     | Very low                                    | 0                          |
| Traffic volume      | Very high                                   | 1                          |
|                     | High                                        | 0.5                        |
|                     | Moderate                                    | 0                          |
|                     | Low                                         | -0.5                       |
| Traffic composition | Very low                                    | -1                         |
|                     | Pedestrians, cyclists and motorised traffic | 2                          |
|                     | Pedestrians and motorised traffic           | 1                          |
|                     | Pedestrians and cyclists only               | 1                          |
| Parked vehicles     | Pedestrians only                            | 0                          |
|                     | Cyclists only                               | 0                          |
|                     | Present                                     | 0.5                        |
|                     | Not present                                 | 0                          |
| Ambient luminance   | High                                        | 1                          |
|                     | Moderate                                    | 0                          |
|                     | Low                                         | -1                         |
| Facial recognition  | Necessary                                   | Additional requirements    |
|                     | Not necessary                               | No additional requirements |

*pedestrians, friendly or otherwise, who may be in close proximity*'.

An early distinction between types of road user occurred in the 1930s when the British Minister of Transport set up a committee to examine the efficient provision of road

lighting with particular reference to '*the requirements of residential and shopping areas*'.<sup>6</sup> This led to recommendations for only two classes of lighting – traffic routes and other roads requiring lighting – with the

intention that lighting on traffic routes should be sufficiently good for drivers to proceed safely without the use of headlights.<sup>6</sup>

The 1992 British Standard recommended three lighting classes for subsidiary roads, these having horizontal illuminances of 3.5lux, 6.0lux and 10lux, with the choice defined by a narrative description of the typical application.<sup>33</sup> These illuminances were derived largely from a field study in which a small group of people evaluated the 'general impression' of lighting in 24 locations using a nine-point category rating scale.<sup>34</sup> The three horizontal illuminances were proposed as they corresponded to ratings of good (7), adequate (5) and poor-to-adequate (4) on the nine-point scale. The results, however, are likely trivial, being influenced by stimulus range bias,<sup>35</sup> and the field survey did little more than stretch the range of illuminances encountered in the survey to fit the response scale. Stimulus range bias means that a field survey in which a different range of illuminances had been observed would have indicated that different illuminances correspond to ratings of good, adequate and poor, and this can be seen in the earlier, but unfortunately unconsidered, field survey reported by de Boer.<sup>35,36</sup>

While it is possible in hindsight to criticise evidence for the 1992 British standard, there was at least an intention to base the guidance on empirical evidence, and that is not apparent in later guidelines. In 1995, CIE recommended six lighting classes, with average horizontal illuminances ranging from 1.5lux to 20lux.<sup>32</sup> In 2003, EN 13201-2:2003 also recommended six lighting classes but with a narrower range of illuminances (2.0lux to 15lux),<sup>37</sup> and this range was retained in later updates to standards.<sup>1,3</sup> Other than the Simons *et al.* field study described above, the empirical evidence for these recommendations, if any, is unknown.

Table 7 shows the light levels recommended for pedestrians and Table 8 shows

the weightings provided with which to determine which of the six lighting classes of Table 7 is appropriate for a given situation. These are the recommendations of CIE,<sup>1</sup> but those of EN 13201-1:2014 and EN 13201-2:2015 are similar.<sup>2,3</sup> This similarity between the two documents is unsurprising since '*many of the members on the CIE committee are also members of the CEN committee*',<sup>38</sup> which is not the same as independent groups reaching similar conclusions.

There are a number of unknowns in these data. First, consider that the fundamental element is the mean horizontal illuminance: there is no published explanation of the basis for these values. This lack of support means designers are unable to consider whether their requirements are met and researchers have no basis for direct criticism.

Second, consider the supplementary illuminance values. The ratio of minimum to average horizontal illuminance is 0.2 in every class, which suggests convenience rather than an empirical basis. For the facial recognition criteria, the ratio of horizontal illuminance to vertical illuminance is about one-third and the ratio of horizontal illuminance to semi-cylindrical illuminance is 0.2, again suggesting convenience rather than an empirical basis. There are no known reasons for these criteria and the consistent ratios suggest they were not independently evaluated but are simply an arbitrary ratio.

Additional criteria for facial recognition are provided for situations where facial recognition is considered to be necessary, but without comment as to when facial recognition may or may not be necessary. The additional criteria are minimum values of vertical or semi-cylindrical illuminance to be considered alongside minimum horizontal illuminance. The face of another person tends to be largely a vertical surface and hence ensuring an adequate illuminance on the vertical plane may be beneficial. Semi-cylindrical illuminance is provided as an



alternative measure, possibly because the basis of this measure (the averaged illuminance on the curved surface of an upright semi-cylinder) is believed by some to better characterise the ability to evaluate faces.<sup>39</sup> This is unlikely to be the case because a single value of semi-cylindrical illuminance provides no more information about spatial distribution than does a single value of vertical illuminance. The belief in semi-cylindrical illuminance appears to come from two studies, which plotted semi-cylindrical illuminance against results of facial recognition experiments,<sup>40,41</sup> but without fair comparison of the alternatives,<sup>39</sup> and ignoring that other studies<sup>34,42,43</sup> had concluded that semi-cylindrical illuminance did not offer an advantage over horizontal or vertical illuminance.<sup>39</sup>

Third, consider that a lighting class is chosen with consideration to five parameters: travel speed, traffic volume, traffic composition, parked vehicles and ambient luminance (Table 8). An immediate response to these parameters is that they have limited relevance to the stated purposes of road lighting, i.e. to *'enable pedestrians to discern obstacles or other hazards in their path and be aware of the movements of other pedestrians, friendly or otherwise, who may be in close proximity'*.<sup>1</sup> Instead, they relate largely to the potential for, and severity of, collision with a motor vehicle. Whilst that is clearly an important consideration, the disconnection between the stated aims of lighting and the approach to choosing how much light is provided does not provide confidence that the intended purpose will be met.

There is some evidence that travel speed,<sup>44</sup> traffic volume,<sup>45</sup> traffic composition<sup>46</sup> and the presence of parked vehicles<sup>47</sup> are associated with the risk of accident/injury to pedestrians. There is not, however, any evidence that differences between the options are fairly represented by a weighting of 1.0 in all cases, in particular since the options are not clearly defined, and there is no evidence that

the weightings should be considered to be cumulative. Guidance for Australia and New Zealand provides an alternative set of weighting factors,<sup>48</sup> for which the options are better defined (e.g. there are quantitative values of traffic volume rather than being labelled very high, high, moderate, etc.) and the weightings appear to be more nuanced.

This means the weighting factors may be leading to lighting design conditions that are not appropriate, possibly too high and leading to excessive energy consumption and light pollution, or too low and leading to insufficient visual benefit for pedestrians. For example, while a mixed traffic composition may benefit from a higher illuminance than single-type traffic, this approach does consider whether the illuminance provided by the lower P-classes (e.g. class 4 or 5) may already be sufficient to meet the demands of mixed traffic.

### 3. The need for new standards

A fundamental need for standards to be reviewed is that they do not appear to be founded in robust empirical evidence. Such evidence is needed first to show that the assumed benefits of lighting do exist (i.e. improved visibility, improved safety, improved feeling of safety), and second to show how these benefits might be affected by changes in context and changes in lighting. Furthermore, within recent years, there have been developments in the technology of road lighting and the technology of research, and developments in our understanding of vision and the side-effects of road lighting.

#### 3.1. Developments in science and technology

Waldram<sup>6</sup> and the online archive of Simon Cornwell<sup>49</sup> describe developments in the technology of road lighting. In 1405, the Aldermen of The City of London were ordered to see that a lighted lantern was



hung outside every house along the road ('highway' in the original), followed in 1461 by a standard specification for the candles. Gas lamps were first used in London in 1807, followed a few years later, in 1816, by arguments in the Cologne Zeitung newspaper against lighting at night (with arguments including that *'the fear of darkness will vanish and drunkenness and depravity increase'*). Arc lamps were used to light public areas in Paris (1878) and Cleveland (1879). In London, arc lighting and incandescent lighting were introduced in the 1880s.

The introduction of discharge lamps in the 1930s is described by Waldram<sup>6</sup> as the third milestone in street lighting, because *'engineers were presented with lamps with almost the simplicity of the filament lamp, with three times the efficiency and twice the life. Public lighting could be provided on a scale and to a level which was previously not economically possible'*. One problem with discharge lamps compared with the filament and gas lighting they replaced, was that they *'gave light of an unfamiliar colour which has strange and unflattering effects on personal appearance'*; new installations were a matter of public interest with the result that *'local authorities began to demand better lighting and to be prepared to pay for it'*.<sup>6</sup>

Low pressure sodium (LPS) lamps were first installed in 1932, high pressure mercury vapour in 1933, fluorescent in 1946 and high pressure sodium (HPS) in 1966.<sup>49</sup> There are three limitations with these types of lamp. First, there were limited options for SPD, which for LPS and HPS lamps meant a yellowish-orange appearance and a low colour rendering index. Second, these were large lamps (LPS lamps in particular) and gave limited opportunity for optical control, leading to an assumption that if one part of the roadway was well lit, then an adjacent footpath would also be well lit. Third, other than some types of fluorescent lamp, they have switching-on cycles, which can require

several minutes to reach full output. These limitations are removed with the implementation of Solid State Lighting (Light Emitting Diodes – LEDs) in roadways and outdoor areas. LEDs can have very fine optical control due to the small size of individual units, almost limitless control over SPD if sufficient primaries are used, and can be switched on and off instantaneously. The introduction of LEDs has thus led to new requirements for new recommendations associated with spectrum, spatial distribution (e.g. the surround ratio and specific sidewalk requirements<sup>50</sup>) and dynamic control. The small physical size of LEDs renders new applications possible. For example, using self-luminous road studs as lane markers may provide a better solution than overhead road lighting in some situations.<sup>51</sup> This is likely to reduce sky glow and energy consumption.

While visual conditions under road lighting are likely to fall within the mesopic region, where both rods and cones provide significant responses, road lighting recommendations are given using photopic quantities. That is, the recommended illuminances (or luminances) are derived from the CIE standard photopic observer<sup>52</sup> and hence ignore any contribution from the rods (and short wavelength sensitive cones). Since rods and cones display different spectral sensitivities, a photopic-only approach may not be adequately accounting for changes in the SPD of road lighting. That limitation has become more important since the widespread introduction of LEDs which, compared with sodium and mercury lamps, significantly enhance the opportunity to change and tune SPD.

One recent development in road lighting measurement is the establishment of a system for mesopic photometry,<sup>53</sup> with work currently ongoing to establish how it should be applied in practise.<sup>54</sup> The mesopic system was derived from two parallel bodies of work, the European MOVE consortium<sup>55–58</sup> who used

laboratory experiments with three representative visual tasks – can it be seen, how quickly and what is it? – and the Lighting Research Center<sup>59</sup> who used reaction time to detection of peripheral targets in experiments of ascending practicality related to driving: An abstract target,<sup>60</sup> a driving simulator,<sup>61</sup> and driving on a test track.<sup>62</sup> The mesopic visual response is essentially a weighed combination of the scotopic (S) and photopic (P) responses, and hence the CIE mesopic system<sup>53</sup> provides the weighting factor according to the level of adaptation and the S/P ratio of lighting, this being established by consensus between the two bodies of work. A focus of current research is how to define the level of adaptation.<sup>63,64</sup>

While there is now a system for mesopic photometry still to be resolved is the situations where it should be applied. For some driver-related activities, mesopic models may not be applicable,<sup>65,66</sup> a result of the diminishing use of peripheral vision during driving on main roads, the ever changing adaptation luminance due to the dynamic nature of drivers' eye movements, and the simultaneous use of headlights. The CIE system has been applied, however, in pedestrian lighting recommendations,<sup>5,67–69</sup> to characterise the illuminance reduction permitted when using lighting of greater short-wavelength content, this being of benefit for tasks such as obstacle detection<sup>70,71</sup> and spatial brightness perception.<sup>72</sup> Alongside the S/P ratio, a minimum value of colour rendering is also prescribed, arbitrarily set at  $R_a = 60$  for consistency with the previous version of BS5489,<sup>73</sup> to avoid encouraging the use of extremely high S/P ratios.<sup>68</sup>

There have also been developments in technology associated with road lighting research.

- *In-situ* light measurement techniques with cameras and illuminance meters linked to a GPS coordinates to evaluate lighting installations over large distances<sup>15</sup>;

- An efficient form of lighting would be to light only what road users tend to look at. While eye tracking has long been possible, the recent development of mobile eye tracking has made it much easier to investigate where people tend to look whilst travelling<sup>74–77</sup>;
- Systems that allow for monitoring of in-vehicle driver behaviour and the assessment of the impact of roadway conditions on that behaviour<sup>78</sup>;
- The calculation of road surface luminance (and other properties) is a complex task. One development that reduced the effort demanded was the introduction of the desktop personal computer.

A further development may change radically the approach to lighting, at least on traffic routes. That is the introduction of autonomous (driverless or hands-free) motor vehicles,<sup>79</sup> which offer the promise of fewer accidents due to automated collision avoidance systems. The need for lighting is reduced if the driver is not required to search for hazards, provided of course that all vehicles are autonomous and that the collision avoidance system do not fail, which is a high expectation. One potential benefit of the detection systems is that they may be able to communicate with the road lighting system to allow the road lighting to be adjusted (e.g. switched on or luminance increased) in response to an approaching vehicle.

### 3.2. Side-effects of road lighting

The aim of lighting guidance should be to ensure that the correct quantity and quality of lighting is used, where and when it is of benefit. Lucas *et al.*<sup>80</sup> referred to the management and use of light being similar to administering a drug: light has both benefits (positives) and unwanted side-effects (negatives) giving the need to control the dosage of the light so as to provide the maximum benefit whilst minimising the negatives.

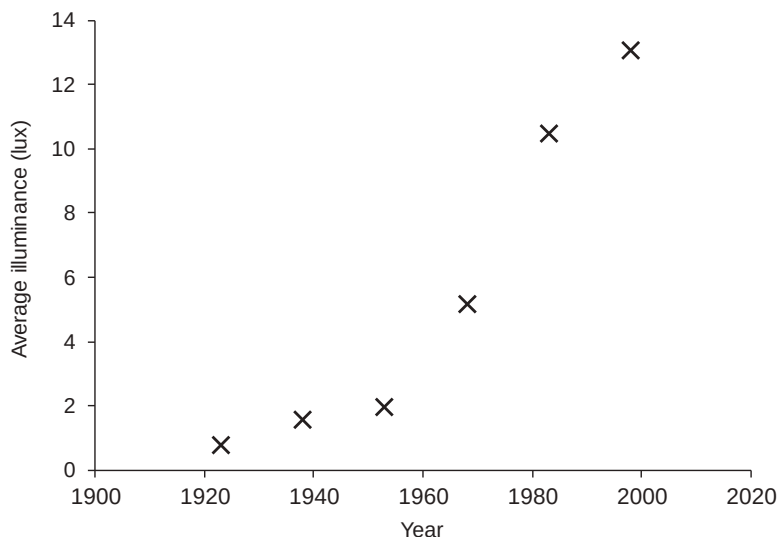


**Figure 2** The average illuminance of street lighting in Britain has tended to increase<sup>81,82</sup>

One reason to suspect that light levels are on the high side and could be reduced is that they have tended to rise with time. For example, the maximum recommended illuminance for subsidiary roads in the UK increased from 10 lux in 1992<sup>33</sup> to 15 lux in 2003.<sup>37</sup> Figure 2 shows the tendency for the average illuminance of street lighting in Britain to increase with time, as determined by Crabb *et al.*<sup>81</sup> from data presented by McNeill.<sup>82</sup> Changes in technology have moved towards lamps of greater efficacy and light levels may have increased, because there was an ability to do so, not because there was evidence of a benefit to be gained from higher light levels.

In 1972, Waldram discussed the ‘sky haze’ due to street lighting.<sup>83</sup> The discussion of sky glow has continued,<sup>84–87</sup> showing, for example, that the use of LEDs of high CCT (6500 K) increases scattered light and hence sky glow compared with conventional sources of lower CCT.<sup>85</sup> Too much light or an inappropriate quality of light might also lead to wasteful energy consumption,<sup>88</sup> to light trespass on property<sup>89</sup> and to unwanted

impact on the natural environment.<sup>90</sup> While there are strong lobbies to reduce the impacts of these externalities, by using lower light levels, restricted spectral tuning or optical control, recommendations still need to meet the intended benefits for road users, e.g. a pedestrian’s ability to detect a trip hazard or a driver’s ability to detect a pedestrian on the carriageway. For this, we need robust evidence of how such benefits are affected by changes in lighting and this is not evident in existing standards.

One impact of lighting side-effects is that there may be a need to consider additional or alternative recommendations. The average illuminances and uniformity of current standards may no longer be sufficient and future standards may need to include maximum light levels, limitations for SPD and spatial distribution and exposure doses.

#### 4. Lighting for drivers

Research undertaken to establish the benefits of road lighting for drivers can be divided into

three broad types: Laboratory studies of visual function, driving performance investigated using simulators or test tracks and studies of the relationship between different types of lighting and the frequency (and/or severity) of road traffic collisions. The first of these shows how lighting affects those aspects of fundamental visual functions considered pertinent to driving. The second considers holistic driving performance or visual function within the context of other cognitive demands of driving. The third considers how lighting affects the outcome of driving performance.

#### 4.1. Laboratory studies of visual function

The relationship between light level (luminance) and visual performance tends to follow a plateau-escarpment relationship<sup>28</sup>; at low light levels, an increase in luminance brings significant increase in visual performance (the escarpment), but a point is reached beyond which further increase in luminance no longer increases visual performance (the plateau). Identifying this point of transition is one approach to establishing the optimum luminance for a task.

Identification of a target is an on-axis task and performance may be characterised by acuity. For foveal acuity, the data suggest that higher luminance may enhance acuity but do not suggest that changes in SPD have significant effect.<sup>91–93</sup> SPD is expected to have an effect on visual performance, in mesopic conditions, for targets that stimulate regions of the retina beyond the fovea, either by size or by off-axis location. This can be seen in the study by Lewis<sup>94</sup> who measured threshold luminance contrast of back-illuminated transparencies of sinusoidal contrast gratings, which subtended a visual field of approximately 13° wide and 10° high. At luminances of 10.0 and 3.0 cd/m<sup>2</sup>, there was no difference between the three lamps examined (MH, HPS, LPS), but as the average photopic luminance decreased further into the mesopic

(1.0 and 0.1 cd/m<sup>2</sup>), then an effect of SPD became apparent, with the MH lamp having significantly lower relative luminance contrast threshold than the HPS or LPS lamps. It should be noted that further research indicated that in a driving environment, the mesopic effect was minimised at higher speeds do the reduction in the use of the peripheral vision and blur due to visual flow through the field of view.<sup>65</sup>

The reaction time to detection of a target is suggested to be of direct relevance to driving performance as the speed of detection plays an important role in perceptual judgements made by the driver and can be easily translated into stopping distances.<sup>95</sup> Several studies<sup>60,94,96,97</sup> have investigated detection rate and reaction time to detection, for on-axis and off-axis targets, under different luminances and SPDs. The effect of SPD on detection can be characterised by the S/P ratio (the ratio of scotopic (rod) to photopic (cone) photoreceptor responses). For off-axis targets, at luminances within the mesopic region, lighting of higher S/P ratio tends to reduce the reaction time to detection and increase detection rate. For example, in He *et al.*,<sup>60</sup> who compared reaction times under HPS and MH lamps to the onset of an achromatic 2° disc, presented 15° off-axis, the benefit of higher S/P ratio was observed for luminances below approximately 1.0 cd/m<sup>2</sup>. The significance of SPD for the detection of peripheral targets may, however, depend on the characteristics of the target and the independent variable used to quantify detection.<sup>98</sup>

Researchers have attempted to develop a model of lighting based on visual performance. Hills considered the visibility of tail lights, road surface obstacles and pedestrians, and characterised this using the luminance difference between the target and background and the visual size of the target.<sup>99</sup> Davison reported that the association between fundamental measures of visual performance

(e.g. acuity) and driving performance was weak and suggested instead the need to consider contrast sensitivity.<sup>100</sup> VL provides one way of doing this. Consider the luminance of a target object and its background: VL is the ratio of the actual difference in luminance to the luminance difference at threshold, calculation of this threshold giving consideration to contrast polarity, observation time and observer age.<sup>27</sup> As VL increases above 1.0, an object starts to appear in silhouette. Subsequent research has been carried out to explore VL and establish the value of VL needed for adequate visibility.<sup>101,102</sup> Most recently, Buyukkinaci *et al.*<sup>103</sup> found that  $VL \geq 7.0$  ensured the target could be detected, established using four target reflectances (0.2 to 0.5) under four classes of lighting (M2 to M5): note that these are higher levels of visibility than adopted in Appendix A of CIE115:1995.<sup>32</sup>

Detection is affected by the size and reflectance (and hence luminance) of the target.<sup>99</sup> A standardised target of size 200 mm × 200 mm is used in some studies, this being considered the smallest size of object which might be dangerous to traffic.<sup>104</sup> At 100 m ahead this subtends a size of 7 min. CIE115:1995 refers to a smaller target (180 mm × 180 mm) but located at a closer distance, 83 m ahead of the observer, and which hence subtends a similar visual size. In CIE115:1995, the STV target had a luminance reflectance of 20%. Reflectance is an interesting issue for hazard detection. Road lighting illuminates the road surface and an object is revealed by negative contrast (silhouette) against the light background: objects of low reflectance are easily perceptible. Vehicle head lighting illuminates vertical surfaces and an object is revealed in positive contrast against the dark background; objects of high reflectance are easily visible but those of low reflectance are not.<sup>104</sup>

Some studies have revealed limitations of the STV approach. Lecocq<sup>105</sup> raised concern

about the use of STV in wet conditions; Menard and Cariou<sup>102</sup> suggested that the small target was of little use in evaluating the visibility of pedestrians; Raynham<sup>31</sup> questioned the validity of such a simple object for real obstacles.

One limitation of vision-based models is that they tend to consider only one, or a limited number of, the myriad features of a visual task (size, contrast, location of target) encountered in the real world. The next approaches to be considered overcome this limitation by considering the outcomes of a change in lighting, on either driving behaviour or accident rates.

#### 4.2. Driving performance

Driving performance can be examined whilst using a simulator or driving a real car on either a test track or open road. Following studies which had examined peripheral detection in laboratory situations,<sup>60,61</sup> Akashi *et al.*<sup>62</sup> examined detection while participants drove along a test track. Rather than using an abstract response task to note detection of a peripheral target, their test participants were required to use the brake and accelerator pedals to indicate detection. While such an approach is a step toward better ecological validity compared with button pressing, it was still a direct response to detection.

Measures of driving performance include the mean and variance of vehicle speed and lateral position, or driver actions such as steering wheel control.<sup>106</sup> In a simulator study, Shahar *et al.*<sup>51</sup> examined lane control on a curved section of rural road, the road being either unlit (i.e. no road lighting but headlighting was in use), conventionally lit, or unlit but using self-luminous (LED) road studs. They examined the standard deviation of lateral position because this gives some idea of the driver's control over the vehicle. For left-hand turns, the standard deviation of lateral position was lower for driving with road studs than for either the lit or unlit



road: for right-hand turns, there was a smaller standard deviation for the road studs than the unlit road, but not smaller than for the lit road.

In a large scale field study, Li *et al.* fitted approximately 2500 cars across seven states of the USA with data collection systems, including video and in-vehicle sensors.<sup>107</sup> Every trip in these vehicles was monitored for more than one year. The resultant database provides a rich database of driver behaviour. The lighting data collection of the previously described project was captured in two US states that overlap with the driver behaviour data collection.<sup>15</sup> Combining these two data sets allows for an analysis of the impact of lighting in specific portions of the roadway.

Initial results suggest, for example, that increasing the illuminance of the near-side lane (right-hand lane in the US) at an interchange reduced the driver speed and lateral acceleration (Table 9). In this research, the ramps at entrances to the roadway (EN categories) and exits from the roadway were divided into five sections for analysis. The significant driver behaviour changes in each of these areas were then calculated and shown with an arrow. The arrow pointing up

indicates an increase in the metric considered (i.e. speed, lateral acceleration, etc.) and an arrow down represents a decrease. These results show that the lighting can impact a driver's behaviour, and hence that light in specific locations on the roadway can promote a behaviour that provides a higher level of safety. A single light level for all sections of a roadway may not be the most effective approach.

#### 4.3. Lighting and road accidents

Investigating the association between changes in lighting and the frequency and/or severity of road traffic accidents is an outcomes-based approach to setting light levels. While it does not directly examine why a change in lighting leads to measured outcome, accident reduction is the benefit part of the cost-benefit approach used in some cases to justify installation of road lighting. For example, a UK manual assumes reductions in personal injury accidents of 10% on motorways and dual carriageway roads and 12.5% on single carriageway roads.<sup>108</sup> In contrast, in New Zealand, it is assumed that upgrading or improving lighting leads to a 35% reduction in crashes.<sup>26</sup>

**Table 9** Impact of an increase in the illuminance on driver behaviour

| Analysis segment                   | Traffic type | Right-lane illuminance |     |     |     |     | Overall illuminance |     |     |     |     |
|------------------------------------|--------------|------------------------|-----|-----|-----|-----|---------------------|-----|-----|-----|-----|
|                                    |              | EN1                    | EN2 | EN3 | EN4 | EN5 | EN1                 | EN2 | EN3 | EN4 | EN5 |
| Speed                              | Ramp         | –                      | –   | ↘   | ↘   | NS  | –                   | –   | NS  | ↗   | NS  |
|                                    | Through      | NS                     | NS  | NS  | NS  | NS  | NS                  | NS  | ↗   | NS  | NS  |
| Longitudinal acceleration rate     | Ramp         | –                      | –   | ↗   | ↗   | ↗   | –                   | –   | ↗   | ↘   | ↘   |
|                                    | Through      | NS                     | NS  | ↗   | ↗   | ↗   | NS                  | NS  | NS  | ↘   | ↘   |
| Longitudinal acceleration variance | Ramp         | –                      | –   | NS  | NS  | NS  | –                   | –   | NS  | NS  | NS  |
|                                    | Through      | NS                     | NS  | NS  | ↘   | NS  | NS                  | NS  | NS  | NS  | NS  |
| Lateral acceleration rate          | Ramp         | –                      | –   | ↘   | ↘   | ↘   | –                   | –   | ↗   | ↗   | NS  |
|                                    | Through      | ↘                      | NS  | ↘   | NS  | ↘   | ↗                   | NS  | ↗   | ↗   | ↗   |
| Lateral acceleration variance      | Ramp         | –                      | –   | NS  | NS  | NS  | –                   | –   | NS  | NS  | NS  |
|                                    | Through      | NS                     | NS  | ↘   | NS  | NS  | NS                  | NS  | ↗   | NS  | NS  |
| Lane offset                        | Ramp         | –                      | –   | NS  | NS  | ↘   | –                   | –   | NS  | NS  | ↗   |
|                                    | Through      | NS                     | NS  | NS  | NS  | NS  | NS                  | NS  | NS  | NS  | NS  |

These data are for the entrance ramp.<sup>107</sup>

↘ indicates a decrease in the behaviour; ↗ indicates an increase in the behaviour.

NS: not significant; EN: entrance category.



In 1992, the CIE published a report which examined 62 studies of lighting and road accidents from 15 countries.<sup>109</sup> These suggested new or improved lighting led to accident reductions after dark in the range of 13% to 75%, although only approximately one-third demonstrated statistical significance. One interesting point is that they found '*No definitive relationship between accident reduction and parameters of lighting*'.

The 2009 Cochrane Collaboration review<sup>110</sup> of road lighting and traffic accidents identified 17 controlled before-after studies, including the Box study described above, conducted in the USA, UK, Germany and Australia and published from 1948 to 2006. There are fewer studies here than in the CIE review because Cochrane reviews apply strict inclusion criteria. Of the 17 studies, 12 investigated the effects of newly installed street lighting, four investigated the effects of improved lighting, and one study investigated both new and improved lighting. Effectiveness of lighting was determined using a rate ratio of accidents before and after the change to lighting compared with the corresponding ratio in a control area. The review found, for example, that installing road lighting in a previously unlit road led to a rate ratio of 0.45 (95% confidence interval 0.29 to 0.69), which implies a 55% reduction in crashes compared to that in the control area.

Advances in technology mean it is now much easier to collect and analyse larger data samples and that can be seen in more recent studies. For example, Wanvik considered 763,000 injury accidents on Dutch roads over a 20-year period (1987–2006).<sup>24</sup> The analysis used an odds ratio approach, comparing lit and unlit roads in daylight and after dark, and determined that on lit roads injury accidents after dark were reduced by 50%. This agrees well with the 55% reduction found in the Cochrane review. Within these data, it can be seen that the benefit of road

lighting is reduced during adverse weather and poor road surface conditions and that there is a larger benefit for pedestrians and cyclists than occupants of motorised vehicles. Yannis *et al.*<sup>25</sup> considered 358,485 police-recorded road accidents in Greece, 1996 to 2008, and also found that on lit roads, there were fewer accidents than on unlit roads. One study used night/day crash ratios to investigate effects of lighting on crash frequency for a specific part of the road – intersections.<sup>111</sup> They examined 22,058 accidents at 6464 intersections in one US state (Minnesota) over a 4-year period (1999–2002). Lit intersections were associated with a 12% lower night/day crash ratio than unlit intersections.

Comparing accident rates between lit and unlit roads tells us nothing about the influence of changes in light level or other characteristics, and to do that a large number of sites with different light levels are needed – this was the approach used in the USA by Box (Figure 1).<sup>14</sup> Using large datasets help to overcome limitations of a road accident approach to establishing light levels associated with events being infrequent and having multiple causation factors.<sup>100</sup>

A similar study was carried out in the UK.<sup>112,113</sup> Data were collected from 89 two-way urban roads, each at least 1 km long, and with a 30mph speed limit, within a 3-year period (1974–1977). The photometric measurements and the accidents analysed were only those for dry conditions. Average road surface luminance was found to be the best predictor of the night/day accident ratio, and the best-fit trend suggests an increase in luminance from 0.5 to 1.0 cd/m<sup>2</sup> reduces the night/day ratio from approximately 0.57 to 0.42, a 15% reduction in accidents at night (Figure 3). This increase in luminance is approximately equal to an increase from 0.7 to 1.4 foot candles (assuming a diffuse road surface reflectance of 20%), for which the Box data (Figure 1) suggest a reduction in accidents at night of approximately 3% for

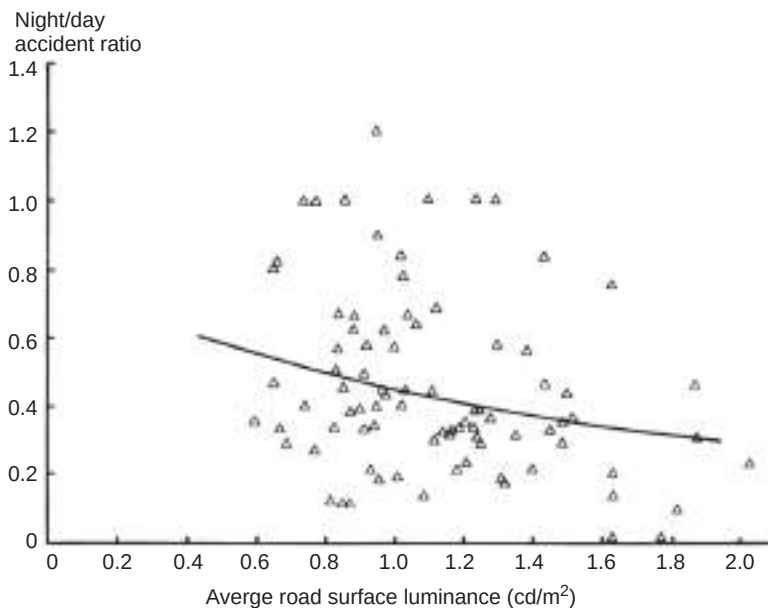


**Figure 3** Night/day accident ratio plotted against average road surface luminance. The curve is the best-fitting exponential through the data after weighting each ratio for the number of accidents to which it relates (after Hargroves and Scott<sup>113</sup>)

the six-lane roads but an increase of over 100% for the four-lane roads. One reason for the differences is the speed limit, being lower in the roads examined by Scott<sup>112</sup> but is also likely to be affected by factors such as road geometry and traffic volume.

Jacket and Frith<sup>26</sup> examined 7944 crashes across 270 km of road in New Zealand in the period 2006 to 2010. This analysis used night/day crash ratios to determine the effect of changes in lighting, lighting being measured in the field. They found a 19% reduction in after-dark crashes (across all types of reported accident) for each 0.5 cd/m<sup>2</sup> increase in average luminance, a similar reduction to that reported by Hargroves and Scott.<sup>113</sup> The reduction varied with context, ranging from 15% for crashes on wet roads to 56% for midblock collisions with pedestrians.

Gibbons *et al.*<sup>15</sup> examined 83 000 crashes in the period 2007 to 2012 over 2000 miles of road in the USA, with the lighting being

measured across the whole of these roads. This work used the night to day crash rate ratio (number of crashes per million vehicle miles during the night/number of crashes per million vehicle miles during the day) to determine the relationship between light level and safety. The results suggest that increased illuminance leads to a reduction in the night/day crash ratio, this relationship changing for different types of road, but that at some point, an illuminance is reached beyond which further increase in illuminance is unlikely to bring further benefit in terms of safety: This point identifies the optimum illuminance. For freeways, this optimum was 5.0 lux. This is lower than illuminances determined (assuming road reflectance class R2 with  $q_0 = 0.07$ ) from the recommendations of IESNA<sup>4</sup> (9 lux) and CIE<sup>1</sup> (21 lux for class M2). That the optimum light level from Gibbons *et al.* for a freeway is significantly less than current recommendations indicates

an opportunity to reduce light levels on this class of road by around 50% without increasing the night/day crash ratio.

Comparison of results or recommendations is not always straightforward because of differences in approaches to specifying context. CIE guidance defines context by user (driver or pedestrian) and within each of these a lighting class is selected using a series of criteria that have been determined to be related to safety such as vehicle speed, traffic volume and presence of parked vehicles (Table 6). The IESNA system relates lighting recommendations to road type (Tables 2 and 3) and does not consider these other criteria.

Many studies<sup>14,15,26,113</sup> use the ratio of nighttime to daytime road accidents as the measure of effectiveness of changes in lighting – better lighting reduces the night/day crash ratio. Using this ratio, however, involves making an implicit assumption that changes in traffic densities, level of alcohol intoxication, level of driver fatigue and driver demographics from day to night are the same for roads lit to different levels and this may not be correct.<sup>114</sup>

One approach to controlling these differences is to take advantage of the clock change associated with Daylight Savings Transition (DST). Typically, adjustment to DST means that the clock is advanced by one hour in spring and set back by one hour in autumn. The effect of this change is that a certain period of time, close to either dawn or dusk, is suddenly changed from daylight to darkness (or vice versa), whilst the traffic density, level of alcohol intoxication, level of driver fatigue and driver demographics are unlikely to have changed. Any change in accident rates in these periods, before and after the clock change, can plausibly be ascribed to the change in ambient light.

Sullivan and Flannagan adopted this approach to investigate fatal road accidents.<sup>115</sup> They compared crash rates (1987 to 1997) across the USA occurring in the

weeks before and after the Spring and Autumn DST clock changes. While this study did not examine changes in the level of road lighting, it does provide some evidence of the types of road accident that are likely to be prevented by light. Specifically, collisions involving pedestrians were found to be up to seven times more likely in darkness than during daytime, the risk being greater for collisions on straight, high speed rural roads than at intersections. In contrast, crashes involving a single vehicle were only marginally more likely in darkness.

The DST approach employs clock change to establish a period of time in which accidents may be attributed to changes in ambient light rather than to other causes. There are limitations of this approach, for example, the use of a single hour of the day reduces the sample size, and the change in light may be confounded by changes in transport choice<sup>116</sup> and seasonal variation in weather and road surface conditions. Johansson *et al.*<sup>117</sup> used an alternative approach, identifying a case hour that was in either darkness or daylight according to seasonal variation in sunrise and sunset times. Data from the whole year can be considered. To account for other seasonal variations, an odds ratio approach was used, meaning that dark/day changes in the case hour were compared against contemporary changes in a control hour. They used this method to analyse three sets of accident data (Sweden, 1997–2006; Norway, 1996–2005; the Netherlands, 1987–2006). Table 10 shows the odd ratios pooled across these three data sets, for urban and rural roads. Note that an odds ratio of 1.0 indicates the same risk of accident in darkness as in daylight. These data suggest a more modest increased risk of accident after dark than the seven-fold increase reported by Sullivan and Flannagan.<sup>115</sup>

Inadequate lighting is not the only cause of road accidents. It was concluded by CIE that

**Table 10** Odds ratio of accident risk in darkness

| Road user     | Odds ratio of accident risk |       |
|---------------|-----------------------------|-------|
|               | Urban                       | Rural |
| Pedestrians   | 2.08                        | 2.29  |
| Cyclists      | 1.52                        | 2.37  |
| Car occupants | 0.94                        | 1.21  |

Note: Data are the pooled estimate of accidents in Sweden, Norway and the Netherlands, after Johansson et al.<sup>117</sup>

*‘the installation of lighting cannot be expected to result in a reduction in accidents if there is a major non-vision problem at any particular site’.*<sup>109</sup> The assumed association between lighting and accidents can lead to pressure being applied to a local authority to install lighting in response to an accident without it being certain that the underlying cause was lack of lighting; this may prevent resources from being diverted to where they will be most effective.<sup>118</sup>

A further caveat to the accident frequency approach is that driving performance can be hindered by distraction<sup>119–121</sup> and this has been identified as a significant cause of road accidents.<sup>122,123</sup> Drivers are less responsive to hazards when distracted by actions such as using a mobile phone, which can cause a greater distraction, and significantly slower reaction times, than that associated with the legal limit for blood alcohol level.<sup>124</sup>

#### 4.4. Comparing approaches

Research undertaken to establish the benefits of road lighting for drivers can be divided into three broad types: effects on visual function measured in the laboratory, driving performance on simulators or test tracks and the frequency and type of road traffic collisions. Either of these approaches could be used to set road lighting standards. In some cases, standards have migrated between different approaches; for example, the IESNA first set a light level based on crash data (the Box data),<sup>125</sup> then tried to move to a

vision-based system (STV approach),<sup>30</sup> and has since returned to the original accident-based format.<sup>4</sup> These documents had some internal inconsistencies, but ultimately, the approaches have shown similar light levels to be selected with some slight variation based on roadway type with some roadways assuming they need a higher level than they do when crash data are reviewed. As an example, the illuminance criteria for Freeway Class A of 6.0 lux became 0.6 cd/m<sup>2</sup> for an R1 road class.

An advantage of the vision-based approach is the direct link between the independent (changes in lighting) and dependent (visual response) variables. If vision was the only factor influencing driving performance and traffic collisions, then all three approaches would reveal similar relationships with lighting, but that is not the case.<sup>126</sup> Laboratory studies and simulators or test tracks tend to adopt a metric of interest (e.g. detection distance) to determine the effect of changes in lighting, with the assumption that this is directly related to safety. Driving performance is also influenced by fatigue, alcohol consumption and cognitive distraction, which change the relationship between lighting and performance. If the primary target of road lighting is to promote safe travel along a road, then standards should be guided by collision-based analyses. However, these demand more research effort than vision-based analyses due to the rarity of roadway crashes and the independent archiving of lighting data and accident data. In the meantime, research linking lighting to driver visual performance and behaviour must be used to determine light levels.

New lighting design approaches and research has shown then we can modify behaviours with the roadway lighting, which allows us to determine lighting needs in specific areas of the roadway.<sup>107</sup> This will ultimately determine the best approach to lighting a roadway with the maximal benefit to the driver.

## 5. Lighting for pedestrians

### 5.1. The visual needs of pedestrians

In 1950, Waldram stated that “*probably the most important problem to be solved is the lighting of residential roads... The methods used hitherto have generally been small-scale imitations of traffic route methods and have achieved the worst of both worlds: there is room for some careful experiment and a new approach in this field.*”<sup>6</sup> The foundations of lighting for pedestrians were set by Caminada and van Bommel.<sup>40</sup> Prior to this point, lighting research related to pedestrians had largely considered only their visibility to drivers<sup>127–129</sup> rather than addressing the direct needs of pedestrians. From a common sense approach, Caminada and van Bommel suggested three key criteria to be detection of obstacles, identification of persons and pleasantness. Some verification of the likely importance of the first two of these criteria was gained using mobile eye tracking in a natural, outdoor urban setting.<sup>76–77</sup> Eye tracking reveals those locations on which gaze is directed but without revealing the attention being paid to that object of view: what this work did was use a dual task (additional cognitive load) to reveal the more important of these visual fixations.

One issue not raised by Caminada and van Bommel was the contribution of lighting to promote reassurance to walk after dark, in other words, to increase the level of perceived safety or reduce the fear of crime. Directly asking people as to whether lighting makes them feel safer may lead the witness toward the desired answer regardless of whether it was the intended response. The benefit of road lighting was however demonstrated in a study using an unfocused approach that aimed deliberately to reduce the focus on lighting or fear.<sup>130</sup> This was to ask people to provide photographs of locations where they would and would not be happy to walk alone, after dark and then use these images as visual

prompts in a subsequent interview where they were asked to explain their choices of locations. The presence of road lighting featured in a similar proportion of responses as did access to help and the physical features of an environment associated with prospect and refuge, and these more than any other factors. The importance of light was also confirmed by others.<sup>131</sup>

Locations that are considered to be brighter tend to be associated with higher levels of reassurance<sup>132,133</sup> and brightness is influenced by both the level and SPD of lighting. Regarding the benefit of light level, studies examining two or more illuminances tend to find the higher illuminance to provide the safer environment,<sup>35,134</sup> regardless of whether the illuminances observed were relatively low (0.24 lux and 1.31 lux),<sup>135</sup> or relatively high (15 lux, 25 lux and 50 lux).<sup>136</sup> In some studies, responses are sought before and after a change to the lighting, with that change tending to be an increased light level and/or a whiter SPD, and these tend to find a favourable response to the change – greater reassurance. What we do not know, however, is whether the favourable response was due to a change *per se*, a Hawthorne-like response where any change would have led to greater reassurance, or because of the actual changes in lighting conditions.

Two studies reveal directions that might provide resolution. First, consider the field survey reported by Knight,<sup>137</sup> which was largely designed to demonstrate that MH lighting would be considered safer than the HPS lighting it replaced. Knight also included a reverse change, in which the MH lighting was replaced with HPS lighting, and the results suggest a statistically significant reduction in the perception of safety ( $p < 0.05$ ). This gives some confirmation that observers were evaluating the effect of lighting and not just responding to a change. Second, Boyce *et al.*<sup>42</sup> introduced the day-dark approach in which ratings of reassurance are captured both



during daytime and after dark, and the effectiveness of lighting is evaluated against the difference between the daytime and after dark ratings. The advantage of this approach is that it leads towards an optimum illuminance rather than towards ever-higher illuminances. Boyce *et al.* investigated car parks in the US and their results suggested an illuminance of 30 lux was required to reduce the day-dark difference to 0.5 units on their 1–7 response scale. The day-dark method has since been applied to pedestrian footpaths and day-dark differences of 0.5 units on the response scale (1 = very dangerous to 6 = very safe) correspond to illuminances of 7.0 lux (a field study in Sheffield, UK) and 10 lux (a field study in Rome, Italy).<sup>138</sup>

There is evidence that SPD affects brightness under the low light levels of road lighting, this evidence coming from studies using a range of contexts, procedures and specific SPDs.<sup>72,137,139–146</sup> These studies tend to show that an increase of radiant power in the short-wavelength region enhances spatial brightness. There is on-going consideration regarding whether this is best characterised by the rod receptors or by some combination of the s-cone receptor and ipRGC,<sup>146,147</sup> and with the adequacy of horizontal illuminance as a measure for spatial brightness.<sup>148</sup> Any proposals need to consider practicality alongside precision.

One reason for investigating reassurance is that greater reassurance is assumed to promote the decision to walk rather than use motorised transport for local journeys: Foster *et al.* found that for every increase of one level on a five-point Likert scale measure of perceived safety, the amount of time spent walking within the neighbourhood increased by 18 minutes per week.<sup>149</sup> This decision could be investigated directly by counting the numbers of pedestrians walking in different lighting conditions but this would require careful matching of test and control locations to ensure the only difference was lighting.

In one study,<sup>116</sup> the effect of ambient light level on travel choice was investigated using the DST clock-change approach used by others to investigate road accidents.<sup>115</sup> the numbers of pedestrians and cyclists during the case period were significantly higher during daylight conditions than after-dark, and this relationship was subsequently confirmed using a second method of analysis.<sup>150</sup>

Road lighting should aid the detection of pavement obstacles that might otherwise result in a fall, and the associated research has focussed on the ability to detect pavement irregularities such as a raised paving slab. This is important because falls on public footpaths are a significant problem in terms of the number of cases, the severity of the resulting injury and the national cost.<sup>151–154</sup> Four studies have investigated how changes in lighting affect obstacle detection in peripheral vision, two using a scale model<sup>70,155</sup> and two studies using larger apparatus to improve ecological validity<sup>71,156</sup>; a further study investigated the ability to safely navigate obstacles following a sudden reduction in light level.<sup>157</sup>

Further work sought to identify the critical height obstacle that pedestrians ought to be able to detect, rejecting the widely cited (and apparently unsubstantiated) rule of 25 mm, and instead suggesting 10 mm to be the critical height.<sup>158</sup> In all, 10 mm is the approximate lower quartile of the range of minimum foot clearance when walking along a flat surface and the lower limit of the range of heights associated with the most frequent number of tripping accident compensation claims.

Laboratory trials show that while higher illuminances lead to increased detection probability, this reaches a ceiling in the region of 2.0 lux; observer age and light source spectrum (characterised using the S/P ratio) affect detection only at low illuminance (0.2 lux).<sup>70,71,155</sup> Consideration of these results alongside those of Boyce<sup>157</sup> suggests that a minimum photopic illuminance of 1.0 lux is



sufficient light for pedestrians of all ages to safely detect and avoid trip hazards under any type of lamp. Still to be resolved are the influences of disability glare and the spatial distribution of light.

Pedestrians make judgements about the intentions of other people, for example to inform the decision of whether or not to continue walking in the same direction or to take action to avoid approaching any closer. After dark, road lighting should assist this judgement. Early work on this topic examined identity recognition judgements.<sup>41,141,159</sup> One conclusion drawn from this work was that lamp spectrum does not influence the performance of the identity task. Other studies, however, concluded that there is a significant effect of SPD<sup>137,160</sup> and these data contributed to an assumed benefit of better colour quality in revised guidance.<sup>68</sup> Subsequent research first examined methodology, proposing that different procedures may lead to different conclusions,<sup>161,162</sup> that facial emotion recognition from expression is a more suitable task than identity recognition,<sup>163–165</sup> that a brief duration of 500 ms better resembles typical behaviour than does continuous observation,<sup>166,167</sup> and that the stop-distance approach used in many studies may not lead to the same conclusions as evaluations made at the desirable observation distance of 15 m.<sup>166,167</sup> In studies carried out using facial emotion recognition, SPD is not suggested to be a critical parameter.<sup>168–171</sup> One question still to be resolved is whether a measure of vertical illuminance is needed to characterise this task or whether it is safe to assume that horizontal illuminance at the road surface is sufficient.

Cyclists are another category of vulnerable road user and their needs have received even less attention in lighting research than for pedestrians. Such research is desirable because cyclists are at high risk of a road accident,<sup>172</sup> and there are policies in many countries to promote cycling as a sustainable

travel alternative to motorised vehicles. There is evidence that changes in practice and policy would be advantageous,<sup>172</sup> that improvements in the design and location of cycle lamps could improve safety,<sup>173–175</sup> and that reflective clothing enhances conspicuity after dark.<sup>176</sup> Many cyclists appear reluctant, however, to use these aids to safer cycling, with on-road surveys in the UK suggesting that only around 25%–58% of cyclists use both front and rear lamps.<sup>177–179</sup>

## 5.2. Drivers' detection of pedestrians

While there is a need to consider what pedestrians would like to see, a significant benefit to pedestrians of road lighting is that it may help to increase their visibility to drivers and hence reduce the frequency of road traffic collisions involving pedestrians. Globally, over 270,000 pedestrians die each year.<sup>180</sup> Within Europe, approximately 20% of road fatalities involve pedestrians and cyclists.<sup>181</sup> In the UK in 2015, there were 186,189 road accident casualties of all severities, of which 28,869 were killed or seriously injured (KSI): within this, 408 pedestrians were killed and 4940 seriously injured.<sup>182</sup>

Studies using the DST approach to the analysis of accident records provide clear evidence that ambient light offers significant benefit to a reduction in road collisions involving pedestrians.<sup>115,126,183</sup> One benefit of road lighting for pedestrian detection is that it can offset the reduction in detection distance brought about by glare from the headlamps of on-coming vehicles.<sup>184</sup>

Regarding the amount of light needed to detect pedestrians, some evidence may be gained by considering lighting at pedestrian crossings. There is however no agreement as to the optimum light level for pedestrian crossings nor where to measure it. ANZ guidance<sup>185</sup> suggest horizontal illuminances of 16 lux (local roads) or 32 lux (arterial roads).

CIE also recommends horizontal illuminances, with averages of 20 lux in residential areas and 30 lux in commercial areas.<sup>186</sup> US guidance<sup>4</sup> suggests instead to use vertical illuminances (at 1.5 m height), these being 10 lux and 2 lux for areas of high and medium pedestrian conflict, these data as determined from test track studies.<sup>187</sup>

A limitation of specifying a single value of illuminance is that it does not account for local conditions: it may be too low if visual adaptation is raised by extraneous local lighting or by a generally high level of road lighting. In the UK, TR12 of the Institution of Lighting Professionals overcomes this by recommending an illuminance relative to that of the road in which the crossing is placed, which is itself chosen partly with consideration to the surrounding environment.<sup>188</sup> Specifically, it suggests horizontal illuminances are 3.5 times (and vertical illuminances are 2.0 times), the horizontal illuminance of the road. For average road illuminances specified in BS5489-1:2013, these ratios lead to horizontal illuminances from 7.0 lux to 52.5 lux and vertical illuminances of 4 lux to 30 lux.<sup>5</sup> While this may be an interesting approach, the basis of the multiplication factors is unknown.

With conventional overhead lighting, a pedestrian moves between areas of positive and negative contrast when using a crossing. Between these areas, the contrast approaches zero and the pedestrian is difficult to see. An alternative solution was reported by Bullough *et al.*<sup>189</sup> in which the overhead lighting is replaced by low level bollards with a vertical, linear light source, placed just ahead of the crossing and aimed towards pedestrians on the crossing. This places the pedestrian in permanent positive contrast by illuminating vertical surfaces of the pedestrian rather than the road surface. The results of simulations and field trials suggested that pedestrian visibility is increased, glare to drivers is significantly reduced, and installation costs are reduced.

Other factors than lighting are involved in the detection of pedestrians. First, consider expectation: in some circumstances, a driver does not expect to encounter pedestrians and this reduces their conspicuity,<sup>190</sup> leading to the 'looked but didn't see' phenomenon. Second, pedestrians tend to render themselves less visible to drivers by wearing dark clothing; there is a tendency for pedestrians to over-estimate their visibility to drivers and under-estimate the benefit of reflective clothing,<sup>191</sup> and to avoid using devices known to significantly enhance visibility such as reflective markings to highlight bio-motion<sup>190</sup> or active visibility aids.<sup>192</sup> Third, a potentially significant approach to reducing accident frequency is to consider legal responsibility for accident compensation.<sup>193</sup> In the UK, the victims (e.g. a pedestrian or cyclist) of collisions with cars must seek compensation for their injuries by proving that the car driver was at fault (i.e. negligent), causing harm to the cyclist by failing to uphold a reasonable standard of driving. An alternative approach is that of presumed liability, where it is presumed that the car driver is responsible for any collisions and must pay 100% of the compensation for the victim's personal injuries unless the driver can prove that the victim was significantly at fault. If drivers are thus motivated to change the manner in which they consider the safety of vulnerable road users, this may benefit road safety regardless of any change in road lighting.

In recent years, there has been a tendency (within the UK at least) to switch off or dim road lighting at certain times of the night as an energy saving measure. Steinbach *et al.*<sup>194</sup> examined the impact of these actions on crime rates and traffic collisions across 62 local authorities in England and Wales of four energy saving changes to road lighting; permanently switching off, reducing the number of hours switched on at night (part-night), reducing the output (dimming) and replacing

the widely used (in the UK) sodium lamps for whiter light sources. Regarding crime, it was found that neither switching-off nor part-night strategies affected crime rates, but that there was weak evidence of a reduction in crime associated with white light and dimming strategies. Regarding traffic collisions, the study found no evidence that either strategy led to an increase: this is somewhat surprising given the results of other studies suggesting lighting a previously unlit road reduces the after dark crash rate,<sup>24,25,109,110,111</sup> and that lower light levels are associated with increased crash rates.<sup>15,26,113</sup>

A further problem with such energy saving strategies is that we do not know how it will affect behaviour. In one study, lighting was initially dimmed (to 20%, 40% or 60%) but switched to 100% (85 lux) when a test participant walked past a motion sensor: walking speed along a 19 m path was slower in those trials where lighting was initially dimmed compared to those in which it was maintained at full output.<sup>195</sup>

## 6. Moving forward

With pressure being placed on the lighting industry to make responsible choices to control the side-effects of road lighting, and with developments in the science and technology of lighting and lighting research, there is an ongoing need for standards to evolve. An effective standard is one that is related to the intended benefits for road users – an aid to vision to be able to travel safely, to feel safe and to minimise the risk of road collisions. While there appears to be little, if any, credible empirical support for light levels recommended in much current road lighting guidance, data are emerging that will allow standards to be better informed by empirical evidence.

In addition to the quantification of lighting, there may be a need to change the parameters that are quantified. For pedestrian lighting, this may be a measure of vertical illuminance instead of or in parallel to horizontal illuminance. For drivers, there may be a move away from standards apparently based on STV towards alternative models such as Relative Visual Performance<sup>196</sup> or the Cumulative Probability Index where the probability of a driver seeing objects in the roadway can be used for the analysis of the lighting needs<sup>197</sup> and for determining visibility.<sup>29</sup>

Such issues are discussed in technical committees such as those of Division 4 in the CIE. Currently, there are active technical committees considering lighting for drivers (TC4-51), pedestrians (TC4-52) and the impact of glare (TC4-33), and working groups considering lighting for the elderly and cyclists. In North America, the IESNA Roadway Lighting Committee is preparing a revision of all of their standards, trying to link lighting needs to driver performance.

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## A Brief Overview on Light Pollution

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**Abstract.** Rapid urbanisation across the globe has resulted to exponential population boomed inhabiting the big cities and urban areas. Unfortunately, this also means more people are now experiencing light pollution (LP) without ever realising it. Vigorous development and economic growth contributed to a sweeping increase in artificial light usage, which further deteriorate the natural dark sky. Alteration in the circadian rhythm of human, plants and animals and loss of naked-eye observable astronomical bodies, are only among the few of LP impacts. However, LP is considered newly recognised anthropogenic pollution where little initiatives have taken in addressing it. This study employs qualitative method of literatures review with using the 4W1H questions (i.e *What, When, Which, Why* and *How*) derived from an online search query data visualisation tool called “Answer The Public”. These keyword questions act as a guideline in providing general overview on LP issue while answering commonly asked questions by the Internet users. Furthermore, this paper attempts to foresee future directions in LP research.

### 1. Introduction

The world’s urban dwellers exceed the rural for the first time in mankind history in 2007, where 68% of the global population projected to live in urban areas by 2050 [1]. This scenario worsens many anthropogenic pollution including light pollution (LP) with 6% increase of artificial lights every year over the past 6 decades [2]. Moreover, technological advancement such as production of cheaper light, broader lamp spectrum, and changes in direction and total flux could drastically transform the night sky [3]. Consequently, two third of the global population are now living under light polluted sky [4]; [5], where most US populace experienced 50% brighter than natural nightscape [3]. Excessive and often ineffective artificial lights coming from commercial, industrial and residential buildings [5], vehicles, street lights and highway roads and outdoor public areas that can extend more than hundreds kilometres out of the city peripheries [6, 7].

An obvious effect of LP is the limitation in observable astronomical bodies detected by naked eye [8]. In 2014, 36% of the world’s populace were unable to see the Milky Way from their homes [3]. Man-made LP also alters the natural circadian clock-metabolism of plants, animals and even detrimental to human health [8, 9, 10]. Previous researches show adverse impacts of LP on nocturnal animals and insects which disrupt their natural reproduction, nesting behaviour, migration, causing disorientation, blindness and high mortality due to exhaustion [4,7,11].

Despite being repeatedly highlighted over the past years by academicians, researchers and international agencies, LP still remains as an underrated global issue. Researches on individual-level effects of LP were still relatively new, where research on its ecosystem-level and long-term



cumulative effects remains unexplored [12]. Hence, the purpose of this paper is to provide an overview on LP issue via answering the 4W1H questions (i.e *What*, *When*, *Which*, *Why* and *How*). This paper hopefully aids to raise awareness on LP and sparks new ideas and perspectives on its future research.

## 2. Methodology

The focus of this study is to provide an overview of non-technical and easily understandable explanations on LP issue, especially for the public, fellow new academician and researcher. As mentioned before, this paper uses the 4W1H questions (i.e *What*, *When*, *Which*, *Why* and *How*) as guidelines in explaining the LP issue holistically. These set of question were derived from an online search query data visualisation tool named “Answer The Public”. This new search engine provides sets of data in the forms of questions, prepositions and alphabetical list related to the public query. Keyword “Light Pollution” was keyed in using this search tool and total of eight question modifiers showing the results related to the keyword. The eight question modifiers were (*Which*, *Who*, *What*, *When*, *Why*, *How* and *Are*) [13]. However, only the 4W1H questions mentioned above were selected and deemed significantly important to be answered in this paper. The details of the questions and answers are further discussed in next section. This research also adopted qualitative method, which is through literature review from numerous conducted studies by other researcher. This helps to grasp better understanding on the previous, current and also future direction on LP related research that will add on the body of knowledge.

## 3. The 4W1H of Light Pollution

The 4W1H questions which namely are *What*, *When*, *Which*, *Why* and *How* are used as the main approaches in this paper to comprehensively review the LP concern.

### 3.1 *What*

In this section, few *What* questions are highlighted and further discussed, which are:-

- What is light pollution?
- What are light pollution sources?

**3.1.1 *What is light pollution?*** Human first discovered fire and use it as a source for heat, cooking, protection from wild animals and also lighting that help to extend their daytime activities during the night [14]. Artificial lights have proven vital to mankind civilisations and revolutions. However, one of the disadvantages in the introduction of anthropogenic light sources is the pollution of natural dark night ambiance. LP is basically defines as the changes in natural level of nightscape produced by excessive man-made light sources [6,15,16]. Astronomically, LP is the limitation in observable astronomical bodies due to the scattering of artificial light in the atmosphere. In term of ecology, LP refers to the alteration of natural light patterns that degrades flora, fauna and human health [4]. This also includes drastically enhanced illumination, momentary and unpredicted illumination and direct glare due to over lighting and light trespass from the surrounding built environment [5,11].

**3.1.2 *What are light pollution sources?*** By nature, the only source of natural light during the night are from the moon, stars, aurorae, cloud covers and reflective surrounding surfaces such as ice and snow. On the contrary, LP is caused by over lighting; light trespass and glare resulted from residential, commercial and industrial areas [4]. Sources of LP include “skyglow”, illuminated buildings and skyscrapers, streetlights, motorways, fishing boats, cruise ships, security lights, vehicles lamps, off-shore oil platforms flares and undersea research vessels [11]. These inefficient lighting emitted from it source, scatter off atmosphere dust or aerosols particles and reflected back to Earth as skyglow [17]. The advancement in creating cheaper and more efficient lamps also contributed to the mass usage of artificial lights. The lighting technology evolves throughout history course starting from burning animal grease; to incandescent light bulbs and to the present Light Emitting Diodes (LED) [18].

### 3.2 *When*

In this section, one *When* question are highlighted and further discussed, which is:-

- When is the best time to measure light pollution?

**3.2.1 *When is the best time to measure light pollution?*** The best time to quantify the amount of LP level in urban areas is in the evening, between 1-2 hours after sunset. This is due to the high anthropogenic activity that requires artificial lights especially from residential, commercial, industrial and transportation sectors [10]. Research suggested that the amount of light usage is lower as night shifting nearer to daylight. These light sources usually improperly shielded, wrongly directed, overly lighted and/or overly crowded which can cause glare, confusion and skyglow. As forested areas especially the protected ones, usually free from artificial light use, it is approximately around 2-3 hours after the sunset to attain complete dark surrounding.

Furthermore, it is utmost important to recognise other factors that might affecting sky brightness measurements. Among the key factors are moon condition, sunset time, cloud cover and existing surrounding albedo surfaces [4]. Moon conditions such as the moon phase and moon height are known to affect sky brightness magnitude reading both on ground and space up to 7-magnitude difference [9]. Hence, it is advisable to take measurements during moon phase below than 0.5 in to attain more accurate data. Increased cloud cover and albedo surfaces contributed to higher light reflectance known as albedo effect. The higher the albedo effect, the lower the amount of incoming solar radiation absorbed by the Earth atmosphere, hence higher occurrence of skyglow. The Okta Scale ranging from 0 (total clear sky) to 8 (total overcast sky) is used to assess the amount of cloud cover prior taking any measurements [9].

### 3.3 *Why*

In this section, few *Why* questions are highlighted and further discussed, which are:-

- Why light pollution need to be reduced?

**3.3.1 *Why light pollution need to be reduced?*** The main reason why LP need to be addressed accordingly is because to ensure the Earth sustainability as a habitable planet for every creatures. Increasing evidences suggesting the adverse impacts of LP are alarming, not forgetting it uncertain contributions toward climate change. LP hinders the human's ability to see the Milky Way resulted from the brighten nightscape. Long distance traveling away from the LP nucleus is necessary to reach a really dark sky [5]. Ecologically, LP alters the natural day-night circadian clock metabolism. This can led to disruptive biological effects of biotic organisms such as plants, animals, insects and human. Deterioration evidences in both epidemiological and physiological level of human health related to artificial light exposure at night becoming more vivid each year. This includes insomnia, sleep disorder and deprivation, mood swings, early-onset diabetes, obesity and promote breast and prostate cancer risk [8,19].

Open areas within urban surrounding act as corridors and refuges for urban animals. However, this also means that these animals are more vulnerable to LP exposure especially the nocturnal ones [4]. Natural behaviours of nocturnal fauna such as foraging, communication, mating, reproduction and migration pattern are heavily disrupted by the altered night sky. For instance, nearly 10,000 migratory birds are either injured or killed due to crashing on skyscrapers in New York every year [19]. These plethoric consequences of LP demand this issue to be recognised and attended with both local and global scale actions.

### 3.4 *Which*

In this section, few *Which* questions are highlighted and further discussed, which are:-

- Which area is light pollution most commonly occurred?
- Which countries have the highest and lowest light pollution index?

*3.4.1 Which area is light pollution most commonly occurred?* LP is a product of excessive artificial light usage from anthropogenic activities. Most of these activities usually concentrated in urban areas and city centres. Walker Law suggested that the number of population, type of economic behaviours and distance from population nucleus have strong influence on the sky brightness level of particular place [20]. Hence, as rapid urbanisation resulted to drastic increase in urban dwellers and economic enhancement, artificial lights consumptions becoming ever greater to cater the ceaseless demands. It is estimated that 49% land area of the EU and 23% of the USA currently inhabit under at least 50% brighter sky than natural at the zenith [5].

*3.4.2 Which countries have the highest and lowest light pollution index?* The number of artificial lights usage increase proportionately with the economic growth. This is true for many countries but some even outpaces the economic affluence [12]. Ironically, introduction in higher efficiency and inexpensive lights leads to it increase usage that aggravates LP level. Thus, it can be suggested that most urban areas in both developed and developing countries of the world are now experiencing LP and vice versa. The country with the most polluted night sky is Singapore as 100% of their population eyes are unable to fully dark-adapt to night vision due to the brighten nightscape. This was followed by populations in Kuwait (98%), Qatar (97%), United Arab Emirates (93%), Saudi Arabia (83%), South Korea (66%), Israel (61%), Argentina (58%), Libya (53%), Trinidad and Tobago (50%) where all of their population living under extremely polluted skies [16]. On contrary, more than three-quarters of populations in Chad, Central African Republic and Madagascar inhabit under pristine night sky environment and able to see the Milky Way clearly with naked eyes. The countries and territories with the largest unpolluted areas are Greenland (99.88%), Central African Republic (99.71%), Niue (99.55%), Somalia (98.8%), and Mauritania (98.6%) [16].

### 3.5 How

In this section, few *How* questions are highlighted and further discussed, which are:-

- How to measure light pollution?
- How light pollution can have adverse impacts on local biodiversity?
- How light pollution can be reduced?

*3.5.1 How to measure light pollution?* Quantifying LP usually involves determining the illumination of a particular place. Basically, illumination is the quantity of light incident (photons) per unit area. The measurement usually is in SI unit of Lux per square meter per second with consideration of the light spectral wavelength [11]. The most common, robust and user-friendly device used to measure sky brightness level is the Sky Quality Meter (SQM; Unihedron) in the unit of mag/sec<sup>2</sup>. This portable yet accurate light meter has led to drastic increase in LP studies globally. Hence, contributed to deeper understanding of LP patterns and allowing comparative studies across different regions [15, 21].

With a standard error of 10% (0.1 mag arcsec<sup>-2</sup>), SQM devices become very popular for its easiness and accuracy among the non-highly qualified researchers and astronomers. The simplest, hand-held photometer that is the SQM-L model is best suited for gathering in-field data. This device can measure light incident from various angles and help to generate an all-sky brightness map [22]. In term of geographical area mapping, one requires to record measurement one after another, of the selected locations of a grid [23, 24]. The SQM-LU and SQM-LE models are used to take and register data constantly and require to be linked to a computer via USB or Ethernet connection. These units are also designed to be used at fixed monitoring station or can be mounted on vehicles with GPS information to map extended areas [22].

There are few natural elements that can deviate the sky brightness magnitude measurements and are vital to be recognised prior the experiments. These include amount of cloud cover, brightness of the moon and presence of aerosol particles. For instance, high amount of cloud cover in urban areas resulted to higher albedo effect that reflects emitted artificial light, hence increasing the sky

brightness. An overcast sky can approximately have 3 to 18 times brightness impact compared to a clear sky [9].

**3.5.2 How light pollution can have adverse impacts on local biodiversity?** The ecological LP can have various negative effects to the natural organism which mainly causing orientation or disorientation, and attraction or repulsion from the brighten night sky. These largely affect the flora and fauna natural behavioural and population size. Plants that are extensively exposed to artificial lights tend to leaf out quicker, having later leaf loss, longer growth period and mortification in composition. Disruption in activities such as scavenging, mating, offspring production, migration and communication are common influences of LP towards animals and insects [11].

One of the major impacts of LP is the disorientation of nocturnal animals that are attracted to intense anthropogenic lighting. For instance, excessive artificial lights have immense effects on sea turtle population. The new turtle hatchlings will scan their surrounding for visible horizon and crawl away from dark, tall elevation towards areas of brighter, low horizon. Unfortunately, the artificial lights coming from the nearby built environment can mask their sea-finding ability, hence decreasing hatchlings survival chances [25].

Furthermore, the altered nightscape enhances predation, which often benefits the diurnal predators and reptiles that can forage under artificial lights. In contrast, nocturnal animals that failed to adapt with such changes tend to forage less, which may disrupt predator-prey relationship. For instance, the squirrel treefrog (*Hyla squirrela*) ability to properly scavenge at illumination level as low as  $10^{-5}$ , but cease when the lighting is above  $10^{-3}$  lux [11].

The negative impacts of artificial light on organism reproductive fitness have been proven by numerous researches evidence. The male *Lithobates clamitans* or commonly known as green frogs that inhabiting artificially illuminated ponds, invest less time calling for mates than the ones inhabiting naturally dark ponds. Similarly, the male winter moths, *Operophtera brumata* that live in a well-lit environment, have low sensitivity towards their female pheromones [26]. These evidences highlighted clearly suggest that there is a strong relationship between LP and biotic behavioural traits and its biological processes.

**3.5.3 How light pollution can be reduced?** Theoretically, LP is one of the easiest anthropogenic pollutions to be addressed. The simple logic in reducing LP is to efficiently light the needed space, and leaving the rest naturally dark as it is. The Dark-Sky Association (IDA) aim to reduce skyglow via improved awareness, better lighting design and implementing standard lighting guidelines and regulations [5]. Few suggestions in raising public awareness on LP issue are through awareness campaigns and encouraging more public-participation based research. For example, the “Dim It Campaign” held in Hong Kong calls for major corporations to switch off their lights for an hour to allow stargazing activity from Victoria Harbour [27].

Better lighting design includes installing properly shielded light fixtures and directing the intended light efficiently. Some states in the US make mandatory of fixing special cut-off hoods or translucent prism over lamps to effectively lower the light intensity and properly direct the light at its intended surface. Besides, lights should also be directed from top down to avoid light trespass and light directed to atmosphere that led to skyglow. Lighting ordinance such as limiting light intensities, allowing lamp with only specific amount of power usage and denote times when non-crucial lighting to be dimmed or switch off can helps to reduce sky brightness [27].

#### 4. Conclusions

The annual global expenditure on outdoor lighting, measures to tens of billion dollars. This not only wasting one’s country revenues but also wasting our limited available natural resources and aggravating climate change phenomenon. The sweeping evidences of LP detrimental impacts prove that it is a global issue that requires local scale adaptation and mitigation measures. Simple practical



solutions and better enforcement on lighting ordinance can go a long way in fighting against LP. This paper focusing on providing a comprehensive and understandable overview on LP, using the 4W1H questions as a guideline in answering the public concerns.

Some recommendations for future research are:

- The impacts of LP towards an entire biotic and abiotic organism in an ecosystem.
- The contribution of LP in enhancing climate change phenomenon.
- The current lighting technology and techniques that is feasible to be implemented in order to reduce light pollution.
- The summary of lighting ordinance that were enforced around the globe.

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## Research



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# A linear systems approach to protect the night sky: implications for current and future regulations

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The persistent increase of artificial light emissions is causing a progressive brightening of the night sky in most regions of the world. This process is a threat for the long-term sustainability of the scientific and educational activity of ground-based astronomical observatories operating in the optical range. Huge investments in building, scientific and technical workforce, equipment and maintenance can be at risk if the increasing light pollution levels hinder the capability of carrying out the top-level scientific observations for which these key scientific infrastructures were built. Light pollution has other negative consequences, as e.g. biodiversity endangering and the loss of the starry sky for recreational, touristic and preservation of cultural heritage. The traditional light pollution mitigation approach is based on imposing conditions on the photometry of individual sources, but the aggregated effects of all sources in the territory surrounding the observatories are seldom addressed in the regulations. We propose that this approach shall be complemented with a top-down, ambient artificial skyglow immission limits strategy, whereby clear limits are established to the admissible deterioration of the night sky above the observatories. We describe the general form of the indicators that can be employed to this end, and develop linear models relating their values to the artificial emissions across the territory. This approach can be easily applied to other protection needs, like e.g. to protect nocturnal ecosystems, and it is expected to be useful for making informed decisions on public lighting, in the context of wider spatial planning projects.

## 1. Introduction

The persistent increase in the emissions of artificial light [1] is giving rise to a progressive deterioration of the natural night,

with detrimental consequences for the environment [2,3], science [4], cultural heritage [5], energy consumption [6,7], and, arguably, human health [8,9], actively studied within the interdisciplinary field of light pollution research [10]. One of the most visible effects of light pollution is the loss of the darkness of the night sky, due to the atmospheric scattering of the light emitted by artificial sources [11–14]. In the visible band, this scattered light reduces the luminance contrast between the celestial objects and their immediate surroundings, preventing the vision of faint objects that, in the absence of artificial light, would be clearly detected. The consequences for the preservation of the intangible cultural heritage associated with the contemplation of the starry skies are a matter of widespread concern [5]. The same effect of loss of contrast takes place in any other photometric band affected by the visible and near-infrared emissions from outdoor lighting sources.

Light pollution poses a serious threat for the long-term sustainability of first-class astronomical observatories. These key scientific infrastructures, in which huge investments have been and are made throughout decades, may find their work jeopardized by the increased levels of scattered light from urban populations, rural settings, industrial areas, mines, and the road and transportation networks in their area of influence. The effects of light pollution can be detected at hundreds of kilometres from the sources. Any increase of the artificial light emissions cooperates to hinder the possibility of carrying out the top-level science for which the observatories were built and equipped. This phenomenon is not new: the first Western modern observatories, built around the eighteenth century AD were located within the main towns or their immediate surroundings. The sky at these locations brightened along the nineteenth and, particularly, the twentieth centuries, making it necessary to relocate the observatories in remote sites less affected by light pollution (and with lower turbulence and higher transparency than urban skies can provide). The history of the great Californian observatories is paradigmatic. Lick, Mount Wilson and Palomar mountain observatories started with nearly pristine skies when their construction began, around 1880, 1905 and 1936, respectively. They experienced an increase of pollution that brightened their skies to about three, eight and two times compared to the natural values. The process of deterioration of the night sky did not stop in the twentieth century. Nowadays, light from artificial sources can be detected, with different degrees of intensity, in practically all ground-based observatories. As with many other environmental threats, the persistent increase of this one may easily get unnoticed in short periods of time to the casual observer, but its accumulated effects are clearly noticeable in periods of the order of several years. Very often, when these effects are finally evident, the situation gets considerably difficult to remediate.

The rising awareness about this problem led several governments to issue a set of legal regulations aiming to curb the growth of light pollution, particularly in the vicinity of the observatories. Some examples of it are the Spanish Law 31/1998 ‘about the protection of the astronomical quality of the Observatories of the Institute of Astrophysics of Canary Islands’, and the recent norms issued by the government of Chile. Additional regulations have been approved by several countries to address the environmental and energy expenditure aspects of light pollution (Italian regions, Slovenia etc.). Most of the existing regulations, however, are almost exclusively based in what can be termed the ‘individual source’ approach, that is, they set relatively strict limits to the amount of light, directionality, spectral composition and switching times of the individual light sources (either individual luminaires, or individual installations comprising generally of a small set of luminaires), in an effort to contain the total emissions of light. Slovenia added to these rules a cap in *per capita* energy consumption but note that this does not stop the possible increase of emitted light, as light efficiency increases over time with technology advancements. Two important improvements to this general trend shall be mentioned. The 1989 lighting code of Flagstaff (AZ, USA), established global limits on the amount of lamp lumen per acre in four zones near the US Naval Observatory Flagstaff Station and Lowell Observatory’s Anderson Mesa, to limit the brightening of the sky over these sites [15]. Similarly, the 2012 City of Tucson/Pima County Outdoor Lighting Code (AZ, USA), establishes a lumen cap on the total outdoor light output per acre of developed areas ([https://webcms.pima.gov/UserFiles/Servers/Server\\_6/File/Government/Development%20Services/Building/OLC.pdf](https://webcms.pima.gov/UserFiles/Servers/Server_6/File/Government/Development%20Services/Building/OLC.pdf)) ‘to preserve the relationship of the residents of the City of Tucson, Arizona and Pima County, Arizona to their unique desert environment through protection of access to the dark night sky’.

It seems clear that imposing conditions on individual sources or small patches of the territory as the only strategy does not guarantee by itself the preservation of the quality of the skies, unless the total emissions are kept below the critical level beyond which the damage to the observatories’ skies would be noticeable. In this paper, we develop a complementary, top-to-bottom approach, aimed to effectively ensure that the light pollution levels of the observatory skies do not surpass some agreed critical limiting values.

This approach is based on the use of quantitative indicators of the quality of the night sky, continuous night sky brightness monitoring to assess compliance, and decision-making support tools to determine the maximum amount of light emissions in the surrounding territories that are compatible with the preservation of the observatory skies. The practical application of this approach requires addressing three main issues: (i) choosing the appropriate indicators of the quality of the night sky, and establishing their acceptable limiting values, (ii) developing a quantitative model relating the values of these indicators to the artificial light sources existing in the region around the observatory, and (iii) allocating among the surrounding municipalities and other local administrative bodies the possible quota of new light emissions (in case the present value of the indicators still did not reach the limiting values, and it could be accepted to increase the emissions in spite of its detrimental consequences) or distributing the burden of reducing the emissions (in case the critical values of the indicators have been surpassed).

The best light pollution indicators for astronomical observatories are still under discussion. A definite proposal was made some time ago by the International Astronomical Union (IAU) [16]. This provision establishes that ‘the increase in sky brightness at 45° elevation due to artificial light scattered from clear sky should not exceed 10% of the lowest natural level in any part of the spectrum between wavelengths 300 and 1000 nm except for the spectral line emission from low-pressure sodium lamps as set out in Recommendation 2 (...)’. Although this provision would very likely need to be updated for the current lighting technologies, it is a good example of the kind of global indicators to which we refer in this work.

In this paper (§2), we focus on developing the basic aspects of the point (ii) above, that is, the model linking the values of arbitrary linear indicators to the emissions of the sources. Some general considerations on admissible deterioration limits, quota allocation and long-term planning are made in §3. Several results used in §2 are formalized in the appendix.

## 2. The linear propagation of light pollution

### 2.1. Sky quality indicators and the point spread function of artificial lights

Ground-based astrophysical observations are carried out with detectors operating in several photometric bands [17], with different fields of view and angular resolutions depending on the instrument type, and with different scientific goals. However, they share something in common: the basic physical quantity at the root of the signal provided by most detectors in the optical frequency range is the total spectral radiance  $L_T(\mathbf{r}'', \boldsymbol{\alpha}'', \lambda)$ , with units  $\text{W m}^{-2} \text{sr}^{-1} \text{nm}^{-1}$ , or  $\text{photon s}^{-1} \text{m}^{-2} \text{sr}^{-1} \text{nm}^{-1}$ . The radiance field provides information about the radiant power ( $\text{W}$  or  $\text{photon s}^{-1}$ ) incident at point  $\mathbf{r}''$  from the direction  $\boldsymbol{\alpha}'' = (z'', \varphi'')$ , being  $z''$  the zenith angle and  $\varphi''$  the azimuth, per unit surface ( $\text{m}^2$ ) around  $\mathbf{r}''$ , per unit solid angle ( $\text{sr}$ ) around  $\boldsymbol{\alpha}''$  and per unit wavelength interval ( $\text{nm}$ ) around  $\lambda$ . Additional variables of  $L_T$  like the time,  $t$ , and the polarization state of the light,  $\mathbf{p}$ , are not explicitly included here for the sake of simplicity. Most raw measurements provided by the detectors can be expressed in terms of this basic physical function.

In what follows we use some results whose formalization can be found in the appendix. Additional information on the physical quantities and notation used here can be found in references [18,19]. Due to their finite aperture, field of view and spectral resolution, the raw signal  $B_T$  provided by any detector, working within its linearity range or after the nonlinearities have been compensated for, is proportional to a spatial, angular and spectral-weighted average of the incident radiance. This can be expressed as  $B_T = \mathcal{L}_1\{L_T\}$ , where  $\mathcal{L}_1$  is a linear operator whose particular form depends on the photometric quantity being measured and the particular specifications of the instrument.  $B_T$  can be any quantity linearly related to the radiance, for instance the brightness of the night sky in any particular observation direction (e.g. the zenith) and spectral band, the average brightness of the upper hemisphere or of some region around the horizon, the horizontal irradiance, the vertical or averaged vertical irradiance and many others, expressed either in absolute values or in values relative to some pre-defined reference level.

The total radiance  $L_T$  incident on the observing instrument is itself composed of two terms: the natural radiance,  $L_N$ , which carries information about the universe around us, and the anthropogenic one,  $L$ , the artificial radiance produced by the atmospheric scattering of the light from outdoor light sources. The detected signal is then given by  $B_T = \mathcal{L}_1\{L_N\} + \mathcal{L}_1\{L\} \equiv B_N + B$ , where  $B_N$  is the component carrying science information about the natural sources (comprising celestial bodies,

zodiacal light and airglow) [20,21] and  $B$  is the component associated with light pollution. To fully exploit the performance of the available instruments, minimizing the value of  $B$  is a must. The Michelson contrast between the light coming from the direction of the science object and its immediate surroundings is given by  $\gamma = 1/[1 + (2B/B_N)]$ , being thus reduced, sometimes considerably, with respect to its ideal value of unity. Similarly, the Weber contrast  $w = B_N/B$ , widely used in vision science, decreases as the light pollution component increases. Even if the value of  $B$  could be precisely known for the site and the moment of the observations, based on theoretical models, and then subtracted from  $B_T$  to obtain  $B_N$ , its presence wastes part of the dynamical range of the detector due to the combined effects of quantization and photon noise, reducing its effective resolution in a way that cannot be fully compensated by modifying the aperture settings or exposure times. This also applies to naked-eye observations of the starry sky, since the changes in the eye sensitivity afforded by its luminance adaptation capability (from photopic to scotopic, across the mesopic range [22]) cannot compensate for this effect, even if some marginal increase or decrease of the luminance contrast can be achieved as a consequence of the spectral sensitivity shift associated with the different luminance adaptation levels.

The values of  $B$ , either absolute or relative to  $B_N$ , are thus suitable indicators of the quality of the skies above observatories, in what regards the detrimental effects of light pollution. The particular form of the optimum indicator or set of indicators for a given observatory is contingent on the quality criteria adopted in each case by the observatory managers, taking into account the specifications of the operating instruments and the characteristics of the celestial bodies to be studied with them. Irrespective of their detailed form, however, they can be expressed as the action of the linear operator  $\mathcal{L}_1$  on the artificial radiance  $L$ , such that  $B = \mathcal{L}_1\{L\}$ . A few exceptions exist to this rule: some potentially useful indicators, as e.g. the maximum artificial radiance of the night sky or its average brightness expressed in  $\text{mag arcsec}^{-2}$  [22], cannot be obtained linearly from  $L$  since neither the max function nor the logarithmic scale in  $\text{mag arcsec}^{-2}$  are linear functions. However, these particular indicators can be straightforwardly computed once the values of  $L$  have been determined using a linear transformation on the sources' radiance (see appendix).

As shown in equation (A 4), the artificial radiance at the observer location,  $L$ , is linearly dependent on the radiance  $L_s$  of the artificial light sources located in its surroundings, such that we can write  $L = \mathcal{L}_2\{L_s\}$ . Combining this equation with the one for the light pollution indicator,  $B = \mathcal{L}_1\{L\}$ , one immediately gets  $B = \mathcal{L}_1\{\mathcal{L}_2\{L_s\}\} = \mathcal{L}\{L_s\}$ , where  $\mathcal{L} = \mathcal{L}_1 \circ \mathcal{L}_2$  is the linear operator resulting from the composition of the actions of  $\mathcal{L}_1$  and  $\mathcal{L}_2$ . The general form of the  $\mathcal{L}$  operator is shown in the appendix. As it is also shown there, under the very general assumption that the sources are factorable, that is, that their radiance can be expressed as the product of a spatial and a spectral-angular term such that  $L_s(\mathbf{r}', \boldsymbol{\alpha}', \lambda) = L_1(\mathbf{r}') L_2(\boldsymbol{\alpha}', \lambda)$ , the value of the indicator  $B(\mathbf{r})$  at an observatory located at  $\mathbf{r}$  is related to the spatial distribution of the radiance  $L_1(\mathbf{r}')$  of the artificial light sources by

$$B(\mathbf{r}) = \int_{A'} K(\mathbf{r}, \mathbf{r}') L_1(\mathbf{r}') d^2\mathbf{r}', \quad (2.1)$$

where  $K(\mathbf{r}, \mathbf{r}')$  is the point spread function (PSF) of the light pollution produced by the artificial light sources, that is, the amount in which a unit radiance light source located at  $\mathbf{r}'$  contributes to the total value of  $B$  at  $\mathbf{r}$  [18,19]. The PSF depends on the choice of the indicator used to describe the night sky quality, the specifications of the detector, the atmospheric conditions, in particular, the distribution and type of aerosols, the ground spectral reflectance, the presence or not of obstacles either natural (relief, trees etc.) or artificial (buildings) and the angular and spectral radiating patterns of the luminaires,  $L_2(\boldsymbol{\alpha}', \lambda)$ . The integral is extended to  $A'$ , the region around the observatory encompassing all relevant artificial sources, being  $d^2\mathbf{r}'$  the surface element of the territory.

Whereas the exact value of the PSF (for a given set of atmospheric conditions) may be strongly dependent on the individual values of  $\mathbf{r}$  and  $\mathbf{r}'$ , in many cases of practical interest the PSF can be approximately considered to be shift-invariant, that is,  $K(\mathbf{r}, \mathbf{r}') = K(\mathbf{r} - \mathbf{r}')$  so that it only depends on the relative position of the observatory with respect to each source. This approximation can be applied, e.g. to a homogeneous territory with a layered atmosphere, or if an averaged PSF is computed for a given set of atmospheric and geographical conditions. If the PSF is shift-invariant the superposition integral in equation (2.1) becomes a two-dimensional convolution and the full toolbox of Fourier transform methods can be applied to efficiently calculate the value of the indicator  $B(\mathbf{r})$  over a wide area of the territory in a single step [19], instead of computing it sequentially for each observing point by a repeated application of equation (2.1). This option is particularly useful if the value of the



indicator shall be calculated for all pixels of a large region, like a dark sky reserve, a national park, or a whole country or set of countries.

The  $K(\mathbf{r}, \mathbf{r}')$  PSF can be calculated by computing the effects of a single point source using suitable radiative transfer models and appropriate atmospheric characterization [23]. Several PSFs have been developed in the literature for the zenithal brightness, the brightness in arbitrary directions and the average brightness of the upper hemisphere relative to its nominal natural value [24–31]. The same procedures can be applied to determine the PSF for other linear indicators of the quality of the night sky.

## 2.2. Changes in the sky quality indicators due to changes in lighting installations

The linear relationship in equation (2.1), suggests an easy way to assess the effects of changes in lighting installations. If the new installed luminaires have the same angular and spectral patterns as the existing ones, the PSF  $K(\mathbf{r}, \mathbf{r}')$ , which implicitly depends on  $L_2(\alpha', \lambda)$ , will be the same for the old and new sources, and any incremental change  $\Delta L_1(\mathbf{r}')$  in the emissions of the surrounding territory will give rise to a change in the indicator

$$\Delta B(\mathbf{r}) = \int_{A'} K(\mathbf{r}, \mathbf{r}') \Delta L_1(\mathbf{r}') d^2 \mathbf{r}'. \quad (2.2)$$

Note that the condition of the equality of the angular and spectral radiation patterns of the new and the old installations is not required to be fulfilled by each individual light source, but by the aggregated emissions of all luminaires (including the reflections in pavements and façades) contained within the territory element  $d^2 \mathbf{r}'$ . In case these aggregated emissions would result in a substantially different form of the function  $L_2(\alpha', \lambda)$ , then it may be convenient to recalculate the form of the PSF  $K(\mathbf{r}, \mathbf{r}')$  that, as stated above and shown in equation (A 10) of the appendix, implicitly depends on it.

Note also that any local change in the lighting installations,  $\Delta L_1(\mathbf{r}')$ , univocally determines, via equation (2.2), the change that will experience the indicator,  $\Delta B(\mathbf{r})$ . However, the inverse is generally not true: any given change of the indicator can be achieved in multiple ways, by redistributing the artificial emissions among all elements of the territory. The basic reason is that the transformation in equation (2.2) cannot be inverted to get a unique  $\Delta L_1(\mathbf{r}')$  from  $\Delta B(\mathbf{r})$  if  $\Delta B(\mathbf{r})$  is specified only for an individual observatory,  $\mathbf{r}$ . Infinite choices for  $\Delta L_1(\mathbf{r}')$  are in that case possible, providing the same  $\Delta B(\mathbf{r})$ . This will be relevant for adopting decisions on how to allocate between different local communities the admissible increase of emissions or the required reductions thereof, something we address in more detail in §3.

## 2.3. Calculating the indicators with geographical information system

Equation (2.1) lends itself well to be interpreted in terms of georeferenced matrices, which can be processed with geographical information system software (GIS). Here, we recall the main steps, described in detail in [18,19]. The emissions function  $L_1(\mathbf{r}')$  is usually available as a georeferenced raster with pixels of finite size, specified in some coordinate reference system [32]. Frequently these input files are provided in a WGS84 reference frame, with pixels of uniform latitude-longitude angular size (e.g.  $15 \times 15 \text{ arcsec}^2$ , for the VIIRS-DNB composites [33]). In such cases it is convenient to reproject the files to a grid of pixels of uniform size in linear dimensions (m or km), like e.g. any of the universal transverse Mercator (UTM) projections used in the official cartography of many countries [32]. The integrand in equation (2.1) can be interpreted then as the pixel-wise product of an emissions matrix  $\mathbf{L}$ , an example of which is shown in figure 1a, whose elements are given by  $L_{ij} = L_1(\mathbf{r}_{ij}') \sigma$  where  $\sigma$  is the area ( $\text{m}^2$ ) of the uniformly sized reprojected pixels, and a PSF matrix  $\mathbf{K}$ , figure 1b, whose elements are  $K_{ij} = K(\mathbf{r}, \mathbf{r}_{ij}')$ , that is, the PSF function centred on the point of observation,  $\mathbf{r}$ , with coordinates reflected in the origin,  $(x, y) \rightarrow (-x, -y)$ . The element-wise product ("·") of these matrices gives rise to the weighted sources matrix  $\mathbf{W} = \mathbf{K} \cdot \mathbf{L}$ , figure 1c, where each pixel  $W_{ij} = K_{ij} L_{ij}$  displays the absolute contribution of its sources to the value of the overall indicator  $B(\mathbf{r})$ . The final value of  $B(\mathbf{r})$  is given by the sum over all pixels of  $\mathbf{W}$ ,

$$B(\mathbf{r}) = \sum_{i,j} K_{ij} L_{ij} = \sum_{i,j} W_{ij}. \quad (2.3)$$

Accordingly, any change in the amount of emissions of an individual pixel,  $\Delta L_{ij}$ , translates into a proportional change in the indicator,  $[\Delta B(\mathbf{r})]_{ij} = K_{ij} \Delta L_{ij}$ . Equal changes in the absolute emissions of different pixels will give rise to different changes in the indicator due to the different weighting factors  $K_{ij}$ .



**Figure 1.** (a) The emissions matrix  $L$ , according to the VIIRS-DNB stable light sources [33], 2015 yearly composite, with the limits of the Galician municipalities superimposed on it (red). Each pixel of this matrix gives the radiance ( $\text{nW cm}^{-2} \text{sr}^{-1}$ ) detected by the VIIRS-DNB radiometer. (b) the PSF matrix  $K$  calculated for the artificial zenith sky brightness according to the model of Cinzano & Falchi [25] for an atmosphere with clarity index 1 (visibility 26 km) centred in the astronomical observation site of San Xoán, Guitiriz ( $43^{\circ}13'31.17'' \text{ N}$ ,  $7^{\circ}55'37.44'' \text{ W}$ ), displayed here in a grey-level logarithmic scale. (c) The weighted sources matrix  $W = K \cdot L$ . Each pixel of this matrix gives the absolute contribution of the light sources contained within it to the final value of the zenith sky brightness in the Johnson V band at the observing site, in radiance units.

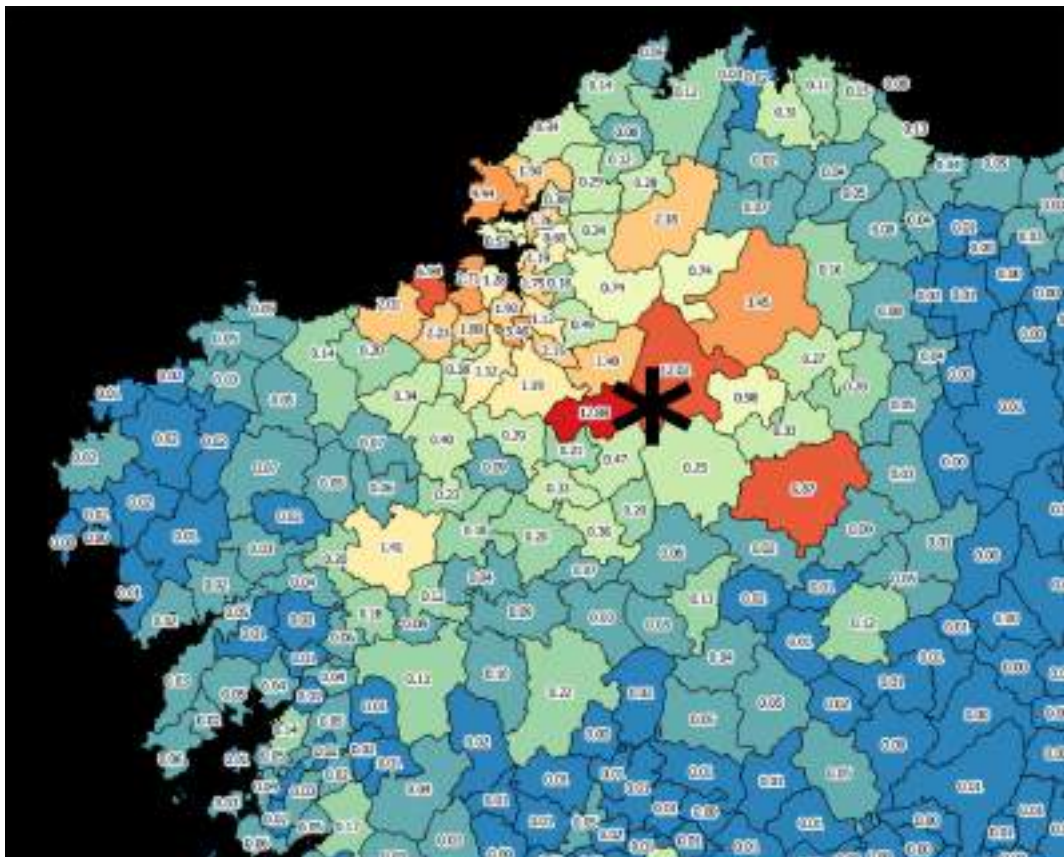


**Figure 2.** The relative contribution of the emissions of each municipality to the artificial zenith sky brightness at the Guitiriz observing site (asterisk).

For making informed decisions on public lighting it is often convenient to group the pixel contributions according to the administrative division of the territory, particularly in terms of the local bodies in charge of that service. Figure 1a,c displays in red the limits of the municipalities, which are the main responsible bodies of outdoor lighting in Galicia, an autonomous community within Spain. The absolute contributions of the individual pixels to the overall indicator for which they were calculated (the artificial zenith night sky brightness at an astronomical observations site in the municipality of Guitiriz, computed for the photometric Johnson V band in agreement with the Cinzano & Falchi model in [25]) can be added at the municipality level, resulting in the relative contribution map shown in figure 2, where the per cent contribution of the aggregated emissions of

each municipality is shown. These calculations, as well as the coordinate reference system reprojections that may be needed, can straightforwardly be made using free GIS applications, as e.g. QGIS [34]. The relative contribution of each municipality to the total value of the indicator allows to easily determine the changes that will experience the indicator for any projected increase or decrease of the municipality emissions relative to its present levels.

Some caution shall be exercised when selecting and using satellite radiance datasets to perform these calculations. For instance, the panchromatic VIIRS-DNB band is not sensitive to wavelengths shorter than 500 nm, missing the blue peak of phosphor-coated LED sources, whereas it detects the NIR peaks of high-pressure sodium lamps. The radiance detected by satellites is also dependent on atmospheric conditions and ground albedo variability [35]. These and other potential variability factors must be judiciously taken into account. Note that the relative contributions of municipalities or districts to the light pollution over the observatories calculated following the approach described in this paper are relatively robust against the spectral passband of VIIRS-DNB, if the mix of lighting technologies used in every pixel of the territory can be considered to be approximately the same. Regarding the atmospheric and ground albedo variability of the detected radiance, this makes it more difficult assessing the actual time evolution of the source emissions. However, it could be considered as an advantage rather than a drawback: as a matter of fact, the emissions relevant for light pollution are not just the raw emissions of the luminaires, but the effective amount of light radiated from each pixel of the territory. In this sense, the fact that VIIRS-DNB datasets record this variability could be a useful asset rather than something to correct.

### 3. Admissible indicator limits, emission quota allocation and long-term planning

The sustained increase of the artificial light emissions suggests that a preservation strategy based on imposing conditions on the photometric specifications of the individual luminaires is not, *per se*, sufficient to ensure that the quality of the night skies over the reference astronomical observatories (or any other protected area, which may well include the whole territory of a country) will be maintained in the long term. An effective protection of the night skies requires additional provisions, which we summarize here in the following three subsections:

#### 3.1. Admissible indicator limits

Any effective public policy on light pollution mitigation requires adopting a clear decision about the levels of deterioration of the night sky considered not admissible (the *red lines* not to be surpassed). The increase of artificial sky brightness progressively hinders the capability of the observatories to perform top-level science tasks, and for each type of astrophysical study there are levels of light pollution that would not allow carrying it out with the required accuracy and precision (due to the reduction in the dynamic range and effective resolution of the detectors caused by the combined effects of quantization and photon noise). The observatory managers should then decide the limiting values of the indicators that can be considered admissible. This is a kind of decision that bears many aspects in common with the ones that have to be taken in other environmental problems, as e.g. setting limits on the harmful concentrations of particulate matter in the atmosphere (PM<sub>2.5</sub>, PM<sub>10</sub>). Regarding light emissions, if the present values of the indicators are smaller than the limits, adopting a criterion of prudence would be strongly advisable, by keeping the overall weighted emissions in or below their present values as a sensible strategy to better ensure the protection of the night skies. New installations could be made at the expense of decreasing in an equivalent amount the emissions in other places of the region. Conversely, if the present values of the indicators surpass the admissible values, a definite and planned transition process must be designed and put in practice, involving overall reductions in the weighted source emissions, by reducing the absolute emissions and/or by redistributing them spatially across the territory. Examples of present-day distributions of territorial contributions, from pixel level to whole municipalities, can be found in [18,31]. Note also that astronomers' goals are not the only ones that are at stake: environmental and landscape preservation concerns may advise adopting indicator limits even more restrictive than those required to ensure the quality of astronomical observations. In such cases, the strictest limits should be agreed and enforced. Finally, the quality indicators do not have to be restricted to a single-point site. They can be defined for whole zones of the territory, as e.g. in (<https://www.epa.gov/visibility/regional-haze-program>;

<https://www.darksky.org/our-work/lighting/public-policy/mlo/>). The general formalism for defining such kind of territorially weighted linear indicators has been described in [18].

### 3.2. Emission quota allocation

As described in §2.2, any increment or reduction of the value of a light pollution indicator can be achieved in multiple ways, by readjusting the light emissions of the intervening elements of the territory. In any case, the territorial distribution of the increment or decrement of emissions must be made taking into account a wide variety of social factors. A given increase or reduction of emissions could be allocated uniformly for all elements of the territory, or in an amount proportional to the present emissions. However, these easy mathematical options would surely fail to fulfil basic criteria of social equity. The small communities located close to astronomical observatories, for instance, contribute to the deterioration of the night skies above the scientific installation in a proportionally bigger amount than others located far away, for the same absolute level of emissions, due to the larger values of their  $K_{ij}$  factors. Should these communities bear the charge of reducing their emissions in the same proportion as others, or should they be allowed to make lesser reductions (or even moderate increments where needed) at the expense of larger reductions in distant communities?

### 3.3. Long-term planning

Long-term planning is a key issue. In many cases, any individual operation of remodelling of outdoor lighting will imply a modest increase of the emissions ( $\Delta L_{ij}$ ) in comparison with their global present values ( $L_{ij}$ ). The change in the overall light pollution indicators after such remodelling operation is then expected to be relatively small. However, any increase of an indicator, albeit modest, spends part of the available light emissions increase budget. Any new installation authorized nowadays will effectively reduce the available quota of admissible additional emissions, hindering the margins for authorizing new projects in the future. The public bodies in charge of outdoor lighting shall then have a strategic plan of development (either allowing increasing emissions or ensuring to reduce them, depending on the cases) that contemplates the long-term evolution of both the science tasks and the social needs. This is a dimension that shall be included in any spatial planning project in the concerned territories. Several cap and trade mechanisms can be used to adaptively correct the initial quota allocation in case of changing priorities or emerging social needs.

These three requirements are science-informed ones, but they are essentially political issues. They reflect the tension between conflicting interests and needs [36–41] and should be addressed with the democratic participation of stakeholders, as a relevant aspect of community management and spatial planning.

## 4. Conclusion

The preservation of the darkness of the natural skies is a requisite for the long-term sustainability of the operations of astronomical observatories. The increasing amount of light pollution represents a threat that shall be addressed before the situation deteriorates beyond permissible levels. This requires defining a suitable set of sky quality indicators and agreeing their admissible limits. The indicator values can be related to the radiance of the artificial light sources through linear models that allow to assess the absolute and relative contribution of each patch of the territory to the deterioration of the night sky above the observatory. Since the relationship between artificial sky brightness and light emissions is linear, any increase of the emissions contributes to further deteriorating the present levels of light pollution. Simply putting limits on the characteristics of individual lighting installations, albeit necessary, is insufficient to address this problem. Setting overall indicator limits, distributing the emissions quota among the affected communities, and planning with a long-term perspective are necessary requisites of an effective light pollution control policy.

**Data accessibility.** All data sources used in this work are in the public domain. No additional materials would be required to conduct an attempt at replication. VIIRS-DNB composites are available, among other options, from [33]. The Galician municipalities' border shapefile can be downloaded from <http://centrodedescargas.cnig.es/CentroDescargas/equipamiento.do>

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## Appendix A

### A.1. Spectral radiance and night sky brightness measurements

Due to their finite spatial, angular and spectral resolution, each independent channel of an astrophysical detector located at  $\mathbf{r}$  and pointing towards  $\boldsymbol{\alpha}$  provides a total signal  $B_T(\mathbf{r}, \boldsymbol{\alpha})$  that, within its linear response range and leaving aside noise, is proportional to a weighted average of the incident radiance,  $L_T(\mathbf{r}'', \boldsymbol{\alpha}'', \lambda)$ , which can be expressed as

$$B_T(\mathbf{r}, \boldsymbol{\alpha}) = \int_{\Lambda} \int_A \int_{\Omega} R(\mathbf{r}, \boldsymbol{\alpha}; \mathbf{r}'', \boldsymbol{\alpha}''; \lambda) L_T(\mathbf{r}'', \boldsymbol{\alpha}'', \lambda) d^2 \boldsymbol{\alpha}'' d^2 \mathbf{r}'' d\lambda, \quad (\text{A } 1)$$

where  $R(\mathbf{r}, \boldsymbol{\alpha}; \mathbf{r}'', \boldsymbol{\alpha}''; \lambda)$  is a combined spectral, aperture and field-of-view sensitivity function describing the relative response of the instrument to the radiance of wavelength  $\lambda$  incident from the direction  $\boldsymbol{\alpha}''$  on the point  $\mathbf{r}''$  of the input pupil, when the instrument, located at  $\mathbf{r}$ , points towards  $\boldsymbol{\alpha}$ . The angular integral is extended to  $\Omega$ , the whole set of relevant directions, being  $d^2 \boldsymbol{\alpha}'' = \sin z'' dz'' d\varphi''$  the solid angle element in a spherical coordinate system with its polar axis coincident with the pointing direction of the detector. The spatial integral is extended to the area  $A$  of the input pupil of the system, being  $d^2 \mathbf{r}'' = dx'' dy''$  the area element in Cartesian coordinates. The wavelength integral is extended to the whole spectrum,  $\Lambda$ .

Equation (A 1) is in fact a very general one, encompassing a wide variety of quantities measured by astrophysical instruments (see additional formalization details in [42]). The different types of instruments and their associated photometric bands are characterized by the  $R$  function. In many cases of practical interest this function can be factored as the product of independent terms such that  $R(\mathbf{r}, \boldsymbol{\alpha}; \mathbf{r}'', \boldsymbol{\alpha}''; \lambda) = P(\mathbf{r}, \mathbf{r}'') F(\boldsymbol{\alpha}, \boldsymbol{\alpha}'') S(\lambda)$ , where  $P(\mathbf{r}, \mathbf{r}'')$  is the input pupil function,  $F(\boldsymbol{\alpha}, \boldsymbol{\alpha}'')$  is the function characterizing the instrument field of view, including vignetting, and  $S(\lambda)$  is the photometric band in which the observations are carried out.  $P$  and  $F$  are usually normalized such that their volumes are unity, whereas  $S$  is traditionally normalized to 1 at its peak. For instance, for a point-like detector with a very small field of view that measures the night sky radiance in the Johnson–Cousins  $V$  band, we have  $P(\mathbf{r}, \mathbf{r}'') = \delta(\mathbf{r} - \mathbf{r}'')$  and  $F(\boldsymbol{\alpha}, \boldsymbol{\alpha}'') = \delta(\boldsymbol{\alpha} - \boldsymbol{\alpha}'')$ , where the  $\delta$  stand for Dirac-delta distributions, and  $S(\lambda) = V(\lambda)$ , such that the brightness of the night sky measured at that location and in that direction is given by the usual expression

$$B_T(\mathbf{r}, \boldsymbol{\alpha}) = \int_{\Lambda} V(\lambda) L_T(\mathbf{r}, \boldsymbol{\alpha}, \lambda) d\lambda, \quad (\text{A } 2)$$

where  $B_T(\mathbf{r}, \boldsymbol{\alpha})$ , which natively has radiance units ( $\text{W m}^{-2} \text{sr}^{-1}$ , or  $\text{photon s}^{-1} \text{m}^{-2} \text{sr}^{-1}$ ), can be expressed in the traditional logarithmic scale of *magnitudes per square arcsecond* ( $\text{mag arcsec}^{-2}$ ) by means of a straightforward transformation [22]. Note that many additional photometric quantities can be expressed as particular cases of equation (A 1). For instance, the irradiance  $E_T(\mathbf{r}, \boldsymbol{\alpha})$  within the  $S(\lambda)$  band (units  $\text{W m}^{-2}$ , or  $\text{photon s}^{-1} \text{m}^{-2}$ ), produced on the input pupil of the instrument by a patch of the sky of solid angle  $\omega$  can be written as

$$E_T(\mathbf{r}, \boldsymbol{\alpha}) = \int_{\Lambda} S(\lambda) \int_{\omega} L_T(\mathbf{r}, \boldsymbol{\alpha}'', \lambda) \cos(\boldsymbol{\alpha}, \boldsymbol{\alpha}'') d^2 \boldsymbol{\alpha}'' d\lambda, \quad (\text{A } 3)$$

and the same holds for many photometric quantities routinely measured in astrophysics and light pollution research (for a description of some of the latter, see [43]).

A key feature of equation (A 1) is that the detected signal  $B_T(\mathbf{r}, \boldsymbol{\alpha})$  can be expressed as the result of the action of an integral linear operator  $\mathcal{L}_1$ , with parameters  $\mathbf{r}$  and  $\boldsymbol{\alpha}$ , acting on the variables  $\mathbf{r}'', \boldsymbol{\alpha}''$  and  $\lambda$  of the spectral radiance, such that  $B_T(\mathbf{r}, \boldsymbol{\alpha}) = \mathcal{L}_1\{L_T\}$ .

### A.2. The point spread function of light pollution

The radiance of the night sky due to light pollution  $L(\mathbf{r}'', \boldsymbol{\alpha}'', \lambda)$  is caused by the emissions of the artificial light sources located in the surrounding territory, up to distances that can reach hundreds of kilometres.

The emissions of any source can be characterized by its spectral radiance,  $L_s(\mathbf{r}', \boldsymbol{\alpha}', \lambda)$ , where  $\mathbf{r}'$  is the source location and  $\boldsymbol{\alpha}' = (z', \phi')$  are the zenith angle and the azimuth, respectively, of the emission direction measured in the source's reference frame. The light emitted by the source propagates through the atmosphere being progressively attenuated by absorption and scattering. A fraction of this light, after undergoing one or several scattering events, propagates in the direction of the observer and contributes to the build-up of the light pollution radiance  $L(\mathbf{r}'', \boldsymbol{\alpha}'', \lambda)$ . The amount of scattered light is determined by the properties of the molecular and aerosol components of the atmosphere.

The radiance  $L_s(\mathbf{r}', \boldsymbol{\alpha}', \lambda)$  of the emissions of the artificial lamps used in outdoor lighting is sufficiently low to ensure that the propagation of light through the atmosphere takes place in a linear regime, avoiding nonlinear phenomena like thermal lensing, two-photon absorption and similar. This means that the light pollution spectral radiance arriving at the observer can be expressed as the sum of the contributions of all surrounding sources by means of a weighted integral of the kind

$$L(\mathbf{r}'', \boldsymbol{\alpha}'', \lambda) = \int_{\Omega'} \int_{A'} G(\mathbf{r}'', \boldsymbol{\alpha}''; \mathbf{r}', \boldsymbol{\alpha}'; \lambda) L_s(\mathbf{r}', \boldsymbol{\alpha}', \lambda) d^2\boldsymbol{\alpha}' d^2\mathbf{r}', \quad (\text{A } 4)$$

where the kernel  $G(\mathbf{r}'', \boldsymbol{\alpha}''; \mathbf{r}', \boldsymbol{\alpha}'; \lambda)$  is the spatial and angular PSF of the light pollution radiance, that is, the radiance produced at the observer location  $\mathbf{r}''$  from the direction  $\boldsymbol{\alpha}''$  due to a unit amplitude artificial light source located at  $\mathbf{r}'$  emitting in the direction  $\boldsymbol{\alpha}'$ . The integrals are extended to all possible emission directions in the source's reference frame,  $\Omega'$ , and to the whole territory containing artificial lights,  $A'$ . The precise form of the function  $G(\mathbf{r}'', \boldsymbol{\alpha}''; \mathbf{r}', \boldsymbol{\alpha}'; \lambda)$  depends on the details of the radiative transfer model used to compute the atmospheric propagation (e.g. single versus multiple scattering), the particular conditions of the atmosphere (specially the aerosol concentration profiles, albedos and angular phase functions), the spectral reflectance of the intervening terrain (through its bidirectional reflectance distribution function), and also on the presence of obstacles that could block the propagation of light in certain emission directions before it gets scattered towards the observer. A set of widely used models are available to determine  $G(\mathbf{r}'', \boldsymbol{\alpha}''; \mathbf{r}', \boldsymbol{\alpha}'; \lambda)$  for different atmospheres and with different levels of analytic and numerical complexity. The interested reader may want to consult [23–31] for full details of the most used ones.

Equation (A 4) can be interpreted as the result of an integral linear operator,  $\mathcal{L}_2$ , with parameters  $\mathbf{r}''$  and  $\boldsymbol{\alpha}''$ , acting on the variables  $\mathbf{r}'$ ,  $\boldsymbol{\alpha}'$  and  $\lambda$  of the spectral radiance of the outdoor lights, such that  $L(\mathbf{r}'', \boldsymbol{\alpha}'', \lambda) = \mathcal{L}_2\{L_s\}$ . Combining this equation with the one for the light pollution indicator,  $B(\mathbf{r}, \boldsymbol{\alpha}) = \mathcal{L}_1\{L\}$ , one immediately gets  $B(\mathbf{r}, \boldsymbol{\alpha}) = \mathcal{L}_1\{\mathcal{L}_2\{L_s\}\} = \mathcal{L}\{L_s\}$ , where  $\mathcal{L} = \mathcal{L}_1 \circ \mathcal{L}_2$  is the linear operator resulting from the composition of the actions of  $\mathcal{L}_1$  and  $\mathcal{L}_2$ . The explicit form of this action is

$$B(\mathbf{r}, \boldsymbol{\alpha}) = \int_{\Lambda} \int_A \int_{\Omega} \int_{\Omega'} \int_{A'} R(\mathbf{r}, \boldsymbol{\alpha}; \mathbf{r}'', \boldsymbol{\alpha}''; \lambda) G(\mathbf{r}'', \boldsymbol{\alpha}''; \mathbf{r}', \boldsymbol{\alpha}'; \lambda) L_s(\mathbf{r}', \boldsymbol{\alpha}', \lambda) d^2\boldsymbol{\alpha}' d^2\mathbf{r}' d^2\boldsymbol{\alpha}'' d^2\mathbf{r}'' d\lambda. \quad (\text{A } 5)$$

A simplified and useful expression can be obtained by making the only approximation we will use to apply this model, namely, that the artificial light sources are factorable [19] such that

$$L_s(\mathbf{r}', \boldsymbol{\alpha}', \lambda) = L_1(\mathbf{r}') L_2(\boldsymbol{\alpha}', \lambda). \quad (\text{A } 6)$$

This means that the light sources in the relevant surrounding territory have the same angular and spectral emission patterns,  $L_2(\boldsymbol{\alpha}', \lambda)$ , just differing in the absolute amount of emissions,  $L_1(\mathbf{r}')$ . Whereas this approximation may not hold for individual sources, it is expected to be valid for the overall emissions from patches of the territory with the typical pixel size of satellite imagery (of order of hundreds of metres long and wide). The dimensions of  $L_1$  and  $L_2$  can be arbitrarily chosen, as far as their product,  $L_s$ , has dimensions of spectral radiance.

By substituting equation (A 6) into equation (A 5) we get

$$B(\mathbf{r}, \boldsymbol{\alpha}) = \int_{\Lambda} \int_A \int_{\Omega} \int_{\Omega'} \int_{A'} R(\mathbf{r}, \boldsymbol{\alpha}; \mathbf{r}'', \boldsymbol{\alpha}''; \lambda) G(\mathbf{r}'', \boldsymbol{\alpha}''; \mathbf{r}', \boldsymbol{\alpha}'; \lambda) L_1(\mathbf{r}') L_2(\boldsymbol{\alpha}', \lambda) d^2\boldsymbol{\alpha}' d^2\mathbf{r}' d^2\boldsymbol{\alpha}'' d^2\mathbf{r}'' d\lambda. \quad (\text{A } 7)$$

Changing the order of integration and regrouping terms

$$B(\mathbf{r}, \boldsymbol{\alpha}) = \int_{A'} \left[ \int_{\Lambda} \int_A \int_{\Omega} \int_{\Omega'} \int_{\Lambda} R(\mathbf{r}, \boldsymbol{\alpha}; \mathbf{r}'', \boldsymbol{\alpha}''; \lambda) G(\mathbf{r}'', \boldsymbol{\alpha}''; \mathbf{r}', \boldsymbol{\alpha}'; \lambda) L_2(\boldsymbol{\alpha}', \lambda) d^2\boldsymbol{\alpha}' d^2\boldsymbol{\alpha}'' d^2\mathbf{r}'' d\lambda \right] L_1(\mathbf{r}') d^2\mathbf{r}' \quad (\text{A } 8)$$

or, equivalently, and simplifying the notation using  $B(\mathbf{r}, \boldsymbol{\alpha}) \equiv B(\mathbf{r})$  (the value of  $\boldsymbol{\alpha}$  can be considered as an implicit parameter of  $B$  and  $K$ )

$$B(\mathbf{r}) = \int_{A'} K(\mathbf{r}, \mathbf{r}') L_1(\mathbf{r}') d^2\mathbf{r}', \quad (\text{A } 9)$$



where  $K(\mathbf{r}, \mathbf{r}')$  is the overall PSF

$$K(\mathbf{r}, \mathbf{r}') = \int_A \int_{\Omega} \int_{\Omega'} \int_{\Lambda} R(\mathbf{r}, \boldsymbol{\alpha}; \mathbf{r}'', \boldsymbol{\alpha}''; \lambda) G(\mathbf{r}'', \boldsymbol{\alpha}''; \mathbf{r}', \boldsymbol{\alpha}'; \lambda) L_2(\boldsymbol{\alpha}', \lambda) d^2 \boldsymbol{\alpha}' d^2 \boldsymbol{\alpha}'' d^2 \mathbf{r}'' d\lambda, \quad (\text{A } 10)$$

This PSF depends on the kind of indicator and measuring instrument through  $R(\mathbf{r}, \boldsymbol{\alpha}; \mathbf{r}'', \boldsymbol{\alpha}''; \lambda)$ , on the atmospheric and geographical conditions through  $G(\mathbf{r}'', \boldsymbol{\alpha}''; \mathbf{r}', \boldsymbol{\alpha}'; \lambda)$ , and on the luminaires angular and spectral radiation pattern through  $L_2(\boldsymbol{\alpha}', \lambda)$ . For any set of such conditions a specific PSF shall be calculated.

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# **Alternativas y Antecedentes para la Actualización de la Normativa sobre Contaminación Lumínica**

**Informe Proyecto de Título de Ingeniero Eléctrico**



**Escuela de Ingeniería Eléctrica  
Facultad de Ingeniería**

**Valparaíso, 14 de julio de 2020**



Alternativas y Antecedentes para la Actualización de la  
Normativa sobre Contaminación Lumínica

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Informe Final para optar al título de Ingeniero Eléctrico,  
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## Resumen

La contaminación lumínica representa un problema importante en la sociedad actual, ya que afecta a las personas, a los animales y a las plantas, modificando los ciclos luz-oscuridad del día y la noche, por lo que es necesario que la actual normativa chilena se actualice.

La Commission Internationale de l'Eclairage en su CIE 126: Guía para minimizar el brillo del cielo, estandarizó una forma de controlar y medir el brillo del cielo, a partir de la medición del contraste, además presentó algunas medidas correctivas como la zonificación para realizar niveles de restricción, reducción de potencia programada, el uso de lámparas y luminarias monocromáticas, el control de la emisión de flujo luminoso hacia el hemisferio superior y el control de los factores de reflexión de las superficies. Estas medidas correctivas fueron tomadas por muchos países como base para realzar sus normativas sobre contaminación lumínica.

En el mundo cada vez son más países los que crean normativas para combatir la contaminación lumínica, principalmente buscando proteger sus cielos para la observación astronómica. También existen otros estados o países que se fundamentan en sus necesidades medio ambientales como es el caso de la legislación de Florida que busca proteger eclosión de las tortugas marinas, que confunden la luz de las luminarias con la luz de la luna, lo que provoca que se muevan en dirección opuesta al mar lo que produce su muerte. Las Islas Canarias en España fueron pioneras en legislaciones sobre contaminación lumínica para protección de cielos para observación astronómica, posteriormente Hawái (Estados Unidos), Lombardía (Italia), fueron las siguientes que mostraron avances importantes en cuanto a las restricciones.

En 1998 se crea la primera normativa chilena sobre contaminación lumínica, el DS N° 686/98 MINECON y posteriormente en el año 2012 el DS N° 43/2012 MMA que es la actual legislación nacional. Esta normativa se encuentra al nivel de las más importantes del mundo, posee restricciones importantes de emisión de flujo hacia el hemisferio superior y de espectro. Además, posee una fiscalización en el efluente que permite certificar las luminarias antes de su instalación en los proyectos de iluminación. Pese a ello se encuentran en evaluación nuevas restricciones a la actual normativa.

Palabras claves: contaminación lumínica, sky-glow, iluminación, normativa chilena sobre contaminación lumínica, alumbrado público.

## Abstract

The light pollution represents a major problem in today's society, since it affects people, animals and plants, modifying the light-dark cycles of day and night, so it is necessary for the current Chilean regulations to be updated.

The Commission Internationale de l'Eclairage in its CIE 126: Guide for minimizing sky glow, standardized a way to control and measure the brightness of the sky, based on the measurement of contrast, also presented some corrective measures such as the zoning to carry out restriction levels, programmed power reduction, the use of monochromatic lamps and luminaires, control of the emission of luminous flux to the upper hemisphere and control of surface reflection factors. These corrective measures were taken by many countries as a basis for enhancing their regulations on light pollution.

In the world, more and more countries are creating regulations to combat light pollution, mainly seeking to protect their skies for astronomical observation. There are also other states or countries that are based on their environmental needs, as is the case of Florida legislation that seeks to protect hatching from sea turtles, which confuse the light of the luminaries with the light of the moon, causing the sea moves in the opposite direction, causing its death. The Canary Islands in Spain were pioneers in legislation on light pollution for sky protection for astronomical observation, later Hawaii (United States), Lombardy (Italy), were the next to show significant progress in terms of restrictions.

In 1998 the first Chilean regulation on light pollution was created, DS N° 686/98 MINECON and later in 2012 DS N° 43/2012 MMA, which is the current national legislation. This regulation is at the level of the most important in the world, it has important restrictions on the emission of flux to the upper hemisphere and spectrum. In addition, it has an effluent control that allows the luminaires to be certified before their installation in lighting projects. Despite this, new restrictions to the current regulations are under evaluation.

Key words: light pollution, sky-glow, lighting, Chilean regulations on light pollution, public lighting.



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## Introducción

En la actualidad, Chile es el lugar más importante en el mundo para la observación astronómica. Esto se debe a que los cielos del norte de nuestro país poseen una transparencia única, además las bajas precipitaciones que se producen en la zona por estar emplazada en el desierto más árido del mundo favorecen su claridad.

La calidad del cielo, junto con condiciones políticas y económicas estables y favorables, han posibilitado la instalación de diversos proyectos astronómicos, dentro de los que destacan el Observatorio AURA, que posee telescopios en el Cerro Tololo y Cerro Pachón, El observatorio ESO que posee telescopios en La Silla y Paranal, el Observatorio CARNEGIE que se encuentra en Las Campanas, e incluso el proyecto ALMA, en el Llano de Chajnantor. Además, se estima que el año 2025, cuando todos los proyectos estén operando, el país, concentrará el 70% de la capacidad de astronómica a nivel mundial. Por lo tanto, la calidad de los cielos de la zona norte de nuestro país constituye un patrimonio ambiental que es necesario preservar.

El gran problema que amenaza la calidad de los cielos del norte es la contaminación lumínica generada por el alumbrado exterior, que en los lugares donde se concentra la población genera un brillo del cielo nocturno, lo que produce una disminución en el contraste, afectando así la calidad de los cielos para la observación astronómica. La contaminación lumínica se manifiesta en el aumento del brillo del cielo nocturno, por reflexión y difusión de la luz artificial en los gases y en las partículas del aire urbano, de forma que disminuye la visibilidad de las estrellas y demás objetos celestes.

Además de afectar la calidad de los cielos nocturnos la contaminación lumínica afecta directamente los seres humanos, al igual que casi todas las formas de vida en la tierra, los seres humanos adherimos al ciclo circadiano como nuestro reloj biológico. Este es un patrón de sueño y vigilia regulado por el día y la noche. En respuesta a este ciclo nuestro organismo posee ciclos hormonales que se ven afectados, como es el caso de la melatonina, que al inducir al sueño nos mantiene saludables, ya que esta hormona nos permite descansar, reparar tejidos y estimular el sistema inmunológico entre otros efectos beneficiosos. La exposición a la luz artificial durante la noche inhibe la producción de melatonina exponiendo al ser humano al riesgo de contraer enfermedades.

La contaminación lumínica también tiene efectos sobre la flora y fauna de los ecosistemas, se conocen diversos efectos causados en determinadas especies migratorias que se guían por la luz de las estrellas, o como la muerte masiva por deshidratación de determinadas tortugas marinas desorientadas por las luces en sus playas natales.

La Comisión Internacional de Iluminación, también conocida como la CIE por su título francés, la Commission Internationale de l'Éclairage, es la encargada de preparar y publicar normas, informes y otras publicaciones relacionadas con todos los asuntos relacionados con la ciencia, la tecnología y el arte en los campos de la luz y la iluminación, con el objetivo general de estandarizar estos temas a nivel mundial, nos entrega variadas herramientas, formas de medición y medidas correctivas para combatir el brillo del cielo en su informe técnico CIE 126: Guía para minimizar el brillo del cielo de 1997. Esta guía ha servido para desarrollar normas y procedimientos en los campos de la luz y la iluminación. Además, la CIE nos entrega la Guía para la limitación de los efectos de la contaminación lumínica producida por instalaciones de iluminación exteriores en donde se define la contaminación lumínica y se exponen los problemas que puede producir en las personas, animales y plantas.

En el área internacional, cada día se suman más países que legislan sobre la contaminación lumínica, apoyados en las diversas investigaciones que se han realizado sobre los posibles riesgos que esta representa, países como España que con el impulso del Instituto de Astrofísica de Canarias logra impulsar una de las primeras normativas de contaminación lumínica en el mundo. En Italia se crean normativas para la contaminación lumínica en 15 de las 20 regiones del país, además de la normativa no obligatoria creada por el Ente Italiano Di Normazione UNI que es aplicable a todo el país. En Estados Unidos 18 estados además del Distrito de Columbia y Puerto Rico tienen leyes vigentes para reducir la contaminación lumínica, en este país resaltan algunas normativas que no son en específico para proteger los cielos para la observación astronómica, además de tener en el condado de Hawaii una de las normativas más antiguas del mundo. En México el Estado de Baja California promulgo leyes para proteger el Observatorio Astronómico Nacional San Pedro Mártir. En Croacia pese a tener solo el Observatorio Astronómico de Višňjan, se encuentra elaborando una normativa para combatir la contaminación lumínica en el país. Y finalmente Francia, que se encuentra trabajando en las actualizaciones a su normativa de contaminación lumínica. Cada país trabaja en su normativa impulsado desde sus propios problemas medio ambientales o directamente para proteger sus respectivos observatorios astronómicos.

En este momento está vigente en nuestro país el DS N° 43/2012 MMA, que regula las emisiones de contaminación lumínica en la atmosfera en las regiones de Antofagasta, Atacama y Coquimbo, pero en este momento está siendo revisado, debido a que el decreto supremo N° 93, de 1995, del Ministerio Secretaría General de la Presidencia, establece que las normas ambientales deben ser revisadas al menos cada 5 años, tal como lo establece en el artículo 32, inciso cuarto de la ley N° 19.300.

El DS N° 43/2012 MMA, abarca la totalidad del territorio de las regiones de Antofagasta, Atacama y Coquimbo, en esta zona restringe la emisión de flujo luminoso hacia el hemisferio superior,

además posee restricciones en tres sectores del espectro electromagnético. Será necesario revisar si este decreto es suficiente para combatir la contaminación lumínica en Chile.

### **Objetivo general**

- Analizar las diferentes alternativas para la actualización de la normativa chilena sobre contaminación lumínica.

### **Objetivos específicos**

- Analizar los efectos de la contaminación lumínica en personas, animales, plantas y como afecta la observación astronómica.
- Estudiar la postura La Comisión Internacional de Iluminación ante la contaminación lumínica y sus recomendaciones para combatir el problema.
- Analizar las normativas internacionales más relevantes, para considerar posibles soluciones que hayan funcionado en otros países y que sean viables en el nuestro.
- Analizar el DS N° 686/98 MINECON y el DS N° 43/2012 MMA, para revisar los aspectos más relevantes y posibles mejoras ante la nueva actualización.
- Proponer alternativas viables para la actualización de la normativa chilena.

# 1 Contaminación Lumínica

La contaminación lumínica se puede definir como la emisión del flujo luminoso de fuentes artificiales nocturnas en intensidades, direcciones y/o rangos espectrales inadecuados e innecesarios para la función a la que está destinada.

## **Efectos en los seres humanos**

Los seres humanos han evolucionado con los ciclos de luz-oscuridad del día y la noche como casi todas las formas de vida en la tierra, los seres humanos adherimos al ciclo circadiano nuestro reloj biológico. Este es un patrón de sueño y vigilia regulado por el día y la noche. En respuesta a este ciclo nuestro organismo produce una hormona llamada melatonina, la que al inducir al sueño nos mantiene saludables, ya que éste nos permite descansar, reparar tejidos y estimular el sistema inmunológico entre otros efectos beneficiosos. La exposición a la luz artificial durante la noche puede causar la inhibición de la producción de algunas hormonas como la melatonina, exponiendo al ser humano al riesgo de contraer enfermedades. Además, el exceso de brillo impacta la visión, ya que debido a la mala iluminación exterior esta se degrada al disminuir el contraste, limitando la habilidad para ver en la noche. Las personas mayores se ven especialmente afectadas por este fenómeno. Los componentes ultravioletas y azules de la luz son potencialmente los más dañinos, como lo señala el comité científico de la Unión Europea [1].

Algunas personas con enfermedades que las hacen fotosensibles afirman que las lámparas de bajo consumo (principalmente lámparas compactas fluorescentes y diodos emisores de luz (LED)), que van sustituyendo a las lámparas incandescentes, empeoran sus síntomas e influyen en un gran número de enfermedades. También defienden que las medidas de protección, tales como cubrir las lámparas con una segunda envoltura disminuyendo así las emisiones UV, no son eficaces.

La contaminación lumínica tiene como manifestación más evidente el aumento del brillo del cielo nocturno, por reflexión y difusión de la luz artificial en los gases y en las partículas del aire urbano, de forma que se disminuye la visibilidad de las estrellas y demás objetos celestes.

## **Efectos en animales y plantas**

Desde la “Guía sobre la limitación de los efectos de la luz molesta de la instalación de iluminación exterior” [2], se puede extraer que la contaminación lumínica tiene efectos directos sobre



animales y plantas salvajes. Insectos, mamíferos, anfibios, reptiles, aves, peces y plantas ven afectados sus ciclos naturales producto de las alteraciones en sus ciclos de día noche.

El aumento en la ocupación del territorio debido a la expansión de las ciudades y los asentamientos humanos provoca que los hábitats, ecosistemas y comunidades sensibles, se encuentren expuestos al impacto de la luz artificial en la noche, así como a los efectos directos de la contaminación atmosférica que reducen la calidad del cielo nocturno. Nuestro conocimiento actual de la gama completa de consecuencias ecológicas derivadas de la pérdida de calidad del cielo nocturno es todavía muy limitado. Se hace necesario tomar una mayor conciencia y responsabilidad de la necesidad de profundizar en la investigación y el desarrollo de metodología científica capaz de evaluar el alcance de estos fenómenos. Actualmente se tiene abundante información sobre los efectos causados en determinadas especies migratorias que se guían por la luz de las estrellas, o sobre fenómenos tan evidentes como la muerte masiva por deshidratación de determinadas tortugas marinas desorientadas por las luces en sus playas natales. Pero la extensión de la noche artificial en el medio natural provoca otros impactos no tan conocidos o evidentes. Entre ellos destaca la alteración de los ciclos de ascenso y descenso del plancton marino, lo que afecta a la alimentación de las especies marinas, o las incidencias desfavorables sobre el equilibrio poblacional de muchas especies, resaltando ámbitos como la perturbación de la numerosísima fauna de insectos nocturnos y el equilibrio depredador-presa.

### **Efectos sobre la observación astronómica**

La contaminación lumínica es uno de los principales factores que amenazan la calidad del cielo para la observación astronómica. Es un problema que afecta principalmente a las ciudades y se produce cuando se aumenta el nivel de luz en el ambiente nocturno, producto de la iluminación artificial.

Esto se genera cuando la luz no es eficientemente dirigida para iluminar el suelo o las construcciones, sino que se dispersa hacia el cielo, afectando la posibilidad de ver las estrellas y el cielo nocturno.

Como se menciona en el DS N° 43/2012 MMA [3], la calidad astronómica de los cielos de las regiones de Antofagasta, Atacama y Coquimbo de nuestro país constituye un valioso patrimonio ambiental y cultural reconocido a nivel internacional como el mejor existente en el hemisferio sur para desarrollar la investigación astronómica.

La contaminación lumínica tiene como manifestación más evidente el aumento del brillo del cielo nocturno, por reflexión y difusión de la luz artificial en los gases y en las partículas del aire urbano, de forma que se disminuye la visibilidad de las estrellas y demás objetos celestes.

### **Conservación del cielo nocturno**

El Comité del Patrimonio Mundial de la UNESCO, en su 34° reunión celebrada en Brasilia (Brasil 2010), aprobó el estudio sobre los Sitios Patrimonio de la Astronomía y Arqueoastronomía, elaborado en el marco del Año Internacional de la Astronomía en 2009. Dicho estudio identifica ciertos lugares del mundo como patrimonio astronómico, entre los cuales se encuentra el Norte

de Chile, Canarias, Hawaii y Namibia, denominados como “Ventanas del Universo”, por ello es necesario proteger este importante recurso con una legislación

**Eficiencia energética**

La contaminación lumínica es el único tipo de contaminación que al evitarla puede llegar a producir un ahorro energético. Una luminaria que se encuentra instalada de manera que genere emisión de flujo hacia el cielo o en direcciones donde no es requerida, está generando un derroche de energía, esta energía a lo largo del país constituye un enorme gasto energético que puede ser evitado.

## 2 CIE 126: Guía para minimizar el brillo del cielo

La Comisión Internacional de Iluminación, también conocida como la CIE por su título francés, la Commission Internationale de l'Eclairage, es una institución que se dedica a la cooperación mundial y al intercambio de información sobre todos los asuntos relacionados con la ciencia y el arte de la luz y la iluminación, el color y visión, fotobiología y tecnología de imagen.

En la mayoría de los países del mundo tal como sucede en nuestro país, las observaciones astronómicas se ven perturbadas por la luz de las instalaciones de iluminación exterior. Parte de la luz se dispersa en la atmósfera y forma un halo luminoso. El fenómeno se conoce como Skyglow o brillo del cielo.

La CIE presentó el año 1997 la “Guía para minimizar el brillo del cielo”, en la cual presenta los aspectos teóricos y ofrece recomendaciones sobre los valores máximos permitidos para las instalaciones de iluminación en relación con las necesidades de las observaciones astronómicas, incluida la observación casual del cielo.

Los principales aspectos de la CIE número 126 o “Guía para minimizar el brillo del cielo” serán analizados a continuación.

### 2.1 Terminología

Se definen ciertos términos que se utilizarán para definir conceptos explicados en la “Guía para minimizar el brillo del cielo”

#### **El contraste**

Se define el contraste  $C$  entre un objeto relativamente pequeño con contornos definidos y su fondo inmediato como:

$$C = \frac{L_o - L_b}{L_b} \quad (2-1)$$

Con  $L_o$  la luminancia del objeto y  $L_b$  la luminancia del fondo. El contraste es un factor determinante en la visibilidad de los objetos. Los objetos con contornos borrosos se pueden usar una definición alternativa basada en una cuadrícula con bandas alternas claras y oscuras, con variaciones de luminancia sinusoidal:

$$C = \frac{L_1 - L_2}{L_1 + L_2} \quad (2-2)$$

Con  $L_1$  el más alto valor de luminancia en las bandas claras y  $L_2$  la mínima luminancia en las bandas oscuras.

### **Luz molesta**

Derrame de luz que, debido a los atributos cuantitativos, direccionales o espectrales en un contexto dado, provoca molestias, disconformidades, distracciones o una reducción en la capacidad de ver información esencial.

### **Sky glow**

El brillo del cielo nocturno que resulta de la reflexión de la radiación (visible y no visible), dispersada desde los componentes de la atmósfera (moléculas de gas, aerosoles y partículas) en la dirección de la observación. Se compone de dos componentes separados como sigue:

1. Sky glow natural: Es la parte del brillo nocturno atribuida a la radiación de cuerpos celestes y a procesos luminiscentes en la atmósfera superior de la tierra.
2. Sky glow artificial: Es la parte del brillo del cielo que es atribuible a fuentes de radiación hechas por el hombre (por ejemplo, iluminación artificial exterior), incluida la radiación que se emite directamente hacia arriba y la radiación que se refleja desde las superficies de la tierra.

### **Derrame de luz o stray light**

Es la luz emitida por una instalación de iluminación que queda fuera de los límites de la propiedad o zona para la cual está diseñada la instalación de iluminación.

### **Relación de salida de luz hacia el hemisferio superior (ULOR)**

Es la proporción del flujo de las lámparas de una luminaria que se emite por encima de la horizontal cuando la luminaria está montada en su posición normal de diseño.

### **Relación de salida de luz hacia el hemisferio superior instalada (ULOR<sub>ins</sub>)**

Es la proporción del flujo de una luminaria que se emite por encima de la horizontal cuando la luminaria está montada en su posición instalada, que puede ser diferente a su diseño.

## 2.2 Unidades de medición

La ingeniería de iluminación y la astronomía dependen de la fotometría. Los fundamentos son los mismos, pero las convenciones y las unidades prácticas son diferentes. En ingeniería de iluminación, las unidades fotométricas suelen estar relacionadas con la visión fotópica: el lumen (lm, la unidad de flujo luminoso), la iluminancia (lm/m<sup>2</sup> o lux), la intensidad luminosa (lm/sr o cd) y la luminancia (cd/m<sup>2</sup>). Las unidades fotométricas se ponderan de acuerdo con la curva de sensibilidad ocular, la conocida curva fotópica  $V(\lambda)$ .

En astronomía, la clasificación visual del objeto cósmico se basa en la 'magnitud' de los objetos luminosos, por ejemplo, las estrellas a medida que se presentan al ojo (mesópico). La escala de magnitud es esencialmente una escala logarítmica, donde una diferencia de magnitud de 5 se relaciona con una relación de flujo de 100. Se elige arbitrariamente una magnitud de 0; corresponde a un muy brillante, ya no sean las estrellas más brillantes. La fotometría astronómica se basa en el flujo de radiación de los objetos cósmicos. El flujo total medido por un determinado sistema de detección depende de la distribución espectral del flujo emitido por el objeto y de la distribución de sensibilidad espectral del detector (incluidos los filtros, si los hay). Por razones tradicionales, el flujo se expresa nuevamente en términos de magnitud. Debe tenerse en cuenta que el concepto 'magnitud' se usa de dos maneras distintas.

Como resultado de la diferencia en las definiciones (especialmente la ponderación de acuerdo con la respuesta espectral del detector), no hay una conversión directa de cantidades de ingeniería astronómica a iluminación. En la "Guía para minimizar el brillo del cielo", todos los valores fotométricos se expresan en unidades fotométricas fotópicas (lumen, lux, cd / m<sup>2</sup>, etc.). Se utiliza el siguiente factor de conversión: "una luminancia de  $3,2 \times 10^{-6}$  [cd/m<sup>2</sup>] corresponde a una magnitud de 26,33 por arsec<sup>2</sup>.

La influencia del brillo del cielo se evalúa comparando la luminancia con la luminancia del cielo en las condiciones de observación más favorables a la Tierra. El cielo nunca está absolutamente oscuro, incluso cuando se evitan todas las influencias hechas por el hombre. Por lo general, se toma para el mínimo práctico de la radiación de fondo natural el valor de magnitud 21,6 por arsec<sup>2</sup>, correspondiente a  $3,52 \times 10^{-4}$  [cd/m<sup>2</sup>].

## 2.3 Elementos que general el brillo del cielo

El resplandor del cielo es el resultado de la luz que se proyecta hacia el hemisferio superior y luego se dispersa de regreso a la superficie de la tierra. Parte de la luz parásita se proyecta directamente hacia arriba. Por lo general, esto se debe a un proyecto iluminación mal diseñado o instalado; Sin embargo, también puede ocurrir cuando la luz se dirige hacia arriba a propósito. Otra contribución importante a la luz parásita es la luz que está bien dirigida a los objetos, pero reflejada por ellos. Las superficies de las carreteras, el vidrio y los edificios reflejan una buena cantidad de luz incidente, y la luz reflejada generalmente sube.

Las principales fuentes de luz parásita que pueden interferir con las observaciones astronómicas son:

- Anuncios luminosos y vallas publicitarias
- Iluminación de áreas de ventas, estacionamientos, patios agrícolas, patios ferroviarios
- Iluminación de edificios, discotecas y monumentos
- Iluminación de invernaderos
- Iluminación de sitios industriales, aeropuertos y sitios de construcción
- Iluminación de instalaciones deportivas
- Alumbrado público y vial

Es muy difícil dar una idea general sobre la relevancia de cada una de estas fuentes de brillo del cielo. El peso relativo varía de un lugar a otro y está determinado en gran medida por las regulaciones nacionales o locales.

## 2.4 La formula del brillo del cielo

Para comprender el efecto del resplandor del cielo (difuso), uno debe darse cuenta de que todas las observaciones, tanto visuales, fotográficas como electrónicas, de objetos emisores de luz son esencialmente una observación de contraste. Tal como se definió el contraste en la terminología, la luminancia de un objeto será  $L_o$  y la luminancia de su fondo, contra la cual se debe observar el objeto, será  $L_b$ , el contraste  $C$  se define convencionalmente como se definió en la ecuación (2-3).

La luz dispersa en la atmosfera genera un velo ligero que se extiende sobre el campo de observación. Este velo también tiene una luminosidad, que se llamará  $L_v$ . la luminancia del velo debe agregarse a todas las luminancias en el campo de observación. Todos los contrastes se reducirán, como se puede mostrar, de la siguiente manera:

$$C' = \frac{(L_o + L_v) - (L_b + L_v)}{(L_b + L_v)} = \frac{L_o - L_b}{L_b + L_v} \quad (2-3)$$

Ya que el nominador permanece igual y el denominador siempre es mayor:

$$C' < C \quad (2-4)$$

Cuando el objeto a observar es una estrella, se podría suponer que su luminancia observada es igual a la luminancia (intrínseca) de su superficie y, por lo tanto, es mucho mayor que  $L_v$ . Sin embargo, mientras que una estrella distante es una aproximación geométrica cercana a una "fuente puntual", su imagen en el instrumento con el que se realizan las observaciones no es un punto en absoluto. la imagen nunca puede ser más pequeña que un cierto tamaño límite, incluso con una excelente óptica de "difracción limitada".

Para el ojo desnudo, que está bastante lejos de ser limitado por difracción, el diámetro mínimo de cualquier objeto visual es equivalente a casi un minuto de arco. Esto significa que, a simple vista,  $L_o$  no es muy grande. Por lo tanto, incluso para muy buenos observadores y en condiciones excelentes, el límite para la detección a simple vista es de aproximadamente la sexta magnitud.

La magnitud limitante se deduce de la definición de (diferencia en) magnitud:



$$m = 2,5 \cdot \log \left[ \frac{I_1}{I_2} \right] \quad (2-5)$$

Donde  $I_1$  e  $I_2$  son las intensidades luminosas de las dos estrellas que se comparan. El uso de la intensidad luminosa para caracterizar una estrella está sujeto a las restricciones establecidas en la sección 2.2 Unidades de medición.

Al evaluar la influencia del brillo del cielo, la luminancia más pequeña para las condiciones más favorables es  $L_{01}$  y bajo las condiciones de brillo del cielo  $L_{02}$ . La luminancia de fondo es  $L_b$  y  $L_v$  respectivamente. Con  $L_v = a \cdot L_b$ , y de acuerdo con las ecuaciones analizadas en el punto anterior, para la observación en el umbral de la sensibilidad de contraste,  $C$  es igual a  $C'$ :

$$C = C' = \frac{L_{01} - L_b}{L_b} = \frac{L_{02} - L_b}{L_b + a \cdot L_v} \quad (2-6)$$

Cuando  $L_b$  es pequeño en comparación con  $L_{01}$  y  $L_{02}$ ,  $L_b$  puede ignorarse en los denominadores. La ecuación anterior se convierte en:

$$(a + 1) = \frac{1}{\left[ \frac{L_{01}}{L_{02}} \right]} \quad (2-7)$$

Al insertar  $L_{01}$  y  $L_{02}$  para  $I_1$  e  $I_2$  en la ecuación anterior, se obtiene:

$$m = -2,5 \cdot \log[a + 1] \quad (2-8)$$

con  $m$  aumento en el umbral, o la disminución en la magnitud límite como resultado de la luminancia del velo. Esta fórmula es la fórmula del brillo del cielo.

## 2.5 Mediciones de resplandor del cielo

La guía también propone algunas formas de monitoreo del cielo nocturno, a través, de diversos métodos, que se detallan a continuación:

### Estudios de área

Por muchas razones, pueden ser necesarias encuestas sobre grandes áreas. El método debe ser simple y barato, y las evaluaciones deben ser realizadas por aficionados o incluso por laicos. Actualmente se utilizan dos sistemas.

1. Límite de evaluación de estrellas: Dentro de un área determinada del cielo (por ejemplo, entre cuatro estrellas conocidas) se cuenta el número de estrellas visibles. A partir del conocimiento de las magnitudes de las estrellas, se puede evaluar la magnitud de las estrellas que son "apenas" visibles (la estrella límite). Cuando se tiene en cuenta, por ejemplo, al utilizar los datos epidemiológicos bien conocidos sobre la distribución de la

agudeza visual, el método se puede utilizar a gran escala. No se recomienda el uso de binoculares, porque la calidad óptica de los binoculares varía considerablemente.

2. Evaluación por fotografías: Las evaluaciones fotográficas utilizan una gran cantidad de observadores aficionados que toman fotografías con una cámara normal (estacionaria) y con una película de diapositivas normal del área cenital en su propio vecindario. La cámara debe tener una longitud focal de 50 - 55 mm y una relación F de 2,0 o menos. Las exposiciones se realizan en 400 películas de diapositivas inversas en color ASA en una parada de 4, con un tiempo de exposición de 80 segundos. A partir de la relación en la densidad de la película entre el fondo y la pista de estrellas conocidas, se puede evaluar la luminosidad del cielo.
3. Evaluaciones continuas: Se pueden realizar levantamientos continuos o casi continuos mediante el monitoreo del brillo del cielo. Estos levantamientos se realizan en ubicaciones seleccionadas, por ejemplo, en una ubicación que se considera como el sitio de un observatorio mayor. Los datos para un período de al menos un año (para incluir cualquier variación estacional) proporcionarán información adecuada sobre la idoneidad de esa ubicación. La encuesta se puede hacer con el equipo fotométrico estándar que está disponible en todos los observatorios principales. Por lo general, las mediciones del brillo del cielo no incluyen elevaciones inferiores a 15 grados. En muchos casos, las medidas se continúan después de la construcción del observatorio. Actualmente, se recopilan los datos de varios observatorios importantes de todo el mundo.
4. Monitoreo del cielo a través de telescopios: Para realizar un monitoreo preciso del sitio en los observatorios existentes, se pueden usar telescopios astronómicos normales con el equipo estándar para realizar fotometría. Esto se hace en muchos observatorios de forma rutinaria.

## **2.6 El sistema CIE para zonificación**

La zonificación es un sistema que se establece como una base para las regulaciones ambientales. La idea básica es que, en caso de que la actividad contaminante no pueda evitarse por completo, las consecuencias ambientales de la contaminación no son igualmente perjudiciales para todos los lugares. Las zonas y los requisitos de zona se establecen en relación con las actividades (humanas y no humanas) en estas zonas.

La zonificación no detiene la contaminación ambiental, pero puede servir como marco de referencia para la legislación y regulación anticontaminación, como se puede observar en la Tabla 2-1.

Tabla 2-1: Descripción de las zonas ambientales según el Sistema de Zonificación CIE

| Clasificación de zona | Descripción                                                                                                                                                               |
|-----------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| E1                    | Área con paisajes intrínsecamente oscuros: Parques nacionales, áreas de excepcional belleza natural, donde las carreteras generalmente no están iluminadas                |
| E2                    | Área de "bajo brillo": generalmente áreas residenciales urbanas y rurales exteriores, donde las carreteras están iluminadas según el estándar de carreteras residenciales |
| E3                    | Área de "brillo del distrito medio": generalmente áreas residenciales urbanas                                                                                             |
| E4                    | Área de "alto brillo del distrito": generalmente áreas urbanas que tienen un uso mixto de suelo residencial y comercial con alta actividad nocturna                       |

Para la iluminación exterior general, para cada zona, se establecen límites para la emisión de luz de la instalación en su conjunto y del equipo a utilizar. Para limitar la interferencia de las luminarias a las observaciones astronómicas, la introducción de zonas tiene dos propósitos. Por un lado, permiten determinar los requisitos de iluminación en relación con las actividades astronómicas que se realizan o planifican en esa zona en particular; por otro lado, permiten determinar los requisitos de iluminación en otras zonas, adyacentes o no, en relación con esas actividades. Los requisitos cuantitativos se analizan a continuación.

## 2.7 Recomendaciones para límites de brillo de cielo

En la Tabla 2-2, que se presentará a continuación se presentan las recomendaciones para la limitación del brillo del cielo. Se dan como el valor máximo permitido de  $ULOR_{ins}$  (la relación de salida de luz ascendente instalada), expresada como un porcentaje del flujo luminoso de la luminaria para cada una de las cuatro zonas ambientales. Este límite es válido para cada luminaria individual en esa zona. Cabe mencionar que el  $ULOR_{ins}$  total por zona, o el  $ULOR_{ins}$  promedio por zona serían los valores más relevantes. Actualmente, sin embargo, no hay medidas cuantitativas disponibles para estas cantidades.

Los valores citados en la tabla que se presentará a continuación se considerarán valores limitantes. Los diseñadores de iluminación deben hacer todo lo posible para cumplir con las especificaciones de zonas más bajas para todos los diseños de iluminación. Eso implica que los ingenieros de iluminación deberían tratar de diseñar instalaciones donde la contaminación lumínica sea menor que la requerida para la zona donde se ubica la instalación. Por lo tanto, las especificaciones recomendadas en la Tabla 2-2 solo deben usarse para aquellas instalaciones en aquellas zonas más bajas para las que no son posibles especificaciones más estrictas.

Tabla 2-2: Recomendaciones para límites de brillo de cielo.

| Clasificación de zonas | ULOR <sub>ins</sub> (%) | Actividad astronómica                              |
|------------------------|-------------------------|----------------------------------------------------|
| E1                     | 0                       | Observatorios de norma internacional               |
| E2                     | 0 – 5                   | Posgrado y estudios académicos                     |
| E3                     | 0 – 15                  | Estudios de pregrado, observaciones de aficionados |
| E4                     | 0 - 25                  | Observación casual del cielo                       |

La contaminación lumínica en un punto en una zona específica (el 'punto de referencia', por ejemplo, observatorios astronómicos, parques naturales, etc.) está determinada no solo por la iluminación en esa zona sino también por la iluminación en las zonas vecinas, así como por las dimensiones de estas zonas. Deben tenerse en cuenta los requisitos de iluminación en zonas alrededor de esa ubicación específica. La influencia de la iluminación en las zonas vecinas sobre el brillo general del cielo en la ubicación de referencia (punto de referencia) depende de la distancia entre los límites de la zona y el punto de referencia.

En la tabla que se presentará a continuación, se dan recomendaciones para la distancia mínima entre el límite de una zona y el punto de referencia. Esta distancia es crítica para el tamaño límite de diferentes zonas alrededor de una ubicación con una clasificación de zona específica; se determinará en la dirección más desfavorable con respecto a las fuentes de resplandor del cielo. Los valores citados en la tabla se derivan de la experiencia práctica en un número limitado de estudios de casos.

La evaluación completa de los requisitos de iluminación para la reducción de la influencia del brillo del cielo consiste en la combinación de las Tablas 2-1 y la Tabla 2-2. Las distancias dadas dan como resultado una restricción de brillo del cielo a un nivel que es "simplemente aceptable". Para garantizar condiciones de observación favorables, se recomienda duplicar las distancias indicadas.

Tabla 2-3: Distancia mínima (en km) entre el límite de la zona y el punto de referencia.

| Clasificación de zonas circundantes (Km) hasta el límite del entorno |         |             |         |
|----------------------------------------------------------------------|---------|-------------|---------|
| Clasificación de zona<br>del punto de<br>referencia                  | E1 – E2 | E2 – E3     | E3 – E4 |
| E1                                                                   | 1       | 10          | 100     |
| E2                                                                   |         | 1           | 10      |
| E3                                                                   |         |             | 1       |
| E4                                                                   |         | Sin límites |         |

## 2.8 Medidas correctivas

La forma más obvia de evitar o al menos reducir la perturbación de las observaciones astronómicas es evitar la iluminación que no es estrictamente necesaria. La cantidad de luz molesta de las instalaciones que es necesaria se puede reducir mediante varias medidas correctivas.

1. Reducción de potencia programada: Apagar las luces por completo puede interferir con otros aspectos importantes de la sociedad. En la mayoría de los casos, los requisitos cambian durante la noche; Después de un cierto momento (fijo o flexible) en el tiempo, la iluminación puede reducirse. La forma más sencilla de apagar las luces cuando ya no se necesitan. Para situaciones en las que después del horario límite todavía se necesita algo de luz, se pueden usar múltiples linternas de fuente. Una solución más energéticamente eficiente es usar atenuadores. Muchos estatutos y ordenanzas locales imponen restricciones de tiempo en el uso de tales instalaciones de iluminación.
2. Luz monocromática: Una de las formas más efectivas para reducir la interferencia es el uso de fuentes de luz (cuasi) monocromáticas, la guía recomienda el uso de lámparas de vapor de sodio de baja presión, pero en la actualidad este tipo de lámparas se encuentran obsoletos, dando paso a nuevas tecnologías como las lámparas de vapor de sodio de alta presión y las luminarias LED que ya poseen tecnología monocromática.
3. Uso de filtros: Cuando no se pueden usar lámparas que emitan luz monocromática, filtrar la radiación cerca de los extremos de la región visible del espectro puede reducir la interfaz. Estas regiones contribuyen poco a la sensación visual. Varios estatutos y ordenanzas para áreas cercanas a los observatorios restringen la emisión de la radiación

en estas regiones espectrales. Esto se puede hacer mediante la elección de la fuente de luz o mediante filtros incorporados en las luminarias.

4. Control de la emisión hacia el hemisferio superior: Consiste principalmente en evitar que la luz se emita por encima de la horizontal. En muchos casos, las medidas para reducir el ULOR y el ULORinst son similares a las de mejorar la eficiencia de la iluminación. Es posible usar viseras o paralúmen para evitar la emisión.
5. Influencia de los factores de reflexión de las superficies: En muchos casos, el factor de reflexión en los alrededores se puede adaptar al uso del suelo en la zona. Como la visibilidad (o la eficiencia de la tarea) casi siempre aumenta al aumentar la luminancia, generalmente el nivel de iluminación general puede ser menor cuando las superficies relacionadas con la tarea tienen un factor de reflexión alto. La luminancia es proporcional al flujo luminoso instalado y al reflejo. Por lo tanto, una superficie oscura requiere más lámparas (o más fuertes) que una superficie de color claro para llegar a la misma luminancia. Sin embargo, la mayoría de los demás parámetros técnicos de la luz (luz molesta, deslumbramiento) son directamente proporcionales al flujo luminoso instalado. En otras palabras, las superficies oscuras relacionadas con tareas a menudo conducen a una 'sobreluminación'. Un ejemplo es la superficie de una carretera. Lo mismo vale para los campos de juego en estadios deportivos, etc. Por otro lado, la luz reflejada contribuye considerablemente a desperdiciar luz. Por lo tanto, el factor de reflexión de las superficies no relacionadas con la tarea debe ser lo más bajo posible. En la práctica, sin embargo, a menudo no es posible manipular las características reflexivas en el mundo real.



## 3 Escenario Internacional

Debido a los muchos efectos negativos producidos por la contaminación lumínica, algunos países, alrededor del mundo decidieron realizar normativas al respecto, a continuación, se revisarán algunos reglamentos que se han realizado a nivel mundial. Estas normas fueron elegidas porque sirvieron de guía para muchos países en materia de prevención del brillo del cielo, así como también se incluyen normativas que se encuentran en desarrollo donde se pueden apreciar medidas cada vez más restrictivas, tanto en emisión hacia el hemisferio superior como en el espectro, a través de la temperatura de color correlacionada, entre otras.

### 3.1 Ley de protección de los cielos de España

El Gobierno Español a propuesta del parlamento de las Islas, aprobó el 31 de octubre de 1988 la Ley sobre Protección de la Calidad Astronómica de los Observatorios del Instituto de Astrofísica de Canarias Ley 31 de 1988 [4], del 31 de octubre y el 13 de marzo de 1992 se aprobó el Reglamento que la regula Real Decreto 243 de 1992 [5]. Posteriormente a lo largo de los años se creó un reglamento que regula la eficiencia energética en instalaciones de alumbrado exterior y sus instrucciones técnicas complementarias Real Decreto 1980 de 2008 [6] e ITC-EA-03 [7]. Estos reglamentos se detallan a continuación:

#### Islas Canarias, RD 243 de 1992

Debido a que la atmósfera por encima de las cumbres de las islas de Tenerife y de La Palma reúne condiciones excepcionales para realizar observaciones astronómicas, se comenzaron a concentrar telescopios y otras instalaciones astrofísicas muy importantes al amparo de Acuerdos Internacionales, establecidos por España. Para evitar el deterioro de estas condiciones privilegiadas como consecuencia del incremento de la luz parásita debida al alumbrado de exteriores, al funcionamiento de emisoras radioeléctricas o a la contaminación atmosférica producida por las industrias y servicios, incluidos las estelas y los gases de escape de los aviones se decidió realizar un reglamento al respecto, sobre protección de la calidad astronómica de los Observatorios del Instituto de Astrofísica de Canarias.

Se expondrán los puntos más importantes respecto a la contaminación lumínica a continuación:

1. El alumbrado de exteriores puede ser degradante de la calidad astronómica de los observatorios en la isla de La Palma, quedan sujetos a las limitaciones establecidas en la Ley 31 de 1988, de 31 de octubre, sobre protección de la calidad astronómica de los observatorios del Instituto de Astrofísica de Canarias (IAC), en la forma establecida en el presente Reglamento.
2. Se considera alumbrado de exteriores, a los efectos de este Reglamento, todo tipo de alumbrado realizado con instalaciones estables o esporádicas, en recintos abiertos para su utilización nocturna. De acuerdo con esta definición, serán considerados fundamentalmente como alumbrados exteriores los siguientes: Alumbrado vial. Alumbrado ornamental y de parques. Alumbrado de instalaciones deportivas. Alumbrado de instalaciones recreativas. Anuncios luminosos. Alumbrado de seguridad Alumbrado de escaparates zonas comerciales. Alumbrado exterior de viviendas particulares.
3. Están excluidas del ámbito de aplicación del régimen de protección, la luz producida por la combustión de gas natural u otros combustibles, la iluminación de aeropuertos que sea necesaria para garantizar la navegación aérea y la iluminación de vehículos automóviles.
4. Todos los alumbrados de exteriores deberán evitar la emisión de luz por encima del horizonte y habrán de realizarse de forma y con lámparas que produzcan la mínima perturbación de las observaciones astronómicas.
5. En todo alumbrado exterior la distribución espectral de la luz emitida por las lámparas ha de ser tal que la suma de las radiancias espectrales para todas las longitudes de onda menores de 440 nm sea inferior al 15 por 100 de su radiancia total. Si es superior deberá aplicarse un filtro que cumpla el límite anterior. El filtro deberá ser sometido a inspección con una periodicidad mínima de dos años.
6. Las luminarias para alumbrado vial deben estar construidas de modo que toda la luz emitida se proyecte por debajo del plano horizontal tangente al punto más bajo de luminaria. Las luminarias deben instalarse sin ninguna inclinación.
7. En el alumbrado vial las únicas lámparas permitidas serán las de vapor de sodio a baja presión. El uso de las de alta presión podrá autorizarse únicamente en determinadas zonas urbanas y siempre con la correspondiente autorización o licencia, de conformidad con lo establecido en este Reglamento.
8. No podrá utilizarse en el alumbrado vial las lámparas de vapor de mercurio color corregido y halogenuros metálicos.
9. Las instalaciones de alumbrado vial dispondrán bien de dispositivos para controlar el flujo luminoso o bien de doble lámpara por luminaria que permitan reducir el flujo luminoso a un tercio del normal a partir de las doce de la noche, sin detrimento de la

uniformidad. Esta reducción no será aplicable cuando la iluminancia normal sea inferior a los niveles establecidos para la seguridad vial.

10. El alumbrado ornamental de edificios públicos monumentos y jardines podrá realizarse con cualquier tipo de lámparas, siempre que permanezca apagado después de las doce de la noche. Se procurará que la luz vaya siempre dirigida de arriba hacia abajo.
11. El alumbrado de instalaciones deportivas y de recreo podrá efectuarse con cualquier tipo de lámparas, pero deberá permanecer apagado después de las doce de la noche. Dicho límite horario podrá prolongarse para actividades singulares, en los términos de la correspondiente autorización.
12. En los anuncios luminosos podrán utilizarse tubos de descarga de alta tensión a través de hidrógeno, helio, neón, argón, kriptón, xenón o mercurio a muy bajas presiones, así como lámparas fluorescentes, incandescentes o sodio de baja presión, siempre que los anuncios queden apagados a partir de las doce de la noche. No podrán utilizarse proyectores o láseres con fines publicitarios recreativos o culturales.
13. Para evaluar el efecto (I) de un núcleo, con un flujo total de F lúmenes instalados a una distancia en kilómetros d, del observatorio del Roque de los Muchachos, se aplicará la siguiente fórmula empírica.

$$I = \frac{F}{3,5 \cdot 10^5 \cdot d^{1,1} \cdot e^{0,07 \cdot d}} \quad (3-1)$$

La suma de los efectos I de todos los núcleos urbanos situados en cualquier sector de 45 grados, cuyo vértice sea el observatorio del Roque de los Muchachos, no podrá exceder de la unidad, una vez aplicado el correspondiente factor de simultaneidad. Para cada zona de la isla de La Palma, no se podrán rebasar los límites de flujo total instalado que figura en el anexo a este Reglamento.

### **Reglamento de eficiencia energética en instalaciones de alumbrado exterior RD 1890 de 2008 y sus instrucciones técnicas complementarias ITC-AE-03**

Este reglamento tiene como objetivo establecer las condiciones técnicas de diseño, ejecución y mantenimiento que deben reunir las instalaciones de alumbrado exterior, pese a ser diseñado para mejorar la eficiencia y ahorro energético, así como la disminución de las emisiones de gases de efecto invernadero, posee una sección que limita el resplandor luminoso nocturno o contaminación lumínica, determinando los niveles de emisión de flujo hacia el hemisferio superior.

La tabla 3-1 que se obtiene desde la ITC-AE-03, plantea la clasificación de las diferentes zonas en función de su protección contra la contaminación lumínica, según el tipo de actividad a

desarrollar en cada una de las zonas, esta tabla está claramente influenciada por la Guía para minimizar el cielo nocturno de la CIE.

Tabla 3-1: Descripción de las zonas de protección contra la contaminación luminosa

| Clasificación de zona | Descripción                                                                                                                                                                                                                                                          |
|-----------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| E1                    | Área con entornos o paisajes oscuros: Observatorios astronómicos de categoría internacional, parques nacionales, espacios de interés natural, áreas de protección especial (red natura, zonas de protección de aves, etc.), donde las carreteras están sin iluminar. |
| E2                    | Área de brillo o luminosidad baja: Zonas periurbanas o extrarradios de las ciudades, suelos no urbanizables, áreas rurales y sectores generalmente situados fuera de las áreas residenciales urbanas o industriales, donde las carreteras están iluminadas.          |
| E3                    | Área de brillo o luminosidad media: Zonas urbanas residenciales, donde las calzadas (vías de tráfico rodado y aceras) están iluminadas.                                                                                                                              |
| E4                    | Área de brillo o luminosidad alta: Centros urbanos, zonas residenciales, sectores comerciales y de ocio, con elevada actividad durante la franja horaria nocturna.                                                                                                   |

Se limitarán las emisiones luminosas hacia el cielo en las instalaciones de alumbrado exterior, con excepción de las de alumbrado festivo y navideño. El flujo hemisférico superior instalado a instalar en cada zona E1, E2, E3 y E4, no superará los límites establecidos en la Tabla 3-2 que también se obtiene desde la ITC-AE-03 con valores similares a los entregados por la Guía para minimizar el cielo nocturno de la CIE.

En la Zona E1 se utilizarán lámparas de vapor de sodio. Cuando no resulte posible utilizar dichas lámparas, se procederá a filtrar la radiación de longitudes de onda inferiores a 440 nm.

### Control del Brillo del Cielo Nocturno

En Galicia, se ha implementado un sistema de medición del brillo del cielo nocturno en paralelo con las mediciones meteorológicas, esta red es fruto de la colaboración entre MeteoGalicia [8] y la Universidad de Santiago de Compostela, siendo su principal función monitorizar de forma continua la evolución del brillo del cielo en diferentes lugares de Galicia, poniendo los datos adquiridos a disposición de la ciudadanía y de la comunidad científica.

La Red utiliza detectores de luminancia SQM-LR (Unihedron, Canadá). Estos detectores están equipados con un sensor de luz TSL237, un sensor de temperatura y un microcontrolador encargado de compensar la influencia de la temperatura en las lecturas del sensor y formatear la

información para su envío a través de una interfaz RS232. Las medidas proporcionadas por los sensores SQM-LR vienen dadas en mag/arcsec<sup>2</sup> que corresponden a una banda fotométrica propia que abarca la mayor parte del espectro visible.

Tabla 3-2: Valores límite del flujo hemisférico superior instalado

| Clasificación de zonas | Flujo hemisférico superior instalado $FHS_{inst}$ |
|------------------------|---------------------------------------------------|
| E1                     | $\leq 1 \%$                                       |
| E2                     | $\leq 5 \%$                                       |
| E3                     | $\leq 15 \%$                                      |
| E4                     | $\leq 25 \%$                                      |

### 3.2 Reglamentos de Protección de los cielos de Italia.

En 1999 se creó la primera normativa para regular la contaminación lumínica en Italia la cual fue la UNI 10819, que, pese a no ser una normativa obligatoria, sirvió como punto de partida para otras normativas a nivel regional.

La norma UNI 10819 fue rápidamente sustituida por la ley regional en Lombardía en el año 2000 y posteriormente por las diferentes leyes de cada región, siendo 15 regiones de un total de 20, las que crearon sus respectivas legislaciones, las regiones del país que crearon sus respectivas normativas fueron: Lombardía 17/2000, Emilia-Romagna 113/2003, Marche 10/02, Lazio 23/00, Campania 13/02, Veneto 22 / 97, Toscana 37/00, Piamonte 31/00, Valle de Aosta 17/98, Basilicata 41/00, Abruzzos 12/05, Umbría 20/05, Puglia 15/05, Friuli-Venecia Julia 15/07, Liguria 22/07) que cubren una gran parte de la población italiana y las principales ciudades (Milán, Roma, Venecia, Florencia, Bolonia, Nápoles).

A continuación, se revisan los principales aspectos de la UNI 10819 y la ley regional de Lombardía que se consideran los modelos seguidos por las otras normativas del país.

#### La UNI 10819 [9]

En Italia en 1999 la UNI (Ente Nazionale Italiano di Unificazione), que es reconocida por el Estado italiano y por la Unión Europea, y representa la actividad legislativa italiana en la Organización Internacional de Normalización (ISO), y Comité Europeo de Normalización (CEN), creó la normativa UNI 10819 para regular la contaminación lumínica.

Esta norma proporciona los requisitos de los sistemas de iluminación externos para limitar la dispersión hacia el hemisferio superior del flujo luminoso proveniente de fuentes de luz artificial.

No considera la limitación de la luminancia nocturna del cielo, debido al reflejo de las superficies iluminadas o a condiciones locales particulares, incluida la contaminación atmosférica. La norma se aplica sólo a las plantas de nueva construcción.

El propósito de la UNI 10819 es proteger los observatorios astronómicos profesionales y no profesionales, prohibiendo o limitando el uso de la iluminación, en un área de 25 km para el primero y 10 km para el segundo. Para los observadores profesionales, en un radio de un kilómetro, se prohíben los haces de luz fijos o giratorios, que emiten cualquier emisión hacia el hemisferio superior o que pueden reflejarse hacia el cielo, los valores se pueden apreciar en la Tabla 3-3, esta normativa está fuertemente influenciada por la Guía para minimizar el brillo del cielo de la CIE.

Tabla 3-3: Zonificación propuesta en la UNI 10819.

| Clasificación de zona | Descripción                                                                                                                                                                                        |
|-----------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Zona 1                | Área altamente protegida, con iluminación limitada como por ejemplo los observatorios astronómicos. Radio desde el centro de observación $R = 5 \text{ Km}$ .                                      |
| Zona 2                | Área protegida alrededor de la zona 1 o alrededor de observatorios nacionales. Radio desde el centro de observación $R = 5, 10 \text{ o } 15 \text{ Km}$ dependiendo de la importancia del centro. |
| Zona 3                | Territorio nacional no clasificado en zonas 1 y 2.                                                                                                                                                 |

En función de la distancia de los centros de observación oficialmente reconocidos, el territorio municipal se clasifica idealmente en una de las áreas indicadas anteriormente, si el mismo territorio está dividido en varias partes por los círculos de influencia, a cada parte se le debe asignar el área respectiva de pertenencia o El área más protegida se extiende a toda el área municipal.



Tabla 3-4: Clasificación de los tipos de instalaciones regulados.

| Clasificación de zona | Descripción                                                                                           |
|-----------------------|-------------------------------------------------------------------------------------------------------|
| Tipo A                | Instalaciones donde la seguridad es una prioridad, por ejemplo, alumbrado público, áreas verdes, etc. |
| Tipo B                | Instalaciones deportivas, centro comercial e instalaciones recreativas, instalaciones de jardín.      |
| Tipo C                | Plantas de interés ambiental.                                                                         |
| Tipo D                | Instalaciones publicitarias.                                                                          |
| Tipo E                | Plantas ornamentales temporales (luces navideñas).                                                    |

La UNI 10819 introduce un parámetro llamado "Relación de emisión más alta" (Rn) que representa el porcentaje de flujo luminoso emitido hacia arriba por un sistema de iluminación en relación con el flujo total producido.

Los tipos de luminarias destinadas a cada sistema están definidos por el PRIC (plan regulador de iluminación municipal), que establece el valor máximo de Rn para cada uno de ellos de modo que en general en todo el territorio municipal los valores prescritos por la tabla o por las regulaciones municipales si se exceden los existentes. Para cumplir con el estándar, un sistema (o simplemente un dispositivo) debe cumplir con el requisito indicado en la Tabla 3-5.

Tabla 3-5: Valores límite del parámetro Rn

| Clasificación de zonas | Planta tipo A (Carretera) Rn % | Planta tipo A (No vial), B, C, D Rn % |
|------------------------|--------------------------------|---------------------------------------|
| Zona 1                 | < 1                            | < 1                                   |
| Zona 2                 | < 3                            | < 3                                   |
| Zona 3                 | < 3                            | < 23                                  |

### La ley regional de Lombardía

La Ley Regional de Lombardía n. 17 de 2000, la resolución posterior del consejo regional n. 7/6162, la ley regional n.38 de 2004 y la actualización del 2015 [10], se consideran entre las más avanzadas

del mundo y esto por algunas características innovadoras en comparación con otras regulaciones que operan en el sector.

En primer lugar, la ley regional cubre todo el territorio y no solo áreas pequeñas alrededor de áreas particulares cerca de observatorios o parques naturales (zonas de amortiguamiento). Esto se debe a que tiene como objetivo proteger a toda la población de la contaminación lumínica.

Además, esta ley utiliza la intensidad luminosa de las luminarias como un parámetro técnico y ya no es el antiguo método de flujo disperso en el hemisferio superior.

Estas normas tienen como objetivo principal la reducción de la contaminación lumínica, el consumo de energía y proporcionan los siguientes criterios para la iluminación exterior:

Características técnicas de los sistemas:

- Intensidad luminosa máxima para  $\gamma \geq 90^\circ$ , entre 0 y 0,49 cd por 1000 lm.
- Uso de lámparas con alta tecnología y eficiencia luminosa, tales como sodio de alta y baja presión. Solo en los casos en que es esencial una alta reproducción cromática es posible utilizar lámparas de sodio de amplio espectro, halogenuros metálicos, fluorescentes compactas y de luz blanca.
- Luminancia  $\geq 1$  [cd/m<sup>2</sup>] para todas las superficies iluminadas, sujeto a las diversas disposiciones relacionadas con la seguridad.
- Reducción de la emisión de luz dentro de las 24:00 horas en una extensión no inferior al 30 %, siempre que la seguridad no se vea comprometida.
- Para los sistemas existentes, se debe cambiar la inclinación de las luminarias de modo que para  $\gamma \geq 90^\circ$  la intensidad luminosa no exceda de 0,49 cd por 1000 lm.
- Relación entre la interdistancia y la altura de las fuentes de luz no inferior a 3,7. Se permiten soluciones alternativas solo en la medida en que sean funcionales para la mejor eficiencia general certificada de la planta.

Criterios adicionales para instalaciones específicas:

- Instalaciones extraurbanas: iluminación de autopistas, circunvalaciones, circunvalaciones, etc. debe garantizarse con el uso, preferiblemente de lámparas de sodio de baja presión (o alta presión).
- Áreas grandes: la iluminación de estacionamientos, plazas, plazas y otras superficies similares debe garantizarse con el uso, preferiblemente, de lámparas de sodio de alta o baja presión.
- Centros históricos y rutas comerciales: evitan que el flujo luminoso sea interceptado significativamente por el follaje de los árboles.
- Instalaciones deportivas: las lámparas de halogenuros metálicos están permitidas cuando se necesita una alta reproducción cromática, el uso de proyectores asimétricos para sistemas a gran escala; Cuando se prevé la filmación de la televisión, es posible combinar

haces concentrados. Sistemas de variación de luminancia en relación con actividades o eventos (entrenamiento, competencias, etc.).

- La iluminación de los edificios y monumentos debe estar pastando de arriba a abajo; solo en casos de probada inaplicabilidad del método y solo para artefactos de valor artístico, arquitectónico e histórico comprobados, se permiten otras formas de iluminación siempre que los haces de luz permanezcan dentro del perímetro de este, la luminancia no exceda de 15 lux. La emisión máxima fuera del indicador que debe encenderse no supera los 5 lux y los dispositivos se apagan a las 24:00 horas.
- Para las señales con su propia iluminación, el flujo total emitido no debe exceder los 4500 lm.

Criterios adicionales para zonas de amortiguación:

- Las nuevas plantas deben estar equipadas con lámparas de sodio de alta o baja presión; en caso de imposibilidad material de lámparas con eficiencia y reguladores de flujo similares.
- Los dispositivos altamente contaminantes como globos, globos con aletas de protección, sistemas de luz indirecta, linternas o similares, deben tener para  $\gamma \geq 90^\circ$ , intensidad luminosa  $\geq 15$  cd por 1000 lm.
- Las instalaciones existentes, si bien mantienen los niveles mínimos de seguridad, si es necesario, se pueden usar con variadores de flujo, se pueden dividir en un 50 % entre las 11:00 p.m. durante el período de tiempo solar y las 12:00 a.m. en el periodo de verano.

Excepciones:

- Todas las fuentes de luz internalizadas.
- Plantas construidas con un máximo de 3 centros de luz con fuentes de luz con una emisión máxima de 1500 lm cada uno.
- Plantas construidas con más de 3 centros de luz con fuentes de luz con una emisión máxima de 1500 lm cada una y flujo total emitido desde todos los centros de luz de menos de 2250 lm por  $\gamma \geq 90^\circ$ .
- Fuentes de luz temporales que están apagadas o apagadas antes de las 20:00 durante el período de tiempo solar y antes de las 10:00 pm durante el período de verano.
- Instalaciones deportivas: en instalaciones deportivas con más de 5000 asientos, se permite una intensidad luminosa máxima  $> 0,49$  cd por 1000 lm por  $\gamma \geq 90^\circ$  siempre que se apaguen antes de las 24:00.

### 3.3 Reglamentos de prevención de contaminación lumínica de México

A medida que van creciendo las poblaciones cercanas al observatorio astronómico San Pedro Mártir, se buscó a través del gobierno municipal de Ensenada un mecanismo que pudiera prevenir el aumento de la contaminación lumínica, con el tiempo los municipios de Mexicali y Tijuana siguieron su ejemplo. Siguiendo los antecedentes de grandes observatorios localizados en Arizona y Hawaii en Estados Unidos, y en las Islas Canarias en España, se promulgó en el

municipio de Ensenada el 29 de septiembre de 2006 el Reglamento para la Prevención de la Contaminación Lumínica en el municipio de Ensenada, Baja California [11]. Posteriormente los municipios de Mexicali [12] y Tijuana [13] aprobarían sus respectivos reglamentos basados en el de Ensenada.

El reglamento considera fundamentalmente como alumbrados exteriores los siguientes:

- Alumbrado público vial;
- Alumbrado ornamental y de parques;
- Alumbrado de instalaciones deportivas y recreativas.;
- Alumbrado de estacionamientos públicos y privados;
- Alumbrado de áreas industriales y turísticas;
- Anuncios publicitarios iluminados;
- Alumbrado de seguridad; y
- Alumbrado exterior de viviendas particulares.

Están excluidas del ámbito de aplicación del régimen de protección:

- La luz producida por la combustión de gas natural u otros combustibles; excepto en la zona de máxima protección lumínica del observatorio astronómico en San Pedro Mártir, de acuerdo con las disposiciones que dicte el Comité Técnico Asesor.
- La iluminación que sea necesaria para garantizar la navegación aérea y marítima.
- La iluminación en vehículos móviles.
- Toda iluminación de emergencia necesaria por los Departamentos de Policía, Bomberos u otro servicio de emergencia.
- Las luminarias de precaución requeridas por las disposiciones legales aplicables.

Los alumbrados de exteriores deberán evitar la emisión de luz por encima del horizonte y habrán de realizarse en forma y con lámparas que produzcan la mínima perturbación de las observaciones astronómicas.

Para la instalación y funcionamiento del alumbrado público y ornamental, se observará lo siguiente:

- Las luminarias para el alumbrado público deberán estar construidas de modo que toda la luz emitida sea proyectada por debajo del horizonte referido al punto más bajo de las luminarias. Las luminarias deben instalarse sin ninguna inclinación.
- En el alumbrado público las lámparas permitidas serán las que establezca el Comité Técnico Asesor.

- El alumbrado ornamental de edificios públicos, monumentos y jardines podrá realizarse con cualquier tipo de lámparas siempre que permanezca apagado después de las doce de la noche. Se procurará que la luz vaya siempre dirigida de arriba hacia abajo.

Para la iluminación de instalaciones deportivas y recreativas, se estará a las siguientes disposiciones:

- El alumbrado de instalaciones deportivas y de recreo, públicas o privadas, podrá efectuarse con cualquier tipo de lámparas, pero deberá permanecer apagado después de que el evento concluya o al cierre de estas.
- Todas las luminarias utilizadas deberán proporcionar un alto grado de corte para minimizar la luz hacia arriba y el deslumbramiento.

Para la instalación y funcionamiento de anuncios publicitarios iluminados, se estará a las siguientes disposiciones:

- En los anuncios en negociaciones podrán utilizarse cualquier tipo de lámparas siempre que los mismos queden apagados al momento de cerrar al público.
- Las luminarias utilizadas en un anuncio exterior deberán ser montadas en la parte superior de la estructura. El alumbrado de anuncios desde la base queda prohibido.
- Los anuncios espectaculares deberán permanecer apagados a partir de las 11:00 p.m. hasta el amanecer.

Están prohibidos y se autorizarán solamente de forma temporal y para eventos de corta duración:

- Fuentes de luz láser. El uso de fuentes de luz láser o cualquier otra luz similar de alta intensidad para propaganda o entretenimiento cuando es proyectada sobre el horizonte.
- Faros buscadores. La operación de haces buscadores con propósitos publicitarios.

La iluminación exterior temporal que no cumpla con los requerimientos puede ser permitida después de considerar:

- Los beneficios públicos o privados que resultaran en la iluminación temporal;
- Cualquier problema de incomodidad o seguridad que resulte del uso de la iluminación temporal, y
- La duración de la iluminación no conforme con este Reglamento.

Las solicitudes de autorización para la iluminación exterior temporal que no sean mayores a treinta días serán resueltas por la Dependencia competente en base a los lineamientos que previamente establezca el Comité Técnico Asesor. Cuando su permanencia sea por más de treinta días, se requerirá la aprobación del propio Comité.

Con la finalidad de supervisar y mejorar lo previsto en el presente reglamento, se formará un Comité Técnico Asesor para la Prevención de la Contaminación Lumínica en el Municipio de Ensenada [14]. El cual tiene como objetivo el prevenir, reducir y evitar la contaminación lumínica que se proyecta hacia la oscuridad natural del cielo, y de la luz intrusa; así como promover el

ahorro y consumo eficiente en el uso de la energía eléctrica. Con el fin de asegurar la continuidad de las acciones de planeación, y lograr el equilibrio en materia de decisiones, así como definir un proceso de renovación escalonado, en cada uno de los representantes de los sectores de la sociedad civil, estos deberán ser elegidos al octavo mes de haber iniciado la administración municipal en funciones y su encargo tendrá una duración de hasta 3 años, con derecho a una reelección.

### **3.4 Leyes estatales y distritales sobre contaminación lumínica, Estados Unidos.**

En Estados Unidos hay 18 estados, además de los Distritos de Columbia y Puerto Rico que tienen leyes vigentes para reducir la contaminación lumínica al año 2016. La mayoría de los estados que han promulgado la llamada legislación de "cielos oscuros" lo han hecho para promover la conservación de la energía, la seguridad pública, los intereses estéticos y las capacidades de investigación astronómica.

Se analizarán las normativas detallando solamente los aspectos más relevantes de cada legislación, a excepción de la normativa de Hawái que se analizará a fondo por ser una de las pioneras en legislaciones sobre contaminación lumínica.

En la descripción de las diferentes normativas se nombrarán luminarias totalmente blindadas o de corte total (o completo), estas luminarias no emiten luz directa sobre los 90°, pero no tienen limitación en la intensidad en la región entre 80° y 90°.

#### **Estado de Arizona**

En Arizona, su reglamento sobre medio ambiente, indica que todas las luminarias para exteriores estén total o parcialmente protegidas, excepto las luminarias incandescentes de 150 vatios o menos y otras fuentes de 70 vatios o menos. La iluminación de emergencia y construcción están exentas. Se permiten dispositivos que no cumplan con los requisitos, siempre que se extingan entre la medianoche y el amanecer mediante un dispositivo automático.

#### **Estado de Arkansas**

La ley ambiental de Arkansas en el capítulo 8 indica que requiere que los accesorios de iluminación al aire libre instalados con fondos públicos estén protegidos, a menos que un municipio, condado o servicio público determine que el costo de adquirir accesorios protegidos será prohibitivo. Además, requiere que cada servicio público de electricidad ofrezca una opción de servicio de iluminación blindada a los clientes. Se pueden aplicar excepciones como sistemas de iluminación de navegación en aeropuertos u otra iluminación necesaria para la seguridad de la aeronave; y accesorios de iluminación exterior que son necesarios para la seguridad de los trabajadores en granjas, ranchos, lecherías o corrales de engorda o instalaciones industriales, mineras o de petróleo y gas.



**Estado de Colorado**

Requiere nuevos accesorios de iluminación al aire libre instalados por o en nombre del estado que utilizan fondos estatales para cumplir con los siguientes requisitos:

- Se tienen en cuenta los costos, la conservación de energía, la reducción del deslumbramiento, la minimización de la contaminación lumínica y la preservación del ambiente nocturno natural.
- El accesorio emite solo la luz necesaria para el propósito previsto.
- Se utiliza un accesorio de corte completo cuando la salida es de más de 3200 lúmenes, las luminarias totalmente blindadas no emiten luz directa sobre los 90°, pero no tienen limitación en la intensidad en la región entre 80 ° y 90 °.
- También posee excepciones de seguridad.

**Estado de Connecticut, Delaware, Maryland y Minnesota**

Prohíbe el uso de fondos estatales para instalar o reemplazar un accesorio permanente de iluminación al aire libre en una carretera a menos que:

- El accesorio esté diseñado para maximizar la conservación de energía y minimizar la contaminación lumínica.
- El accesorio emita solo la luz necesaria para el propósito previsto.
- se utiliza un accesorio de corte completo cuando la salida es de más de 1,800 lúmenes.
- Posee excepciones de seguridad.

**Estado de Florida**

Contiene una ordenanza de iluminación modelo para guiar a los gobiernos locales en el desarrollo de políticas que protejan la eclosión de las tortugas marinas de los efectos adversos de la iluminación artificial, proporcionen mejoras generales en el hábitat de anidación degradado por la contaminación lumínica y aumenten la actividad de anidación y la producción exitosas de crías.

**Estado de Maine**

Dirige a la oficina de planificación estatal para que revise los estándares comerciales de iluminación exterior existentes y haga recomendaciones sobre el lenguaje que limitará la contaminación lumínica y fomentará la preservación de cielos oscuros en áreas naturales.

**Estado de Nuevo Hampshire**

Declara que es una política del estado alentar a los municipios a promulgar las ordenanzas y regulaciones locales que consideren apropiadas para conservar la energía, minimizar la contaminación lumínica y el deslumbramiento, y preservar los cielos oscuros como una característica del carácter rural.

**Estado de Nuevo México**

La Ley de Protección del Cielo Nocturno regula los accesorios de iluminación exterior para preservar el cielo oscuro del estado al tiempo que promueve la seguridad, conserva la energía y protege el medio ambiente para la astronomía. Requiere que todos los accesorios de iluminación exterior estén protegidos, excepto los accesorios incandescentes de 150 vatios o menos u otras fuentes de 70 vatios o menos. Prohíbe el uso de iluminación en instalaciones recreativas al aire libre después de las 11:00 p. M. Proporciona multas importantes, para cualquier persona, empresa o corporación que viole la ley. Posee excepciones de seguridad.

**Estado de Nueva York**

Prohíbe el uso de fondos estatales para instalar nuevas instalaciones permanentes de iluminación exterior o para pagar el costo de operar tales instalaciones a menos que se cumplan ciertos requisitos. Estos incluyen el uso de accesorios totalmente blindados en muchos casos y accesorios de baja potencia para la iluminación de carreteras ornamentales. Las disposiciones de la ley no se aplican a los accesorios utilizados por el personal de emergencia, los sistemas de iluminación para la aviación y la seguridad náutica, la iluminación del campo deportivo y la iluminación para túneles y pasos subterráneos de carreteras.

**Estado de Oregon**

Requiere el uso de accesorios de iluminación exterior protegidos cuando se instala o reemplaza una luz en un edificio público. Permite a un municipio renunciar al requisito anterior cuando determina que el uso de un dispositivo de iluminación blindado no es práctico debido al carácter histórico del edificio o por otras razones.

**Estado de Rhode Island**

Requiere la instalación de cualquier unidad de iluminación exterior permanente nueva o de reemplazo por o para una agencia estatal para cumplir con los siguientes requisitos:

- Se considera conservar la energía y minimizar la contaminación lumínica.
- El accesorio nuevo o de reemplazo no permite más del 2% del lumen total en la zona de 90 a 180 grados si el rendimiento total es más de 3200 lúmenes.
- El dispositivo emite la cantidad mínima de luz necesaria para el propósito previsto o la cantidad especificada en las recomendaciones o regulaciones.
- Posee excepciones de seguridad.

**Estado de Texas:**

A pedido de un oficial al mando de una instalación militar, base o campamento, un condado puede adoptar órdenes que regulen la instalación y el uso de la iluminación exterior dentro de las cinco millas de la instalación militar en cualquier territorio no incorporado del condado. La orden debe estar diseñada para proteger contra el uso de iluminación exterior que interfiere con las actividades de entrenamiento militar. La orden puede requerir que se obtenga un permiso del

condado antes de la instalación de ciertos tipos de iluminación exterior, prohibir ciertos tipos de iluminación exterior incompatibles con actividades militares, establecer una tarifa para cubrir el costo de administrar la orden, establecer requisitos para el blindaje de iluminación exterior, y regular los tiempos durante los cuales se pueden utilizar ciertos tipos de iluminación exterior. Los condados sujetos a la ley son aquellos con una población de más de un millón con al menos cinco bases militares y cualquier condado adyacente a ese condado que se encuentre a menos de cinco millas de una instalación, base o campamento. La ley también se aplica a ciertos observatorios astronómicos.

### **Estado de Virginia**

Exige a las agencias estatales que solo compren artefactos de iluminación exteriores protegidos. Proporciona exenciones de este requisito para asuntos operativos, de seguridad o de costos, así como para necesidades estéticas específicas.

### **Estado de Wyoming**

Requiere que los servicios eléctricos ofrezcan tarifas para la iluminación exterior provista por los servicios públicos que brinde una opción para que los clientes eléctricos elijan accesorios diseñados para minimizar la luz que ilumina las áreas no intencionadas y mantener cielos oscuros.

### **Distrito de Columbia**

Dirige la preparación de un informe que recomienda estrategias y estándares para métodos y niveles óptimos de iluminación en el Distrito de Columbia. El informe debe incluir un análisis de los estándares recomendados por la Asociación Internacional del Cielo Oscuro, entre otros.

### **Distrito de Puerto Rico**

Lo siguiente se aplica a las fuentes de emisión al aire libre ubicadas en propiedades privadas:

- Las luces de colores, las luces utilizadas en los letreros y las luces utilizadas con fines decorativos deben tener cortinas e interruptores automáticos de encendido y apagado.
- Los sistemas de iluminación que brindan seguridad o iluminan pasillos, estacionamientos, etc., solo pueden usar fuentes de emisión de sodio a baja presión. Requiere que ciertos sistemas de iluminación se apaguen entre las 11 p.m. y el amanecer del día siguiente.
- Prohíbe ciertos tipos de accesorios de iluminación exterior a menos que lo apruebe el organismo correspondiente. Establece clases para áreas exteriores de acuerdo con sus características de iluminación ambiental.

## Estado de Hawaii

En este estado se encuentran los observatorios astronómicos de Mauna Kea que se encuentran situados cerca del volcán inactivo de mismo nombre. Debido a la administración política de estados unidos su legislación sobre contaminación lumínica es estatal.

Requisitos generales:

- La fuente estándar para todos los tipos de luminarias para exteriores nuevas debe cumplir con los requisitos establecidos en la Tabla A.
- Lámparas existentes. Todos los artefactos de iluminación para exteriores existentes que se instalaron legalmente antes de la implementación de esta ordenanza deberán cumplir con la Tabla A en los diez (10) años posteriores a la adopción de esta ordenanza. Los accesorios existentes de Clase III están exentos.
- Lámparas de vapor de mercurio prohibidas. Las lámparas de vapor de mercurio no deben utilizarse para ninguna instalación nueva de iluminación exterior o para reemplazar cualquier instalación existente. Todos los accesorios de iluminación exterior de vapor de mercurio existentes deberán retirarse dentro de los 10 años posteriores a la implementación de esta ordenanza. La importación y venta de lámparas de Mercury Vapor en el condado de Maui se prohibirá a partir de los 12 meses posteriores a la implementación de esta ordenanza.
- Iluminación residencial. Los artefactos de iluminación de exteriores residenciales deben estar protegidos de modo que no se pueda ver ninguna fuente de luz desde las propiedades adyacentes. Las residencias existentes deberán cumplir con esta sección dentro de los diez (10) años posteriores a la adopción de esta ordenanza. Se permite la iluminación de seguridad en sensores de movimiento temporizado.

Se definieron clases de iluminación para realizar las restricciones, las cuales se muestran en la Tabla 3-6.

En Hawaii se estableció un Comité de Normas de Iluminación al Aire Libre del Condado de Maui, que constata de entre cinco y nueve miembros, nombrados por el alcalde con la aprobación del Consejo. Dando preferencia en la selección de miembros a los residentes del Condado y a una persona de cada una de las siguientes profesiones, intereses especiales o disciplinas: un astrónomo o un especialista en vigilancia espacial; un miembro de la industria del visitante; un biólogo de vida silvestre; un miembro de la comunidad empresarial; y miembros elegidos del público en general.

La normativa Hawaiana otorga el “Derecho de entrada” a los empleados de Obras Públicas y Gestión Ambiental del Condado de Maui y/o sus asignados, el derecho a entrar en una propiedad privada con el propósito de inspeccionar y hacer cumplir la normativa.

Tabla 3-6: Descripción de las clases de lámparas según su uso.

| Clasificación de Clase de lámparas | Descripción                                                                                                                                                                                                                                         |
|------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| clase I                            | Iluminación exterior utilizada para áreas de ventas al aire libre, estaciones de servicio, áreas de comer al aire libre, áreas de montaje o reparación al aire libre, instalaciones recreativas.                                                    |
| clase II                           | Iluminación exterior utilizada para, pero no limitada a, iluminación para patios de equipos, estacionamientos, seguridad exterior y otras aplicaciones similares en las cuales la iluminación general de los terrenos es la principal preocupación. |
| clase III                          | iluminación exterior utilizada para efectos decorativos. Incluye, entre otros, iluminación de cascadas y estanques, paisajismo y pasillos.                                                                                                          |
| clase IV                           | Iluminación de carreteras                                                                                                                                                                                                                           |

Con las clases de lámparas definidas se realizaron las siguientes restricciones de recubrimiento y horarios de uso:

Tabla 3-7: Resumen de Normativa sobre recubrimiento y restricciones horarias en Hawaii.

| Tipo de lámpara | Requisito de blindaje                                                | Restricción de uso                                                       |
|-----------------|----------------------------------------------------------------------|--------------------------------------------------------------------------|
| Clase I         | Todas completamente blindadas, excepto los haluros metálicos.        | Solo los haluros metálicos desde las 11:00 p.m hasta el amanecer.        |
| Clase II        | Todas completamente blindadas, excepto los haluros metálicos.        | Solo los haluros metálicos desde las 11:00 p.m hasta el amanecer.        |
| Clase III       | Todas completamente blindadas, excepto los haluros metálicos y neón. | Solo los haluros metálicos y neón desde las 11:00 p.m hasta el amanecer. |
| Clase IV        | Todas completamente blindadas                                        | Ninguna.                                                                 |

### 3.5 Ley de protección contra la contaminación lumínica de Croacia

Esta Ley OG 14 de 2019 [15], regula la protección contra la contaminación lumínica, indicando a las personas responsables de la protección contra la contaminación lumínica, las medidas de protección contra la contaminación lumínica, la forma de determinar los valores máximos permitidos de iluminación, las restricciones y la prohibición de la iluminación, las condiciones para la planificación, construcción, mantenimiento y reconstrucción de la iluminación externa, el método de medición y monitoreo. iluminación ambiental y otros problemas para reducir la contaminación lumínica ambiental y los efectos de la contaminación lumínica.

Entre las medidas de la ley, se puede destacar en el artículo 10, un proceso de permisos que requiere que los instaladores de iluminación cuenten con una licencia del estado y obliga a los municipios de los gobiernos locales a hacer cumplir la ley de manera proactiva como se detalla en el artículo 6.

Los objetivos de la ley son establecidos en los artículos 2 y 8. Estos incluyen la reducción de la contaminación lumínica en general; la protección de la salud humana, la biodiversidad, la ecología y el desarrollo sostenible; Asegurar el diseño adecuado de la iluminación antes de la instalación; y la reducción del consumo total de electricidad de la iluminación.

En el artículo 3 expresa algunas excepciones, que afectan la iluminación temporal en lugares como los sitios de construcción, junto con la iluminación requerida en casos de emergencias y desastres, así como el uso de la iluminación por parte de los militares y en ciertas situaciones laborales como fábricas.

La nueva ley prohíbe en su artículo 11 los haces de luz hacia el cielo, la iluminación externa de ventanas y puertas, y los letreros y lámparas iluminadas cuya temperatura de color correlacionada exceda los 2200 K en lugares ecológicamente sensibles (aunque a la fecha todavía no se determinan los valores máximos de emisión, se otorgó en un plazo de un año para determinarla). Se requiere la protección de las luces interiores para evitar la contaminación lumínica en el exterior y, aunque está permitido, la iluminación de fachadas arquitectónicas debe limitarse estrictamente a las caras de los edificios y no puede derramarse más allá de esas superficies.

Se determinaron algunas definiciones en el artículo 5, incluida la "iluminación ecológica", que es la única forma de iluminación permitida en el exterior. Se define como "lámpara ecológica" a una lámpara que satisface la necesidad de iluminación artificial de un edificio, objeto o superficie cuya emisión de luz está de acuerdo con las condiciones de protección contra la contaminación lumínica prescritas en esta ley y cuya proporción de flujo de luz que está por encima del plano horizontal es de 0,0%, con una temperatura de color correlacionada máxima de hasta un máximo de 3000 K y que tenga una fuente de luz que no contenga mercurio en ninguna forma.

En los artículos 12 y 13 requiere la presentación de planes de iluminación para garantizar el cumplimiento de la ley.



En los artículos 16, 17 y 18 se especifican los encargados del cumplimiento de la ley mediante un régimen de inspección sólido, estos inspectores serán dirigidos por el Ministerio de Medio Ambiente.

En los artículos desde el 21 al 26 se especifican las infracciones que se pueden cometer con sus respectivas multas monetarias, claramente especificadas.

Finalmente, el artículo 30 especifica los plazos de las unidades de autogobierno local y la Ciudad de Zagreb y el operador de iluminación externa armonizarán la iluminación existente con las disposiciones de esta Ley dentro de los 12 años a partir de la fecha de entrada en vigor de la ordenanza a que se refieren el artículo 9 y el artículo 12 de esta Ley.

### **3.6 Norma francesa sobre prevención, reducción y limitación de la contaminación lumínica**

La normativa francesa NOR: TREP1831126A [16], es una de las más actuales dentro de las normativas mundiales, fue redactada el año 2018 y entrará en vigor en su totalidad el año 2020.

Dentro de sus principales características tenemos:

- Las emisiones de luz artificial de las instalaciones de iluminación exterior y la iluminación interior exterior deben estar diseñadas para prevenir, limitar y reducir la contaminación lumínica, incluidas las perturbaciones excesivas para las personas, la fauna, flora o ecosistemas, que causan pérdidas de energía o que impiden la observación del cielo nocturno.
- Este decreto se aplica a las instalaciones de iluminación:
  - a) Exterior destinado a promover la seguridad del movimiento, las personas y los bienes y la comodidad de los usuarios en espacios públicos o privados, en particular la red de carreteras, excluyendo dispositivos de alumbrado y señalización para vehículos, para alumbrado de túneles, para instalaciones de alumbrado establecidas para garantizar la seguridad aeronáutica, ferroviaria y marítima y fluvial.
  - b) Hay que destacar el patrimonio, tal como se define en el Artículo L. 1 del Código del Patrimonio, el entorno construido, así como los parques y jardines privados y públicos accesibles al público o pertenecientes a empresas, propietarios sociales o condominios.
  - c) Equipamiento deportivo al aire libre o reconocible.
  - d) Edificios no residenciales, que cubren tanto la iluminación de los edificios como la iluminación interior emitida al exterior de estos mismos edificios, excluidas las estaciones de peaje.
  - e) Estacionamientos descubiertos o semicubiertos.

Las instalaciones de iluminación deben estar equipadas con luminarias que garanticen los siguientes requisitos:

- Para la iluminación exterior de estacionamientos los instaladores se deben asegurar de que el valor nominal de la proporción de luz emitida por la luminaria que adquieren arriba la horizontal es estrictamente inferior al 1%, en zonas urbanizadas y fuera de zonas urbanizadas. En el sitio, la instalación de iluminación cumple con las condiciones de montaje recomendadas por el fabricante y, en cualquier caso, garantiza una proporción de luz emitida por encima de la horizontal estrictamente inferior al 4%.
- Para la iluminación de estacionamientos, la proporción de flujo luminoso emitido en el hemisferio inferior en un ángulo sólido de  $3\pi / 2$  sr (ángulo sólido equivalente a un cono de  $75,5^\circ$ ) con respecto al flujo luminoso emitido en todo el hemisferio inferior (CIE Flow Code No. 3) es mayor al 95 %, en zonas urbanizadas y fuera de zonas urbanizadas.
- Para la iluminación exterior de los edificios no residenciales, la temperatura de color correlacionada no debe exceder el valor máximo de 3000 K en áreas urbanizadas.
- La densidad superficial del flujo luminoso instalado (flujo luminoso total de las fuentes en relación con la superficie a iluminar, en lúmenes por metro cuadrado), respeta los valores máximos que se muestran en la Tabla 3-8.

Tabla 3-8: Flujo luminoso total de las fuentes en relación con la superficie a iluminar, en lúmenes por metro cuadrado

| Flujo luminoso total lm / m <sup>2</sup>  | En Zonas Urbanizadas | Fuera de las Zonas Urbanizadas |
|-------------------------------------------|----------------------|--------------------------------|
| Iluminación exterior definida en a        | < 35                 | < 25                           |
| Parques y jardines definidos en b         | < 25                 | < 10                           |
| Edificios no residenciales definidos en d | < 25                 | < 20                           |
| Los estacionamientos definidos en e       | < 25                 | < 20                           |

La normativa francesa posee una fuerte fiscalización, a través, de inspectores capacitados para realizar las verificaciones correspondientes para dar cumplimiento a la normativa.

El ejecutor del proyecto de iluminación deberá poner a disposición de los inspectores los siguientes datos técnicos sobre las instalaciones de las cuales es responsable:

- La proporción (en %) de luz emitida por la luminaria por encima de la horizontal.
- La proporción (en %) de luz emitida por la luminaria en un cono de medio ángulo de 75,5°, en relación con la luz emitida por debajo de la horizontal (Código de flujo CIE No. 3).
- La temperatura de color correlacionada nominal (en kelvin) de la luz emitida por la fuente.
- La potencia eléctrica (en vatios) de la luminaria.
- El flujo luminoso (en lúmenes) nominal de la fuente.

Las disposiciones de esta normativa entran en vigor el 1 de enero de 2020 para las instalaciones ligeras puestas en servicio después de esta fecha.

## 4 Escenario Nacional

La calidad astronómica de los cielos de las regiones Antofagasta, Atacama y Coquimbo de nuestro país, constituye un valioso patrimonio ambiental y cultural reconocido a nivel internacional como el mejor existente en el hemisferio sur para desarrollar la actividad de observación astronómica, permitiendo a esta zona del país albergar varios observatorios astronómicos, como los de Cerro Tololo, La Silla, Las Campanas y Alma. Debido a esto es necesario proteger la calidad ambiental de los cielos de las regiones señaladas amenazadas por la contaminación lumínica producida por las luminarias de la ciudad y de la actividad minera e industrial de los territorios.

En Chile en el año 1996, el Ministerio Secretaría General de la Presidencia, a través del Consejo Directivo de la Comisión Nacional del Medio Ambiente, aprobó el primer programa priorizado de normas que inició la elaboración del ante proyecto de norma de emisión y regulación de la contaminación lumínica. Siendo la primera normativa aprobada el Decreto Supremo N° 686 el 3 de mayo 1998.

### 4.1 Decreto Supremo N° 686

La primera normativa sobre contaminación lumínica en Chile establece la cantidad máxima permitida de emisión lumínica hacia los cielos nocturnos, medida en el efluente de la fuente emisora. Como se puede leer en el DS N° 686/98 MINECON [17]. A continuación, se expondrán los puntos más relevantes de la normativa:

Objetivo de protección ambiental y resultados esperados: La norma tiene por objetivo prevenir la contaminación lumínica de los cielos nocturnos de las regiones de Antofagasta, Atacama y Coquimbo, de manera de proteger la calidad astronómica de dichos cielos, mediante la regulación de la emisión lumínica. Se espera conservar la calidad actual de los cielos señalados y evitar su deterioro futuro.

El DS N° 686/98 MINECON no se aplica a las siguientes fuentes emisoras:

- Aquellas cuya iluminación es producida por la combustión de gas natural u otros combustibles.

- Aquellas destinadas a la iluminación ornamental utilizada durante festividades populares, siempre que no excedan de 60 watt.
- Aquellas que sean necesarias para garantizar la navegación aérea y marítima.
- Aquellas propias de los vehículos motorizados.
- Aquellas de emergencia necesarias para la seguridad en el tránsito de calles y caminos.
- Aquellas destinadas a la iluminación de vitrinas.
- Aquellas destinadas a iluminar espacios cerrados.
- Aquellas destinadas al alumbrado de instalaciones deportivas o recreativas y las destinadas a la iluminación de avisos y letreros, cuando la eficacia luminosa de la fuente de luz utilizada en los casos señalados no sea inferior a 140 lúmenes por watt.
- Los proyectores láser utilizados para fines astronómicos.

Límites máximos permitidos: La cantidad máxima permitida de emisión lumínica hacia los cielos nocturnos, medida en el efluente de la fuente emisora, será la siguiente:

1. Las lámparas cuyo flujo luminoso nominal sea igual o menor a 15000 lúmenes, no podrán emitir, una vez instaladas en la luminaria, un flujo hemisférico superior mayor al 0,8% de su flujo luminoso nominal.
2. Las lámparas de flujo luminoso nominal superior a 15000 lúmenes no podrán emitir, una vez instaladas en la luminaria, un flujo al hemisferio superior que exceda del 1,8% de su flujo luminoso nominal.
3. Tratándose de las lámparas destinadas al alumbrado de vías públicas deberán, además, limitarse al espectro del ancho de banda de luz visible para el ojo humano (entre 350 y 760 nanómetros), para lo cual la eficacia luminosa de las fuentes de luz utilizadas no podrá ser inferior a 80 lúmenes por watt.
4. Las lámparas instaladas en proyectores, las instaladas en luminarias destinadas al alumbrado de jardines, playas, parques y demás áreas naturales, y las destinadas al alumbrado ornamental de edificios y monumentos, cuyo flujo luminoso nominal sea igual o menor a 9000 lúmenes, no podrán emitir un flujo hemisférico superior mayor al 5 % de su flujo luminoso nominal. Estas lámparas deberán ajustarse a lo establecido en el punto 2, incluida la exigencia sobre eficacia luminosa establecida para el alumbrado de vías públicas, cuando su flujo luminoso nominal sea superior a 9000 lúmenes.
5. Las lámparas destinadas al alumbrado de instalaciones deportivas o recreativas se someterán a lo establecido en el punto 2 desde las 2:00 horas AM.
6. Las lámparas destinadas a la iluminación de avisos y letreros no se someterán a lo establecido en el punto 2. Sin embargo, desde la 1:00 horas AM no podrán emitir un flujo hemisférico superior mayor al 0,8% de su flujo luminoso nominal. Dicho porcentaje no

será aplicable a aquellos anuncios y letreros que se ubiquen en recintos comerciales mientras permanezcan abiertos al público.

7. Los proyectores láser no se someterán a lo establecido en el punto 2. Sin embargo, desde las 2:00 horas AM no podrán emitir flujo hemisférico superior, por lo que, en ese horario, no podrán orientarse sobre la horizontal.
8. Los horarios señalados en los puntos 5, 6 y 7 comenzarán a regir una hora después, durante los días sábado, domingo y festivos.

Metodología de medición y control: La medición de la emisión lumínica hacia los cielos nocturnos se realizará en los laboratorios que cumplan con los requisitos señalados en la misma normativa, y bajo las condiciones también establecidas en la misma. Los ensayos se realizarán con una muestra representativa de las luminarias y/o proyectores.

El cumplimiento de la norma se verificará con un informe técnico que así lo establezca, fundado en mediciones realizadas en alguno de los laboratorios señalados en el punto anterior, y cuando la instalación de la fuente corresponda a las condiciones de instalación asumidas para el ensayo. Estas deberán ser consignadas en el mencionado informe técnico.

Fiscalización: Para realizar la fiscalización, el DS N° 686/98 MINECON establece que el organismo de estado competente será la Superintendencia de Electricidad y Combustibles, en colaboración con las municipalidades.

## 4.2 Decreto Supremo N° 43

El 3 de mayo del 2014 entra en vigor el DS N° 43/2012 MMA [3], que es una modernización al DS N° 686/98 MINECON adaptada a los nuevos requerimientos, de forma de compatibilizar la necesaria protección del cielo nocturno patrimonial del norte del país, con los requisitos de seguridad y confort en las vías y calles, áreas verdes, las necesidades industriales, e indirectamente con el ahorro energético.

A partir de la revisión del DS N° 686/98 MINECON, se recopiló información de la aplicación de la norma, de antecedentes internacionales actualizados, de efectos en salud, impacto en la biodiversidad y de propuestas de modificación realizadas por la Oficina de Protección de la Calidad del Cielo del Norte de Chile, OPCC.

Modificaciones respecto a la normativa anterior: Con los antecedentes recopilados, se acordó modificar los siguientes aspectos de la normativa:

1. Aumentar las restricciones a los flujos radiantes generados hacia el hemisferio superior por lámparas y letreros luminosos que se utilizan en alumbrado de exteriores, debido a



que existen antecedentes de un mayor efecto negativo producto del fenómeno de dispersión atmosférica en ángulos cenitales cercanos a los 90°.

2. Aumentar las restricciones con respecto al espectro emitido por las lámparas que se utilizan en alumbrado de exteriores, de forma de prevenir la contaminación lumínica en sectores espectrales que actualmente no la tienen y que puede ser generada por alguna tecnología existente o futura.
3. Incorporar una limitación a los niveles máximos de iluminación para restringir la emisión, al hemisferio superior, por causa de la reflexión en el suelo y las superficies, en base a los valores mínimos recomendados internacionalmente por la Comisión Internacional de Iluminación, CIE. Esta restricción ha sido aceptada en regulaciones existentes en otros países que poseen cielos con calidad ambiental que deben ser protegidos, como es el caso de España.
4. Eliminar las restricciones horarias señaladas en el DS N° 686/98 MINECON, debido a que se hace necesario controlar las emisiones en todo el horario que se manifiesta el cielo nocturno.
5. Establecer una distinción en los letreros publicitarios, entre aquellos iluminados y luminosos. Los letreros iluminados corresponden a aquellos que son iluminados desde su exterior. Para éstos, se incrementan sus restricciones en el sentido de limitar su emisión hacia el hemisferio superior. Los letreros luminosos son aquellos que llevan las lámparas en su interior y operan a través de elementos traslúcidos o transparentes. Estos últimos no están considerados en el DS N° 686/98 MINECON, sin embargo, su efecto acumulativo es significativo, por lo que se establece su definición y regulación, considerando la reciente masificación de televisores de gran formato en base a la tecnología LED y de plasma.
6. Establecer una mayor restricción horaria a aquellos proyectores o dispositivos de iluminación que pueden ser orientados libremente mientras se operan, como los proyectores láser, cañones de luz de discotecas, los utilizados con fines decorativos, señalizaciones de tipo recreativo, culturales y otros similares.
7. Establecer una restricción a la emisión sobre el hemisferio superior para el alumbrado deportivo y recreacional de manera diferenciada de otros tipos de alumbrado de exteriores. Esto se explica porque los recintos deportivos se deben iluminar desde posiciones alejadas, mediante ópticas muy controladas y puntuales, implicando restricciones de diseño diferentes a las utilizadas en las otras aplicaciones aquí nombradas.
8. Establece una restricción cromática específica a la iluminación de balizamientos, como los utilizados en torres de alta tensión, generadores eólicos y otros que requieran advertir su ubicación y altura, preferentemente a la navegación aérea, por razones de limitar la dispersión de la luz en la atmósfera.

Objetivo de Protección Ambiental y los Resultados Esperados: El objetivo de la norma se mantiene del DS N° 686/98 MINECON, el cual es prevenir la contaminación lumínica de los cielos nocturnos de las regiones de Antofagasta, Atacama y Coquimbo, de manera de proteger la calidad astronómica de dichos cielos, mediante la regulación de la emisión del flujo radiante por parte de las fuentes reguladas. Se espera conservar la calidad actual de los cielos señalados, mejorar su

condición y evitar su detrimento futuro. En particular, la presente norma de emisión restringe la emisión de flujo radiante hacia el hemisferio superior por parte de las fuentes emisoras, además de restringir ciertas emisiones espectrales de las lámparas, salvo aplicaciones puntuales que expresamente se indican.

Ámbito Territorial: La norma de emisión se aplicará dentro de los límites territoriales administrativos de las Regiones de Antofagasta, Atacama y Coquimbo.

Fuentes Emisoras: Las fuentes que deben cumplir con la presente norma de emisión son las lámparas, cualquiera sea su tecnología, que se instalen en luminarias, en proyectores o por sí solas, que se utilicen en lo que se denomina Alumbrado de Exteriores. Asimismo, se consideran fuentes emisoras los avisos, los letreros luminosos, los proyectores u otros dispositivos de iluminación posibles de ser movidos mientras se operan, y otros similares. En los casos que las lámparas estén instaladas en luminarias o proyectores, se considerará la emisión conjunta de éstos (conjunto lámpara-luminaria o conjunto lámpara-proyector), para las exigencias que así lo especifican.

El DS N° 43/2012 MMA no se aplicará a las siguientes fuentes:

- Aquellas cuya iluminación es producida por la combustión de gas natural u otros combustibles.
- Aquellas destinadas a la iluminación ornamental utilizada durante festividades populares oficiales, siempre que no excedan los 1500 lúmenes de flujo luminoso nominal por cada lámpara.
- Aquellas que sean necesarias para garantizar la navegación aérea y marítima, salvo los balizamientos tales como aquellos ubicados en torres de alta tensión, generadores eólicos, edificios y similares, en cuyo caso se deberán utilizar lámparas cuyas coordenadas tricromáticas se encuentren entre los siguientes valores:

$$x \geq 0,657, y \leq 0,335, z \leq 0,008.$$

- Aquellas propias de los vehículos motorizados.
- Aquellas lámparas de emergencia necesarias para la seguridad en el tránsito de calles y caminos, y las propias destinadas a la evacuación en caso de eventos catastróficos.
- Aquellas destinadas a la iluminación de espacios cerrados, sin elementos traslúcidos en techumbres, es decir, sin proyección de luz hacia el hemisferio superior en el exterior.
- Los proyectores utilizados para fines astronómicos.
- Las vitrinas que sean iluminadas desde su interior.

Límites máximos de emisión y condiciones de cumplimiento: En el caso de lámparas instaladas en luminarias o proyectores, que se utilizan en alumbrado ambiental, alumbrado funcional, alumbrado industrial, alumbrado ornamental y decorativo, avisos y letreros iluminados, las exigencias serán las siguientes:

1. Una distribución de intensidad luminosa máxima, para un ángulo gama igual a  $90^\circ$ , que esté comprendida entre 0,00 y 0,49 candelas por cada 1000 lúmenes del flujo de la lámpara.
2. Una distribución de intensidad luminosa de 0 candelas, para un ángulo gama mayores a  $90^\circ$ , por cada 1000 lúmenes del flujo de la lámpara.
3. En el caso del alumbrado deportivo y recreacional, el límite de intensidad luminosa máxima será de 10 candelas por cada 1000 lúmenes del flujo de la lámpara, a un ángulo gama de  $90^\circ$ , junto con la adición de una visera que limite la emisión hacia el hemisferio superior. Dicha visera o paralúmen deberá presentar un área similar a la de la superficie emisora del reflector, al objeto de cubrir efectivamente el plano superior del proyector o luminaria.

Límite de emisión de radiancia espectral: Para lámparas instaladas en luminarias o proyectores que sean utilizadas en el alumbrado funcional, ambiental, industrial y ornamental, las exigencias serán las siguientes:

1. La radiancia espectral entre 300 nm y 379 nm no podrá superar el 15 % de la radiancia espectral entre 380 nm y 780 nm.
2. La radiancia espectral entre 380 nm y 499 nm no podrá superar el 15 % de la radiancia espectral entre 380 nm y 780 nm. La radiancia espectral entre 781 nm y 1 micra no podrá superar el 50% de la radiancia espectral entre 380 nm y 780 nm.

Límite de emisión por reflexión: Para el caso de las lámparas instaladas en luminarias o proyectores, que sean utilizadas en el alumbrado funcional, ambiental, industrial y ornamental, los niveles de luminancia e iluminancia medias sobre calzada no excederán más allá del 20% sobre los valores mínimos establecidos en la norma NSEG 9. n71 - Iluminación: Diseño de Alumbrado Público en Sectores Urbanos, de la Superintendencia de Servicios Eléctricos y de Gas (hoy Superintendencia de Electricidad y Combustibles), o la que la reemplace.

Límite de emisión de iluminancia: Los avisos y letreros luminosos no podrán tener una luminancia mayor a 50 cd/m<sup>2</sup> (candela/metro cuadrado).

Condiciones de Cumplimiento para avisos y letreros luminosos: Los avisos y letreros luminosos no podrán ser orientados en ángulos mayores a 0 grados con respecto al plano horizontal que pasa por el centro del área luminosa.

Condiciones de Cumplimiento para cañones de luz o proyectores láser: Todo tipo de cañones de luz o proyectores láser, que puedan ser orientados libremente mientras se operan, como los utilizados en discotecas o similares, no podrán apuntarse por sobre ángulos gama mayores a 70 grados.

El control de esta norma de emisión se realizará mediante la certificación, previa a la instalación, del cumplimiento de los límites de emisión conjunta en el caso de lámparas instaladas en luminarias o proyectores, de la verificación del cumplimiento de los límites de luminancia en el caso de letreros luminosos ya instalados y mediante la verificación de la correcta instalación de

todas las fuentes emisoras, conforme con lo establecido en la presente norma. La certificación, previa a la instalación, del cumplimiento de límites de emisión conjunta en el caso de lámparas instaladas en luminarias o proyectores, se deberá realizar mediante laboratorios autorizados por la Superintendencia de Electricidad y Combustibles.

La fiscalización del cumplimiento de las disposiciones del DS N° 43/2012 MMA, le corresponderá a la Superintendencia del Medio Ambiente.

**Plazo de Cumplimiento para Fuentes Existentes:** En el DS N° 43/2012 MMA se señala que las fuentes emisoras existentes con anterioridad a su entrada en vigor deberán regularizar su situación y cumplir con la norma de emisión en un plazo máximo de 5 años, teniendo que cumplir en el intertanto con el DS N° 686/98 MINECON.

**Plazo de Cumplimiento para Fuentes Nuevas:** Las fuentes emisoras nuevas deberán cumplir con el DS N° 43/2012 MMA en el momento que sean instaladas. La normativa entró en vigor el día 4 de mayo de 2014 para las fuentes nuevas, por lo que el plazo para cumplimiento de las fuentes emisoras existentes con anterioridad a la norma finaliza el día 4 de mayo del 2019, debido a esto se realizó un instructivo con el procedimiento a seguir para regularizar las luminarias fuera de norma.

### **4.3 Instructivo para regularizar luminarias**

Como se establece en la Resolución exenta N° 434, del 28 de marzo de 2019, el procedimiento a seguir será el siguiente:

1. **Levantamiento de información:** El titular del proyecto de Alumbrado de Exteriores deberá efectuar un catastro de todas las luminarias que forman parte de su proyecto o de su territorio comunal, en el caso de municipios. Para este último, se deberán considerar todos los tipos de alumbrado señalados en el artículo 5° N° 1 del DS N° 43/2012 MMA que se encuentren presentes en recintos de tutela o dominio municipal. El catastro deberá ser reportado a la oficina regional de la SMA que corresponda, según la región donde se desarrolla el proyecto, acompañando una carta que señale en el asunto "Antecedentes para regularización de luminarias", junto con el formulario de reporte contenido en el Anexo N° 1 de la presente resolución. Además, se deberá acompañar en formato digital (CD, DVD o Pendrive) la siguiente información:
  - a) De las luminarias declaradas con cumplimiento del DS N° 43/2012 MMA: Certificado de Aprobación que señale cumplimiento de la Norma de Emisión. Plano de ubicación de las luminarias en formato digital (dwg, kml, shp, pdf), con su respectiva georreferenciación.
  - b) De las luminarias declaradas a recambiar próximamente: Indicar en la carta entregada en la oficina regional de la SMA una fecha estimada para su recambio y las razones de fijar dicha fecha.
  - c) De las luminarias declaradas para la regularización: Deberán adjuntar su certificado DS N° 686/98 MINECON o cualquier otra certificación con la que puedan contar respecto de la fotometría de la luminaria; adicionalmente,

deberán acompañar planos de ubicación de las luminarias en formato digital (dwg, kml, shp, pdf), con su respectiva georreferenciación.

2. Solicitud de certificación: De las luminarias declaradas para regularización, se deberá presentar la solicitud de "Certificación para la Regularización de Luminarias" al Laboratorio autorizado por la SEC, acompañando una carta presentada ante la SMA con timbre de recepción de la oficina de partes de la oficina regional correspondiente, y toda la documentación señalada en el punto 1, según corresponda.
3. Aprobación: Una vez aceptada la documentación señalada, se podrá proceder a la aprobación de los lotes de luminarias, entendiéndose por lote como el conjunto de luminarias que comparten la misma marca, modelo, potencia eléctrica y sistema óptico.

## 5 Propuestas de Actualización

Se plantean las siguientes propuestas para mejorar algunos aspectos de la normativa, estas propuestas se establecieron después de analizar cada uno de los aspectos estudiados en el informe, esta información fue recopilada a lo largo del año a modo de ver su viabilidad y posibles incompatibilidades en nuestro país.

### 5.1 Zonificación del territorio nacional

Como se recomienda en la Guía para minimizar el brillo del cielo y en la Guía sobre la limitación de los efectos de la luz molesta de las instalaciones de iluminación exterior y como se ha realizado en normativas de países como España e Italia, es posible realizar una zonificación en nuestro país lo que permitirá realizar restricciones estándar por zonas, aunque debido a nuestra geografía.

Utilizando los datos extraídos desde la Guía para minimizar el brillo del cielo y el programa Google Earth PRO [18], se realizarán 2 ejemplos de zonificación en nuestro país, uno de un observatorio astronómico el cual será considerado como una zona E1 debido a que es una zona de extrema importancia en nuestro país, posteriormente se zonificará un parque nacional, el cual será zonificado como una zona E2, buscando realizar restricciones que ayuden a disminuir el impacto de la iluminación en los ecosistemas.

#### Zonificación de un observatorio astronómico

Se realizará un ejemplo de zonificación utilizando los parámetros de la Guía para minimizar el brillo del cielo, la cual nos permitirá tener una referencia respecto a nuestro territorio. Esta zonificación alrededor del Sitio de Operaciones del Conjunto de antenas ALMA, el cual se encuentra ubicado en las coordenadas 23° 1' 23,5" S, 67° 45' 16,7" O [19], a una altitud de 5000 metros en la segunda región de Chile, en el cual hospeda las antenas de recepción y el correlacionador, que es el procesador de datos más rápido de la historia utilizado en un observatorio astronómico.

De acuerdo con la Tabla 2-1 “Descripción de las zonas ambientales según el Sistema de Zonificación CIE” y la Tabla 2-3 “Distancia mínima (en km) entre el límite de la zona y el punto de referencia” presentadas en el capítulo 2, en una zona E1 tendremos 3 zonas que serán círculos

concéntricos, la primera zona será E1-E2 de 1 kilómetro de radio, la segunda zona será E2-E3 de 10 kilómetros de radio y finalmente la zona E3-E4 de 100 kilómetros de radio.



Figura 5-1: Distancia entre E1 y E2, separada por 1 kilómetro (Fuente: Propia).

Como se puede observar en la Figura 5-1, la primera zona E1 – E2 al ser de solo un kilómetro alrededor del observatorio astronómico es suficiente para cubrir las antenas como el sitio de operaciones, pero no es lo suficientemente grande para afectar a ninguna localidad cercana ya que se encuentra emplazado en pleno desierto de Atacama.



Figura 5-2: Distancia entre E2 y E3, separada por 10 kilómetros (Fuente: propia).



Como se puede apreciar en la Figura 5-2, nuevamente la zona E2 – E3 al ser de solo de 10 kilómetros alrededor del observatorio astronómico no afectará a ninguna localidad cercana, siendo San Pedro de Atacama la más cercana.



Figura 5-3: Distancia entre E3 y E4 de 100 kilómetros (Fuente: propia)

Como se puede apreciar en la imagen anterior, la zona E3 – E4 al ser de 100 kilómetros alrededor del observatorio astronómico, afectará a la localidad de San Pedro de Atacama, pese a esto no afectará a ninguna ciudad de la segunda región, aunque cabe mencionar que en la Guía para minimizar el brillo del cielo dice que para que estos valores de distancia sean realmente significativos deben ser el doble, aunque estos valores solo podrían ser determinados con conocimiento de causa por los mismo observatorios astronómicos.

### Zonificación de un Parque Nacional

Se realizará un ejemplo de zonificación alrededor del Parque Nacional Lago Peñuelas [20], el cual está ubicado la región de Valparaíso, provincia y comuna de Valparaíso en las coordenadas 33°09'08"S y 71°31'50"O. Fue creada mediante decreto ley n.º 859 de 1952. El parque destaca por la protección de las especies de fauna como el cisne cuello negro, lagarto chileno, halcón peregrino, gato colocolo, entre otros. En cuanto a flora, se encuentra en categoría de conservación el belloto del norte, palma chilena, orquídea, lingue del norte, además de especies como: quillay, peumo, litre, boldo, molle, trevo, Algarrobo y espino, por mencionar los más representativos.

Utilizando los parámetros de la Guía para minimizar el brillo del cielo, este parque será zonificado como una zona E2 por su cercanía a grandes ciudades, además se presentará una zonificación alternativa a la publicada por la CIE ya que las extensiones de los Parques Nacionales al ser de varios kilómetros son difíciles de visualizar como una zona puntual.

De acuerdo con la tabla “Descripción de las zonas ambientales según el Sistema de Zonificación CIE” y la tabla “Distancia mínima (en km) entre el límite de la zona y el punto de referencia” presentadas en el capítulo 2, en una zona E2 tendremos 2 regiones de 1 y 10 kilómetros entre zonas.



Figura 5-4: Distancia entre E2 y E3, separada por 1 kilómetro (Fuente: propia).

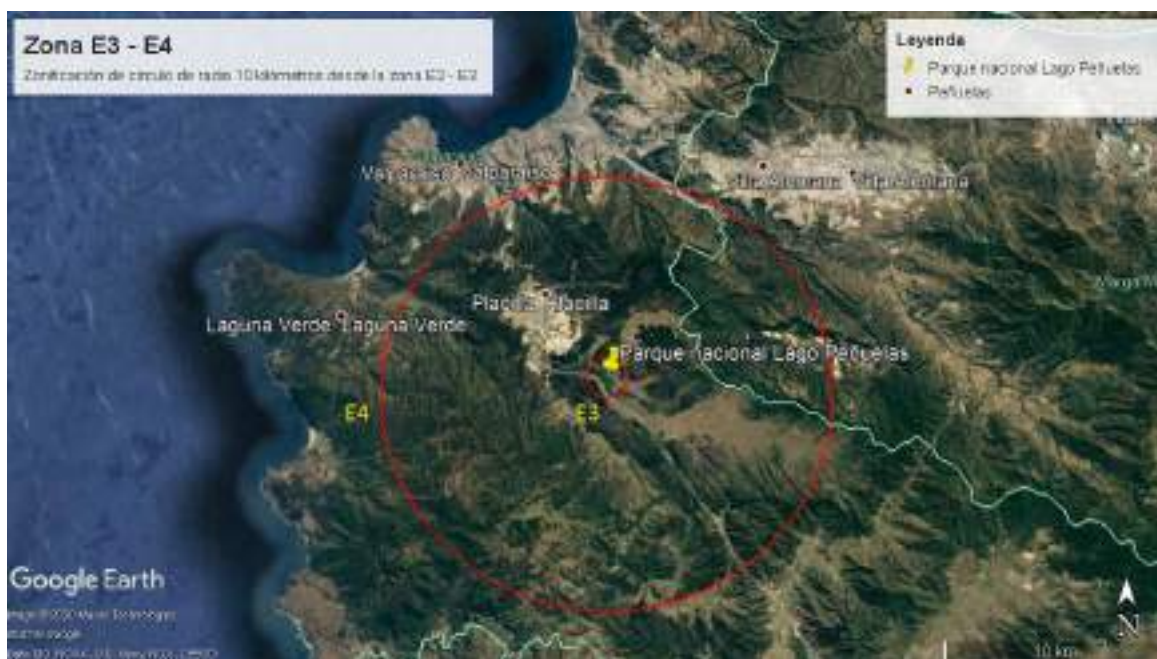


Figura 5-5: Distancia entre E3 y E4, separada por 10 kilómetros (Fuente: propia).



Como se puede apreciar en la Figura 5-4, la primera zona E2 – E3 al ser de solo un kilómetro se encuentra aún al interior del parque, lo cual indica que no representa una real protección para los ecosistemas que lo componen, ya que se puede suponer que en el interior del parque se evitan las instalaciones que puedan afectar a los diferentes hábitats.

Como se puede apreciar en la Figura 5-5, la segunda zona E2 – E3 al ser de 10 kilómetros afectaría algunas zonas de Placilla, Curauma, Valparaíso, Viña del Mar, Quilpué y Villa Alemana.

Dado que sería complicado para las diferentes ciudades realizar una iluminación diferente por sector, sería conveniente que las ciudades que quedaron parcialmente restringidas por la zonificación quedaran totalmente restringidas.

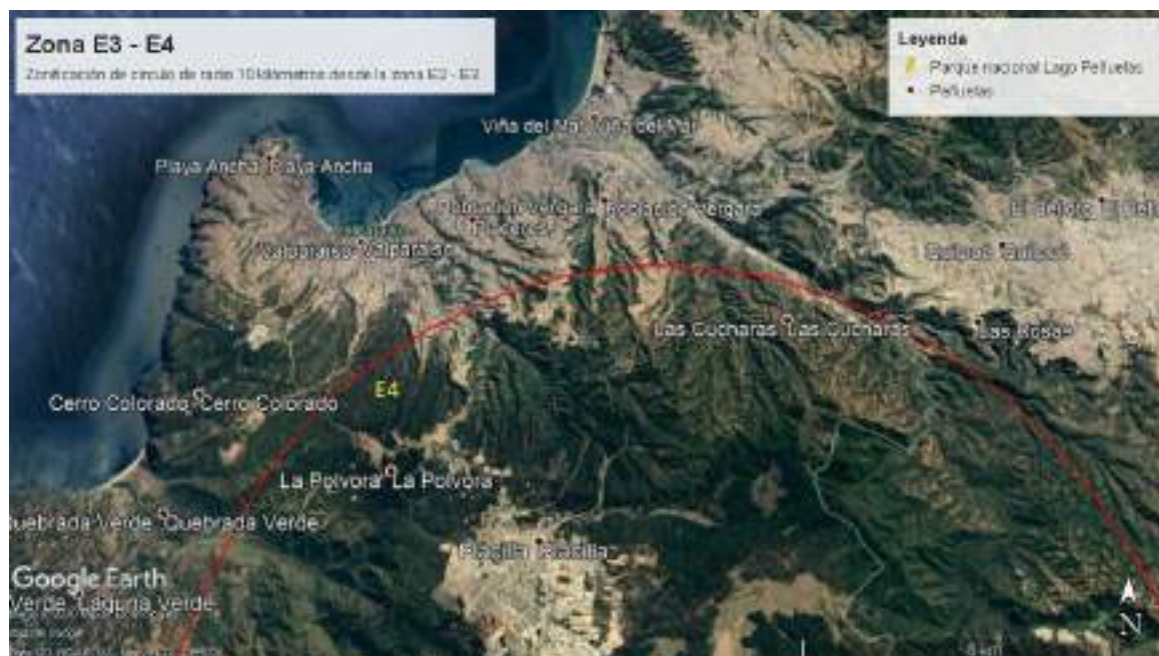


Figura 5-6: Zona E4 sobre parte de las ciudades de Valparaíso, Viña del Mar y Quilpué (Fuente: propia).

Como ya se explica en la Figura 5-4, la primera zona queda totalmente al interior del parque por lo que no representa una protección significativa, por ello se sugiere realizar una zonificación desde los límites exteriores del parque, lo cual nos generaría una zona irregular de un kilómetro de restricción y posteriormente una segunda zona de 10 kilómetros de extensión. En términos generales se sugiere usar el contorno del parque nacional (o zona a proteger) como punto de partida de la zonificación como se aprecia en la Figura 5-7. La principal ventaja de este tipo de zonificación es que permitirá realizar una restricción a zonas irregulares que sobrepasen los límites de los círculos concéntricos de la zonificación estándar.



Figura 5-7: Zonificación utilizando los límites exteriores del Parque Nacional Lago Peñuelas (Fuente: propia).

## 5.2 Restricciones de emisión de flujo hacia el hemisferio superior

De acuerdo con lo establecido en la zonificación del territorio nacional, tendremos 4 zonas donde se deberán aplicar restricciones de emisión de flujo luminoso hacia el hemisferio superior, en el capítulo 2 se presenta la Tabla 2-2 con las recomendaciones para límites de brillo de cielo de la Guía para minimizar el brillo del cielo, donde se restringe, a través, del porcentaje de la relación de salida de luz hacia el hemisferio superior instalada (ULORins), ya que en Chile no se fiscaliza la instalación de las luminarias, se deberá determinar en el efluente a través de la relación de salida de luz hacia el hemisferio superior (ULOR) manteniendo los valores de la tabla de recomendaciones para límites de brillo de cielo.

## 5.3 Restricciones de temperatura de color correlacionada

Las restricciones de temperatura de color correlacionada para las zonas prioritarias deberían ser más restrictivas que las actuales, pese a que DS N° 43/2012 MMA no restringe directamente la temperatura de color correlacionada, el “Límite de emisión de radiancia espectral” que se posee restringe las luminarias por sobre los 3000 K (aproximadamente). Las propuestas de restricción espectral serán expresadas en la Tabla 5-1, los valores de temperatura de color correlacionada considerados para realizar esta restricción fueron tomados de la normativa francesa, que junto a la de Croacia son las más actuales al año 2020.

Tabla 5-1: Restricción por temperatura de color correlacionada para el Sistema de Zonificación.

| Clasificación de zona<br>del punto de<br>referencia | E1 – E2         | E2 – E3  | E3 – E4  |
|-----------------------------------------------------|-----------------|----------|----------|
| E1                                                  | < 2200 K        | < 2200 K | < 3000 K |
| E2                                                  |                 | < 2200 K | < 3000 K |
| E3                                                  |                 |          | < 3000 K |
| E4                                                  | Sin Restricción |          |          |

## 5.4 Restricciones espectrales

Una de las formas que sugiere la Guía para minimizar el brillo del cielo para reducir la interferencia es el uso de fuentes de luz (cuasi) monocromáticas las cuales poseen muy poco contenido de azul en su espectro, como es el caso de las lámparas de sodio de alta presión y las luminarias LED que ya poseen la tecnología para reducir casi en su totalidad la franja que va desde 380 a 499 nm, además es posible la utilización de filtros que restrinjan estos espectros.

## 5.5 Reducción de potencia programada

Pese a que los Reglamentos de Alumbrado Público Peatonal [21] y Vehicular [22], poseen en los Artículos 24 y 27 respectivamente la autorización para disminuir el nivel de iluminación en períodos en que disminuyan los requerimientos de iluminación de los peatones y vehículos, éstos no son obligatorias, quedando a criterio de cada proyecto la posibilidad de realizarlo.

Ya existe la tecnología para reducir la potencia de las luminarias de alumbrado público durante la noche. Apagar las luces por completo puede interferir con otros aspectos importantes de la sociedad. En la mayoría de los casos, los requisitos cambian durante la noche. Después de un cierto momento (fijo o flexible) en el tiempo, la iluminación puede reducirse. Una solución más energéticamente eficiente es usar atenuadores. En el caso de luces publicitarias, de fachadas o monumentos pueden apagarse por completo.

Para que esta reducción de potencia programada sea realizada de manera transversal, es necesario que se genere una obligatoriedad en la medida.

## 5.6 Control y Fiscalización

Se propone mantener el control mediante certificación, además de capacitar a instaladores y fiscalizadores. Además, se propone mantener la fiscalización de las luminarias mediante la certificación previa a la instalación realizada por laboratorios autorizados. Además, es necesario generar un control en terreno de la instalación previo a su funcionamiento, para corroborar que

está cumpliendo la normativa, a través, de la Superintendencia de Medio Ambiente o del organismo fiscalizador que corresponda.

Es necesario tener fiscalizadores que dependan y sean capacitados directamente por Ministerio de Medio Ambiente y que tengan la autorización de inspeccionar y fiscalizar a los responsables de cada proyecto. Además, es necesario obligar a los municipios a hacer cumplir la ley de manera proactiva.

Como sucede en España, se recomienda implementar detectores de luminancia SQM-LR en los diferentes puntos donde se considere que es prioritario mantener un control, estos sensores permitirán determinar la contaminación del cielo a lo largo del territorio, especialmente en los alrededores de las áreas protegidas por presencia de observatorios astronómicos.

## **5.7 Iluminación Ecológica y Parques del Cielo Oscuro**

En la legislación de Croacia se define una Iluminación Ecológica la cual es la única permitida en el territorio, a partir de esto sería interesante que en Chile se comenzara a discutir sobre una definición de Iluminación Ecológica, quedando claro las necesidades técnicas respecto a los problemas medio ambientales que se esperan disminuir, este nuevo tipo de iluminación podría ser considerado para todo el territorio Nacional para la próxima revisión de la normativa. Por lo mismo es recomendable que desde ya se comience a discutir sobre el tema, para que el mercado y las licitaciones se proyecten hacia ese tipo de iluminación.

En algunos países del mundo como Francia y Escocia, están declarando territorios como Parques de Cielo Oscuro, lo cual genera una connotación especial, primero porque se vuelven un atractivo para turismo astronómico ya que es posible ver a simple vista estrellas, los planetas, los meteoros y otros cuerpos celestes claramente, además permiten proteger los ecosistemas que se encuentran insertos en estos. Al ser declarado Parque de Cielo Oscuro, estas zonas adquieren fuertes restricciones de emisión de flujo hacia el hemisferio superior, además de restricciones a las temperaturas de color, pudiendo llegar en el caso de Francia a 2200 K como máximo.

## Discusión y conclusiones

Con todos los antecedentes revisados, podemos concluir que las opciones más viables para realizar una actualización a la normativa sobre contaminación lumínica son:

La creación de Parques de Cielo Oscuros, en las zonas prioritarias del país, principalmente en las zonas donde se encuentran los observatorios astronómicos. Así como en la actualidad se resguardan la segunda tercera y cuarta región, se podría convertir a estas regiones en Parques de Cielo Oscuro. Estos Parques deben tener restricciones máximas con los proyectos de iluminación que se encuentren en su interior o que se proyectan a futuro.

Además de la creación de estos parques será necesario realizar una zonificación en el resto del país, donde se deberá prestar mayor importancia a los Parques Nacionales, que en la actualidad no poseen ningún tipo de limitación respecto a los tipos de iluminación que se emplean en su interior ni en las áreas aledañas. La zonificación que se propone para los Parques Nacionales es en primer lugar considerarlo una zona prioritaria en su interior con las restricciones máximas y generando una segunda zona tomando el contorno del parque como límite de la primera zona y generando una distancia constante alrededor del parque, donde deba existir una restricción menor.

Respecto a las restricciones de los niveles de emisión de flujo hacia el hemisferio superior, es necesario que en las zonas consideradas prioritarias y en los Parques de Cielo Oscuro la emisión de intensidad luminosa sea de 0 candelas, para ángulos gamma mayores a 90°, mientras que para zonas de menor restricción los valores deberán ser acordados en consenso entre las partes afectadas.

Respecto a las restricciones espectrales, es necesario que se disminuya casi en su totalidad el color azul de las luminarias, color que se encuentra entre los 380 nm y 499 nm del espectro visible, pero es necesario realizar un estudio técnico respecto a cuanto será el valor máximo permitido para las zonas prioritarias, Parque de Cielo Oscuro y las zonas de menor restricción. Este estudio debe ser realizado tomando en cuenta los posibles problemas de salud que puede tener la iluminación en las personas y el impacto que puede tener en el medio ambiente y en los ecosistemas. Sobre las restricciones del espectro ultravioleta e infrarrojo, se recomienda mantener la restricción actual de la radiancia espectral que se encuentra en el DS N° 43/2012 MMA, que es en el caso del infrarrojo, que entre la franja de 300 nm y 379 nm no podrá superar el 15% de la radiancia



espectral del espectro visible que está entre 380 nm y 780 nm. Y en el caso del ultravioleta, que entre 781 nm y 1000 nm no podrá superar el 50% de la radiancia espectral del espectro visible que se encuentra entre 380 nm y 780 nm.

En el caso de la temperatura de color correlacionada, también es posible realizar una restricción, en las normativas de Francia y de Croacia que son las más actuales revisadas en este informe, se propone una temperatura de color correlacionada de 2200 K en las zonas prioritarias y en los Parques de Cielo Oscuro. En las zonas de menor restricción se piden luminarias que no superen los 3000 K, ya que en estos países ya se consideró en la normativa que la iluminación puede afectar la salud de las personas. En Chile no se restringe la temperatura de color correlacionada, pero la restricción del espectro que existe genera que las temperaturas de color de las luminarias certificadas por contaminación lumínica excedan por muy pocas unidades los 3000 K.

Otra alternativa que es completamente aplicable en nuestro país es la reducción de potencia programada, en este momento ya existe la tecnología necesaria para aplicar esta medida, la cual puede generar un ahorro energético para el país, así como una reducción del brillo del cielo por reflexión de las superficies. Evidentemente, será necesario realizar un estudio sobre los horarios donde la reducción no afecte la libre circulación de peatones y vehículos. En el caso de luces publicitarias, de fachadas o monumentos pueden apagarse por completo.

Sobre el control, es posible realizar mapas de brillo del cielo utilizando detectores de luminancia SQM-LR, los cuales pueden ser instalados en las diferentes ciudades o sitios de interés, estos sensores permiten tener un control en tiempo real de las posibles variaciones que se pueden producir en el brillo del cielo al poner en marcha algún proyecto nuevo de iluminación.

Sobre la fiscalización, se recomienda mantener la actual fiscalización en el efluente, a través, de laboratorios certificados. También es necesario que existan fiscalizadores en terreno, los cuales puedan fiscalizar la instalación antes de ponerse en marcha para asegurar que el proyecto fue ejecutado según los estándares de la normativa, es necesario que estos fiscalizadores sean capacitados y dependan directamente del Ministerio de Medio Ambiente, para asegurar la correcta aplicación de la normativa.

Así como en países como Croacia se definió una iluminación ecológica y que por normativa es la única permitida en el territorio de ese país, en Chile podría comenzar a definirse una propia iluminación ecológica, la cual nos presente como se quiere que el país se ilumine a futuro, tomando en cuenta los posibles contaminantes presentes en la composición de las luminarias, su emisión de flujo luminoso hacia el hemisferio superior, las temperaturas de color permitidas, las posibles restricciones espectrales y todas las variables de interés medio ambiental. En este momento realizar una obligatoriedad sobre el uso exclusivo de este tipo de iluminación sería demasiado restrictivo, pero es un avance ir definiendo desde ya el cómo se debe realizar, para que la próxima revisión de normativa, sea posible discutir su obligatoriedad.

Finalmente, es necesario mencionar que es importante educar a la ciudadanía sobre la importancia de la buena iluminación, esto permitirá que exista mejor aceptación de luminarias

**Discusión y conclusiones**

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que posean más restricciones, como por ejemplo con temperaturas de color más bajas, las cuales poseen menores índices de reproducción de color.

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# A Tablas Comparativas de Normativas

A continuación, se presentan las tablas resumen de las normativas más importantes estudiadas.

Tabla A-1: Restricción territorial.

| Normativa                                                                                                                    |      | Restricción Territorial |           |                                                             |
|------------------------------------------------------------------------------------------------------------------------------|------|-------------------------|-----------|-------------------------------------------------------------|
| País o Estado                                                                                                                | Año  | Parcial (1)             | Total (2) | Descripción                                                 |
| Hawaii                                                                                                                       | 1988 |                         | X         |                                                             |
| Islas Canarias                                                                                                               | 1992 | X                       |           | Totalidad de La Palma y Parte de Tenerife                   |
| Italia UNI                                                                                                                   | 1999 | X                       |           | No obligatoria, Zonificación                                |
| Lombardía                                                                                                                    | 2000 |                         | X         | Zonas protegidas                                            |
| Texas                                                                                                                        | 2001 | X                       |           | 57 millas de un Observatorio o 5 millas de una base militar |
| Ensenada                                                                                                                     | 2006 |                         | X         |                                                             |
| España                                                                                                                       | 2008 | X                       |           | Zonificación                                                |
| Chile                                                                                                                        | 2012 | X                       |           | Regiones II, III y IV                                       |
| Francia                                                                                                                      | 2018 |                         | X         | Zonas protegidas (3)                                        |
| Croacia                                                                                                                      | 2019 |                         | X         | Zonas protegidas (3)                                        |
| (1): La restricción se aplica a una parte del territorio del país o estado.                                                  |      |                         |           |                                                             |
| (2): La restricción se aplica a toda la superficie del país o estado.                                                        |      |                         |           |                                                             |
| (3): La restricción se aplica a todo el territorio, pero existen restricciones adicionales en determinadas zonas protegidas. |      |                         |           |                                                             |

A Tablas Comparativas **de Normativas**

Tabla A-2: Restricción horaria.

| Normativa                                  |      | Restricción horaria     |                         |                                                                                                                      |
|--------------------------------------------|------|-------------------------|-------------------------|----------------------------------------------------------------------------------------------------------------------|
| País o Estado                              | Año  | Con Restricción Horaria | Sin Restricción Horaria | Descripción                                                                                                          |
| Hawaii                                     | 1988 | X                       |                         | Luminarias por encima de 4050 [Lm] y haluros de metal deben permanecer apagadas desde las 11:00 PM hasta el amanecer |
| Islas Canarias                             | 1992 | X                       |                         | Reducción del flujo luminoso a un tercio del normal a partir de las 24:00 horas y apagado de letreros luminosos      |
| Italia UNI                                 | 1999 |                         | X                       |                                                                                                                      |
| Lombardía                                  | 2000 |                         | X                       | Reducción del flujo luminoso mayor al 30% después de las 24:00 horas                                                 |
| Texas                                      | 2001 | X                       |                         | Determinada por cada condado                                                                                         |
| Ensenada                                   | 2006 | X                       |                         | Solo para letreros espectaculares (1)                                                                                |
| España                                     | 2008 |                         | X                       |                                                                                                                      |
| Chile                                      | 2012 |                         | X                       |                                                                                                                      |
| Francia                                    | 2018 | X                       |                         | Entre 7:00 AM y 1:00 PM o una hora antes y después                                                                   |
| Croacia                                    | 2019 |                         | X                       |                                                                                                                      |
| (1): Letreros de más de 4 metros cuadrados |      |                         |                         |                                                                                                                      |

A Tablas Comparativas **de Normativas**

Tabla A-3: Restricción de emisión en gamma igual a 90°.

| Normativa                                                                        |      | Emisión en gamma = 90° (1) |   |                                |
|----------------------------------------------------------------------------------|------|----------------------------|---|--------------------------------|
| País o Estado                                                                    | Año  | Mayor a 0                  | 0 | Descripción                    |
| Hawaii                                                                           | 1988 |                            |   | No especifica                  |
| Islas Canarias                                                                   | 1992 |                            |   | No especifica                  |
| Italia UNI                                                                       | 1999 |                            |   | No especifica                  |
| Lombardía                                                                        | 2000 | X                          |   | 0,49 candelas por cada KLm (2) |
| Texas                                                                            | 2001 |                            |   | No se especifica               |
| Ensenada                                                                         | 2006 |                            |   | No se especifica               |
| España                                                                           | 2008 |                            |   | No se especifica               |
| Chile                                                                            | 2012 | X                          |   | 0,49 candelas por cada KLm (2) |
| Francia                                                                          | 2018 |                            |   | No se especifica               |
| Croacia                                                                          | 2019 |                            |   | No se especifica               |
| (1): Restricción de intensidad luminosa máxima, para un ángulo gama igual a 90°. |      |                            |   |                                |
| (2): Entre 0,00 y 0,49 candelas por cada 1000 lúmenes del flujo de la lámpara.   |      |                            |   |                                |

A Tablas Comparativas **de Normativas**

Tabla A-4: Restricción de emisión sobre gamma 90°.

| Normativa                                                                                                                                                                                                                          |      | Emisión en gamma > 90° (1) |           |                                                                                                                                                                                                                                    |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|----------------------------|-----------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| País o Estado                                                                                                                                                                                                                      | Año  | Mayor a 0                  | Igual a 0 | Descripción                                                                                                                                                                                                                        |
| Hawaii                                                                                                                                                                                                                             | 1988 |                            | X         | Se exige que las luminarias estén completamente blindadas (2), excepto las de neón y los Haluros metálicos                                                                                                                         |
| Islas Canarias                                                                                                                                                                                                                     | 1992 |                            |           | La luz emitida se debe proyectar por debajo del plano horizontal tangente al punto más bajo de luminaria                                                                                                                           |
| Italia UNI                                                                                                                                                                                                                         | 1999 |                            | X         | En zonas protegidas                                                                                                                                                                                                                |
| Lombardía                                                                                                                                                                                                                          | 2000 |                            |           | 0,49 candelas por cada 1000 Lm                                                                                                                                                                                                     |
| Texas                                                                                                                                                                                                                              | 2001 |                            |           | Determinada por cada condado                                                                                                                                                                                                       |
| Ensenada                                                                                                                                                                                                                           | 2006 |                            |           | Se señala que toda la luz emitida sea proyectada por debajo del horizonte referido al punto más bajo de las luminarias, siendo instaladas sin inclinación. Las lámparas permitidas serán determinadas por el comité técnico asesor |
| España                                                                                                                                                                                                                             | 2008 | X                          |           | Entre 1% y 25% dependiendo de la zona (3)                                                                                                                                                                                          |
| Chile                                                                                                                                                                                                                              | 2012 |                            | X         |                                                                                                                                                                                                                                    |
| Francia                                                                                                                                                                                                                            | 2018 | X                          |           | <1% del total nominal, <4% del total al instalar y 0 en zona protegida                                                                                                                                                             |
| Croacia                                                                                                                                                                                                                            | 2019 |                            | X         |                                                                                                                                                                                                                                    |
| (1): Emisión de flujo luminoso hacia el hemisferio superior.                                                                                                                                                                       |      |                            |           |                                                                                                                                                                                                                                    |
| (2): Completamente blindadas significa que el dispositivo de iluminación exterior está construido de manera que toda la luz emitida por el dispositivo se proyecte debajo del plano horizontal del punto más bajo del dispositivo. |      |                            |           |                                                                                                                                                                                                                                    |
| (3) Zonas determinadas en la Tabla 3-1.                                                                                                                                                                                            |      |                            |           |                                                                                                                                                                                                                                    |

Tabla A-5: Restricción por temperatura de color correlacionada.

| Normativa                                                                                                                                                                                                                  |      | T° de Color Correlacionada (1) |                 |                                    |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|--------------------------------|-----------------|------------------------------------|
| País o Estado                                                                                                                                                                                                              | Año  | Con restricción                | Sin restricción | Descripción                        |
| Hawaii                                                                                                                                                                                                                     | 1988 |                                | X               |                                    |
| Islas Canarias                                                                                                                                                                                                             | 1992 |                                | X               |                                    |
| Italia UNI                                                                                                                                                                                                                 | 1999 |                                | X               |                                    |
| Lombardía                                                                                                                                                                                                                  | 2000 |                                | X               |                                    |
| Texas                                                                                                                                                                                                                      | 2001 |                                |                 | Determinada por cada condado       |
| Ensenada                                                                                                                                                                                                                   | 2006 |                                | X               |                                    |
| España                                                                                                                                                                                                                     | 2008 |                                | X               |                                    |
| Chile                                                                                                                                                                                                                      | 2012 |                                | X               |                                    |
| Francia                                                                                                                                                                                                                    | 2018 | X                              |                 | < 3000 K y < 2400 Zonas protegidas |
| Croacia                                                                                                                                                                                                                    | 2019 | X                              |                 | < 3000 K y < 2200 Zonas protegidas |
| (1): La temperatura de color correlacionada indica el color de una fuente de luz por comparación de ésta con el color del cuerpo negro, es decir, del “radiante perfecto teórico” o sea radia toda la energía que percibe. |      |                                |                 |                                    |

A Tablas Comparativas **de Normativas**

Tabla A-6: Restricción de espectro.

| Normativa                                                                                                           |      | Radiancia espectral (1) |                 |                                                                                                                                     |
|---------------------------------------------------------------------------------------------------------------------|------|-------------------------|-----------------|-------------------------------------------------------------------------------------------------------------------------------------|
| País o Estado                                                                                                       | Año  | Con restricción         | Sin restricción | Descripción                                                                                                                         |
| Hawaïi                                                                                                              | 1988 |                         | X               |                                                                                                                                     |
| Islas Canarias                                                                                                      | 1992 | X                       |                 | Las radiancias espectrales para todas las longitudes de onda menores de 440 nm sean menores al 15% de su radiancia total            |
| Italia UNI                                                                                                          | 1999 |                         | X               |                                                                                                                                     |
| Lombardía                                                                                                           | 2000 |                         | X               |                                                                                                                                     |
| Texas                                                                                                               | 2001 |                         |                 | Determinada por cada condado                                                                                                        |
| Ensenada                                                                                                            | 2006 |                         | X               |                                                                                                                                     |
| España                                                                                                              | 2008 | X                       |                 | Se utilizan lámparas de sodio para zona protegida y en caso contrario se filtra la radiación de longitudes de onda menores a 440 nm |
| Chile                                                                                                               | 2012 | X                       |                 | Menor al 15% del espectro visible (2) de 300 a 379 nm y de 380 a 499 nm<br>Menor al 50% del espectro visible de 781 a 1000 nm       |
| Francia                                                                                                             | 2018 |                         | X               |                                                                                                                                     |
| Croacia                                                                                                             | 2019 | X                       |                 | Se debe evitar la emisión bajo 500 nm                                                                                               |
| (1): Radiancia espectral: Intensidad de energía radiada por unidad de superficie, longitud de onda y ángulo sólido. |      |                         |                 |                                                                                                                                     |
| (2): Espectro visible: radiancia espectral entre 380 nm y 780 nm.                                                   |      |                         |                 |                                                                                                                                     |



## A Tablas Comparativas de Normativas

Tabla A-7: Responsables de fiscalizar.

| Normativa      |      | Responsables de Fiscalizar |    |                                                                                                                                                                                                                                                         |
|----------------|------|----------------------------|----|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| País o Estado  | Año  | Si                         | No | Descripción                                                                                                                                                                                                                                             |
| Hawaii         | 1988 | X                          |    | Comité de Normas de Iluminación al Aire Libre del Condado. Se presenta al condado un informe con la ubicación, el tipo de lámparas de exterior que se utilizarán y una descripción incluidos, entre otros, cortes y dibujos del catálogo del fabricante |
| Islas Canarias | 1992 | X                          |    | Ministerio de Obras Públicas y Transportes, Instituto de Astrofísica de Canarias                                                                                                                                                                        |
| Italia UNI     | 1999 |                            | X  | No obligatoria                                                                                                                                                                                                                                          |
| Lombardía      | 2000 | X                          |    | Los municipios son responsables de hacer cumplir la ley                                                                                                                                                                                                 |
| Texas          | 2001 |                            |    | La corte de comisionados de un condado adoptará órdenes que regulen la instalación y el uso de la iluminación exterior, además se encargará de su fiscalización                                                                                         |
| Ensenada       | 2006 | X                          |    | Comité técnico asesor, a través de un cuerpo de inspectores                                                                                                                                                                                             |
| España         | 2008 | X                          |    | MeteoGalicia (SQM-LR), la administración pública competente exige documentación y se encarga de fiscalizar para asegurar el cumplimiento de la ley                                                                                                      |
| Chile          | 2012 | X                          |    | Superintendencia de Electricidad y Combustibles                                                                                                                                                                                                         |
| Francia        | 2018 | X                          |    | Inspectores, Comunidades involucradas, capacitación de instaladores                                                                                                                                                                                     |
| Croacia        | 2019 | X                          |    | Inspectores acreditados por la Agencia de Acreditación de Croacia, Capacitación de instaladores, Control de las unidades de autogobierno local y la Ciudad de Zagreb sobre los proyectos de iluminación                                                 |

## A Tablas Comparativas de Normativas

Tabla A-8: Multas y sanciones.

| Normativa                                                                                  |      | Multas y sanciones (1) |               |                                                                                              |
|--------------------------------------------------------------------------------------------|------|------------------------|---------------|----------------------------------------------------------------------------------------------|
| País o Estado                                                                              | Año  | Se especifica          | No especifica | Descripción                                                                                  |
| Hawaii                                                                                     | 1988 | X                      |               | Multas, delito                                                                               |
| Islas Canarias                                                                             | 1992 |                        | X             |                                                                                              |
| Italia UNI                                                                                 | 1999 |                        |               | No obligatoria                                                                               |
| Lombardía                                                                                  | 2000 | X                      |               | Multas                                                                                       |
| Texas                                                                                      | 2001 | X                      |               | Presunción de delito, demandas a proyectos que no cumplan la ley                             |
| Ensenada                                                                                   | 2006 | X                      |               | Amonestación, multa, clausura y finalmente revocación de la autorización o permiso municipal |
| España                                                                                     | 2008 | X                      |               | Multas especificadas en el Título V de la Ley 21/1992, de Industria                          |
| Chile                                                                                      | 2012 |                        | X             |                                                                                              |
| Francia                                                                                    | 2018 |                        | X             |                                                                                              |
| Croacia                                                                                    | 2019 | X                      |               | Multas                                                                                       |
| (1): Se especifica directamente en la normativa las multas y sanciones al no ser cumplida. |      |                        |               |                                                                                              |

A Tablas Comparativas **de Normativas**

Tabla A-9: Organismos responsables.

| Normativa      |      | Organismos Responsables                                                                                                                                        |
|----------------|------|----------------------------------------------------------------------------------------------------------------------------------------------------------------|
| País o Estado  | Año  | Descripción                                                                                                                                                    |
| Hawaii         | 1988 | Condado de Hawaii                                                                                                                                              |
| Islas Canarias | 1992 | Ministerio de Relaciones con las Cortes y de la Secretaría el Gobierno                                                                                         |
| Italia UNI     | 1999 | Ente Nazionale Italiano di Unificazione                                                                                                                        |
| Lombardía      | 2000 | Consejo regional de Lombardía                                                                                                                                  |
| Texas          | 2001 | La corte de comisionados del Condado                                                                                                                           |
| Ensenada       | 2006 | El Ayuntamiento, a través, del Presidente Municipal, El Secretario de Administración Urbana, El Director de Ecología de la Secretaría de Administración Urbana |
| España         | 2008 | Ministerio de Industria, Turismo y Comercio                                                                                                                    |
| Chile          | 2012 | Ministerio de Medio Ambiente                                                                                                                                   |
| Francia        | 2018 | Ministerio de Transición Ecológica y Solidaria                                                                                                                 |
| Croacia        | 2019 | Ministerio de Medio Ambiente y Naturaleza                                                                                                                      |

## Article

# Assessment of Citizens' Actions against Light Pollution with Guidelines for Future Initiatives

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**Abstract:** Due to the wide reach of media reports about scientific research and technological tools such as the world wide web (WWW), the Internet, and web browsers, citizens today have access to factual information about the negative impact of artificial light at night (ALAN) on their dark skies, and their health and well-being. This means they can now make educated decisions and take the necessary steps to help protect themselves and their communities from disruptive light pollution. Whilst this action is positive and welcomed, unfortunately, according to collected data, not all such initiatives have been successful. Although our understanding of this groundswell movement is deepening, further studies are required to complete a worldwide picture of the current situation. This paper therefore investigates the various actions taken by citizens, as well as the challenges, methods, and tools involved, regarding good practices initiated by grass roots activism on how to reduce existing and potential light pollution. The results of a comparative analysis of 262 international case studies (lawsuits and online petitions) reveal that, since the 1990s, there has been an increase in the number of legal cases related to light pollution due to the rise in public awareness, the availability of scientific knowledge via the Internet, and the ability to take accurate lighting measurements and perform lighting simulations. Also, in the last decade a new tool for digital participation in the form of online petitions has established a new movement of citizen action to mitigate the effects of light pollution. Based on this information, a seven-step framework involving recommendations for citizen action has been developed. It is expected that this new knowledge will benefit those citizens planning future efforts involving the development, implementation, and monitoring processes of outdoor lighting. Additionally, it might support the evolution of planning and policy approaches that are sustainable and necessary to improve the application and installation of ecologically/biologically responsible illumination for towns, cities, and natural habitats.

**Keywords:** light pollution; human health; LEDs; LED lighting; artificial light nuisance; artificial light at night; ALAN; sky glow; public health; citizens' participation; lighting conflicts; lawsuits; online petitions; e-petitions; Campaign to Protect Rural England; CPRE; International Dark-Sky Association; IDA; Earth Hour; International Dark Sky Places Program; grassroots organizations; NASA Earth Observatory images; review

## 1. Introduction

Current studies demonstrate that urban environments in our modern day have continued to become significantly brighter and more illuminated at night, and that man-made light pollution from outdoor illumination that is misdirected, obtrusive, and unwanted has lately increased by more than two percent per year [1].

In the past, the first people to notice the unprecedented effects of light pollution were professional and amateur astronomers. They observed that sky glow caused the loss of dark night skies and hindered the ability to view the starscape above. This concern fueled expressions of dismay about light pollution and initiated action against it [2]. As the problem worsened, constellations of stars “vanished” and, most importantly, prevented proper astronomical observations and research. Some 40 years later, environmentalists also became publicly vocal about the negative impact of the use of artificial light at night (ALAN) on the environment, ecosystems, and its inhabiting flora and fauna [3]. Unhealthy patterns were witnessed regarding the avoidance of suitable habitats, alterations in reproduction and seasonal migration routes, as well as the reduction in numbers or even the extinction of certain species. When NASA began to release new, high-definition pictures taken from space at night (Figure 1), the true scale and severity of the problem was revealed [4]. As a consequence of this publicity, many more people became aware of the negative impact of light pollution, the avoidable loss of natural darkness, and the unnecessary disappearance of starry skies at night.



**Figure 1.** Global map of Earth at night in 2016, showcasing a composite view of the patterns of human settlements across the planet that produce light pollution. Source: NASA Earth Observatory images by Joshua Stevens, using Suomi NPP VIIRS data from Miguel Román, NASA’s Goddard Space Flight Center.

Leading up to the present time, researchers have offered some understanding into the body of knowledge of light pollution, from philosophy [5], astronomy [6], ethics [7], measurement [8,9], economics [10], policies [11], regulations [12], medicine [13,14], environmental impact [15], to design challenges [16,17], land protection [18], and more. Regrettably, there is still very little research on the impact of light pollution and its mitigation via citizen participation [19,20]. Thus, while enquiry helps to further our understanding of this social shift, more studies are required to complete a worldwide picture of the current situation. Even so, based on the existing case studies presented in this research, it is clear that certain processes are needed to improve the outcome of future actions.

Furthermore, at the turn of the century, significant changes occurred in people’s comprehension of how artificial light affects their physiology and the natural environment, revealing the vast complexity of the processes involved, highlighting too, how much more needs to be learned and understood, and how crucial it is to address the problems that have manifested.

The authors have identified four major contributing factors influencing the formation of citizens' initiatives against light pollution, which are explained in detail in (Figure 2).

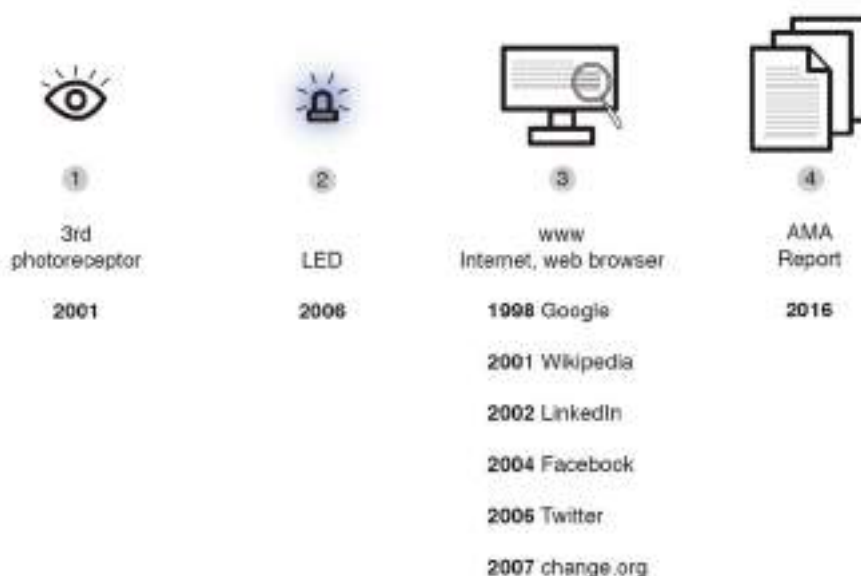


**Figure 2.** Four contributing factors driving citizens' initiatives against light pollution: (1) The discovery of a new photoreceptor in the human eye; (2) the development of solid-state lighting (SSL) technology with blue-rich white light-emitting diodes (LEDs); (3) easy access to information about the negative impact of artificial light at night (ALAN) via new technological tools; (4) the American Medical Association's (AMA) published report about their concerns on the use of artificial light at night.

The first factor occurred in 2001, when a new type of photoreceptor was discovered in the human eye, called intrinsically photosensitive retinal ganglion cells (ipRGCs). It is also known as the third photoreceptor because it is different to the two other rod and cone photoreceptors [21]. This paradigm shift radically changed previous assumptions about ocular anatomy because it meant the eyes have another function completely unrelated to vision, namely, they play a crucial role in setting the circadian clock, upon which health depends. This realization also provided new insight into the importance of exposure to natural light during the day [22], as well as the biological need for darkness during the night [23].

Secondly, the development of solid-state lighting (SSL) technology with sources like blue-rich white light-emitting diodes (LEDs) has dramatically changed the way society illuminates spaces indoors and outdoors [24]. Unfortunately, the lighting industry and public authorities have placed too much focus on the technology's energy, operation, and maintenance savings, without due consideration, investigation, and adequate understanding of the broader reaching, long-term costs which far outweigh them. These costs involve the associated numerous inherent drawbacks which negatively impact the environment, ecosystems, and the health of humans, flora, and fauna [25,26]. Further complicating matters, mounting research confirms that commonly used, high intensity LED light sources, with peaks in disruptive blue wavelengths of light, are inappropriate and harmful to most species [27]. The introduction of new light sources should be preceded by detailed research, not only towards new technical, energy saving aspects, but also to observe and understand the impact these new technologies have on human health and the environment.

Thirdly, the last decade has seen a steady rise in the use of the world wide web, the Internet, and web browsers, which have provided easy access to factual information about the negative impact of ALAN on dark skies, and the health and well-being of humans. Furthermore, the dissemination of this knowledge has increased due to online meetings, webinars, and presentations, and through

professional web-based networks such as LinkedIn. Social media such as Facebook and Twitter have also played a role, as have email and chat messages.

Lastly, in 2016, the publication of a report titled *Human and Environmental Effects of Light Emitting Diode Community Lighting* [28], by the American Medical Association (AMA), motivated concerned citizens to search for information on the issue, allowing them to form their own opinion on the subject. The AMA report was widely criticized by the American lighting industry and its supporters [29–31] as it disclosed the dangers of using new LED lighting, after more research surfaced questioning this new lighting technology. This controversial information spread, and reputable newspapers interviewed scientists and researchers, effectively “translating” scientific research into information that was comprehensible to the non-scientific community [31–34].

As a consequence of the above, informed members of the public have now become actively involved in disputes against light pollution to try to minimize its impact. They have also begun demanding safer, responsible illumination, generating pressure that requires a response from decision-makers. While action has been undertaken in some countries, official reports of successful initiatives are scarce, hence the author’s research into the best methods to help enable effective citizen actions against light pollution.

In order to gain a better overview of the existing situation, the first aim of this study is to create robust science-informed data about the various methods citizens undertake [35] to resolve light pollution disputes. To further support this aim, it seems essential to establish a simple but effective framework which provides inputs on how to deal with the complexity of these lighting related disputes with an easy to follow, step by step process (framework). This new knowledge should assist those planning to take action to improve outdoor lighting in regards to the development and implementation of monitoring processes. Furthermore, this research may also support the evolution of sustainable planning and policy approaches necessary in the application and installation of biologically/ecologically responsible illumination for towns, cities, and natural habitats.

This paper is organized into eight sections. Section 1 places the study in a broad context and highlights why it is important. A literature review of previous work is included, as is a description of how the current study fills the knowledge gap that exists. Section 2 determines the context and impact of the research being performed, by assembling the following factors: Existing background information on light pollution including categories of lighting type nuisance; organizations and their initiatives campaigning against light pollution; the various actions taken by citizens; recommendations on how to measure and minimize light pollution. Section 3 defines the research hypotheses. Section 4 describes the methods (data collection and generation) and protocols (data analysis) applied in the study. Section 5 provides a precise description and summary of the findings about actions that oppose light pollution, which are arranged in a logical sequence. Section 6 discusses the findings and their implications, and explains how they can be interpreted via their perspective of the working hypotheses. Section 7 provides the study’s limitations. Section 8 gives a synthesis of the key points and recommends new areas for future research and action in the field of public participation connected to the mitigation and prevention of light pollution.

## 2. Background Research

Wide-ranging background research was commenced for a period of six months. This inquiry involved an in-depth assessment of published information on external lighting and light pollution that included: Books, scientific research papers, lighting standards, regulations and environmental reports, legal documents of existing case studies, media reports found online, as well as the conduction of in-depth interviews with environmental experts and light pollution activists involved in light pollution disputes. Moreover, the authors have included insights and evidence provided by their previous professional research and hands-on experience based on the following roles: Member of International Dark-Sky Association (IDA) Technical Committee, IDA Delegate, and activism by the leader of the Dunedin Dark Skies Group, all of which involves ongoing work to mitigate light pollution.



## 2.1. Light Pollution and its Impact

Light pollution (LP) is a broad term, and the International Commission on Illumination has yet to agree on a definition to describe the adverse effects of artificial light on the night-time natural environment that also impacts flora, fauna, and humans [36]. Despite this lack of information, some researchers have recognized four distinct forms of LP [37] connected to quantitative, directional, or spectral light attributes, which include: (1) Man-made sky glow; (2) glare; (3) light trespass, and (4) overlighting. As identified below, each source of disturbance might have different effects.

### 2.1.1. Man-Made Sky Glow—The Brightening of the Night Sky Over Inhabited Areas

Man-made sky glow is caused by man-made sources of radiation (e.g., artificial outdoor lighting) and includes radiation that is emitted directly upwards and radiation that is reflected from the surface of the Earth [38]. The use of unfit for purpose, poorly installed street and area lighting can negatively impact the Earth's atmosphere and hinder/prevent astronomical observations (Figure 3). This includes decorative and security building lighting equipment, floodlights on high masts at sports facilities, as well as event, landscape, and advertisement lighting that directs unwanted light into the night sky. Colorful, bright industrial lighting that radiates through glass roofs and the façades of greenhouses into the night sky can also negatively impact astronomical observations [39]. Likewise, the glow above greenhouses can cause visual annoyance at ground level for residents and visitors. (This is why such greenhouses require the installation of blinds.) Sky glow created by cities and towns can even impact terrestrial and aquatic organisms far away from the actual source of light pollution [40,41].



**Figure 3.** A typical city with a common problem: Man-made orange colored sky glow produced by high-pressure sodium light sources. Those cities that have retrofitted LEDs may have sky glow that is white in color. Source: Mike Knell/Flickr.

### 2.1.2. Glare—Excessive Brightness that Causes Visual Discomfort

Glare is an unpleasant sensation produced by bright areas within the field of vision which can negatively impact the visual perception of humans. Discomfort glare is a result of viewing an intense light source (a poorly placed and/or unshielded luminaire). It can cause annoyance, fatigue, and even pain to residents and visitors. Whereas disability glare impairs the perception of objects without

necessarily causing discomfort, but due to a reduction in visibility, can cause annoyance, distraction, or a reduction in the ability to see essential information when driving, walking, and cycling, and may contribute to accidents and injury (Figure 4).



**Figure 4.** Discomfort glare produced by bright white LED light source, experienced by the pedestrians of Rome, in Italy. Source: Gianni Cipriano/New York Times/Redux/eyevine.

### 2.1.3. Light Trespass/Light Spill—Light that Shines Where It Is Unnecessary or Unwanted

Light trespass, also known as light spill or light intrusion, can negatively impact the evening use, enjoyment, and privacy of residential buildings when light from the exterior intrudes into private living rooms, kitchens, balconies, terraces, and gardens. The unfavorable encroachment of light into bedrooms through windows can also negatively impact the quality and duration of human's nighttime sleep, both critical for health and well-being (Figure 5). Light trespass, for instance, can be from lighting that is positioned too close to a building and on street poles which are too high for residential areas, and/or from decorative building illumination, security, sport facility lighting, and/or advertising. When buildings are over lit and illuminated by vibrant, colorful dynamic lighting, it is not only a source of visual disturbance, it can also ruin the character, ambience, and atmosphere of a place [42].

Additionally, dynamic changes in color and brightness can cause traffic accidents due to the distraction they cause. Light trespass is known to negatively impact fauna, especially when inappropriate illumination from glazed buildings acts as an unnatural source of attraction and becomes a physical barrier to migrating birds [43]. Street, sport facility, and event lighting can also cause disorientation and disruption to the biological rhythms of many species, as well as reduce the quality of habitats for birds, insects, bats, turtles, etc.

Furthermore, the inappropriate illumination of structures like bridges can cause numerous problems. For example, the light from a bridge can reflect off the surface of nearby water. It can also penetrate deep into the water, negatively impacting fish and other living organisms [44]. This disruption reduces biodiversity and harms the food chain by adversely interrupting various crucial behavioral patterns including navigation, foraging, mating, rest, and predation. Light trespass can also negatively impact flora (delaying the loss of foliage, accelerating branch growth, and producing a second bloom in autumn) [45].



**Figure 5.** Light trespass/light spill from unshielded 4000 K LED street lighting entering the windows of residential properties in Oamaru/NZ. Source: Damien McNamara.

#### 2.1.4. Over-Illumination—The Excessive Use of Light

Over-illumination is caused by the excessive use of artificial lighting well outside the necessary visual requirements for a specific functional activity and/or aesthetic aspects defined by lighting standards and norms (Figure 6). It can also be created by improper lighting maintenance such as when lighting is not switched off or dimmed throughout the night. (Without the use of timers, occupancy sensors, and lighting controls, energy will also be wasted.)



**Figure 6.** Over-illumination created by the excessive use of artificial lighting well outside the necessary visual requirements, at the Westfield shopping mall in Los Angeles/US. Source: Alonso Reyes/Unsplash.

This type of nuisance can disturb astronomical observations, and can also be a hazard to vehicular and pedestrian traffic due to the creation of high levels of lighting contrast. Furthermore, over-illumination can also impair the nighttime sleep of citizens, as well as the healthy function of local flora and fauna.

## 2.2. Artificial Light at Night Nuisance—Categories of Lighting Types

Most unwanted light pollution (which is recognized as a major cause of disturbance and discomfort for many people), results from incorrectly designed outdoor artificial lighting (a light source which is in an inappropriate place, that emits an inappropriate amount and type of light, at an inappropriate time, in the wrong direction, see Section 2.1.1). Based on the performed research and analyzed cases, the authors have confirmed eight existing categories of lighting types (Figure 7). Each of these categories can be a major source of disturbance, causing artificial light at night nuisance: (1) Street and area lighting; (2) building and nonbuilding structure lighting; (3) industrial and commercial lighting; (4) sports field facility lighting; (5) advertisement lighting; (6) park and garden lighting; (7) safety and security lighting, and (8) event lighting.



**Figure 7.** Eight categories of lighting types responsible for artificial light at night nuisance: (a) Street and area lighting; (b) building and nonbuilding structure lighting; (c) industrial and commercial lighting; (d) sports field facility lighting; (e) advertisement lighting; (f) park and garden lighting; (g) safety and security lighting, and (h) event lighting. Sources: (a) Christian Muller/Fotolia, (b) David Benes/Unsplash, (c) Will Li/Unsplash, (d) Marvin Ronsdorf/Unsplash, (e) Lu Avimitin/Unsplash, (f) Gabriela Torzsa/Unsplash, (g) Dean Jones, (h) Tomek Baginski/Unsplash.

## 2.3. Organizations and Initiatives Campaigning against Light Pollution

At the end of XX-century, grassroots activism for responsible illumination came into existence due to the urgent need to mitigate light pollution. These efforts to protect the nighttime environment by informing/educating the public about the use and application of quality artificial lighting have paid off. Today, there are numerous active organizations and initiatives around the world which are already safeguarding the nighttime sky for future generations to come. The authors point out that the most significant of them listed as follows, emphasize the importance of working with citizens on a close basis.



### 2.3.1. Grassroots Organizations

*The Campaign to Protect Rural England (CPRE)* is one of the oldest and largest charitable environmental organizations based in the UK. Established in 1926, it now has over 40,000 members and supporters [46]. (It was previously known as the Council for the Preservation of Rural England and the Council for the Protection of Rural England.) One of their aims is to protect and improve dark skies by preventing the spread of unnecessary artificial light. The CPRE charity believes that darkness at night is one of the key features of rural areas so it makes a key differentiation between urban and rural zones. CPRE gives local councils expert advice on planning issues and is known for influencing national and European policies.

*The New England Light Pollution Advisory Group (NELPAG)* was founded in the USA in 1993. It provides professional support and resources to help improve issues with obtrusive lighting, facilitating the implementation of state and municipal lighting laws and bylaws, as well as informing the public on the benefits of applying efficient, glare-free exterior night lighting to reduce light pollution [47]. The group is known for organizing and sponsoring meetings in the New England territory for lighting professionals, astronomers, policy makers, journalists, and the general public, to debate the progress of exterior nighttime lighting and to determine appropriate illumination and when to use it.

*The International Dark-Sky Association (IDA)* is one of the oldest and most recognized grassroots organizations in the world. Its mission is to preserve and protect the nighttime environment and the heritage of dark skies through raising awareness about the importance of darkness at night, and to provide education and guidance about quality outdoor lighting [48]. It was first established in the USA in 1988. Local chapters of the IDA were soon created, then later, international chapters were formed too. Today, there are 50 official IDA chapters worldwide, including more than 20 international chapters that represent five continents. This global network of IDA advocates educating decisionmakers, those in municipalities, and the public in their local communities, about the benefits of protecting the night sky. They also help to draft and create lighting ordinance proposals as well as the enacted ordinances themselves needed to minimize light pollution. Within the IDA organization, a technical committee advises the board of directors on emerging issues of outdoor lighting practices that impact the health of humans and the survival of flora and fauna, and works to create relevant policies to mitigate these issues.

In 2020, the IDA signed an agreement with the *Illuminating Engineering Society (IES)*, a recognized technical and educational authority on illumination in the US, for a strategic collaboration to address the global issue of light pollution that negatively affects our environment and the human condition. This collaboration resulted in the creation of *The Five Principles for Responsible Outdoor Lighting* which help protect the nocturnal landscape and the night sky [49]. These principles recommend: (1) To use light only if it is needed—all light should have a clear purpose; (2) to use shielding and direct light only where it is needed; (3) to minimize brightness—light should be no brighter than necessary; (4) to use controls such as timers, sensors, and motion detectors to activate, dim, or turn lighting off; (5) to minimize the amount of shorter wavelength (blue-violet) lighting and to favor the use of warm color temperature of light or less.

*The Commission for Dark Skies (CfDS)*, previously known as the *Campaign for Dark Skies*, is an anti-light pollution campaign group based in the UK that was first established in 1989 [50]. Comprised of a network of local officers (and other members), their aim is to improve lighting in their area by providing guidance and advice to residents. The CfDS is run by the British Astronomical Association.

*The Light-Pollution Abatement Committee (LPA Committee)* was established by the Royal Astronomical Society of Canada in 1991 to implement and maintain actions to reduce light pollution by raising public and government awareness [51]. The members of the committee work on social and legislative transformations that encourage responsible outdoor lighting practices and the conservation of the nighttime environment. They also form coalitions with like-minded groups and organizations.

*CieloBuio—coordination for the protection of the night sky* (CieloBuio—coordinamento per la protezione del cielo notturno) is a non-profit organization established in Italy in 1997. Its aims involve protecting the night sky by raising public awareness about the phenomenon of light pollution and supporting the use of eco-friendly artificial lighting [52]. Between 2000–2009, eight regional light pollution laws were created by members of the organization that included professional and amateur astronomers, environmentalists, and lighting professionals.

*The National Association for the Protection of the Night Sky and Environment* (l'Association nationale pour la protection du ciel et de l'environnement nocturnes—ANPCEN), formerly known as the National Association for the Protection of the Night Sky (ANPCN), is a French association that works to preserve and protect the quality of the night sky by campaigning against light pollution [53]. Founded in 1999 by astronomers, then further supported by naturalists, researchers, lighting professionals, and policy makers, it has evolved to encompass a broader consideration of the challenges of light pollution which now includes biodiversity and landscapes, health and social issues, energy, climate, and waste etc. This association also advises citizens and communities on light pollution issues.

*Dark Skies Advisory Group (DSAG)* was founded in 2009 in Switzerland, to offer advice and assistance in the best interests of the International Union for Conservation of Nature (IUCN) to other organizations in regards to light pollution and dark sky principles [54]. The DSAG specifically relate to the ecological integrity, guest gratitude, and public appreciation of protected areas, and the long term conservation of dark sky values for generations to come. In joining with the IUCN's as an advisory body to the World Heritage Convention, the members guide, evaluate, and make suggestions to the IUCN Secretariat in regards to World Heritage studies and submissions that address or touch upon dark skies and light pollution. The group consists of members of the Urban Conservation Strategies Specialist Group who offer their free time, and answer requests for advice from individual citizens and organizations.

*The Australasian Dark Sky Alliance (ADSA)* is a non-profit organization established in Australia in 2019 to increase awareness about the negative impact of artificial light at night by educating the public and policymakers about night sky conservation [55]. The ADSA also promotes environmentally responsible outdoor lighting, provides advice on the installation of new lighting systems (and the upgrading of existing lighting), and assists in the designation of IDA Dark-Sky Places. The *ADSA Approved Luminaires* label conforms with dark sky principles specific to Australasian standards and guidelines which are considerate of the night sky, ecosystems, wildlife, human health, well-being, and visual comfort.

### 2.3.2. Initiatives to Mitigate Light Pollution

In 1991, the Royal Astronomical Society of Canada (RASC) created its *Light-Pollution Abatement (LPA) Program* [56] to reduce unnecessary glare, light spill, and trespass. Meetings are encouraged at the local level between residents, businesses, government, and the media, to raise awareness about the problems created by light pollution and to spread the word about various solutions, which include practical recommendations to reduce obtrusive lighting. The program is managed by volunteers on the RASC LPA Committee, across Canada.

*Fatal Light Awareness Program (FLAP) Canada* is a program to help mitigate light pollution founded in Toronto, Canada, in 1993. This grassroots community organization is focused on safeguarding migratory birds in the built environment through the following actions: Education, policy development, research, rescue, and recovery. The registered Canadian charitable society is widely recognized as the authority on the prevention of bird-building collision. In 2010, FLAP's knowledge and advocacy work helped create the *BirdSafe Building Standard for Mitigating Night-time Bird-Building Collisions*. This standard provides guiding principles to help reduce the potential for bird-building collisions at new and existing buildings [57].

*International Dark Sky Places (IDSP)* is a conservation program developed by the IDA in 2001 that aims to recognize and protect locations of exceptional nighttime features for future generations, and to

encourage mindfulness about the issues involved [58]. It motivates communities, parks, and protected areas around the world to preserve and protect dark sites through sensible lighting policies and public education. There is a demanding application process that requires candidates to demonstrate robust community support for dark sky protection, as well as adherence to document designation-specific program guidelines. There are already 130 certified IDSPs in the world.

*National Dark-Sky Week (NDSW)* began in the USA in 2003, and is held during the week of the new moon in April, during which, people worldwide switch off their lighting in order to observe the magnificence of the night sky without light pollution [59]. In 2020, the event was held online to celebrate the night and allow people around the globe to learn more via virtual engagement with authors, scientists, and educators, all with the goal of safeguarding the night from light pollution.

*NightBlight* is an initiative created by the CPRE in 2003, for mapping England's light pollution and dark skies [60]. Thanks to the Geographic Information Systems (GIS) data collected by the United States National Oceanic and Atmospheric Administration (NOAA) Suomi NPP satellite, an interactive map was created in 2016, to highlight the patterns of light pollution around the UK, as well as to identify those areas with the darkest skies [61]. *NightBlight* also includes practical and helpful information for local authorities, counties, regions, designated landscapes, and National Character Areas in the form of PDF maps, as well as providing a summary of statistical data.

In 2005, a voluntary program called *Lights Out* began in New York City. Its goal is to reduce the estimated 600 million birds that perish each year from collisions with illuminated buildings in cities across North America [62]. Thanks to its effectiveness, the program has spread [63]. As part of this program, building owners and managers in participating cities agree to turn off or dim all architectural and indoor lighting between 23:00 and 5:00 during spring and autumn, when birds migrate. Over the years, the buildings involved in this program have saved money, reduced energy consumption, lowered the risk of climate change, and caused less harm to wildlife.

Another worldwide initiative is *Earth Hour*, organized by the World Wide Fund for Nature (WWF). This occurs annually, on the last Saturday of March, where communities and businesses turn off all non-essential electric lights, for one hour, from 20:30 to 21:30 (Figure 8). This grassroots movement first began in Sydney, Australia, in 2007, as an event where the lights were switched off in the city to raise awareness about climate change and energy consumption. To date, 7000 cities and towns across 187 countries and territories worldwide have become involved [64]. This symbolic action brings awareness about treasuring our planet and the value of unpolluted dark skies (which can be observed during the event and reported by light pollution researchers) [65].

While it has no real direct impact on the natural environment, humans, flora, and fauna because it is too short, there is still a visual and psychological impact which promulgates the importance of the nocturnal landscape.

Established in 2007, a *Star Count* is another campaign by CPRE to raise awareness about light pollution by including the public in star counting, in order to record the scale of light pollution across the UK in the form of a nationwide survey [66].

*The Stars and Villages label* (Villes et Villages étoilés) is a program developed by ANPCEN in 2011, for French municipalities. It aims to promote not only best lighting practices to ensure better quality of the night and the nighttime environment, but to also implement laws that help reduce and prevent light pollution. This program, approved by the Ministry of Ecology and Inclusive Transition, has a 1 to 5 star rating system, which can be awarded depending on the level of involvement of the municipality in the management of its night lighting. There are already 574 municipalities in France that have been awarded this label [67].

*The International Day of Light* was established by the United Nations (UN) on the 16th of May in 2017 [68,69]. It is a yearly celebration offering a podium for sustained appreciation of the significant role that light plays in the lives of citizens around the world. One of its goals is to foster understanding that technologies and thoughtful design can achieve energy efficiency, and the reduction of light pollution, which is one of the fundamental elements for the conservation of dark skies.





**Figure 8.** Hong Kong skyline with Kowloon Peninsula and Hong Kong Island at night during Earth Hour in 2013 (top), and after (bottom). Source: Apple Daily's figure.

STARS4ALL was another initiative sponsored by the European Union/European Commission under the Horizon 2020 Program, between January 2016 and 2018, to foster research in Europe and create a collective awareness platform for promoting dark skies [70]. Some of the developments involved the creation of the Dark Sky Meter app, which measures the sky brightness and shares it with scientists around the globe, and also a TESS-W photometer designed to measure and provide continuous monitoring of the night sky brightness for light pollution studies.

The IDA's *Criteria for Community Friendly Outdoor Sports Lighting v1.0*, published in 2018, helps to improve the design of outdoor sport facility lighting in order to minimize its sky-glow, light trespass, and glare into surrounding residential areas as well as places where local ecology needs to be protected [71].

The IDA's *Guidance for Electronic Message Centers (EMCs)*, published in 2019, specifies minimum requirements and outlines a set of best management practices in order to decrease the negative impact of illuminated signage in built environments [72].

The handbook, *Blinded by the Light*, published in 2020 by the CfDS, contains some practical suggestions on how to minimize the negative issues of ALAN. It is designed for responsible lighting campaigners advocating against light pollution and those adversely affected by it. It contains three useful appendixes: (1) Lighting assessment principles; (2) a sample letter about poor quality lighting for complainants to use, and (3) simple, non-scientific methods to assess the quality of the night sky [73].

#### 2.4. Lighting Organizations and Their Recommendations to Measure and Minimize Light Pollution

Light pollution is acknowledged as a legal concept only in a limited number of countries around the world. In countries where there is no legislation, citizens can refer in their actions, to the following lighting organizations such as: The *European Committee for Standardization*, the *International Commission on Illumination*, the *Illuminating Engineering Society*, and the *Institution of Lighting Professionals* and their useful documents, which give certain lighting values to be measured, and provide possible ways to handle numerous light pollution issues.

#### 2.4.1. The European Committee for Standardization (CEN)

The European Committee for Standardization (CEN) was founded in Brussels in 1961. It is a public standard organization that brings together the national standardization bodies of 34 European countries [74]. This committee is also responsible for creating the *European Lighting Standard*, which is a technical document designed to be used as a rule, guideline, or definition. The current European standard EN12464-2:2014 called *Light and Lighting—Lighting of Work Places, Part 2: Outdoor Work Places* [75], defines requirements to protect the nighttime environment and control the obtrusive light from exterior lighting installations on flora, fauna, and humans. These requirements are based on four environmental zones. Light trespass on windows can be verified by vertical illuminance, glare can be identified by luminaire intensity, sky glow can be determined by the upward light ratio of a lighting installation, and a building's brightness can be perceived by the observer via its luminance (Table 1).

**Table 1.** Maximum obstructive light permitted for exterior lighting installations. Source: [75].

| Environmental Zone | Light on Properties |             | Luminaire Intensity |             | Upward Light Ratio | Luminance                     |                               |
|--------------------|---------------------|-------------|---------------------|-------------|--------------------|-------------------------------|-------------------------------|
|                    | $E_v$<br>[lx]       |             | $I$<br>[cd]         |             | $R_{UL}$<br>[%]    | $L_b$<br>[cd/m <sup>2</sup> ] | $L_s$<br>[cd/m <sup>2</sup> ] |
|                    | Pre-Curfew          | Post-Curfew | Pre-Curfew          | Post-Curfew |                    | Building Façade               | Sign                          |
| E1                 | 2                   | 0           | 2500                | 0           | 0                  | 0                             | 50                            |
| E2                 | 5                   | 1           | 7500                | 500         | 5                  | 5                             | 400                           |
| E3                 | 10                  | 2           | 10,000              | 1000        | 15                 | 10                            | 800                           |
| E4                 | 25                  | 5           | 25,000              | 2500        | 25                 | 25                            | 1000                          |

E1 represents intrinsically dark areas, such as national parks or protected sites; E2 represents low district brightness areas, such as industrial or residential rural areas; E3 represents medium district brightness areas, such as industrial or residential suburbs; E4 represents high district brightness areas, such as town centers and commercial areas;  $E_v$  is the maximum value of vertical illuminance on properties in lux;  $I$  is the light intensity of each source in the potentially obtrusive direction in cd;  $R_{UL}$  is the proportion of the flux of the luminaire (s) that is emitted above the horizontal when the luminaire (s) is (are) mounted in its (their) installed position, and given in %;  $L_b$  is the maximum average luminance of the façade of a building in cd/m<sup>2</sup>;  $L_s$  is the maximum average luminance of signs in cd/m<sup>2</sup>. Curfew is the time after which stricter requirements (for the control of obtrusive light) will apply. It is often a condition in the use of lighting that is applied by the local planning authority. If not otherwise stated—23.00 hrs is suggested.

#### 2.4.2. The International Commission on Illumination (CIE)

The International Commission on Illumination (CIE) established in Austria in 1913 is the international authority on light and lighting. The CIE consists of CIE national committees from 40 countries, and more than 15 individual members from countries or regions where there are not yet any national committees. The main goals of the CIE are to create a forum for international discussion on matters related to science, technology, and practice in the field of light and lighting, and to exchange information in this field to create basic standards and procedures for measuring light quantities. In addition, the CIE creates standards to be used when defining the rules and procedures in international and national standards in the field of light and lighting, as well as preparing and issuing standards, recommendations, reports, and other publications related to science, technology, and practice.

The CIE 150: 2017 document titled *Guide on the Limitation of the Effects of Obstructive Light from Outdoor Lighting Installations* [76], provides guidance for external illumination to reduce the adverse effects of light pollution. It proposes five different environmental zones (E0–E4) determined by their location and use, and also includes different lighting factors. This advice sets acceptable levels for light trespass into windows from a façade, the allowable maximum average luminance of a façade, and also defines levels for sky glow. The CIE also published another document, the CIE 126: 1987, titled *Guidelines for Minimizing Sky Glow* [77], which gives general guidance for lighting designers and policy makers on the reduction of sky glow. The report briefly discusses the theoretical aspects of sky glow and gives recommendations for the maximum permissible values of lighting installations that take into consideration what is necessary to allow astronomical observations.

#### 2.4.3. The Illuminating Engineering Society (IES)

The *Illuminating Engineering Society* (IES) was founded in the USA in 1906 as the technical and educational authority on illumination. It aims to improve the lit environment by bringing together those with lighting knowledge and translate that knowledge into actions that benefit the public [78]. The organization has about 8000 members worldwide. This consists of engineers, architects, designers, educators, students, contractors, distributors, utility personnel, manufacturers, and scientists. The *Model Lighting Ordinance (MLO)* was developed by the IDA and the IES in 2011. It is a tool to help municipalities develop exterior lighting standards that reduce glare, light trespass, and sky glow by applying five lighting environmental zones (LZ0–4) to classify land use with appropriate lighting levels for each of the zones [79].

Additionally, the MLO also incorporates the backlight-uplight-glare (BUG) rating system for luminaires, which delivers an effective mechanism to control unwanted light [80]. The IES RP-33-14 recommended practice (RP) document, titled *Lighting for Exterior Environments* [81], outlines the environmental considerations of outdoor lighting, especially related to sky glow and light trespass. In addition, this RP provides information on how to assign lighting zones, and how to use the joint IDA-IES *Model Lighting Ordinance (MLO) and User's Guide* as a basis for an outdoor lighting ordinance.

#### 2.4.4. The Institution of Lighting Professionals (ILP)

The *Institution of Lighting Professionals* (ILP) established in the UK in 1924, is a leading professional lighting engineering body, known for providing advice on a wide range of issues, including legislation and regulations that affect the built environment [82]. Their newest document, GN01, titled *Guidance Note 1 for the Reduction of Obtrusive Light 2020* [83], has been updated to include information from CIE 150: 2017. It also provides some useful knowledge about the impact of a light source on the ability to view the night sky that involves the various angles of light that are emitted, and its direct effects on sky glow and glare. Another document, the PLG05, called the *Brightness of Illuminated Advertisement* [84], provides clear guidance on illuminated advertising signs which, if not properly designed, can create unnecessary glare and light trespass.

#### 2.5. Citizens' Actions

Throughout this research, two types of citizens' actions that oppose light pollution were identified: (1) Legal and (2) non-legal. Legal action in the form of civil lawsuits have been known for many years, with the first case connected to the subject identified by the authors as early as 1923 [85], when artificial light started to be widely used outdoors. The dark night sky, which was already brightened by street lighting, soon also became illuminated by high-rise buildings, dynamic advertisements mounted to their façades, floodlights from sports facilities [86], and event searchlights, all of which caused lighting nuisance and increased sky glow. In the past, such legal actions were raised by an individual or groups of citizens [87] or, later on, by businesses such as drive-in theatres that were disturbed by the light trespass from neighboring lighting installations [88]. Lastly, new types of legal cases started to emerge, connected to the environment and health, where groups of concerned citizens filed lawsuits against municipalities who retrofitted existing street lighting with new LEDs [89,90].

At the end of the XX-century, non-legal actions such as face to face lobbying, phone calls, and letter writing campaigns were commonly employed. Before the digital age, the first petitions regarding light pollution were sent via mail delivery. This includes a petition in 1994, to the European Commission Petition Committee by the British Astronomical Associations (BAA) [91]. Today, technology such as the Internet has made it possible to use online services for citizen engagement. Digital participation, known also as e-participation, is explained as “the process of engaging citizens through ICTs in policy and decision-making in order to make public administration participatory, inclusive, collaborative and deliberative for intrinsic and instrumental ends” [92].

The online petition, also known as e-petition or Internet petition, is a form of request which is signed online, typically through a form on a specific website. Upon achieving the required number of signatories, the petition letter may be submitted to the recipient of the petition, often by e-mail. The first citizen online petition about light pollution on a web-based petition host was identified in 2012 [93]. Soon after, online petitions were also created on various websites which belong to governments and organizations. Some national governments such as the UK [94], or the German Government [95], allow their citizens to submit an e-petition. In the UK, Members of Parliament (MPs) can present a petition to Parliament on behalf of their constituents. Organizations such as the European Union (EU) has a dedicated online petition site for any individual or organization based in the EU for an issue related to EU policy or law [96].

Furthermore, this study has identified that there are no online petitions websites worldwide dedicated only to light pollution activism.

### 3. Hypotheses

In order to achieve research objectives and examine current citizen initiatives to mitigate light pollution and their influencing factors, the following hypotheses have been developed:

**Hypothesis 1 (H1).** *Since the 1990s, there has been an increase in the number of legal cases related to light pollution due to the rise in public awareness, the availability of scientific knowledge via the Internet, and the ability to take accurate lighting measurements and perform lighting simulations.*

**Hypothesis 2 (H2).** *In the last decade, a new tool for digital participation in the form of online petitions, has established a new movement of citizen action to mitigate the effects of light pollution.*

### 4. Materials and Methods

This section gives a comprehensive report and clarifies the procedure of data selection and content analysis that was followed in the study to test the research hypotheses.

#### 4.1. Data Selection

Accounts of legal and non-legal international citizens' actions connected to light pollution were chosen as an experimental basis, for finding and selecting a wide sample of case studies [97], along with a detailed source of information about current developments. These were chosen using 10 basic criteria: (1) Only case studies representing lawsuits and digital participation should be included; (2) reported actions should be spread worldwide; (3) all cases reported between the beginning of the XX-century to 2019 should be included; (4) the collected examples should increase the diversity of case studies; (5) only light pollution-related cases should be considered, cases requesting light or more light to be excluded; (6) only artificial electric lighting related cases should be considered (gas lighting installations were excluded); (7) only actions taken by citizens are considered (actions taken by towns, countries, and other organizations are excluded); (8) nuisance connected to traffic (car headlights, etc.) are excluded; (9) the reported actions should be documented in satisfactory detail (cases for which data was lacking were consequently excluded); (10) information regarding case studies should be available free of charge. All data was collected between November 2019 to May 2020, in a process that combined various search strategies.

The performed typical keyword-based search method using the words and phrases: "lighting conflicts", "light pollution", and "ALAN conflicts" for scientific research papers on academic platforms such as Web of Science and Scopus yielded no results. Additional searches on Google Scholar identified only two papers that partially discussed the issues. It is anticipated by the authors that this result is due to the fact that the topic of lighting conflicts in relation to light pollution mitigation is quite new. As a consequence, few studies have been published on this particular subject. This suggests that



this scientific study appears to be particularly significant in recognizing gaps in existing literature. Based on the above outcome, a new search strategy was put in place to identify legal and non-legal actions. First, the legal actions (civil lawsuits) were identified by an organized keyword-search via Internet media articles, environmental reports, and as references of other lawsuits, with an additional 110 cases added, based on research performed in 2017, and provided by Iris Zhou, a Harvard Law School student [98]. Each of the lawsuit cases in the USA were verified on special legal websites: [casetext.com](http://casetext.com), [law.justia.com](http://law.justia.com), [casemine.com](http://casemine.com), [courtlistener.com](http://courtlistener.com), [leagle.com](http://leagle.com) that contained the published lawsuits details.

Furthermore, an additional filter was applied by reading the text of the published case study and involved selecting only those case studies which opposed light pollution; cases which demanded more artificial light were excluded. The basic sample was successfully complemented by way of selecting additional cases in languages other than English (German and Polish) on special legal websites: [gesetze-bayern.de](http://gesetze-bayern.de), [www.schweizer.eu](http://www.schweizer.eu), [saos.org.pl](http://saos.org.pl), [orzeczenia.ms.gov.pl](http://orzeczenia.ms.gov.pl), and in online media news, in order to fill an apparent gap and expand the sample's scope. Interviews with light pollution experts were conducted and five additional case studies were added, which were not identified using the previously mentioned search methods. As a result of these actions, a total of 152 recorded lawsuit case studies were selected, with all of these cases occurring between 1923 and 2019.

Secondly, non-legal actions were identified via online petition websites and online versions of newspaper articles. The first set of case studies in online petition websites were collected via an organized keyword-search which consisted of the following words and phrases: "light pollution", "artificial light at night", "ALAN", "dark sky", "sky glow", "LED", "light obstruction", "light", "light trespass", "light nuisance", and "glare". *Change.org* platform was selected as this is one of the largest online petition sites in the world, having been used by millions of people [99]. This resulted in 102 identified case studies, with five studies excluded due to petitioners requesting more light [100] or making an inappropriate illumination proposal which would cause extensive light pollution [101].

Additionally, a dedicated EU online petition website that was established in 2013 was searched [102]. All petitions appear in the EU portal after the adoption by the Committee on Petitions. After a keyword-search which consisted of the following words and phrases: "light" and "light pollution", this resulted in an additional 20 identified case studies, with 14 studies excluded due to not being directly connected to the topic of light pollution. Additional searches using Google Web Search engine for other online petitions, using search phrase "online petitions against light pollution" identified seven more new cases on the following petition websites: [petition.parliament.uk](http://petition.parliament.uk), [hertfordshire.gov.uk](http://hertfordshire.gov.uk), [gopetition.com](http://gopetition.com), [ipetitions.com](http://ipetitions.com) and [avaaz.org](http://avaaz.org).

The final sample which was analyzed, consisted of a total of 110 recorded online petitions case studies which related to eight categories of lighting types being a source of disturbance (see Section 2.2 for a detailed explanation). All of these cases occurred between 2012 and 2019.

#### 4.2. Data Analysis

The collected case studies were first examined by a qualitative content analysis (QCA) method [103,104]. In order to systematize a larger number of citizens' actions and to obtain viable results, a Microsoft Excel spreadsheet program was employed to record descriptive variables and create a code of categories of data manually, according to the following parameters: Type of action (legal versus non-legal), year, country, number of case studies per year, the achieved case result (success or failure), number of participants per petition, and the current status of the lighting installation—existing versus planned, as well as eight categories of lighting types that create ALAN nuisance.

The second step involved transforming collated qualitative (non-numerical) data into quantitative (numerical) data, for a statistically driven approach and comparison between the number of legal and non-legal actions.

Moreover, a scatterplot [105] was employed to validate two-dimensional data with dots to represent two different variables—one plotted along the x-axis (time/year of action) and the other

plotted along the y-axis (number of lawsuit cases or e-petitions respectively). This provides a visual reference that reveals how much citizens' actions have increased over time. All non-photographic graph figures were created using Microsoft Excel software.

## 5. Results

The growing uncontrolled use of ALAN in urban and natural settings often forces ordinary citizens to take action to mitigate its negative impact on the environment and to protect their health, well-being, and life quality. Our analysis helped to classify the case studies into three distinct action types: (1) Lawsuits, (2) digital participation/online petitions, and (3) other actions involving various parameters such as the duration of action taken, the difficulty level of the submission (ease of setting up a case), the cost involved, and its effectiveness (Table 2). Due to a lack of access to reliable information, other actions have been excluded from the overall analysis and only estimates are provided.

**Table 2.** Citizens' actions opposing light pollution. Source: Authors' elaboration.

| Action Type       |                               | Duration                                                                               | Difficulty Level of Submission | Cost Involved | Effectiveness |                  |
|-------------------|-------------------------------|----------------------------------------------------------------------------------------|--------------------------------|---------------|---------------|------------------|
| Legal actions     | 1. Lawsuits                   | 1a. civil lawsuits<br>1b. criminal lawsuits                                            | long                           | difficult     | yes           | medium           |
| Non-legal actions | 2. Digital participation      | 2a. online petitions (e-petitions) on various web-based petition hosts                 | short                          | easy          | no            | low <sup>2</sup> |
|                   |                               | 2b. online petition (e-petitions) on a dedicated organization's website                | long/medium                    | easy/average  | no            | low <sup>3</sup> |
|                   | 3. Other actions <sup>1</sup> | letter/email-writing complaints, protests, rallies, phone calls, face-to-face lobbying | medium/short                   | average       | no/yes        | medium           |

<sup>1</sup> Due to a lack of access to reliable information, these actions have been excluded from the overall analysis and only estimates are provided. <sup>2,3</sup> Effectiveness has been described as low based on the available results, but because this is such a new participation method, its effectiveness can be improved and developed in the future.

### 5.1. Legal Actions: Lawsuits

Over the past 100 years, the majority of actions in the fight against LP have been legal actions in the form of lawsuits.

It can be seen that in recent decades their number has increased significantly due to the possibility of acquiring knowledge about health and ecology by citizens using the Internet and search engines. Bringing a case to court makes sense in countries where there is a law and/or legal regulations regarding light pollution and light nuisance. This is demonstrated by an example from Shanghai, China, in 2004, when a citizen won their lawsuit case on the day that the city's regulations on light pollution were implemented [106].

The scatter diagram below, reported in Figure 9, describes the association between the variables, including a description of the form, direction, and strength of the association, along with the presence of any outliers [107]. It shows a non-linear, positive, strong, relationship between the number of legal actions and time.

Additionally, in this diagram, a two-point moving average trendline was used to graphically display trends in data more clearly. These results show that since the first law case connected to light pollution identified in 1923, there has been a steady increase in actions observed, with a three-fold increase in the number of lawsuits since 1990. The highest identified number of lawsuit cases in one year was 10 in 2010, and then nine in 2015. This may be due to access to new knowledge on light pollution, thanks to the digital information database to which citizens had access, hence the increase in court cases. In turn, a significant drop in court cases has been visible since 2017, and it can be argued that this is due to the increase in online petitions.

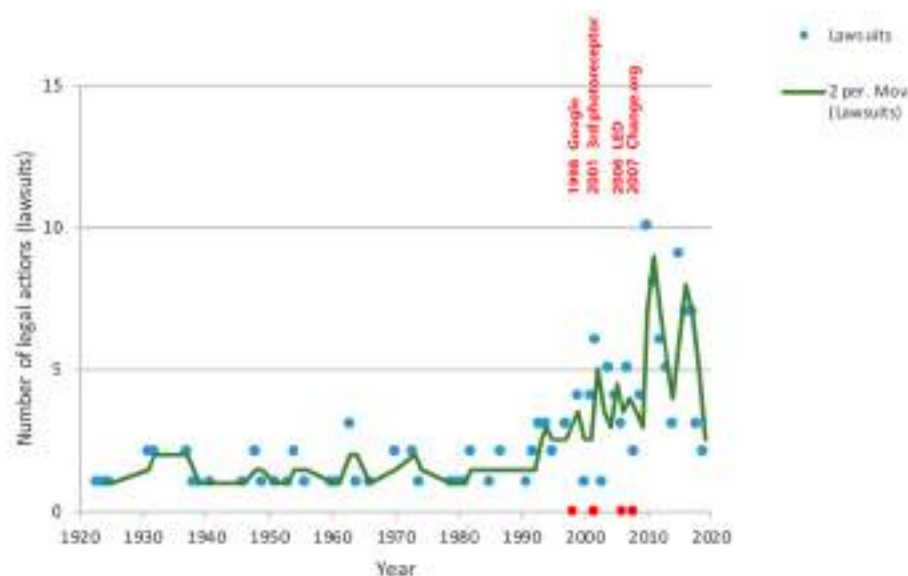


**Figure 9.** A scatter diagram showing the relationship between the maximum achieved number of legal actions (civil lawsuit cases) over time. Source: Authors' data.

The noticeably high number of legal actions in the US compared to other countries (Figure 10), might be related to the fact that in the US, legal actions are well documented, and detailed information is freely available to the public. Additionally, lighting design as a profession has been established in the USA since the 1970s, and the IDA, which is the world's largest and best-known grassroots organization to combat light pollution, is also based in the US. The authors are aware that language and other factors might be a barrier here, impacting the total number of the lawsuits per country (this has been identified as a limitation in Section 7).

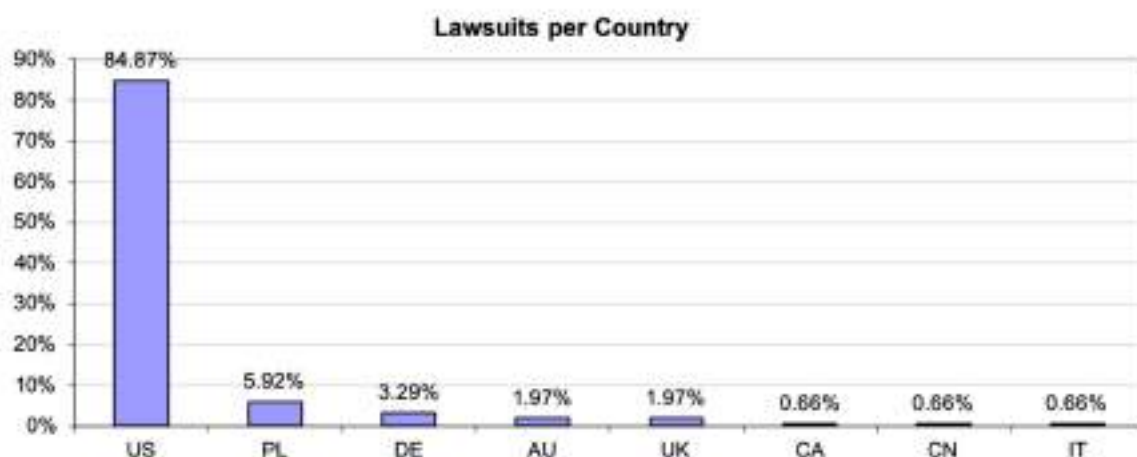


**Figure 10.** Percentage of lawsuit cases in each country since 1923, presented as a composite bar chart. The two-letter country codes were applied based on the International Standard for country codes ISO-3166 [108]. Source: Authors' data.

Out of the eight identified ALAN nuisance categories of lighting types which can negatively impact human health, well-being, and entire ecosystems, the highest offenders seem to be *Building and nonbuilding structure lighting* and *Sport facility lighting*, covering around 25% of the overall cases, followed by *Industrial and commercial lighting* with around 16%, *Street and area lighting*, then *Safety and security lighting* both with around 13%, respectively (Figure 11). Based on information from existing court documents, such high numbers in the first instance are a result of light nuisance in residential neighborhoods, for example, when light directly intrudes into nearby homes which reduces



the enjoyment of properties, and due to the quiet nature of neighborhoods also results in adverse effects on quality of life. Such disruption can cause sleep deprivation which can result in ill health and negative psychological conditions. Lastly, such ALAN nuisance reduces the value of properties. *Park and garden lighting* as well as *Event lighting* both achieve the lowest results of around one percent.

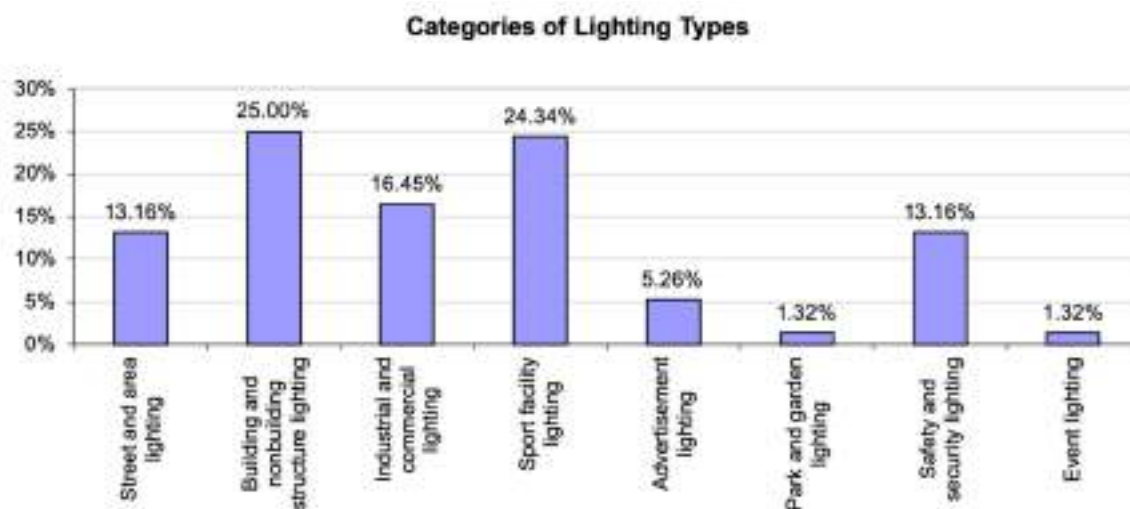


**Figure 11.** Percentage of lawsuit cases based on eight categories of lighting types, presented as a composite bar chart. Source: Authors' data.

There is also a visible increase in recent years in lawsuits connected to planned projects, of around 38%, compared to existing ones which reach around 61% (Figure 12).

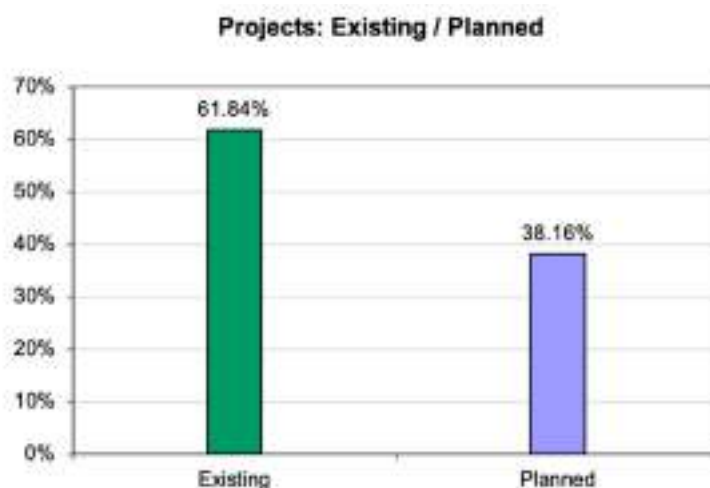


**Figure 12.** Percentage of lawsuit cases since 1923, based on their status: Existing or planned, presented as a composite bar chart. "Planned" refers to future construction projects which require planning permission. Source: Authors' data.

It is important to emphasize here, the value of collaborating with lighting professionals who can evaluate the claim, present expert testimony, and provide reasonable arguments to submit a lawsuit. Today, these professionals employ tools such as illuminance and luminance meters for existing projects and lighting design software for planned projects (lighting simulations), to estimate with great accuracy the impact of sky glow, light trespass, and/or glare. In the past, plaintiffs did not have sufficient legal standing because they often failed to provide substantial evidence that they would be harmed by the lights from a proposed development. This matters because private nuisance claims require proof of the

actual injury suffered, not just potential injury from increased light pollution [109] or the potential of significant negative impacts on the environment [110].

While projects require planning permission, if citizens decide to take action and dispute a proposed project because it may harm their health and/or reduce their life quality, matters can be drawn out and take years to resolve.

There has been almost the same number of successful lawsuits (around 48%) as there has been documented lost cases (around 51%) (Figure 13). The final result of a lawsuit may be affected by the lack of proper substantive preparation of documents and a lack of awareness of the legal processes involved by complainants, as it is recorded in existing court papers. Often, in order to save costs, citizens use self-help and non-legal professionals, rather than paying for lawyers. This may affect the quality of submitted paperwork, as well as the final outcome. Other factors that can hinder success are common issues, such as a lack of knowledge of legal procedures. For instance, the complainant misses filing paperwork by the due date, they are unclear when the problem first began, they may claim injuries which are not actionable under common law nuisance, and there may also be confusion over land use, zoning ordinances, as well as city and state codes, etc.

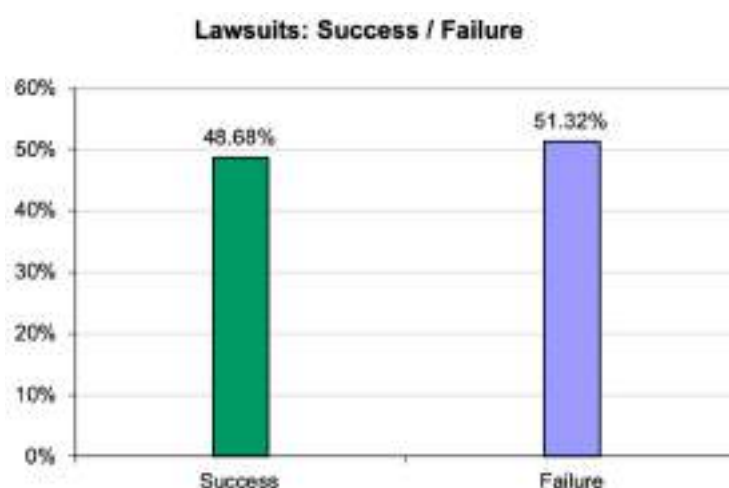


**Figure 13.** Percentage of lawsuit cases since 1923, based on their status: Success or failure, presented as a composite bar chart. Source: Authors' data.

## 5.2. Non-Legal Actions: Digital Participation in Form of Online Petitions

The non-legal actions, in the form of digital participation, such as online petitions to protect dark skies and the health and well-being of humans from light pollution are relatively new tools that have developed in the last ten years.

The scatterplot diagram reported in Figure 14 shows a linear, positive, strong relationship between the number of online petitions and time. Since the first e-petition connected to light pollution was identified in 2012, there has been a steady increase in actions observed in the last decade, with sharp peaks from around the year 2015 onwards.

The highest identified number of e-petitions in one year was 40, in 2019. Additionally, in this diagram a two-point moving average trendline was used to graphically display trends in data more clearly.

Again, the noticeably high number of online petitions in the US (close to 60%) compared to other countries (Figure 15), might be related to the fact that tools such as computer and Internet technologies, including online petition websites, were first developed in the US. Additionally, one could assume that the English language might play a role here, with the higher number of actions undertaken in countries such as the UK, Australia, and Canada, compared to the rest of the world.

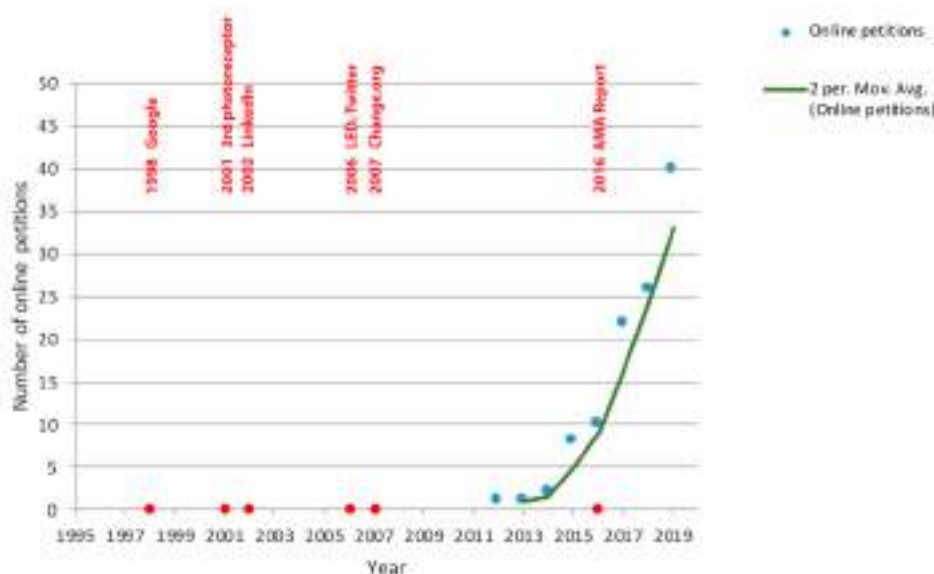


**Figure 14.** A scatterplot diagram showing the relationship between the maximum achieved number of non-legal actions (online petitions) per year. Source: Authors' data.

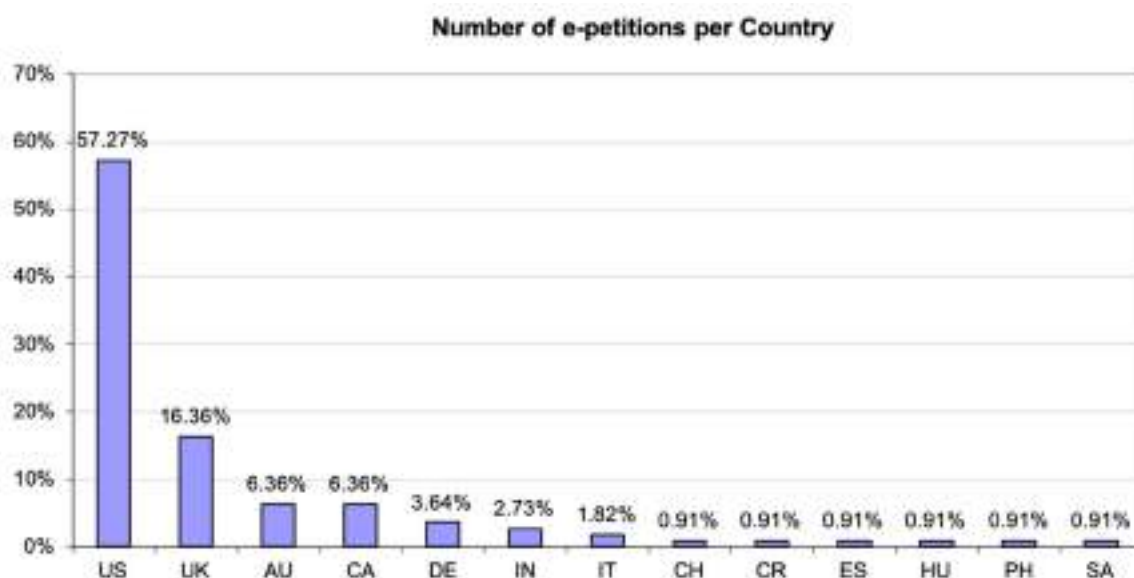


**Figure 15.** Percentage of e-petitions cases based on their country, presented as a composite bar chart. The two-letter country codes were applied based on the International Standard for country codes ISO-3166 [109]. Source: Authors' data.

It was difficult to assign eight categories of lighting types based on the previous categories (Figure 11) in order to establish the percentage of online petition cases, as new categories such as light pollution legislation proposals, and light pollution projects with a wider environmental impact were identified.

Furthermore, it was not possible from the provided information, to identify the exact number of results (success or failure) of e-petitions, as often this information was unavailable on the website, or the petition was still ongoing.

Moreover, the number of participants who signed the petitions will also vary unproportionable, with the ones that related to environmental topics achieving the highest number of signatures—133,536 [111] and 117,950 [112], respectively, compared to petitions that received zero signatures [113]. On many e-petition websites there are no clear rules regarding the number of signatures required in order to be

successful. In the UK, for instance, such rules are provided on the government's website. For example, only British citizens and UK residents may create a petition, and if 10,000 signatures are collected, a petitioner will get a response from the government, whereas, if 100,000 signatures are gathered, the petition will be considered for debate in the UK Parliament [114]. Also, some of the local councils in the UK define the minimum number of signatures per e-petition [115]. For example, the petitioner has a right to present his petition to a meeting of members of the council, subject to the number of people who signed the e-petition. For a county council meeting, 1000 signatures are required, for a Cabinet or Cabinet panel meeting, 250 signatures are required. When achieving 100 signatures, there is an opportunity to raise the issue directly with the executive or local member of the council.

### 5.3. Comparison of Legal and Non-Legal Actions Against Light Pollution

Since 2010, there has been a noticeable increase in the number of online petition cases connected to the impact of ALAN and light pollution. Online petitions have achieved almost 65%, which is almost a two-fold increase in the amount of lawsuit cases (Figure 16).

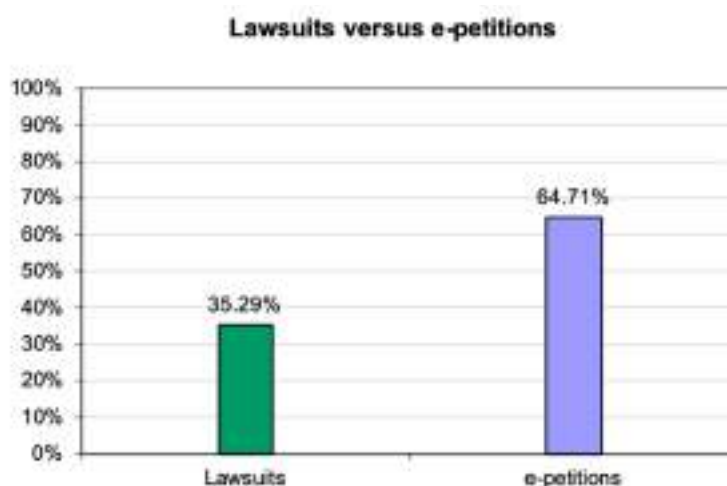


**Figure 16.** Percentage of lawsuits versus e-petitions cases against light pollution in the last decade, presented as a composite bar chart. Source: Authors' data.

## 6. Discussion

In the presented research study, an evaluation of accounts of legal and non-legal international citizens' actions was carried out with the help of mixed research methods to create robust science-informed data about the various methods citizens undertake to resolve light pollution disputes.

The results, presented in Figure 9, support the hypothesis, and highlight the fact that, since the 1990s, there has been a significant increase in legal actions related to light pollution. This is due to the increase in use of the Internet by citizens, that begun in the 1990s, coupled with the availability of online information via Google search engine (1998) and Wikipedia Commons (2001). The continuous increase in the number of online petitions on a dedicated organization's website (Figure 14) support the hypothesis of a new movement of citizens' actions.

These findings indicate that citizen's awareness about LP is evolving. The rapid global evolution of digital technologies has not only changed the behavior and expectations of people concerned about light pollution, it has also greatly influenced their involvement, activity, and participation with such platforms. Therefore, it seems that existing and developing digital technologies will have a significant impact on the way citizens engage in disputes, and they will also help determine how they achieve positive outcomes.

By analyzing this new option for citizens' participation, one can predict that an online petition might become the most preferred tool in the future for successful citizens' actions due to numerous

factors. By gathering participants signatures quickly and easily, online petitions can take communication to the next level and reach a much wider audience. Their duration is also much shorter in time and there is no associated cost involved. This form of action seems to be simple and easy to set up (computer and Internet access are required). Online petitions are also accessible at any time and provide a free-of-charge tool to communicate citizens' concerns.

However, the estimated high number of unsuccessful results of online petitions suggests there is a lack of insight about how to create and execute initiatives that achieve positive outcomes. For this reason, if an online petition has been selected as a method to raise awareness and instigate positive change, it is important to consider the following 10 elements as a guide to success, based on the performed analysis (Table 3).

**Table 3.** Ten aspects to be considered when addressing the nuisance of artificial light at night (ALAN), for a successful online petition result. Source: Authors' elaboration.

| No. | Aspect                                                   | Description                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
|-----|----------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1   | Platform type                                            | There are various websites that provide a petition platform and some of them are well known for achieving political impact. Choosing the correct one might depend upon the matter to be addressed. Is it a local or global light pollution issue? Also, it is recommended to use a petition platform that can perform a search within the website itself, with various key words such as the ones mentioned in Section 4.1, to see if similar petitions exist. |
| 2   | Language chosen                                          | In some light pollution cases, language may be a barrier [116]. As English is the most widespread language worldwide, it seems to be the best for communication (1.5 billion people, approximately 20% of Earth's population speak English). Make your light pollution petition international. Some successful petitions have been translated into a number of different languages [117].                                                                      |
| 3   | Title                                                    | Your title should be informative and specific as it will provide a clear statement to the reader, articulating your aim [118]. Make it short, as this will attract a higher number of viewers and it will be easier to remember. Use well known words or phrases associated with the topic of light pollution as they will most likely be recognized by performed searches.                                                                                    |
| 4   | Recipient(s) of petition/responsible for decision making | It is important to directly address the recipient of the petition with their name, as this will apply pressure for a response [112]. (It will be less effective for instance, to address your petition to the "President of the United States" or "Everyone" [119].) It is also important to check whether those being petitioned are in a position to make changes related to light pollution issues.                                                         |
| 5   | Required number of supporters                            | It is widely believed the success of a light pollution petition depends on how many signatures are gathered, however, this is relative, as what really matters is the issue's status—is it local, regional, or global? Sometimes, limited votes can be enough to instigate a change to reduce light pollution by a local council [120]. A general rule should be the more supporters' signatures collected, the better.                                        |
| 6   | Defining your audience/supporters                        | If the audience is chosen casually and the campaign unsupported by active engagement, initiatives against light pollution can receive fewer supporters, and result in a failed outcome [121].                                                                                                                                                                                                                                                                  |

Table 3. Cont.

| No. | Aspect                                                         | Description                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |
|-----|----------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 7   | Message content                                                | Break down complex matter. Use simple language that is easy to understand, with links to references, reports, and testimonials, etc., on light pollution issues.<br>Your text needs to be concise and succinct, between 150–650 words. Create engaging content, and clearly answer the following two questions: (1) Why are you petitioning? (2) What impact do you hope to achieve through this action against light pollution? A well prepared and determined approach will be taken more seriously from the start. To be seen and heard in today's world of information overload, potential signatories are more likely to support your light pollution petition when they understand its aim and purpose. Keep it personal and authentic. Your supporters will endorse an initiative they can intellectually and emotionally connect with and want to be involved in to make a positive difference. If people do not support your petition, perhaps the message was not communicated in the right way or the topic appeared to be unimportant. It is advisable to engage and consult with researchers, advocates, etc. Always sign your petition on behalf of interest groups, communities, associations, etc., as this can add more credibility and weight to the goal and convince those people who are undecided. |
| 8   | Provide additional eye-catching material in order to stand out | As humans absorb more than 80% of information visually, eye-catching information about light pollution can help explain your subject in a convincing and engaging way [122]. Video can capture and communicate a message to potential signatories in a way that other mediums cannot [123].                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |
| 9   | Spreading the message/attracting your supporters               | Prepare fact sheets and other free material on light pollution and share it at live events to engage with people. Use social media such as Twitter, Facebook, and Instagram, but also send out personal emails to attract more supporters. Write journal articles, create press releases, and connect with journalists and radio presenters to report your light pollution case and share your story [124,125].                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |
| 10  | Delivering your petition and providing feedback to supporters  | It is advisable to arrange a personal meeting to hand over your light pollution petition, and if this is not possible, write a personal letter that includes all signatures. Always update your supporters on the status of your light pollution initiative with short text, pictures, and/or links [126].                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |

In order to empower citizens, it is of utmost importance to allow them to exercise their rights, and to enable them to make informed decisions via easy access to quality, reliable, up-to-date information. Thus, the authors propose the creation of a data repository, in the form of a website platform called *Light Pollution Case Study Actions Database (LPCSA)*, to assemble worldwide data that goes beyond the presented case studies on the subject, which could perform similarly to the Artificial Light At Night Research Literature Database on the IDA website [127]. It is expected that this format will provide a basic structure for such research information and provide a starting point which can be expanded to reflect the findings, and offer new insights and creative approaches for contextualizing this problem. Additionally, creating a single online petition website explicitly related to light pollution issues might be very helpful to improve citizens' actions. Whether such initiatives and research could be embraced should be verified in the future with the IDA and other organizations. Knowledge dissemination of successful non-legal actions to decrease light pollution, via news media coverage and other forms, should be one of the top priorities of activists, as some people might still lack awareness that the negative aspects of ALAN can be resolved through citizens taking action.



## 7. Limitations of the Study

Aside from the contributions stated in Section 6, this enquiry also has its limitations which are acknowledged below:

- The availability of accessible data might be an issue (inaccurate or limited), as not all citizen actions could be found by online searches and/or have been reported by media channels.
- Language can sometimes be a communication barrier. Due to the broad scope of the research, it is highly likely there are lawsuits and online petitions recorded and reported in languages other than English, German, and Polish, which have not been included in this study, therefore, the sample size might not be representative worldwide.
- The number of subject-related keywords used by authors when searching through online petition websites may be restrictive which would prevent all of the cases being found.
- Although information is reliable for legal actions such as lawsuits in the US and UK, in other countries, such information (the exact city where the process has taken place, the name of a defendant, etc.) might be difficult for the public to access due to legal reasons and confidentiality.
- There is often no feedback on the status of an online petition. This might mean that the petition is still ongoing, was unsuccessful, or the petition organizer lost interest in the petition.
- Some legal actions are still unresolved; therefore, these could not be included in the final outcome analysis related to their success or failure.
- The outcomes of analyzed data in the future might be out of date, due to the rapid changes involving the day-to-day sharing of new information.

## 8. Conclusions

In the presented study, information pertaining to active participation by citizens, and practices related to light pollution and their impact, have been collected and analyzed. The research offers significant evidence that there is a global need for effective, non-legal mitigation strategies to address light pollution, which require immediate attention and improvement. It also makes a novel contribution to literature, as to our knowledge, this is the first time such a wide spectrum investigation (not only lawsuits, but also online petitions) has been analyzed on this subject. Moreover, our study also reveals that while public awareness has risen in recent years and numerous actions have taken place, only a few non-legal cases have been successful. These have related mainly to environmental actions and animal welfare. It seems that if the public's approach is well thought through, carefully planned, and fully coordinated, a successful outcome is much more likely to occur.

As there are no well-known guidelines for citizens' actions related to the reduction of the impact of light pollution, a seven-step framework (Table 4) has been developed to provide important insights for the management of the process, which can be adopted by any interested party wanting to take action.

**Table 4.** A practical seven-step process involving guidelines for citizens' actions to reduce light pollution and its impact. Source: Authors' elaboration.

| Step   | Category              | Description                                                                                                                                                                                                                                                                                         |
|--------|-----------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Step 1 | Identify the issue    | Identify the nuisance/source of disturbance created by artificial lighting at night, by answering the following questions: Is it a hazard to safety? Would it produce ecological disturbance of any sort? Can it cause environmental and visual nuisance? Is energy waste visible to the naked eye? |
| Step 2 | Check the regulations | Check the allowed lighting requirements/limits based on environmental zones (permitted level of sky glow, light intrusion into windows, or building luminance) in the area where the obtrusive light issue occurs.                                                                                  |



Table 4. Cont.

| Step   | Category                                             | Description                                                                                                                                                                                                                                                                                                                                                                                           |
|--------|------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Step 3 | Collect the evidence (document and assess the issue) | Take photographs and videos to thoroughly document the issue, keep a diary of observations that record light pollution characteristic with details that include dates and times. If possible, also perform measurements to compare the outcome with the limits allowed in standards and guidelines.                                                                                                   |
| Step 4 | Join forces with others                              | Network with your neighbors and connect with other citizens interested in supporting your actions; be part of a larger group that is involved in similar struggles. Talk to people who might have been through a similar experience to learn from their attempts (mistakes and successes). Educate the public on the presence of light pollution in their community. Seek support from policy makers. |
| Step 5 | Consult experts to reinforce your views              | Consult with authorities on the issue (light pollution experts such as environmentalists, photobiologists/chronobiologists, lighting designers, astronomers, members of local scientific societies, conservation groups, or environmental associations, and others). Your issue should be supported by facts, references, and/or expertise.                                                           |
| Step 6 | Take action                                          | Decide on the most appropriate non-legal action to be taken to resolve the issue (see Table 2). When all options of negotiations have been tried, consult an environmental lawyer if necessary.                                                                                                                                                                                                       |
| Step 7 | Be persistent                                        | A successful outcome might take a few years, therefore, it is important to be patient, consistent with the pressure applied to decision makers, and persistent in your efforts for a favorable resolution.                                                                                                                                                                                            |

Additionally, it is important to highlight the need for collaboration with lighting professionals in this process, as they are knowledgeable about many aspects of artificial lighting. This means solid technical, design, and implementation knowledge can be provided, and any complaints can be professionally evaluated. Also, support arguments for necessary change and improvement can be offered, as some lighting professionals work on a pro bono basis [128,129]. To boot, members of many organizations (see Section 2.4) can provide advice and guidance on negative outdoor lighting practices and the relevant policies needed to mitigate these issues.

It is also strongly recommended that, in the future, before any new construction or refurbishment activity connected to outdoor lighting is planned in residential or natural environments, an Environmental Impact Report (EIR) is conducted by experts for various authorities (central government, the province, or the municipality) to evaluate possible environmental and health effects. Citizens can approach their local municipal authorities with their concerns and pressure these decisionmakers to take the issues further, to instigate positive change with local government. This can help to establish anti-light pollution policies that will enable towns and cities to install ecologically/biologically responsible lighting.

Finally, it is expected that this work will likely solicit debate and extend discussion on the development of specific light pollution mitigation strategies on global/international, national, and regional levels. It may also assist in the necessary improvement of upcoming anti-light pollution related legislations and regulations by policy and planning officers, introducing technical lighting parameters, and zoning and curfew times as a frame of reference. Such provisions will give active

citizens the necessary tools to be well equipped to challenge, and in some cases prevent, the adverse effects of light pollution from ALAN.

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