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Indicators of energy efficiency in road and street lighting: a long way to more sustainable cities

Antonio Peña-García, Evaristo Molero, Ovidio Rabaza

Department of Civil Engineering. University of Granada, 18071, Granada, Spain

Abstract. Public lighting plays a major role in the global figures of energy consumption. Since its final goal is to ensure the safety of people and goods as well as the well-being of its users, it is a clearly basic service. Although the continuous progress in more efficient and sustainable light sources seem to leave a large margin of improvement in terms of energy efficiency, its safety-related peculiarities of public lighting, especially in infrastructures like streets, roads and tunnels, make it a challenge to get good visual performance with minimal energy consumption. Regulations and standards have proposed different coefficients to take account of this efficiency in public lighting with discrete success yet. This work discusses the current situation and presents some proposals with the target of making more sustainable cities without compromising the safety of their citizens.

Key words. Public Lighting, Energy Efficiency, Visual Performance, Safety, Sustainability.

1. Introduction

1.1 The Basic Process in Lighting (BPL).

The vast majority of activities that can be carried out under public lighting in street and road environments, can be reduced to what has been called "The Basic Process in Lighting" (BPL) [1].

This process, fully described from a human-centred perspective by Peña-García, Castillo-Martínez and Erns in 2024, reminds us that almost all the visual tasks are carried out by reflection on one given visual work plane, which plays a central role in the definition of the visual requirements to be settled by regulations and standards and, even more important, in the visual input and consequent output of the users of the street or road.

It consists of five steps that are shown in Figure 1 and describes below:

1. The luminaries emit luminous flux (Φ) with a particular distribution of Luminous Intensity I (α, β).
2. The pavement or road surface receives some luminous flux per unit of surface, which is measured as Illuminance (E). This surface becomes the visual work plane.
3. The visual work plane partially reflects the luminous flux its capability to reflect light in each direction, called reflectance (ρ). This reflection also depends on the spectral composition, that is, the wavelengths present in the light emitted by the luminary. This is quantified by the spectral absorptance and determines the colour of the surface.
4. A luminous flux per unit of solid angle and surface in one given direction is reflected. This quantity is called Luminance (L) and determines the visual input. But, in terms of energy efficiency, safety and protection against light pollution, we are interested only on the luminance directed towards the eyes of the street users.
5. The visual input L, and the circumstances and situation, labelled as "C", determine the output (O) of the pedestrians and drivers in one given road or street. This output is an action that takes some visual reaction time [2] with better or worse performance and efficacy.

Where the photometric quantities Φ, I, E, ρ and L are defined by the Commission Internationale de l'´Eclairage, CIE, in the document "ILV: International Lighting Vocabulary", CIE Publ. S017/E:2020 [3].

The steps above conforming the BPL are schematically shown in Figure 1.

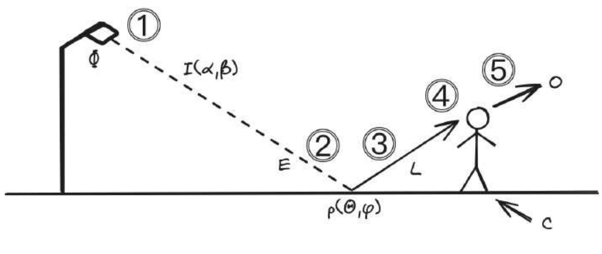

Figure 1. The Basic Process in Lighting (BPL) [1].

From a human-centred perspective, the BPL can be summarized as L+C→O.

It is necessary to remark that the context (C) where the visual process takes place, is complex, mainly in urban environments. The different elements of the streets like trees [4], trash cans, benches, parked cars and other, do not only influence on the luminance directed towards the users' eyes, but also in their perception of safety [1] and other psychological variables.

Once the complex interaction between public lighting and people is well-established, it is necessary to wonder about its impact from the perspective of energy, natural resources and sustainability.

1.2. Efficient public lighting for a rational and sustainable use of energy.

The target of safety and well-being combined with the demanding requirements of regulations and standards on road and street lighting [5 - 7], must be balanced with a high energy efficiency because approximately 20% of total energy consumption is used for lighting of indoor and out-door spaces [8].

In the current framework, it is clear that the high energy consumption of lighting installations, is not just a financial matter. Energy demands impact on raw materials (light sources, luminaries, wiring, electrical equipment etc), solid and gaseous emissions to the rivers, seas and atmosphere, fuel consumption, maintenance and other key parameters to grow according to a sustainable development [9] and achieve the Sustainable Development Goals (SDG) [10], deeply related to lighting as show in Figure 2.

Figure 2. Sustainable Development Goals.

Among these SDG, at least Nrs. 1, 2, 3, 6, 7, 9, 10, 11, 13, 14, and 15 are directly influenced by available public lighting ensuring safety, health, well-being with the lowest possible consumption of energy, materials and emissions.

In the next section, the attempts up to date to quantify the efficiency of public lighting will be presented and their pros and cons, analysed.

2. Efficiency indicators in public lighting: a critical review

Among the different metrics and coefficients to take account of the energy efficiency of lighting installations, there are some of especial importance due to their inclusion in important national regulations and international standards.

They are the following:

1) The Power Density Indicator (D_p) is the power consumed by the installation (light sources, luminaries and auxiliary devices), P, divided by the value of the product of the illuminated surface area or sub-area (A_i) and the calculated maintained E_{av} on this area [5,11, 12]:

$$D_p = \frac{P}{\sum_i A_i E_{av\,i}} \quad (1)$$

where D_p units are $W lux^{-1} m^{-2}$.

Although this parameter is useful to determine the degree of conversion of electric energy in visual one, the definition of the sub-areas may be ambiguous in some kid of installations.

2) Annual Energy Consumption Indicator, AECI (D_E) is the energy consumed by the lighting installation of one given road in one year.

$$D_E = \frac{\sum_{j=1}^{m} \left(P_j t_j\right)}{A} \quad (2)$$

where,

Pj is the operational power associated with the j-th period of operation, in W;
tj is the duration of j-th period of operation profile when the power Pj is consumed, over a year, in h;
A is the size of the area lit by the same lighting arrangement;
m is the number of periods with different operational power Pj. m shall also consider the period over which the quiescent power is consumed. This period would generally be the time when the lighting is not operational, i.e. daylight hours and any nighttime period when the lighting is not lit.

Annual energy consumption indicator (D_E) complements the power density indicator (D_P) for assessment of the energy performance of a particular lighting system.

Standard "Road lighting—part 5: energy performance indicators" (EN 13201-5) [5] establishes the methodology to determine these parameters, including field measurements as shown in Figure 3:

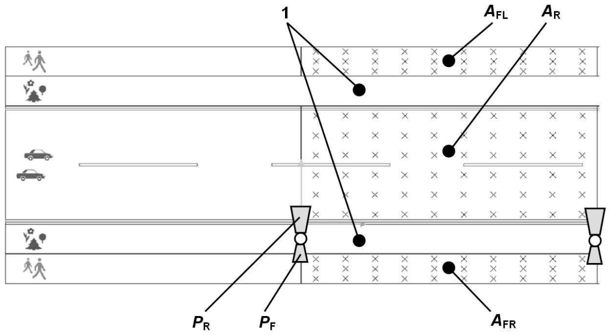

Figure 3. Determination of AECI established by [5].

3) The Energy Efficiency (ε) [6], that is, the average illuminance (E_{av}) on one surface multiplied by its area (A_T), and divided by the total power consumed by the installation, including the light sources and the electrical auxiliary devices (P_T):

$$\varepsilon = \frac{A_T \, E_{av}}{P_T} \qquad (3)$$

Where ε units are lux m^2W^{-1}.

Other standards refer to similar parameters as Installation Luminous Efficacy (η_{inst}) [5].

When dealing with ε, the definition of the illuminated areas is sometimes a problem because the respective flux going to road and sidewalk is not easy to quantify, especially when both, road and sidewalk are illuminated with the same luminary.

4) The Upward Light Ratio (ULR) is the parameter used for the limitation of upward light, an important component of light pollution [13, 14]. ULR is defined as the proportion of the luminous flux of the luminaires of an installation emitted at and above the horizontal as shown in Figure 4 [12]:

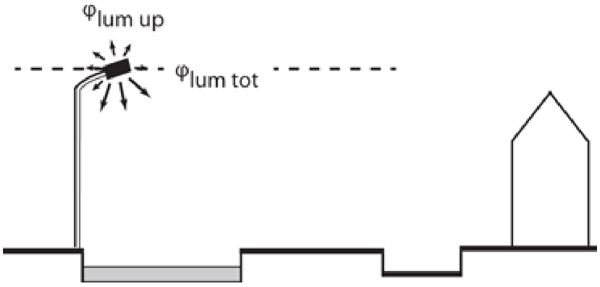

Figure 4. Emitted upwards and downwards luminous flux from a lighting installation. Figure from [12].

As main con, ULR does not consider the effect of light reflected upwards from the illuminated surfaces. This is because ULR is a luminaire related criterion instead of an installation related one.

5) The Upper Flux Ratio (UFR) considers the luminous flux reflected upwards [15]. Indeed, despite the higher or lower capability of the pavement to reflect flux, the UFR takes account of the flux reflected towards inaccurate directions. It is defined by [16]:

$$UFR = \frac{E'_{av}}{E_{av} C_m} \left[1 + \frac{ULOR}{\rho_1 C_u} + \frac{\rho_2}{\rho_1} \left(\frac{DLOR - C_u}{C_u} \right) \right] \qquad (4)$$

where,

E_m and E'_m are the average illuminances achieved and required respectively.
C_m and C_u are the maintenance and utilization factors.
ULOR and DLOR are upwards and downwards ratios to luminary flux.
ρ_1 and ρ_2 are the respective reflectances of visual plan and surroundings.
The meaning behind this expression is to express the ratio of the maximum luminous flux emitted upwards to the minimum luminous flux emitted upwards in an ideal situation, that is, the deviation between projected and real upwards flux.

The real and ideal situations are illustrated in Figure 5:

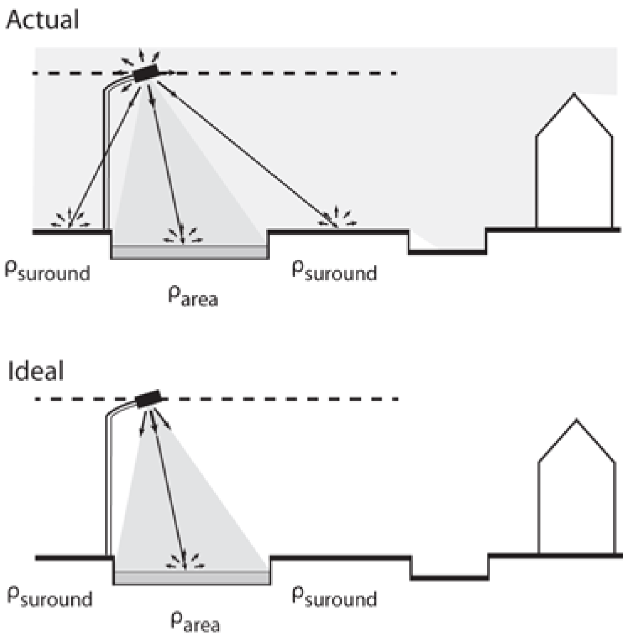

Figure 5. Reflection of light on visual working plane and adjacent areas. Figure from [12].

Despite its utility when compared to URL, UFR does not take account for installations efficiency to produce visual performance from consumed energy and/or emitted luminous flux.

After considering all these parameters trying to quantify energy efficiency from a wide perspective, it is clear that the capability of the pavement to reflect luminous flux and the spatial distribution of this reflection, play a key role in visual performance and potential light pollution. In fact, pavements are an active area of research with the target of safer and more sustainable light installations [17-21].

In summary, several parameters have been defined to take account of the efficiency of lighting installations as well as their impact in energy and environmental terms. The next section presents some considerations about their reliability and limitations and some lines to follow in future research.

3. Discussion and Conclusions

Determining the energy efficiency of lighting installations is a hot topic due to the high impact of these installations on energy consumption, use of raw materials, financial and human resources and environmental impact.

Different metrics and parameters have been defined to quantify the energy efficiency of lighting installations and their effects on the environment, mainly due to light pollution.

However, these parameters have shortcomings in their definitions, especially concerning the lighted areas and their reflective properties since they determine the visual input and the output from road users as considered by the Basic Process in Lighting.

Future research must focus on improved metrics taking account of both, energy efficiency and visual performance.

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