SUSTAINABILITY FOR ENERGY-EFFICENT LIGHTING

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ABSTRACT

The social, environmental and economic side effects of the street lighting are the foremost concern for this thesis, since the expanding use of light at night, along with an inappropriate design, has led a large energy consumption, light pollution and impact on human health and the environment. With increasing consideration on the negative side-effects, it has introduced new recommendations for energy efficient lighting, indicators, and new energy classifications systems to evaluate the energy performance of lighting systems.

According to the literature, the energy classification systems are based on installed power and lighting parameters (luminance or illuminance), which influence by regulating the energy consumption and the light levels entering the eye. However, recent studies on the advances of lighting technologies, i.e. light-emitting diode (LED), control systems and luminaires, and developments in mesopic photometry and its influence in energy reduction and vision performance, demand for new requirements. This implies a new quantification system to measure energy efficiency by incorporating all the elements that affect the overall efficiency of the installation.

Within this context, an alternative tool to aid decision-makers in choosing the best energy efficiency system to be implemented and to support evidence on the energy savings on street lighting was proposed. This alternative approach takes into consideration the improvement of visual performance by correcting the standard photometry system (photopic) by the mesopic system recommended within the CIE 191:2010 and the operational hours of the lighting system, which are usually disregarded by the most commonly used energy classification approaches.

The research outlined in this thesis proposes to use the value function approach that allowed standardizing the proposed energy consumption indicator within a value scale ranging from 0 to 1, which also represents satisfaction degree: the less energy is consumed the more grade of satisfaction. A case study comprising 13 representative streets of the Eixample District of Barcelona was used to validate the alternative approach proposed, and results were compared with those obtained by considering three energy efficiency classifications currently used in Spain, Netherlands and Italy. For the sample, a systematic procedure was carried out to collect data regarding lighting class and geometrical characteristics of the streets, and to the main characteristics of the lighting system.

The results derived from the application of the proposed method can be used straightforwardly to quantify the potential energy savings that can be obtained when using different energy classifications. Moreover, these results provide a critical analysis by pointing out the strengths and weakness of the most significant energy performance indicators along with their corresponding energy classification systems. In conclusion, this thesis constitutes a conceptual and empirical approach to the energy classification systems applied in Europe to the street lighting. Thanks to the methodological contribution and the knowledge obtained, this thesis intends to contribute to improving the energy efficiency-based classification systems, and consequently, to move forward into a sustainable and smart assessment tool.

RESUMEN

La principal motivación para el estudio del alumbrado público en este trabajo, radica en la influencia que éste ejerce a nivel social, ambiental y económico. El aumento del consumo energético, la contaminación lumínica y el impacto tanto en la salud como en el medio ambiente, son efectos secundarios causados por el uso excesivo de la luz durante la noche junto con un diseño inadecuado del alumbrado público. Por ello, han surgido recomendaciones en el ámbito de eficiencia energética, indicadores y sistemas de clasificación energética que ayudan a evaluar las mejoras necesarias para obtener una instalación de alumbrado público eficiente.

La mayoría de los sistemas de clasificación energética están basados en parámetros como la potencia instalada y los niveles de iluminación. Sin embargo, existen estudios que confirman los recientes avances tecnológicos en iluminación y, en el desarrollo de la fotometría mesópica que influye en la reducción del consumo energético y en el rendimiento visual. Esto pone de manifiesto que la evaluación de eficiencia energética del alumbrado público a través de los sistemas de clasificación energética actuales, no deberían basarse solamente en los parámetros básicos, si no que también deberían considerarse otros parámetros que incidan en la eficiencia global de la instalación y que tomen en cuenta las demandas actuales del sector.

En este contexto, se ha propuesto una herramienta alternativa que ayude a los responsables de tomar decisiones a seleccionar e implementar el mejor sistema de eficiencia energética, y a evidenciar los ahorros energéticos en el alumbrado público. Este enfoque alternativo toma en cuenta la mejora del rendimiento visual al corregir el sistema de fotometría estándar (fotópico) por el sistema mesópico recomendado en el reporte técnico CIE 191: 2010, así como las horas de funcionamiento del sistema de iluminación. Estos dos parámetros, generalmente son ignorados por los sistemas de clasificación energética usados comúnmente.

Esta investigación propone utilizar la Función de Valor, la cual refleja el grado de satisfacción del indicador de consumo energético a partir de un valor estandarizado en una escala del 0 al 1: menos energía es consumida, mayor es el grado de satisfacción que se obtiene. El nuevo enfoque se ha validado en un caso de estudio conformado por 13 calles representativas del distrito del Eixample de Barcelona, cuyos resultados fueron correlacionados con tres sistemas de clasificación energética utilizados actualmente en España, Países Bajos e Italia. Se llevó a cabo un procedimiento sistemático para la colección de datos del caso de estudio, donde se obtuvieron las características geométricas de las calles y sus respectivas clases de iluminación, así como las características principales del sistema de iluminación.

Los resultados obtenidos de la aplicación del método propuesto y de las diferentes clasificaciones energéticas, se pueden utilizar de forma sencilla para cuantificar el ahorro energético. Además, estos resultados proporcionan un análisis crítico al resaltar las fortalezas y debilidades de los indicadores de eficiencia energética junto con sus correspondientes sistemas de clasificación energética. En conclusión, este trabajo constituye un enfoque conceptual y empírico de los sistemas de clasificación energética del alumbrado público aplicados en Europa. Gracias al aporte metodológico y al conocimiento obtenido, este trabajo pretende contribuir a la mejora de los sistemas de clasificación basados en la eficiencia energética y, en consecuencia, avanzar hacia una herramienta de evaluación sostenible e inteligente.

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SL	Street Lighting
EPI	Energy Performance Indicator
ECS	Energy classification system
CCT	Correlated Color Temperature
PDI	Power Density Indicator
AECI	Annual Energy Consumption Indicator
SLEEC	Street Lighting Energy Efficiency Criterion
IPEA	Luminaire Energy Efficiency Indicator
IPEI	Lighting System Energy Efficiency Indicator
MIVES	Integrated Value Model for Sustainability Assessment
GEH	Greenhouse Gas Emissions
CIE	Commission Internationale de l'Eclairage
CRI	Color Rendering Index
HPS	High Pressure Sodium (Lamp)
LED	Light Emitting Diode
LPS	Low Pressure Sodium (Lamp)
MH	Metal Halide (Lamp)
FL	Fluorescent lamp
SPD	Spectral Power Distribution
S/P	Scotopic to Photopic Ratio
ipRGC	Retinal Ganglion Cell
ESCO's	Energy Services Companies
TI	Threshold Increment
CCT (K)	Correlated Color Temperature
CRI	Color Rendering Index
NEEAP	National Energy Efficiency Action Plan
FDI	Foreign Direct Invest

1 INTRODUCTION

The main purpose of street lighting (SL hereinafter) is to provide visual performance, visual comfort and visual orientation for drivers and pedestrian users of streets at night, this allowing to proceed with safety and providing a sense of security by identifying hazards, orientation and recognition of other pedestrians (Steve Fotios 2018; van Bommel 2015a). Therefore, energy efficiency of SL systems lies in optimizing the use of energy while guaranteeing the amount of luminous flux necessary to carry out activities at night and meeting the purpose of SL. Unfortunately, this ambitious aim has led to a large energy consumption and light pollution.

With increasing consideration in energy consumption and light pollution, the need to establish recommendations for energy efficient lighting and to introduce new indicators and energy certifications to evaluate and compare the energy performance of different SL systems have been proposed.

In (Boyce et al. 2009; M. Kostic and Djokic 2009) useful recommendations regarding the influencing factors for energy savings in SL were defined. Traditionally, these recommendations are based on changes in technology (lamps, control gear, luminaires), in patterns of use (switches and remote monitoring systems), in standards and contracts (applied only to new installations) and in design optimization (GIS-based street layout and design parameters in SL). However, these recommendations need to be re-organized into new categorization that fit the potential energy-saving opportunities in all the phases of a SL project (design, operational and strategic).

The recommendations suggested are a qualitative contribution since there was no systematic use of energy-based and lighting-based parameters for the comparison of different SL systems (Leccese et al. 2017). For a quantitative contribution, thus enabling for direct comparison of different lighting projects, energy performance indicators (EPI) and energy classification systems (ECS) or energy certifications have been established. The latter are useful to express whether a SL installation is good at performing or not by using an A-G scale, comprehensive for all public.

In Europe most used EPI are Power Density Indicator (PDI) or Annual Energy Consumption Indicator (AECI) (European Committee for Standardization 2015a). Regarding to ECS only few countries in Europe have been working on it; for instance: the energy efficiency indicator (I_{ε}) through the Spanish Royal Decree 1890/2008 (Royal Decree 1890/2008 2008) and its corresponding Complementary Technical Instruction; Netherlands based on the Street Lighting Energy Efficiency Criterion (SLEEC) as a whole system indicator (BRE 2011) and Italy, specifically in the regulations of the Emilia Romagna region (Regional Council of Emilia Romagna 2015). For the latter, two indicators were introduced: A Luminaire Energy Efficiency Indicator (IPEA) and a Lighting System Energy Efficiency Indicator (IPEI).

The EPI's are based on parameters of installed power and luminance or Illuminance, which have an influence in energy reduction through the lighting equipment and regulate the light levels entering the eye. However, given the recent advances in mesopic vision and its influence in energy reduction and vision performance, there is an ongoing need to introduce new parameters into the analysis of energy efficiency. Moreover, some researchers (Kyba et al. 2014; Loe 2003; San Martín Páramo 2011) have suggested a quantification system for measuring energy efficiency that incorporates all the elements that affect the overall efficiency of the installation with respect to time, because *time* has been given little attention in the EPI and ECS existing.

The method used to standardize the EPI proposed in this research was the Value Function (VF) approach. This method is one of the most widely accepted frameworks to standardize different units and magnitudes (Alarcon et al. 2011). It has been used in the MIVES method (Integrated Value Model for Sustainability Assessment), which has been validated in mostly engineering and architectural applications for assessing sustainability (Cartelle Barros et al. 2015; de la Fuente et al. 2017; Del Caño et al. 2015; Gilani et al. 2017; Habibi et al. 2020; Hosseini et al. 2018; Hosseini, Pons, et al. 2020; Pons et al. 2016; Pons and Aguado 2012; Pons and de la Fuente 2013; Pujadas et al. 2017). By applying the VF concept, the indicator is expressed in a value scale between 0 and 1 that represents, respectively, the minimum and maximum grade of satisfaction; this, in terms of the SL, means the less energy is consumed the more grade of satisfaction.

The alternative approach proposed has been used in a case study composed of 13 representative streets of the Eixample District of Barcelona, and results were compared with three energy efficiency classifications proposed by Spain, Netherlands, and Italy.

1.1 PROBLEM STATEMENT

Cities of XXI century have a challenge to tackle Climate Change by means mitigation and adaptation actions, not only because the social metabolism of the city contribute to the causes of it, but also because its threatening consequences. Considering that cities represent 2,7% of the world surface and those are responsible for 75% of global energy consumption and 80% of greenhouse gas emissions (GEH), the scientific community has proposed to reduce GEH 2050 between 50% and 85% compared to 1990 as a goal. At European level, some cities have signed an ambitious agreement called Covenant of Majors where commits to reduce 20% of their GEH emissions by the year 2020. With this local agreement, cities are taking more responsibility because, apart from these being part of the problem, cities can be the key point of the solution.

SL accounts for 8% of global electricity consumption (Karlicek et al. 2017). Official data in Spain reported that exterior lighting in municipalities in 2017 consumed 5,296 GWh of electricity per year, which represents approximately 1 % of all final energy consumption (IDAE 2017) that in turn is translated into 1,276,336,000 kg of CO_2 emitted[1]. Many authors have associated the excessive energy usage in SL not only with the increase of pollution in terms of CO_2 (Carli et al. 2017; Ożadowicz and Grela 2017; Rabaza et al. 2018) but also with light pollution (Davies and Smyth 2018; Stone 2017), damage at environment and human health (Falchi et al. 2011; Green et al. 2015) and with an excessive expenditure by the public administration (Radulovic et al. 2011).

Even though the percentage of final energy consumption sounds minimal, SL has a high potential to reduce their energy consumption. Different studies argue that energy savings in SL ranging from 20% to 50%

[1] Conversion factor used: 1 kWh electricity= 241 g CO2 (OCCC 2020).

can be achieved by the use of efficient ballast, lamps and luminaires (Hermoso Orzáez and de Andrés Díaz 2013; A. Kostic et al. 2012; Mockey Coureaux and Manzano 2013). Other studies were focused on improving quality of lighting have shown that implementing mesopic dimensioning in SL design have also energy saving potential (Jägerbrand 2015; A. Kostic et al. 2012; M. Kostic and Djokic 2009; Ylinen et al. 2011). Therefore, any action to reduce energy consumption in SL will result in a benefit to the environment by reducing CO_2 and light pollution, and to the municipalities by decreasing the bills of electricity.

At the same time, there is an increasing awareness of how to design SL installations under energy efficiency criteria. Recent advances of lighting technologies (e.g. light sources, control systems and luminaires) and developments in science (mesopic vision) place additional challenges on the design of SL installations. The problem relates to the constant use of energy efficiency to refer to any attempt for saving energy. Thus, energy efficiency in SL installations requires new criteria, based in empirical data, to face the challenges of SL sector, which implies move forward into a sustainable and smart SL system.

1.2 HYPOTHESIS AND RESEARCH QUESTIONS

- Hypothesis:

Analyzing numerical EPI and ECS used to measure energy efficiency in SL will provide the basis to propose an alternative energy efficiency classification that considers parameters disregarded, and correlating energy efficiency classification systems in a local case study will allow the validation of the methodologies.

- Research questions:
  - How SL can face the challenge of sustainability?
  - Could energy efficiency classifications for evaluating SL performance help to transform it into a smart system?
  - Is it possible to include other parameters such as time and correction to the mesopic photometry into the current energy efficiency classifications?

1.3 RESEARCH AIMS

The research outlined in this thesis aims at proposing an alternative tool for decision-makers for evaluating the energy efficiency performance in SL systems. This alternative approach integrates both the parameters that affect the overall efficiency of a SL installation and the parameters disregarded.

To this end, the following specific objectives were established:

1) To analyze the most representative both EPI and ECS approaches for SL.
2) To design an alternative energy efficiency classification system in which the governing parameters are taken into consideration to guarantee robust and representative quantitative results.
3) To validate the alternative approach in a representative local case study.
4) To analyze the energy performance of street lighting systems by corelating the current ECS and the alternative approach proposed.

1.4 METHODOLOGY

The research methodology of this thesis is divided in two phases that comprises four actions meant to meet the specific objectives (Figure 1.1). It is divided in two phases comprising 4 steps. The first phase is aimed at developing energy efficiency-based classification for SL proposed (*VF* IQ_{sa}). The second phase is meant to test the new approach to a case study and to validate these results with the three ECS proposed by Spanish, Dutch and Italian guidelines. This method is designed and oriented to aiding decision-makers in choosing the best energy efficiency system to be implemented and to support evidence on the energy savings on SL.

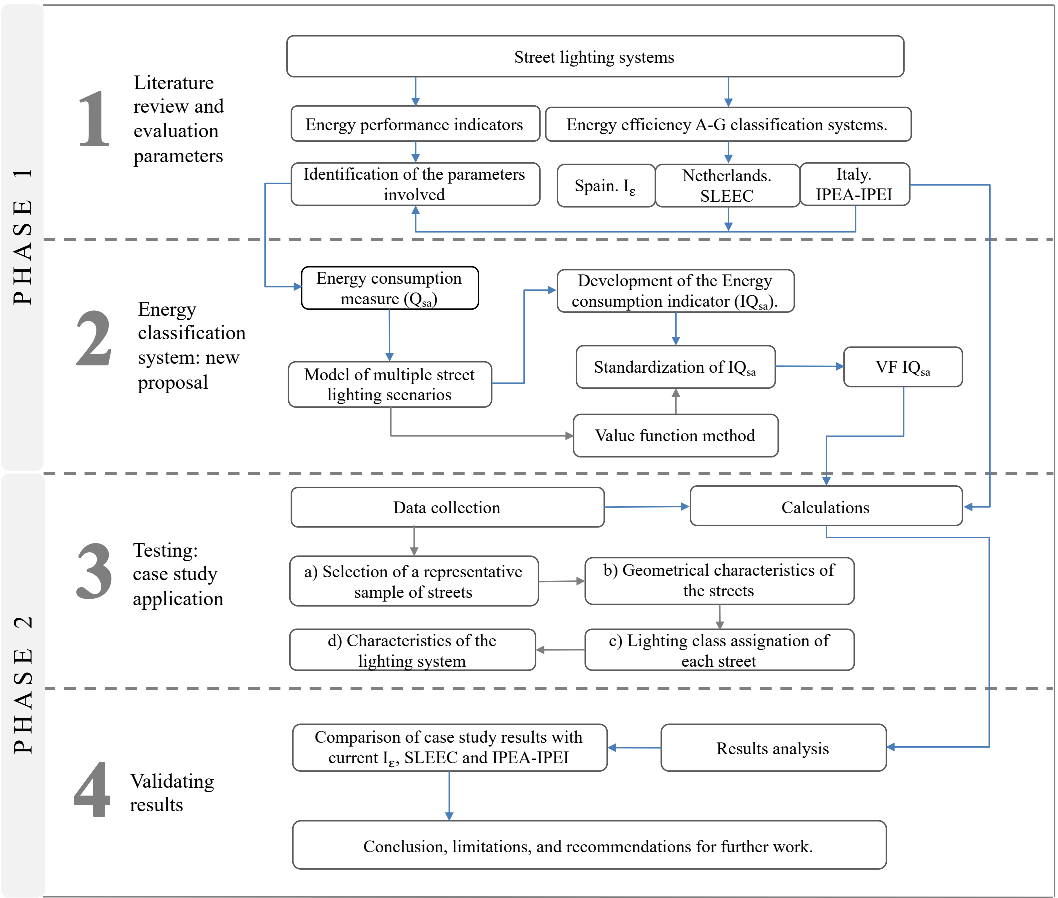


Figure 1.1 Research structure.

1.4.1 Phase 1. Energy efficiency classification for street lighting: new proposal

In this phase, a literature review of the current numerical indicators of energy performance for gauging energy efficiency in a SL installation was made. This review was based primarily on peer-reviewed journal papers, as well as documents published by international organizations and governmental energy agencies. The energy performance indicators were systematically examined to identify the parameters used for gauging energy efficiency in a SL system.

In this regard, an innovate equation for measuring energy consumption (Q_{sa}) was proposed. It considers the parameters disregarded through the introduction of two factors: luminous flux control factor (f_{cf})

and mesopic correction factor (f_{cm}). Q_{sa} was calculated in a wide set of SL scenarios composed by 8 road types with: (1) the corresponding lighting classes (M1, M2, M3, M4, C2, S1, S2, S3); (2) average illuminance levels according to each lighting class, 5 types of lamps (HPS, HPM, MH, LED, FL)[2]; (3) 3 luminous flux control (full flux, bi-level and individual fixture) and (4) 2 types of photometry (photopic and mesopic).

From these results, the reference value energy consumption ($Q_{sa,R}$) were obtained for each lighting class, as an input for calculating the energy consumption indicator (IQ_{sa}) proposed. In addition, the minimum ($IQ_{sa,min}$) and maximum ($IQ_{sa,max}$) values of energy consumption were obtained to define the limits of the value function on the x-axis. Finally, to standardize the indicator IQ_{sa} within a value scale ranging from 0-1, the VF approach was used. The VF allows assessing the energy efficiency (grade of satisfaction) associate to the IQ_{sa} indicator. Figure 1.2 describes the activities to achieve the energy efficiency-based classification for SL.

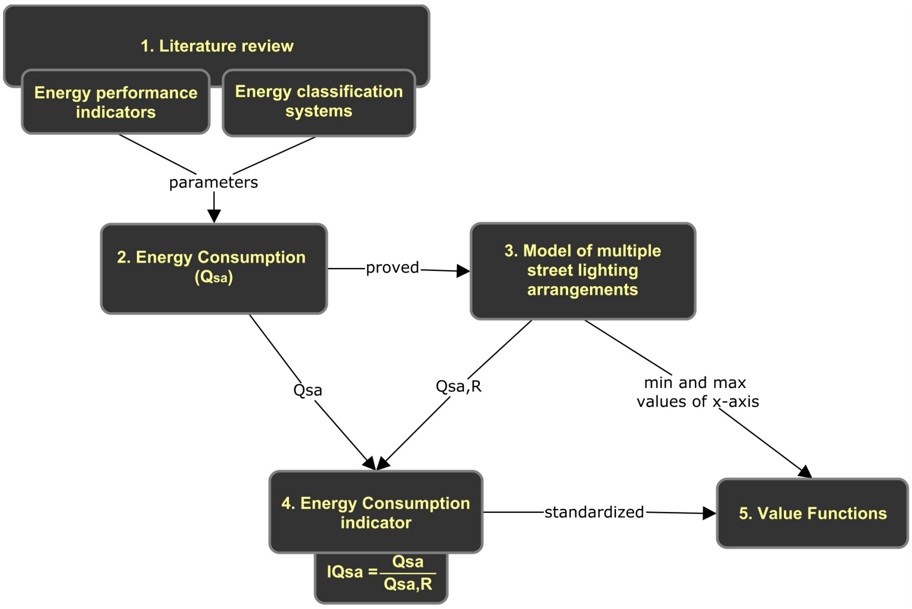


Figure 1.2 Research activities of phase 1.

1.4.2 Phase 2. Validation and correlation

The energy performance of street lighting systems is assessed in a representative section of Barcelona by correlating the energy classification systems proposed by Spain, Netherlands and Italy and the energy efficiency-based classification for SL proposed in this research (*VF* IQ_{sa}). To this end, a systematic procedure was carried out by following the approach presented in Figure 1.1. The steps of the procedure can be listed as follows:

- Step 1) Sample selection: identification of a representative sample of streets in Barcelona.
- Step 2) Shape: data collection for geometrical characteristics of the streets.
- Step 3) Classification: determination of the lighting class of each street.
- Step 4) Lighting: data collection of the main characteristics of the lighting system.

[2] High Pressure Sodium (HPS), High Pressure Mercury (HPM), Metal Halide (MH), Light Emitting Diode (LED), Fluorescent (FL).

- Step 5) Analysis: calculation of the ECS.

The step 1) is performed only once, while the steps from 2 to 5 are repeated for all the streets belonging to the sample.

1.5 THESIS SCHEME

This thesis is divided into five chapters, including the introduction (Figure 1.3). The second chapter identifies and analyses the existing SL systems, highlighting their side-effects, and describes the challenge that SL sector is facing. Furthermore, it discusses the most representative EPI and ECS approaches for SL, as well as the description of the method to standardize the indicator in a 0-1 scale. This chapter concludes describing the research gaps that this thesis is intended to cover. Chapter 3 brings the research body of the thesis where the design principles of the energy classification system are presented. The collected data of the case study are also presented. In Chapter 4, the results derived from the application of the energy classification system proposed herein and the current correlation between the energy efficiency classifications systems are discussed. The last chapter, Chapter 5, gathers the conclusion, limitations, and recommendations for further research.

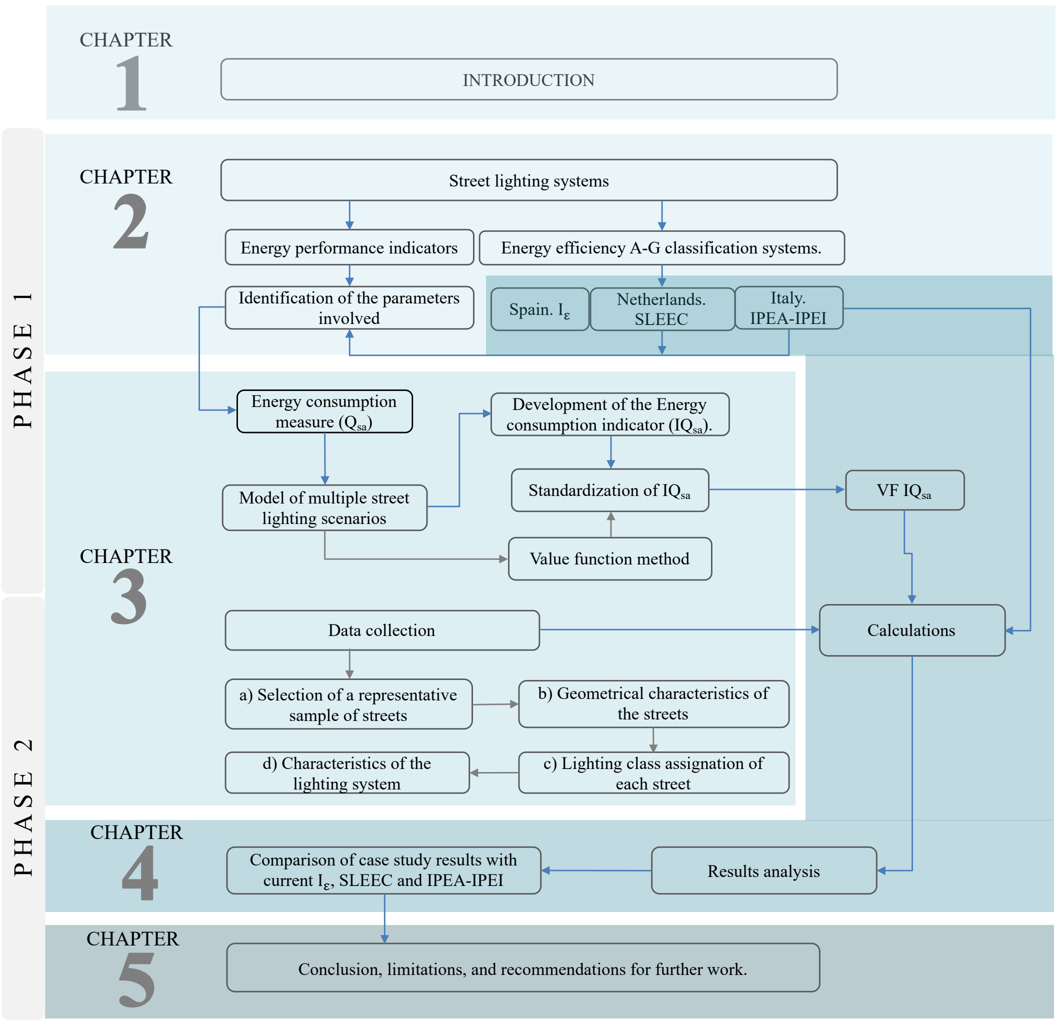


Figure 1.3 Thesis organization.

2 STATE OF THE ART

2.1 STREET LIGHTING PURPOSE

2.1.1 Purpose and benefits of street lighting systems

The purpose of SL is to provide visual performance, visual comfort and visual orientation for drivers and pedestrian users of streets at night, allowing to proceed safety and providing a sense of security by identifying hazards, orientation and recognition of other pedestrians (Steve Fotios 2018; van Bommel 2015a).

European (European Committee for Standardization 2015b) and Spanish lighting standards and guidelines (Royal Decree 1890/2008 2008) provides the lighting requirements, primarily, the amount of light in terms of illuminance or luminance, color and spatial distribution to achieve the purpose of SL. Even though some researches (S. Fotios and Gibbons 2018; Uttley 2015) argue that these requirements do not appear to be well-founded in robust empirical evidence, or at least do not reveal the nature of any evidence, for this thesis, the discussion will be focused in the parameters used to achieve visual performance, visual comfort and visual orientation as benefits obtained from having applied the right lighting for the visual tasks at night.

Bearing this in mind, Table 2.1 resumes the lighting parameters needed to satisfy the visual task at night, where Illuminance (E), Luminance (L) and Spectral Power Distribution (SPD) parameters play a relevant role. The luminance is a metric based in human vision, which describes the luminous intensity per unit area in a direction, specifically that reflected from the road surface towards the driver, therefore luminance is a lighting parameter for motorized traffic and it is limited in adverse weather and wet road surface conditions because of changes of surface reflection (S. Fotios and Gibbons 2018).

The Illuminance is a lighting parameter for pedestrians, cyclist, and residents, which measures luminous flux per unit of area. Pedestrians needs not only lighting information of sidewalks (E_{hor}) to feel security but the façades ($E_{façade}$) and the faces of other people in the street ($E_{semi\text{-}cylindrical}$) as well.

The Spectral power distribution (SPD) of light can influence visual performance because of the variable sensitivity of distinct types of photoreceptors (i.e. rods and cones). S/P ratio measures the relation of the scotopic luminous flux to the photopic luminous flux and represents the relative strengths of the rod and cone visual stimulation produced by the lamp (S. Fotios 2013). This term would be further defined in mesopic section.

SL can do more than enabling vision. By applying the right light, at the right place and the right time would be possible to arrive at SL solutions that will satisfy lighting requirements established by standards while minimizing both the energy use and negative environmental side effects of the light. Fotios *et. al.* (S. Fotios and Gibbons 2018) refers a metaphor into the analysis of management and use of light being similar to administering a drug: light has both benefits (positive) and unwanted side effects (negatives) given the need to control the dosage of the light to provide the maximum benefit whilst minimizing the negatives.

Next section explores the side effects of applying an incorrect quantity and quality of light and will help to provide an understanding of the importance of restricting waste of energy.

Table 2.1 Summary of the parameters that define street lighting objectives.

Purpose of SL	Visual task	Design criteria/parameter	Light level recommended	Data source
Visual performance	Safety: Detecting trip hazard in the pavement: holes, cracks, bumps, etc.	Illuminance: E (lx) SPD: S/P ratio	$E_{min,hor}$ = 2 lx Higher illuminance ≠ better detection Age and SPD significant only at 0.2 lx. Hight S/P ratio.	(S. Fotios and Cheal 2009; Uttley 2015)
	Security: perception of spatial brightness of the area helps to do not feel scared after dark.	Illuminance: E (lx) SPD: S/P ratio	>10 lx ≠ better perceived security $E_{façade}$=1.5 lx Higher color temperature light sources (cooler tinted light) require lower lighting levels. Hight brightness = CMH, FL lamps	(van Bommel 2015a) (S. Fotios and Cheal 2007; Knight 2010; M. Kostic and Djokic 2009)
	Facial recognition: Pedestrian should receive sufficient visual information regarding other persons in that area.	Illuminance: $E_{semi-cylindrical}$ (lx) SPD S/P ratio TI: threshold increment. L_{facial} = cd/m^2	For a recognition distance of 4 m: $E_{semi-cylindrical}$ (lx)= 1 lx Higher S/P ratio L_{facial} =0.1 cd/m^2 (TI= 0) to 0.18 cd/m^2 (TI= 15 %). For a face reflectance of 0.4 this corresponds to 0.8 lx and 1.5 lx semi-cylindrical illuminance, respectively.	(van Bommel 2015a) (S Fotios et al. 2015; Yang 2014)
	Visual orientation and guidance: imply the ability to identify buildings and features of the environment.	Illuminance: $E_{façade}$(lx) SPD: S/P ratio	$E_{façade}$= 1.5 lx and E_m= 5 lx Higher color temperature light sources (cooler tinted light) require lower lighting levels.	(van Bommel 2015a)
Visual comfort and Pleasantness	Brightness of the space.	Illuminance: E (lx)	< 3-5 lx = good perceived brightness	(van Bommel 2015a)
	Color quality of the light sources.	CCT (K) (Correlated Colour Temperature) CRI (Colour Rendering Index)	The perception of comfort increased with CCT=2000 K and CRI= 25 to CCT=2800 and 4200 K and CRI=80.	(Knight 2010)
	Restriction of discomfort glare: the too-bright luminaires has a negative effect on the comfort and pleasantness of users.	Luminaire glare index	For mounting heights greater than 6 m, CIE recommends luminaire glare index values up to 7000, while for more critical mounting heights lower than some 4 m only values of only 4000 are acceptable.	(van Bommel 2015a)
	Visual impact: luminaires and columns can have an impact on the visual scene.	-	-	(van Bommel 2015a)

2.1.2 Side effects of Street lighting

2.1.2.1 Energy consumption

SL is a feature of urban areas and it has defined the modern city, in extending the visibility of its public spaces, inhabitants and itinerants beyond the hours of natural light and changing the meanings of the night for city dwellers (Green et al. 2015). However, the expanding use of light at night has resulted in a large energy consumption in many cities around the world.

The electricity demand for SL varies from country to country as can be seen in Figure 2.1. France consumes about 45 TWh of electricity for lighting of which 10% corresponding to SL sector. In USA, the electric energy consumption for lighting in 2010 reached 690 TWh, and 4% represent the energy consumed by SL. In Russian Federation the overall electrical energy consumption in lighting correspond to 137.5 TWh of which 3 % corresponding to SL sector (Karlicek et al. 2017).

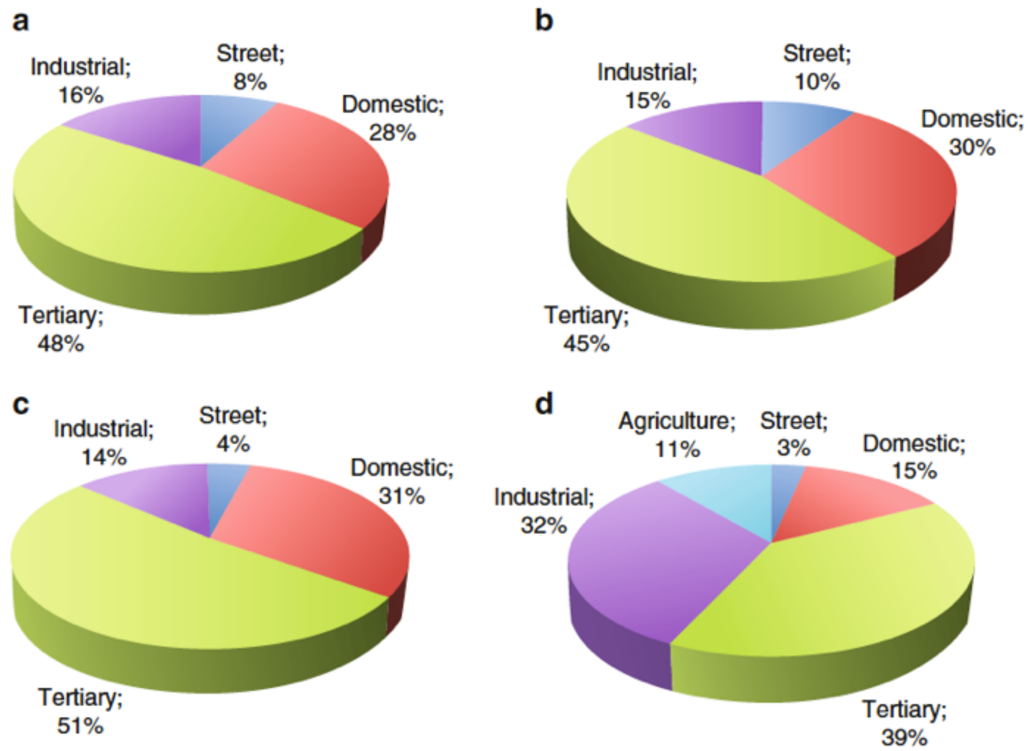


Figure 2.1 Percentage of energy consumption comparison for SL in early twenty-first century (a) Worldwide (2006) 3418 TWh, 8 % SL; (b) France (2006) 45 TWh, 10 % SL; (c) USA (2010) 694 TWh, 4 % SL; (d) Russian Federation (2006) 137.5 TWh, 3% SL. (Karlicek et al. 2017).

Other data in some publications shown up the energy consumption for SL in some countries. For example, energy consumption for lighting in Italy accounts for the 12% of total electricity demand in public sector (Beccali et al. 2015). In 2008, Croatia consumed 0.44 TWh for SL sector that represent 2.8% of total annual electrical consumption of the country (Zdunic 2015a). In UK road lighting and traffic signals consumed 2.5 TWh of electricity annually (2007) (Boyce et al. 2009). In Latin American cities: urban lighting in municipalities accounts for around 3.5 to 4% of total electricity consumption (Mockey Coureaux and Manzano 2013).

Within the context of energy consumption in Spain, SL is a public service that refers to functional, ambient, and decorative lighting systems on roads and public spaces. According to the last inventory, SL on Spain's municipal roads consists of 8,849,839 lamps which, with an average power of 156 W/lamp, annually lead to a net consumption of 5,296 GWh of electricity per year. As a whole, this represents 1 % of all final energy consumption, all in the form of electricity (IDAE 2017).

In this context, energy savings and efficiency measures in this sector are implemented by actions and recommendations aimed at improving the efficiency of SL technologies. These actions are reflected in the different National Energy Efficiency Action Plan (NEEAP) and the Royal Decree 1890/2008 and its complementary technical instructions EA-01 to EA-07 presented in Figure 2.2.

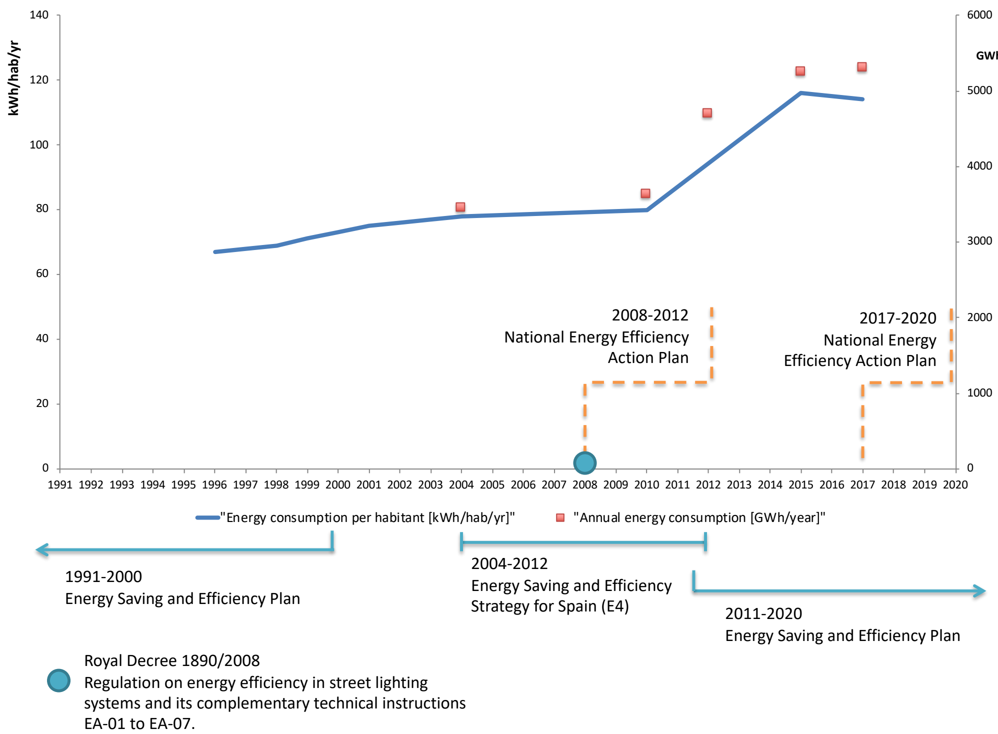


Figure 2.2 Annual energy consumption (GWh/year) and Energy consumption per habitant (kWh/hab/yr) in Spain along with National Energy Efficiency Actions Plans. Data extracted on (IDAE 2007, 2011, 2017; Sánchez de Miguel and Benayas Polo 2019).

The last Energy Saving and Efficiency Plan 2011-2020 constitutes the second NEEAP. This action plan gives continuity to the Energy Saving and Efficiency Strategy for Spain 2004-2012 (E4) which includes a quantification of the energy savings derived from the NEEAP 2008-2012.

Despite the energy saving and efficiency plans proposed at national level along with the Royal Decree 1890/2008, the annual energy consumption in SL has been increased as it can be seen in Figure 2.2. In other hand, the energy consumption per habitant has decreased from 2015 to 2017. This behavior might be due to increase of population and the expansion of database that includes small municipalities.

2.1.2.2 Light pollution

Light pollution is the alteration of natural light levels in the night environment produced by introduction of artificial light (Falchi et al. 2011) or due to introduction of manmade light (Cinzano and Falchi 2013). In this regard, all forms of light pollution can see in Figure 2.3. Skyglow the brightening of the night sky above cities. Light is sent upward directly (bad position of luminaire) or indirect (reflection) decreasing stellar visibility. Glare is the uncomfortable brightness of a light source when viewed against a dark background. An excessive brightness reduce visibility. Light trespass, the spilling of light beyond the boundary of the property on which the light source is located (Institution of Lighting Engineers 2005).

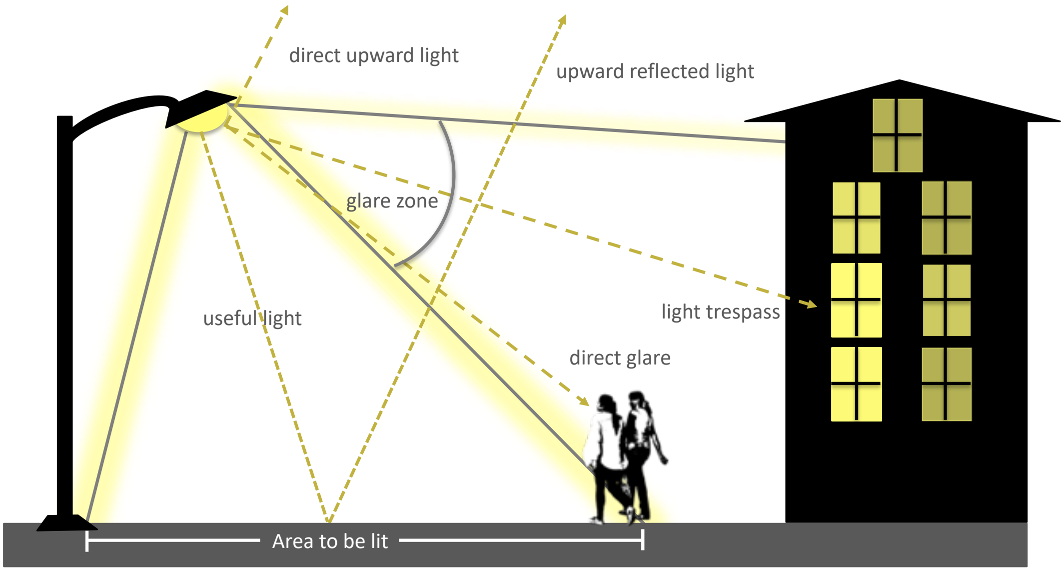


Figure 2.3 Light Pollution terminology. Based on (Institution of Lighting Engineers 2005).

Light pollution is not meant to condemn electric SL, in fact it has done much to enhance urban areas at night and has been directly associated with safety, security and economic development, however a poorly design and unwise used of artificial lighting can present side effects in the following categories:

- Night sky

Light pollution interferes with astronomy by reducing the visibility of galaxies, nebulae, and other celestial objects (Gallaway et al. 2010). It was normally assumed that skyglow came from the luminaires along the street, but an interesting study in a neighborhood in Barcelona shows that, the light flow from the domestic sources (windows) contribute 22% of the total upward luminous flow emitted (García Gil and González Dorta 2016).

- Ecology

An interesting point of view is considering light just like other physical or chemical pollutants, in that way artificial light propagates in the atmosphere altering the natural quantity of light in the involved medium (Cinzano and Falchi 2013). Under this consideration, light pollution is a true atmospheric and environmental problem and its consequences has been studied.

Light pollution does substantial damage to wildlife. It disrupts the migration patterns of nocturnal birds and can cause hatchling sea turtles to head inland, away from the sea, and be eaten by predators or run over by cars (Gallaway et al. 2010).

The author (Raap et al. 2015) studies the impact on sleep in free-living animals, in particular in the morning, and highlights a mechanism for potential effects of light pollution on fitness. Artificial lighting caused experimental birds to wake up earlier, sleep less (–5%) and spent less time in the nest-box as they left their nest-box earlier in the morning.

- Human health

An inappropriate quantity and quality of light lead to light trespass on property resulting in an alteration of the human circadian system.

The roads and cones are photoreceptors connected to the brain via ganglion cells and nerve fibers. Recently, medical scientists discovered that about one percent of our ganglion cells in the eye's retina are sensitive to light, particularly a photoreceptor called the intrinsic photo sensitive Retinal Ganglion Cell (ipRGC) (Berson et al. 2002). Those play a role in the non-visual biological effect of light and are important as regards lighting and health. Therefore, cones and roads, along with ipRGC, are photoreceptors responsible for sending information to our brain to regulate our biorhythms, and therefore our states of alertness and rest.

The circadian system coordinates during a cycle of 24-hour which include light and dark episodes, behavioral and psychological rhythms such as the sleep-awake rhythm, body temperature and heart rate and the rhythm according to which certain hormones are produced (M. S. Rea and Figueiro 2011).

Under the influence of the natural light-dark rhythm, the body temperature and the hormones, cortisol and melatonin that regulate alertness and sleep, vary in day and night. In absences of the synchronization process the body would adopt the wrong rhythm of alertness during the dark hours and sleepiness during the daylight hours.

There is reliable evidence that obtrusive night-light produces serious adverse consequences to human health. Alteration of the circadian clock because of unpleasant glare and annoying illumination in sleeping quarters may cause performance, alertness, sleep and metabolic disorders (Falchi et al. 2011). Exposure to light at night suppresses the production of the pineal hormone melatonin, and since melatonin is an anticarcinogenic agent, lower levels in blood may encourage the growth of some cancers (Brons et al. 2008; Falchi et al. 2011; Gallaway et al. 2010).

Also, melatonin seems to have an influence on coronary heart disease (Falchi et al. 2011). Light at night acts directly on physiology, or indirectly by causing sleep disorders and deprivation, that may have negative effects on several disorders such as diabetes, obesity and others (Falchi et al. 2011)

Another important study to test light intrusion or trespass in Barcelona was carry out by (Moreno García and Martín Moreno 2016). This study reported problems with light intrusion in 57.1% of the 21 streets analyzed in the case study of Sants neighborhood.

- Energy usage

Light pollution is a nuisance and required electricity resulting in the unnecessary emissions of greenhouse gases and contributes to global warming. According to the California Energy Commission, in the United States, roughly 6% of the 4.054 million megawatt hours (MWh) of electricity produced are used for outdoor lighting and about 30% of this is wasted as light pollution (Gallaway et al. 2010).

Barcelona, Bilbao, Madrid and Valencia are cities in Spain with higher emitted power by km^2 (an indicator of light pollution) according to astrophysicist Alejandro Sánchez de Miguel in collaboration with Rebeca Benayas Polo, from GEASig, for SaveStars Consulting SL (Aupí 2019).

Another way to waste energy is by increasing lighting levels in public areas as a deterrent against crime, even though studies have not proven this to affect crime rates (Falchi et al. 2011).

- Social-economic effects

All studies before mentioned have been focusing on human health and environment side effects of light pollution, while studies related to the social-economic impact on light pollution have been neglected; for that, it is worth to show up three studies carry out by (Ngarambe et al. 2018), (Green et al. 2015) and (Gallaway et al. 2010).

The relationship between economic development and light pollution was studied by (Ngarambe et al. 2018). These authors collected field data of illuminance levels on residential windows as a measure of light pollution and land prices as an indicator of economic development. Results showed that there is no significant statistical relation between the two variables, however, the average illuminances of luminaires were seen to be relatively higher in low-land price neighborhoods than in high-land price neighborhoods.

Under the premise that light is similar to other pollutants and economists have studied that environmental problems over the years, (Gallaway et al. 2010) has identified economic variables that contribute to the problem. The study combined unique remote sensing data on light pollution with economic data (GDP, arable land, energy production, foreign direct invest (FDI) and roads) from the World Bank to estimate fractional logic regression light pollution models. Results suggested that light pollution is concentrated in areas with high levels of population and that surface area measures of light pollution are also affected by economic development. The relationship between income and light pollution is non-linear as those might be expected from an Environmental Kuznets Curve (EKZ). Furthermore, other economic factors such as FDI and land use patterns also has a positive impact on light pollution.

A social point of view of the relationship between reduced SL and health was formulated by [14] through ethnographic fieldwork and the household survey. Results of the household survey showed minimal direct impact from reductions of lighting levels in SL on determinants of health for instance: anxiety from fear of crime, constraints on mobility at night. Nonetheless, at a social level reduced lighting may have significant effects in urban and suburban settings where residents associate well-lit streets with competent and trust-worthy government. In conclusion, the wellbeing impacts of reduced lighting at night may reflect not darker streets per se, but the fact that a public good has been removed.

2.1.2.3 Relevant light pollution parameters

According to (van Bommel 2015b), light parameters can be divided into 1) those directly related to the light leaving the location being lighted (installation-bound parameters) and 2) those directly related to the light arriving at the point of disturbance (disturbed-area-bound parameters). In this research, the emphasis is on those lighting parameters used in specifying limits for light pollution by the International Lighting Commission CIE (CIE 2017), since that report uses a mix of both parameters categories.

Table 2.2 shows the light-limiting parameters associated to each form of lighting pollution and with some of their typical properties. All the parameters' definitions are development in appendix A.1 LIGHT POLLUTION PARAMETERS.

On the other hand, circadian rhythms cannot be defined in terms of photometric parameters such as illuminance (lx), luminance (cd/m^2), lamp efficacy (lm/W), but with color temperature and SPD (M. S. Rea and Figueiro 2011), or, a part of timing and exposure duration, the two light variables responsible for the suppression of melatonin production are: 1) light intensity and 2) wavelength (Falchi et al. 2011).

Even the basic question of what the lighting parameters with which light pollution or the restriction of light pollution are can be best described was not yet answered. But, many different answers to this question were proposed and put into local recommendations and standards (van Bommel 2015b).

Table 2.2 Summarizes of the light-limiting parameters as defined by (CIE 2017). Based on (van Bommel 2015b).

	Sky glow			Light trespass		Glare	
Properties	URL	UFR[3]	$I_{90\text{-}100}$	$E_{vert,property}$	$I_{property}$	$L_{façade}$	L_{veil}
At area to be lighted	Y	Y	Y	N	N	N	N
At location of disturbance	N	N	N	Y	Y	Y	Y
Luminaire(s) position as installed	Y	Y	Y	Y	Y	Y	Y
Direct light	Y	N	Y	Y	Y	Y	Y
Direct+reflected light	N	Y	N	N	N	N	N
Critical zone around horizontal	N	N	Y	N	N	N	N
Impulse for design to required lighting level	N	Y	N	N	N	N	N

N=No apply, Y=apply. ULR =Upward Light Ratio (-); UFR= Upper Flux Ratio (-); $I_{90\text{-}100}$ =Luminous intensities near the horizontal (cd); $E_{vert,property}$= Vertical Illuminance on Façades(lm/m^2); $I_{property}$ =Luminous Intensity (cd); $L_{façade}$=Façade Luminance (cd/m^2); L_{veil}=Veiling Luminance(cd/m^2).

Spain has published a standard to improve energy savings and efficiency, to limit glare and light pollution and to reduce intrusive or annoying light levels (Royal Decree 1890/2008 2008). The Royal Decree 1890/2008 has developed a system for dividing areas into different environmental zones, from E1 to E4,

[3] The hypothetical ideal situation has an UFR value of 1. The larger the UFR value of a real installation, the further away it is from the ideal situation, and indeed the higher the sky glow will be.

having an ascendant restriction according to the brightness of the environment. Table 2.3 provides the Spanish standard definition of these zones together with the maximum values of light-limiting parameters.

Table 2.3 Light pollution limitations for exterior lighting installations.

Light-limiting parameters	Maximum values			
	E1 Intrinsically dark areas: National parks and starlight reserves.	E2 Rural or small village locations.	E3 Small town centers or urban locations.	E4 Town/city centers and commercial areas.
URL %	≤ 1	≤ 5	≤ 15	≤ 25
$E_{vertical}$ (lx)	2	5	10	25
$I_{ligh\ intensity}$ (cd)	2500	7500	10000	25000
$L_{average,façade}$ (cd/m^2)	5	5	10	25
$L_{max,façade}$ (cd/m^2)	10	10	60	150
$L_{max,advertising\ singns}$(cd/m^2)	50	400	800	1000
	Road classification			
	No road lighting	ME5	ME3/ME4	ME1/ME2
TI (threshold increment)	15% based on adaptation luminance of 0.1cd/m^2	15% based on adaptation luminance of 1cd/m^2	15% based on adaptation luminance of 2 cd/m^2	15% based on adaptation luminance of 3 cd/m^2

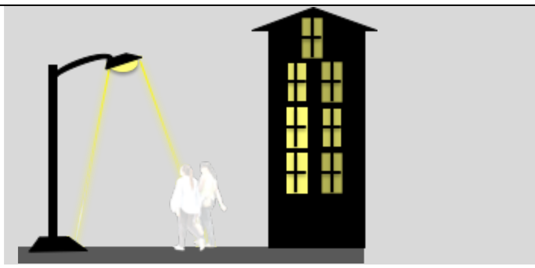
2.1.3 Recommendations to mitigate side-effects of SL

It has been proven that an efficient manner for mitigating the negative effects of a lighting installation is to provide light what needs to be lit using the minimum level required for the task to be made. Table 2.4 provides a practical recommendation to avoid the most common mistakes in design SL.

These recommendations were collected from different sources and the general conclusions derived from this is to use lamps and luminaires to produce the minimum of spill light. For instance, to avoid lamps with SPD within shorter wavelengths (blue-greenish light)[4] with high color temperature (>3000 K); and using luminaires with URL= 0, as well as reflectance of the road and surrounding areas.

[4] Light with "blue-greenish light" scatters more on the aerosol particles of the sky and therefore increases sky glow relative to that produced by yellowish-red light with its longer wavelengths. The International Dark-sky Association IDA, suggests that the wavelengths of light sources employed in a wide area around professional observatories, should be limited to greater than 500 nm in order to restrict sky glow (IDA 2010).

Table 2.4 Practical recommendations to mitigate side effects in lighting at night.

	No	Yes
Direction		
	• Full Shielding: Do not allow luminaires to send any light directly at and above the horizontal (i.e. ULOR=0 for all classes). • Limiting the area of lighting. • Light - including facade lighting - should always shine downwards. • Ground-recessed spotlights that radiate the light upward should be avoided. • Reflectance of the road and surrounding areas are also important.	
Color		
	• Strongly limit the short wavelength 'blue' light. • Lamps used for outdoor areas should have a correlated color temperature of 3000 K or lower.	
Intensity		
	• Install controls to dim or turn off lights, when not in use. • Use only as much light as needed for the specific purpose. • Eliminate over lighting: Avoid luminances or illuminances greater than the minimum required for the task, and dim lights when the application allows it. • Aim for zero growth of the total installed flux.	

Based on: (Falchi et al. 2011) (LoNNe 2017) (van Bommel 2015b).

2.2 CHALLENGES IN STREET LIGHTING SYSTEMS

SL sector is facing new challenges because of the change in global context. New challenges require new actions. Some key challenges were identified based on current researchers and projects experiences.

2.2.1 Sustainability

The world's population expects to keep growing. Estimates have placed the total population at 9 725 billion by 2050 (URBANET 2016). As global populations increase, cities have also grown, leading to an increase in urbanization.

The United Nations estimated 2007 was the year when, for the first time, more people in the world lived in urban than in rural areas. People move into cities for economic or professional opportunities, for example, these movements demands public services such as public SL.

The global urban population is expecting to grow. By 2050, it is projected that 68% of the world's population will live in urban areas (an increase from 54% in 2016) (Ritchie and Roser 2019). Based on these tendencies, cities will face a boom of new or renovate infrastructure (roads, buildings, bridges, commercial centers, etc.) that should be lit. The question is, SL sector is ready to face this challenge?

One action for facing urbanization becomes in the cities by promoting the reduction of carbon emission. One of the most important policy tools to reduce carbon emission is the "Convent of Majors", which aim to meet and overcome the European Union 20% CO_2 reduction aim by 2020, and some municipalities have endorsement their commitment until 2030 (European Union 2008). In this sense, SL as a part of the public spaces of the city and a large consumer of electricity, has a high potential to reduce its energy consumption and contribute to mitigate the climate change.

Sustainability calls for social, environment and economical approach. However, in the last years, sustainability in lighting systems has been associated to the fact that the net saving in installed power (consumption per luminaria, number of luminaires, and electrical auxiliary devices) and the net economical investment (Peña-García 2018). Certainly, energetic, and economic considerations are essential for a sustainable lighting, but it is equally important for social and environment aspects.

Other perspective that considers social and environmental aspects is provided by (van Bommel 2015c) who defines lighting sustainability as "balancing the positive effects of lighting with the negative impacts of that lighting on the environment". According to this view, the positive effects of SL systems, that can be fit into the social dimension, are: reduce night-time accidents for drivers and pedestrian, contribute to the feeling of security of residents, preventing social isolation, of the elderly and young woman, and contribute to the attractiveness of a commercial area, among others. Those actions having a negative impact on the environment are listed below:

- The use of polluting or hazardous materials such as mercury in fluorescent, high-pressure sodium, and metal halide lamps.
- The use of non-renewable materials, and especially the use of materials with limited availability such as the rare-earth metals needed for the phosphors used in white LEDs.
- The waste of energy and the associated emissions of greenhouse gases such as carbon dioxide (CO_2), Sulphur dioxide (SO_2) and nitrogen dioxide (NO_2).
- The light pollution that disturbs residents, astronomers and wildlife.

As a conclusion, SL sustainability calls for balancing social, economic, and environment dimension as can be seen in Figure 2.4.

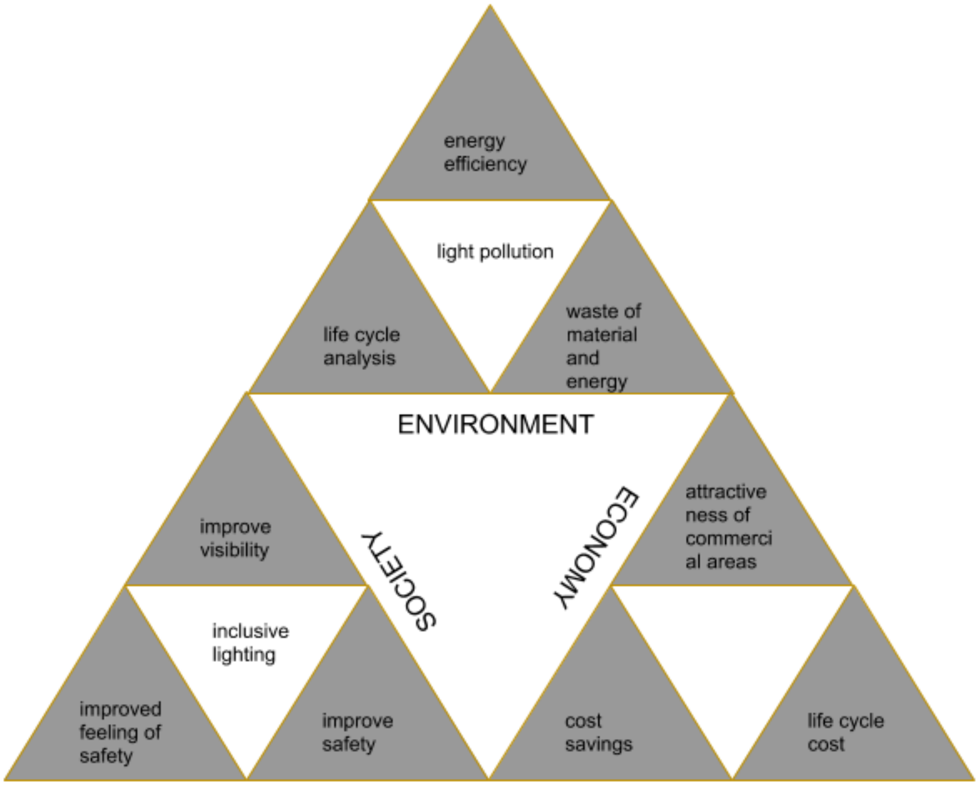


Figure 2.4 Social, environment and economic approach of SL. Based on (Casciani and Rossi 2012; van Bommel 2015c).

2.2.2 Technological innovation and development in science

2.2.2.1 Light sources

Lamp sources, luminaires design, lighting control, electronic ballast, and renewable technology advances at a rapid pace. Technology innovation has the power to drive changes towards a smart street lighting by designing SL systems that considers variables such as weather, traffic, air pollution, massive social events, pandemics events. As a result, it can be achieved a SL that ensures the quality and quantity of light needed to meet the needs of the road users at night.

The limitations of the discharge lamps such as low pressure sodium (LPS), high pressure sodium (HPS) and Fluorescent (FL) were vanished owe to the introduction of LED (Light-emitting diode) (S. Fotios and Gibbons 2018). The limitations for LPS and HPS are related with the SPD of the lamps, those have a yellowish-orange appearance and low color rendering index. LPS lamps are large and with limited optical control. FL lamps contain mercury, a neurotoxin. There are no protocols for recycling or disposal (80% are thrown into landfill). Ultraviolet light can escape from defective tube coatings to burn skin or damage the retina at close range (Zielinska-Dabkowska 2018), in addition, they require several minutes to reach full out due to they have switching-on cycles.

Whereas LED lamps have fine optical control because of the small size of individual units, almost limitless control over SPD, and can be switched on and off instantaneously (S. Fotios and Gibbons 2018). Changing LED lamps with a dimming schedule in a SL project could lead to energy savings of 49% (Jägerbrand 2016). Similarly, the research carry out by (Djuretic and Kostic 2018) conclude that when using quality LED instead of quality HPS luminaires energy savings could be between 31% and 60% when applying multi-stage dimming scenarios.

Some considerations should consider by using LED lamps. These emit bluer light of short wavelengths than HPS lamp. Blue rich lighting can increase the amount of sky glow leading to a 10% - 20% increase when replacing HPS lamps (CEI 2017; IDA 2010; Jägerbrand 2015). Moreover, these still use heavy metals such as nickel, lead and copper and emit electromagnetic radiation from wireless lighting controls (Zielinska-Dabkowska 2018).

2.2.2.2 Mesopic Vision

It is well-known that road lighting applications fall within mesopic region even though luminances and illuminances recommended by standards are based in photopic function V(**λ**) (Eloholma 2005; S. Fotios 2013; Viikari 2007; Ylinen et al. 2011), which increases the energy consumption by over-dimensioning SL.

Human eye perceives light thanks to photoreceptors (cones and rods) located in the retina. The rods are highly light-sensitive (507 nm) and are principally responsible for the detection of rough shapes and movement but cannot distinguish colors. Cones are less sensitive to light (555 nm), but can distinguish colors and ability to see fine detail (van Bommel and Rouhana Abdo 2019). For human vision under low light conditions (less than 0.005 cd/m^2), scotopic vision is used and rods in the retina are activated, while photopic vision is based under well-lit conditions (over 5 cd/m^2) and dominated by the use of cone cells in the retina. There is an intermediate stage, called mesopic vision in which both cones and rods are activated then detail and color can be seen. Therefore, cones and roads are photoreceptors with different spectral sensitivities that are continuously adapting to the quantity (luminance) and quality (SPD of the lamp) of light.

The recommended system CIE 191:2010, defines the scotopic V'(**λ**) and photopic V(**λ**) spectral luminous efficiency functions as lower and upper limits of the mesopic region which covers photopic luminances between about 0.005 cd/m^2 to 5 cd/m^2 (Commission Internationale de L'Eclairage 2010). This system enables calculation of an effective mesopic luminance through the correction factors contained in the Table 11 of the technical report CIE 191:2010. These were determined according to the photopic luminance and the S/P ratio of the lamp, which is the ratio between the scotopic-weighted spectrum, according to V'(**λ**), and the photopic-weighted spectrum, according to V(**λ**) (van Bommel 2015d). The mesopic system was derived from European MOVE consortium (Eloholma 2005; Eloholma et al. 2004; Viikari 2007) and the Lighting Research Center (M. Rea et al. 2004). To calculate mesopic values, it is necessary the weighting factor according to the level of adaptation and the S/P ratio of lighting, this being stablished by consensus between the two groups above mentioned (S. Fotios and Gibbons 2018). Table 2.5 gives approximate S/P values for different lamps and summarizes the correction factors for photopic luminances within the range of SL application. Light with a higher S/P ratio with a low light level, will generally have a higher effective mesopic luminance. For example, at a photopic luminance of 2 cd/m^2 the use of the recommended system results in a change of between -2% and 6% for lamps with S/P ratios of 0.65 for HPS and 2.05 for cool-white LED, respectively. The mesopic luminance provides an indication of the efficacy of the lamp within the mesopic region, taking account of the light's spectral qualities.

Table 2.5 S/P ratios for different lamp and their corresponding correction factors.

Lamp	S/P	Photopic luminance (cd/m^2)				
		0.3	0.5	1	1.5	2
Yellow low pressure sodium (LPS)	0.25	-18%	-14%	-9%	-6%	-5%
Yellow-white high pressure sodium (HPS)	0.65	-8%	-6%	-4%	-3%	-2%
Warm-white metal halide (MH)	1.25	5%	4%	3%	2%	1%
Warm-white LED	1.45	9%	7%	5%	3%	3%
Cool-white metal halide	1.85	17%	13%	9%	6%	5%
Cool-white LED	2.05	21%	16%	11%	8%	6%

While visual conditions under SL are likely to fall within the mesopic region, SL recommendations are given using photopic quantities. This could be a limitation since the introduction of LEDs which significantly enhance the opportunity to change and tune SPD (S. Fotios and Gibbons 2018).

Pedestrian lighting recommendations (S. Fotios and Goodman 2012) used CIE system to characterize the illuminance reduction permitted when using lighting of greater short-wavelength content (lamps with high S/P–ratio), this being of benefit for a task such as obstacle detection (S. Fotios and Cheal 2009) and spatial brightness perception (S. Fotios and Cheal 2011). Therefore, lamps with high S/P – ratio are more effective under mesopic conditions and, thus, the luminance on the road surface can be reduced without affecting visibility of the users (A. Kostic et al. 2012). In conclusion, the aspects of lighting to be important for visual performance are the amount of light, the spectrum of the light and the distribution of the light on and around the object.

2.2.2.3 Smart City

Smart cities describe a city that wants to increase citizen quality of life, safety and energy savings with intelligent management, active citizen participation and Information and Communication Technology (ICT) integration (Marco et al. 2017). For SL systems, "smart" falls into optimizing the performance of public lighting systems (Sędziwy 2015). Fallowing this idea, many researchers have been development improvements of the SL systems in any of the project phase: design, operational or strategic.

2.3 ENERGY EFFICIENCY

Energy efficiency in SL has become a relevant and researched topic in recent years. The need to take into account energy efficiency in the SL systems, particularly in urban areas, is because of the growth of interest in global warming, which encourage the search for efficient ways to reduce energy consumption, light pollution and impact on human and the natural environment, as well as for decreasing the bills of electricity in municipalities. Hence, energy efficiency recommendations in SL are very welcome since the potential of reduction in electricity consumption is high and possible. Different studies argue that energy savings in SL ranging from 20% to 50% can be achieved by the use of efficient ballast, lamps and luminaires (Hermoso Orzáez and de Andrés Díaz 2013; A. Kostic et al. 2012; Mockey Coureaux and Manzano 2013). Other studies concerned to improve quality of lighting have shown that the implementation of mesopic dimensioning in SL design have also energy saving potential (Jägerbrand 2015; A. Kostic et al. 2012; M. Kostic and Djokic 2009; Ylinen et al. 2011).

In response to this need, there are several researchers investigating tools meant to support administrations and designers to achieve the optimal performance in a SL installation, by minimizing energy consumption, while maintaining the highest standards of quality without diminishing visual performance and comfort.

The literature on energy efficiency and consumption reduction for SL could be divided into three main categories: design, operational and strategy, depending of phase of the SL project. Furthermore, these recommendations may be related with co-benefits such as energy efficiency, smart street sighting, design, light pollution, waste resources, renewable energy, security, safety, visual performance, and public healthy and cost savings. In this sense, a systematic research publications review of SL, focusing on empirical evidence to improve energy efficiency, was performed and, as a result, 52 recommendations were derived.

Recommendations at the design level are related to the design parameters such as height and inclination of the lighting unit, overhang of the lighting pole, interdistance between the poles and GIS-based street layout (Table 2.6). At the operational level, those refer, identify and describe real-time interventions to improve the efficiency of SL systems by using controls, stabilizers, ballasts, etc. (Table 2.7). And, at strategy level, by investigating solutions that change the existing SL configuration to improve its efficiency through actions such as using LED lamps, ESCO´s technical-economic solutions, substitution of lamps, mathematical models, redesign of lighting networks (Table 2.8).

Table 2.6 Recommendation for design level and its co-benefits.

Author	Recommendation	Co-benefit
(Zalesinska and Gorczewska 2016)	Apply the type and way of lighting control as describe in "Lighting of Roads for Motor and Pedestrian Traffic", CIE Publication No 115, 2010, Vienna.	Design
	Improve photometric, electric and utility parameters of the applied light sources and luminaires.	Energy Efficiency Design
(Sedziwy and Kotulski 2016)	Optimization based on a uniformed street layout, "customized" optimization relying on accurate coordinates (e.g., GIS (Geographic Information System)-based) of the road and luminaires.	Design
(Murray and Feng 2016)	Using spatial analytics, including GIS and spatial optimization.	Design
(Rabaza et al. 2018)	Apply an innovative method for compiling information on lighting levels, uniformity and energy consumption in geographic information systems (GIS).	Design Smart Street Lighting
(Zdunic 2015b)	Installation angle luminaire SR parameter type of optical cover arrangement of lighting poles supplementation of luminaires (quantity of luminaires).	Design Energy Efficiency Visual performance
(Zalesinska and Gorczewska 2016)	The lighting class selected during the design stage.	Design Energy Efficiency

Table 2.6 (Continued).

Author	Recommendation	Co-benefit
(M. Kostic and Djokic 2009)	Photopic luminance levels are recommended in case of using metal-halide lamps.	Design Energy Efficiency Visual performance
(al Irsyad and Nepal 2016)	The use of capacitor improves power factor that reduce dissipated power losses on the electrical grid. The function of the capacitor bank is also to improve power factor of SL system. Low power factor raises electricity current that produces higher power dissipation or heat losses on the cable.	Energy Efficiency Design
(M. Kostic and Djokic 2009)	Special attention should be given to the determination of the SL class. Since all the photometric requests and, consequently, lamp power and pole spacing depend on the SL class, considerable energy savings could be achieved by its adequate determination.	Energy Efficiency Design
(Mockey Coureaux and Manzano 2013)	The use of higher maintenance factors during the design stage guarantees a significant saving of energy. An improvement of 5% in the maintenance factor can end up producing savings of 10% in the energy consumption.	Energy Efficiency Cost savings
(M. Kostic and Djokic 2009)	Degree of protection of at least IP65 are recommended for efficient luminaires. Luminaires characterized by the power factor of at least 0.95 are recommended	Energy Efficiency Cost savings Light Pollution
(Hermoso Orzáez and de Andrés Díaz 2013)	Before implementing a system with the dimmable electronic ballasts, take into account their crucial problems: high initial investment, low financial profitability, long payback periods, high rate of failure due to thermal sensitivity.	Cost savings
(M. Kostic and Djokic 2009)	Based on the lighting design, an economic comparison of the upgrade and redesign solutions can be done, by the application of the accepted cost-discount method.	Design Cost savings
(al Irsyad and Nepal 2016)	The renewable energy-based SL system has higher operational cost for replacing battery valued USD 100 every two years.	Renewable energy
(M. Kostic and Djokic 2009)	It is recommended using a correct value of maintenance factor because guarantees reduction of cost and electricity consumption at the whole SL installation.	Design Energy Efficiency

Table 2.7 Recommendation for operational level and its co-benefits.

Author	Recommendation	Co-benefit
(Burgos-Payán et al. 2012)	Controlling the operating hours of the installation by using astronomical clocks, which program the on and off depending on the geographical area.	Energy Efficiency Smart Street Lighting
(Sedziwy and Kotulski 2016)	Dimming, scheduled lighting class reduction, adapting dimming level to an actual environment state, others.	Energy Efficiency
(M. Kostic and Djokic 2009)	Apply the use of dimming systems is recommended for SL. Step-dimming ballasts, which are used in luminaires with HPS lamps, can only provide 100% and 50% of the rated lamp luminous flux and, therefore, can be applied if the allowable reduction in lighting level is not lower than 50%.	Energy Efficiency

Table 2.7 (Continued).

Author	Recommendation	Co-benefit
(Gutierrez-Escolar et al. 2015)	Using electronic ballasts because they are considered more energy efficient than electromagnetic ballasts.	Smart Street Lighting Energy Efficiency
(Burgos-Payán et al. 2012)	Electronic ballast allows the reduction of power consumption by introducing an additional inductance embedded in the iron core of the primary inductance.	Energy Efficiency Cost savings
(Gil-De-Castro et al. 2013)	Some increase in efficiency can be obtained by replacing the electromagnetic ballast of an HPS lamp by an electronic ballast.	Energy Efficiency
(al Irsyad and Nepal 2016)	The electronic ballast potentially replaces magnetic ballast to reduce ballast energy losses.	Energy Efficiency
(Lobão et al. 2015)	Take into account the losses in the cables of the SL installation contributes to the efficiency.	Energy Efficiency Cost savings
	Thanks to the reduction of the overvoltage time it is possible to obtain an additional saving of about 5-7%.	Energy Efficiency
(Beccali et al. 2015)	Electrical auxiliary devices provide real-time management of the energy demand, control and solving of the system fails, economic costs control and ordinary extraordinary maintenance management	Energy Efficiency Cost savings Smart Street Lighting
(Burgos-Payán et al. 2012)	With the remote management system can regulate the level of brightness of the lights according to the time of the night, providing a high brightness level busiest times and reducing consumption less busy hours.	Energy Efficiency Smart Street Lighting Visual performance Light Pollution
(Sedziwy and Kotulski 2016)	Improving reflective properties of a road surface.	Energy Efficiency Visual performance
(Zalesinska and Gorczewska 2016)	The type and reflective properties of the applied road surface that impact the achievement of various levels of average luminance on a road with the same lighting system.	Energy Efficiency Visual performance
(M. Kostic and Djokic 2009)	Measurements for determining the road surface reflection properties are recommended.	Energy Efficiency Visual performance
(al Irsyad and Nepal 2016)	The alternative is an adaptive SL system called smart street lighting system that could dim the lamp based on either traffic intensity probability or real time sensing.	Smart Street Lighting
(Jagadeesh, YM; Akilesh, S; Karthink 2015)	Implementation of low-cost sensor based street lights with dynamic which reduces the energy consumption and CO_2 emission. It comprises IR sensor, PIR sensors, low cost embedded controller and storage device.	Smart Street Lighting Energy Efficiency

Table 2.7 (Continued).

Author	Recommendation	Co-benefit
(Gutierrez-Escolar et al. 2015)	Control of hours: Changing the use of pattern of the twilling switches by establishing an approximation of the numbers of burning hours using the latitude and the level of natural light required to turn the lighting system on or off.	Smart Street Lighting Energy Efficiency
(Burgos-Payán et al. 2012)	Replacement of older fixtures and lamps with the newer, improved ones can improve efficiency.	Energy Efficiency

Table 2.8 Recommendation for strategy level and its co-benefits.

Author	Recommendation	Co-benefit
(Gutierrez-Escolar et al. 2015)	Installing on/off switching systems, with hourly on/off schedules on weekdays and holidays, twilight switches and/or astronomical switches.	Energy Efficiency Smart Street Lighting
(Beccali et al. 2015)	Replacing lamps and/or luminaires with other having good optics and high efficiency lamps, to reduce the lighting dissipation and to provide correct luminance levels on road surfaces, to avoid glare phenomena and to improve the color rendering.	Energy Efficiency Light Pollution Visual performance Safety Public Healthy
(Sedziwy and Kotulski 2016)	Replacing HID (High-Intensity Discharge) (e.g., mercury-vapor, sodium-vapor, metal-halide) lamps with LEDs.	Energy Efficiency Visual performance
(Gutierrez-Escolar et al. 2015)	Remove street lamp globes: upward reflected light and thereby light pollution.	Energy Efficiency Light Pollution Public Healthy
(Balsys et al. 2011)	The lighting system power reduction by approximately 50% is possible using advanced LED A technology only. LED A=130lum/W.	Energy Efficiency Visual performance
(Zalesinska and Gorczewska 2016)	LED road luminaires feature a wide range of luminous fluxes (over 31 000 lm), high light output ratio (over 92%) and high luminous efficacy (over 125 lm/W). Thanks to their excellent characteristics they can be successfully used for road illumination with higher lighting classes, whose normative parameters could be satisfied, recently, only with high pressure sodium lamps.	Design
(S. Fotios and Goodman 2012)	Using lamps that they have a CIE General Color Rendering Index of Ra>=60, then the average illuminance can be reduced by an amount that is determined using the new CIE system for mesopic photometry and depends on the scotopic/photopic ratio of the lamp.	Visual performance Design Energy Efficiency
(Lobão et al. 2015)	Using dimming ballast, which reduces SL energy consumption during the dimming period. It does not take into consideration actual traffic and weather. The alternative is an adaptive SL system called smart SL system.	Smart Street Lighting
(Burgos-Payán et al. 2012)	Flow regulators header is another technique to reduce energy consumption of outdoor lighting installation. It is a technique that basically comprises reducing the supply voltage lamp–ballast.	Energy Efficiency

Table 2.8 (Continued).

Author	Recommendation	Co-benefit
(Beccali et al. 2015)	Installing luminous flow regulators on switchboards.	Energy Efficiency Smart Street Lighting
(Gil-De-Castro et al. 2013)	Reduction of the luminance level (dimming) during hours with reduced traffic density. This will reduce electrical energy consumption, which will lead to a cost reduction.	Energy Efficiency Cost savings
(Gutierrez-Escolar et al. 2015)	The main advantage of stabilizer lighting systems is that they can avoid overvoltage situations. This overvoltage situation is the main reason for the shortened lifetime of lamps.	Energy Efficiency Cost savings
(Beccali et al. 2015)	Using Information and Communication Technologies. This device allows the digital information transmission through the electrical grid and/or radio waves. By the point-to-point control, it is possible to manage a large data series to improve the quantity and quality of information available for the citizen. The system could allow the "combination" of lighting infrastructures with many "smart services".	Smart Street Lighting
(Gutierrez-Escolar et al. 2015)	Benefits of solar energy in SL can achieve energy savings per day of 603 kWh and reach up to 315 per year of total autonomous days of operation. Here the energy savings were about 86%.	Renewable energy Energy Efficiency Design
(Valentová et al. 2015)	One of the most often mentioned benefits is the reduction of costs of operation and maintenance. The comparative advantage of LEDs, over other technologies, would be the reduced operation and maintenance costs, which is mainly due to a longer life-time of LEDs.	Energy Efficiency Cost savings Waste Resources
(Gutierrez-Escolar et al. 2015)	Changing the standards or changing the technology of the lamps for saving energy.	Energy Efficiency Light Pollution Public Healthy
(Burgos-Payán et al. 2012)	LED luminaires are considered as the solution to get greater savings on outdoor lighting, due to low consumption and maintenance.	Energy Efficiency Visual performance Cost savings

The literature analysis made in Figure 2.5 shows that 60% of the recommendations of previous tables are linked to energy efficiency co-benefit, which means that too much effort has been made to improve energy efficiency during the three phases of the SL project. Another important insight is that cost savings can be achieved in the design phase of the SL project. Smart Lighting and Visual performance co-benefits in the literature has been increasing in the last decade. Light pollution, public health, renewable energy and waste resources co-benefits are a new opportunity area to investigate.

These recommendations suggested in literature are a qualitative contribution since there was no systematic use of energy-based and lighting-based parameters for the comparison of different SL systems (Leccese et al. 2017). For a quantitative contribution, thus enabling for direct comparison of different lighting projects, energy performance indicators (EPI) and energy classification systems (ECS) or energy certifications have been established. The latter are useful to express whether a SL installation is good at performing or not by using an A-G scale, comprehensive for all public.

How energy efficiency is defined affects how its indicators are derived. In this sense, the energy performance of a lighting system can be assessed through parameters that evaluate the energy efficiency of the system or its energy consumption (Aghemo et al. 2018). For SL systems, several approaches such as EPI and ECS have been proposed up to now and these are gathered in Table 2.9.

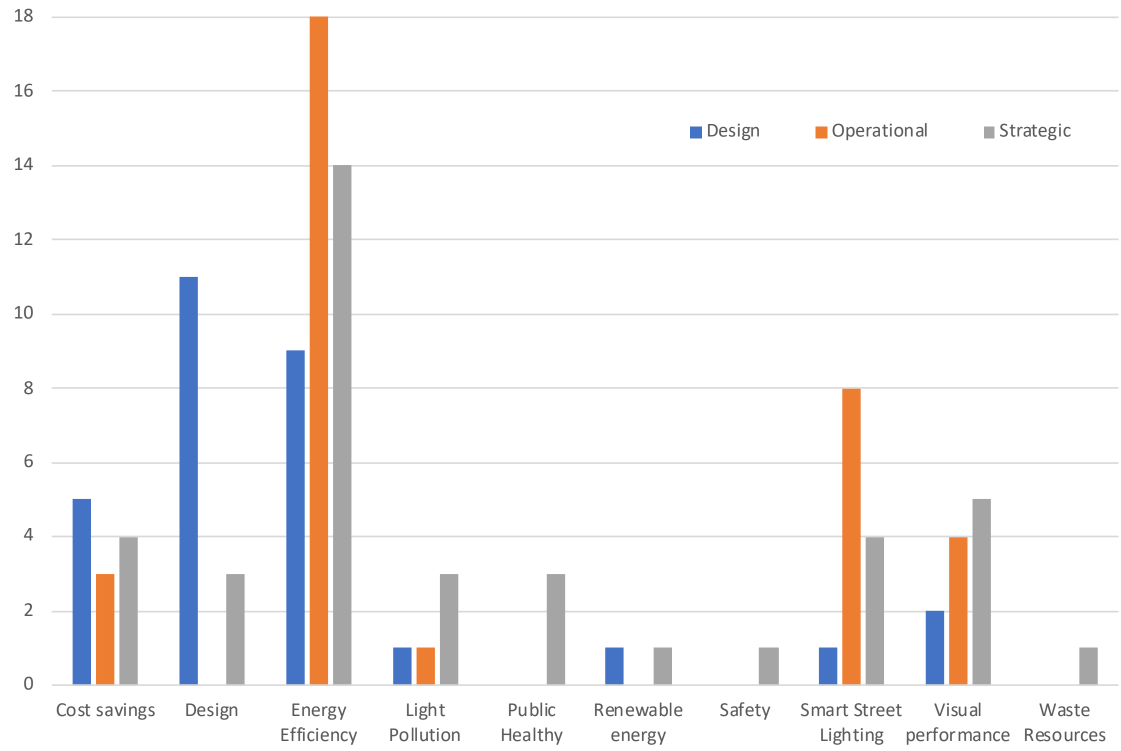


Figure 2.5 Analysis of co-benefits related to each recommendation.

Power Density Indicator (PDI) and Annual Energy Consumption Indicator (AECI) are the most widespread energy performance indicators, since these can be found in the new version of European regulations EN 13201-5:2015 (European Committee for Standardization 2015a). PDI ($W/m^2 \cdot lx$) states the power needed for a SL system to meet the lighting requirements while AECI (Wh/m^2) states the annual electrical energy consumption for a SL system, using 4000h of operation as a reference value. Both shall be always presented and used together for assessing the energy performance of a particular lighting system (Gasparovsky 2015). Installed Luminous Efficacy η_{ins} (lm/W) is introduced in EN 13201-5:2015 as an additional metric. It is meant to assess the installation luminous efficacy considering losses of luminous flux.

Additionally, there are energy indicators such as the installed power per length (PL) or area (PA) that can be easily calculated by simulation tools (Relux or Dialux) (Doulos et al. 2019). The PL (W/km) is calculated from the system power of luminaires used and the number of luminaires per kilometer while PA (W/m^2) is the installed power of the lamps per unit area of the illuminated surface (Gasparovsky 2015).

On the other hand, only a few European countries have been working on the implementation of ECS or energy certifications with an energy class scale ranging from A to G, with class A indicating the most efficient installation, for instance, Spain (Royal Decree 1890/2008 2008) and Italy (Regional Council of Emilia Romagna 2015); or through voluntary programs such as the Netherlands (BRE 2011). Another significant energy classification for the assessment of SL energy performance was proposed by (Pracki 2011), this being based on the installed and normalized power densities of the whole road lighting system, and another proposed by (Gasparovsky 2015) relaying on PDI/AECI indicators. These systems are supported by levels of exigency that depend on the EPI used and on the minimum energy efficiency performance requirement established into each country standard.

Although several approaches such as EPI and ECS have been proposed up to now (Table 2.9), to the best of the authors' knowledge, only a few studies deal with the analysis of parameters involved to evaluate the energy efficiency performance of a SL system, proposing new ECS. For example, Gutierrez-Escolar et al. (2017) based on the Spanish standard (Royal Decree 1890/2008 2008), analyzed the governing parameters used to calculate the energy efficiency indicator I_ε proposing an evaluation system which asses five magnitude, i.e. lamps, energy efficiency index, light pollution, renewable energy contribution and harness of the luminous flux using dimming. Pracki (2011) analyzed the parameters influencing the installed power demand, the installed and normalized power density, resulting in a new classification system for the energy efficiency of road lighting. Gasparovsky (2015) proposed an energy A-G scale based on PDI/AECI indicators. Leccese et al. (2017) analyzed, compared and discussed the indicators PDI, AECI and the Luminaire Energy Efficiency Indicator (IPEA), and a Lighting System Energy Efficiency Indicator (IPEI) applied with different SL solutions and technologies for 20 roads in the historic town of Pisa, Italy. Conclusions of this study are also summarized in Table 2.9.

Aiming at attaching energy savings in SL installations, the Netherlands NL Agency (Ministry of Economic Affairs, Agriculture, and Innovation) has developed an energy efficiency A-G label. It is based on the Street Lighting Energy Efficiency Criterion (SLEEC) is a whole system indicator which embraces the efficiency of the lamp, ballast and luminaires (BRE 2011) and is based on the European Lighting Standard EN 13201-5 (European Committee for Standardization 2015a; Wajer et al. 2009).

Table 2.9 Parameters involved in the energy performance indicators for street lighting systems.

Ref.	Indicators	Equations	Units	Energy class	Application	Positive	Negative	Suggested parameters
(European Committee for Standardization 2015a)	Power Density Indicator (PDI)	$\mathrm{PDI} = \mathrm{P} / \sum_{j=1}^{N} (\mathrm{E} \cdot \mathrm{A})$	$W/(m^2 \cdot lx)$	No	New and existing lighting installations	Flexible indicator, applicable to roads consisting of different lanes and uses. Easy interpretation: High PDI values, scarcely lit roads (Leccese et al. 2017)	It does not consider luminance values fixed by technical standards (Leccese et al. 2017)	-Luminous efficacy (lm/W) -Time of operation (h) -Mesopic design (S/P ratio)
(European Committee for Standardization 2015a)	Annual Energy Consumption Indicator (AECI)	$\mathrm{AECI} = \sum_{j=1}^{M} (\mathrm{P} \cdot \mathrm{t}) / \mathrm{A}$	Wh/m^2	No	New and existing lighting installations	Useful in lighting systems with different operation profiles (total or partial switch-off) (Leccese et al. 2017)	It does not consider: illuminance and luminance values required by the technical standards (Leccese et al. 2017)	-Luminous efficacy (lm/W) -Mesopic design (S/P ratio)
(European Committee for Standardization 2015a)	Installation luminous efficacy (η_{ins})	$\eta_{\mathrm{inst}} = \mathrm{C_L} \cdot \mathrm{f_m} \cdot \mathrm{f_u} \cdot \mathrm{R_{LO}} \cdot \eta_{\mathrm{source}} \cdot \eta_{\mathrm{P}}$	lm/W	No	New and existing lighting installations	Additional indicator useful to define the installation luminous efficacy (Gasparovsky 2015)	-	It should be complemented with other power energy indicators.
(Gasparovsky 2015)	Installed power per road length (P_L)	$\mathrm{P_L} = \frac{\mathrm{P}}{\mathrm{Lg}}$	kW/km	No	New lighting installations	Used in many lighting software (Gasparovsky 2015)	It does not consider road widths and lighting quality (Gasparovsky 2015)	- E (lx) - L (cd/m^2) - Luminous efficacy (lm/W)
(Gasparovsky 2015)	Installed power per area (P_A)	$\mathrm{P_A} = \frac{\mathrm{P}}{\mathrm{A}}$	W/m^2	No	New lighting installations	Simple power density indicator used in many lighting software (Gasparovsky 2015)		- Time of operation (h) - Mesopic design (S/P ratio)

Table 2.9 (Continued).

Ref.	Indicators	Equations	Units	Energy class	Application	Positive	Negative	Suggested parameters
(BRE 2011)	Street Lighting Energy Efficiency Criterion (SLEEC)	$\mathrm{SE} = \frac{\mathrm{P}}{\mathrm{E} \cdot \mathrm{A}}$ $\mathrm{SL} = \frac{\mathrm{P}}{\mathrm{L} \cdot \mathrm{A}}$	$W/(lx \cdot m^2)$ $W/((cd/m^2) \cdot m^2)$	A-G label	New lighting installations	Integrate important factors such as area of illuminated target; illuminance or luminance parameters depend on the lighting application. Useful for quick verifications (Gasparovsky 2016). It takes into account efficiency of the lamp, ballast and luminaire and by using SLEEC values can punish oversized (BRE 2011).	-	-Luminous efficacy (lm/W) -Time of operation (h) -Mesopic design (S/P ratio)
(Regional Council of Emilia Romagna 2015)	Luminaire Energy Efficiency Indicator (IPEA)	$\mathrm{IPEA} = {}^{\eta_a}/_{\eta_r}$ $\eta_a = \eta_{source} \cdot \eta_{supply} \cdot \mathrm{Dlor}$	[-]	A-G label	New and existing lighting installations	It takes into account the performance of lamps and of power suppliers, and the percentage of the luminous flux emitted downward (Leccese et al. 2017)	It does not consider aspects of lighting design and luminaire operation (Leccese et al. 2017). This indicator has to be periodically updated (Leccese et al. 2017).	It should be complemented with other power energy indicators.

Table 2.9 (Continued).

Ref.	Indicators	Equations	Units	Energy class	Application	Positive	Negative	Suggested parameters
(Regional Council of Emilia Romagna 2015)	Illuminance based Lighting systems Energy Efficiency Indicator (IPEIE)	$\mathrm{IPEI_E} = \mathrm{K_E}(\frac{\mathrm{SE}}{\mathrm{SE_R}})$ $\mathrm{SE} = \frac{\mathrm{P}}{\mathrm{E} \cdot \mathrm{A}}$ $\mathrm{k_E} = \mathrm{k_1} \cdot \left(\frac{\mathrm{E}}{\mathrm{E_R}}\right) + \mathrm{k_2}$	[-]	A-G label	New and existing lighting installations	Includes both the illuminance and luminance levels. And the comparison with the limit values fixed by the technical standards (Leccese et al. 2017)	The calculation of this indicator is unclear with roads composed of sidewalks and carriageways (Leccese et al. 2017).	-Luminous efficacy (lm/W) -Time of operation (h) -Mesopic design (S/P ratio)
(Regional Council of Emilia Romagna 2015)	Luminance based Lighting systems Energy Efficiency Indicator (IPEIL)	$\mathrm{IPEI_L} = \mathrm{K_L}(\frac{\mathrm{SL}}{\mathrm{SL_R}})$ $\mathrm{SL} = \frac{\mathrm{P}}{\mathrm{L} \cdot \mathrm{A}}$ $\mathrm{k_L} = \mathrm{k_1} \cdot \left(\frac{\mathrm{L}}{\mathrm{L_R}}\right) + \mathrm{k_2}$	[-]	A-G label				
(Royal Decree 1890/2008 2008)	Energy Efficiency indicator ($\mathrm{I_\varepsilon}$)	$\mathrm{I_\varepsilon} = \frac{\varepsilon}{\varepsilon_\mathrm{R}}$ $\varepsilon = \varepsilon_\mathrm{L} \cdot \mathrm{f_m} \cdot \mathrm{f_u}$ or $\varepsilon = (\mathrm{A} \cdot \mathrm{E})/\mathrm{P}$ $ICE = \frac{1}{I_\varepsilon}$	$\mathrm{m^2 \cdot lx/W}$	A-G label	New and existing lighting installations	Applied to different road types and average services illuminances (BRE 2011).	This indicator does not consider enough parameters (Gutierrez-Escolar et al. 2017). The energy efficiency levels proposed by this indicator are low (Light Naturally 2014).	-Time of operation (h) -Mesopic design (S/P ratio)

Table 2.9 (Continued).

Ref.	Indicators	Equations	Units	Energy class	Application	Positive	Negative	Suggested parameters
(Pracki 2011)	Normalized Power Density (PN)	$P_N = P_D \cdot \frac{1}{L} = \frac{1}{Q \cdot LE \cdot UF \cdot MF}$	(W/m^2)/ (cd/m^2)	A-G label	New and existing lighting installations	This evaluation includes the impacts of the applied lighting equipment, the reflection properties of the road surface, and the maintenance factor (Pracki 2011).	Illuminance or Luminance values are not considered (Rabaza et al. 2016)	-Time of operation (h) -Mesopic design (S/P ratio)

P (W) total electrical power installed, including the lamps and electrical auxiliary devices. *E (lx)* average illuminance value. *L (cd/m^2)* average luminance value. *A or S (m^2)* is the street surface area to be lit. *Lg (km)* road length. η *(lm/W)* luminous efficacy. *T (h)* duration of operating time. f_m or *MF (-)* maintenance factor. f_u or *UF (-)* utilization factor. η_a *(lm/W)* luminous efficacy of the lighting system. η_r *(lm/W)* standard luminous efficacy. η_{source} *(lm/W)* luminous efficacy of the lamp. η_{supply} *or* η_P *(-)* power supply efficacy (Lamp nominal power (W) / input power supply (W)). *Dlor* ratio between the luminous flux emitted downwards by the luminaire and the total luminous flux emitted by the lamps. k_1 constant value equal to 0.476. k_2 constant value equal to 0.524. SE_R *(W/(lx·m^2))* Standard SLEEC. E_R *(lx)* limit values of illuminance required by technical standards for the corresponding lighting class. SL_R *(W/((cd/m^2)·m^2)* Standard SLEEC. L_R*(cd/m^2)* limit values of luminance required by technical standards for the corresponding lighting class. ε_L *(lm/W)* luminous efficacy of lamps and electrical auxiliary devices. $I\varepsilon$ Energy efficiency indicator. ε *(m^2 · lx/W)* Energy efficiency of a street lighting installation. ε_R*(m^2 · lx/W)* reference value of energy efficiency. ICE (-) Energy consumption indicator. P_D (W/m^2) installed power density for the road lighting installation. *Q* or C_L *(-)* road surface luminance coefficient. *LE (lm/W)* luminous efficacy of the lighting system. R_{LO} *(-)* optical efficiency of luminaires.

SLEEC can be expressed as the ratio between the total power consumed by all installed luminaires including lamps, ballast and control gears *P* (W), and the product of the luminous parameter (lx or cd/m^2) and the area *A* (m^2) to be lit (Table 2.9). The luminous parameter depends on the photometric measure used in the calculation of the SL system for specific road classes. For illuminance-based road classes, the SLEEC indicator is given by W/lx·m^2 (SE), and for luminance-based road classes is given by W/cd/m^2·m^2 (SL).

The levels of the Energy efficiency classification (SLEEC) are shown in Table 2.10. SE is the SLEEC when illumination is used in the formula. SL is the SLEEC when luminance is used.

Table 2.10 Energy Efficiency SLEEC classification of street lighting installation.

Label	SE (W/lx · m^2)	SL (W/((cd/m^2) · m^2)
A	0 – 0.014	0.075 – 0.224
B	0.015- 0.024	0.225 – 0.374
C	0.025 – 0.034	0.375 – 0.524
D	0.035 – 0.044	0.525 – 0.674
E	0.045 – 0.054	0.675 – 0.824
F	0.055 – 0.064	0.825 – 0.974
G	0.065 – 0.074	0.975 – 1.124

SLEEC indicator has been used in both research and energy classification for SL systems. For instance, the approach used in reference (Rabaza et al. 2013) was SLEEC indicator with the aim to present a multi-objective evolutionary algorithm for a quick planning of lighting installations which guarantees maximum energy efficiency. In the other hand, aiming at achieving energy savings in SL, the Netherlands NL Agency (Ministry of Economic Affairs, Agriculture, and Innovation) developed an energy efficiency A-G label based on SLEEC indicators. Likewise, New Zeeland and Australia accepted SLEEC indicator as the basis of their energy classification scheme (Light Naturally 2014).

SLEEC is the most complex indicator, as it was suggested by (Gasparovsky 2015); however, operational time in the SL system is disregarded.

The Luminaire Energy Efficiency Indicator IPEA (lm/W) and Lighting systems Energy Efficiency Indicator IPEI were introduced in the regulations of the Emilia Romagna region from Italy (Regional Council of Emilia Romagna 2015), aiming at enabling the assessment of the overall energy performance of a particular lighting system and to promote energy saving in public lighting and reduce light pollution (Leccese et al. 2017; Regional Council of Emilia Romagna 2015).

The IPEA is the radio between the luminous efficacy and the standard luminous efficacy related to the best technology available on the market (Table 2.9). The values of (η_r) are indicated in the regulation (Regional Council of Emilia Romagna 2015) in function of the lamp nominal power and of the type of road.

The IPEI is an indicator based on SLEEC indicator aiming at assessing the energy performance of a lighting system. The calculation of IPEI requires the illuminance ($IPEI_E$) or on the luminance ($IPEI_L$) values depending of the lighting class assigned to the road, and a reference value of SLEEC indicator (SE_R or SL_R) and a correction factor k_E or k_L is needed as well. Formulas can be seen in Table 2.9.

According to (Leccese et al. 2017), the calculation of this indicator is unclear with roads composed of lanes with different limit values of the lighting parameters (i.e. sidewalks and carriageways) and lighted by a single type of luminaire. Comparing with other indicators, IPEI is included a comparison with the limit values fixed by the technical standards. As a constraint, IPEI disregard the operational time of the SL system.

The energy class for a luminaire or for a public lighting system is determined by comparing the obtained IPEA or IPEI value, respectively, with the labeling scheme shown in Table 2.11.

Table 2.11 Energy efficiency classification for luminaires (IPEA) and public lighting systems (IPEI).

Class	IPEA	IPEI
A++	1.15< IPEA	IPEI < 0.75
A+	1.10 < IPEA ≤ 1.15	0.75 ≤ IPEI < 0.82
A	1.05 < IPEA ≤ 1.10	0.82 ≤ IPEI < 0.91
B	1.00 < IPEA ≤ 1.05	0.91 ≤ IPEI < 1.09
C	0.93 < IPEA ≤ 1.00	1.09 ≤ IPEI < 1.35
D	0.84 < IPEA ≤ 0.93	1.35 ≤ IPEI < 1.79
E	0.75 < IPEA ≤ 0.85	1.79 ≤ IPEI < 2.63
F	0.65 < IPEA ≤ 0.75	2.63 ≤ IPEI < 3.10
G	IPEA ≤ 0.65	3.10 ≤ IPEI

The energy efficiency indicator (I_ε) proposed by Spain is defined in the Royal Decree 1890/2008 and its complementary technical instruction EA-01 (Royal Decree 1890/2008 2008). This classification uses a scale from A to G to rate how much efficient is a SL installation and it is aiming at improving energy savings and efficiency in Spain.

Energy efficiency (ε) is calculated by either the radio between the average maintained illuminance per road area and the total electrical power installed, including the lamp and auxiliary devises or by incorporating lamp efficacy, maintenance factor, utilization factor (Table 2.9). It is noteworthy that the normative does not mention in which cases it is better to use any of them.

The energy class for a SL installation is determined by comparing the obtained Energy Efficiency index (I_ε) value with the labelling scheme shown in Table 2.12. As can be observed, the lower energy consumption is the better the energy class of the lighting installation.

Table 2.12 Energy efficiency classification based on I_ε.

Energy Class	Energy Consumption Index (ICE)	Energy Efficiency Index ($\mathbf{I_\varepsilon}$)
A	ICE < 0.91	$I_\varepsilon > 1.1$
B	0.91 ≤ ICE < 1.09	$1.1 \geq I_\varepsilon > 0.92$
C	1.09 ≤ ICE < 1.35	$0.92 \geq I_\varepsilon > 0.74$
D	1.35 ≤ ICE < 1.79	$0.74 \geq I_\varepsilon > 0.56$
E	1.79 ≤ ICE < 2.63	$0.56 \geq I_\varepsilon > 0.38$
F	2.63 ≤ ICE < 5	$0.38 \geq I_\varepsilon > 0.20$

The Energy Efficiency Index (I_ε) is the ratio between the energy efficiency of a public lighting installation (ε) and the reference value of energy efficiency (ε_R) related to the illuminance level projected on the road; while the Energy Consumption Index (*ICE*) is the inverse of I_ε .

An analysis carry out by (Gutierrez-Escolar et al. 2017) argued that the unexpected results achieved in urban lighting energy consumption in Spain might be due to the unit measured, which could be inappropriate, or due to the lack of governing parameters when performing the assessment. Moreover, Australian and New Zeeland lighting programs also use I_ε to establish minimum energy efficiency requirements, these being lower than those accepted in Spain. However, these values are based on road illuminance levels, which are significantly higher in Spain when comparing with those fixed in Australia and New Zeeland (Light Naturally 2014).

Although the previous recommendations bring some co-benefits such as energy efficiency, smart street sighting, design, light pollution, waste resources, renewable energy, security, safety, visual performance, and public healthy and cost savings, helping at solving several issues related to the energy efficiency SL systems; and the EPI and ECS help to evaluate and compare the energy performance of different SL systems, they lack on three aspects.

First, the lighting industry sector has improved the energy efficiency and life-cycle cost of lighting in recent years. The technological advances for LED lamps, control system and luminaires enhance the approaches of SL that can be used for reducing energy consumption in any of the phases (design, operational or strategy) and moving forward into smart and sustainable SL. The introduction of LED has led to new requirements for new recommendations associate with spectrum, spatial distribution and dynamic control (S. Fotios and Gibbons 2018).

Second, EPI and ECS are based basically on parameters of installed power and luminance or Illuminance, which have an influence in energy reduction through the lighting equipment and regulate the light levels entering the eye. However, given the recent advances in mesopic vision and its influence in health and vision performance, there is an ongoing need to introduce new parameters such as SPD (S/P ratio) into the analysis of energy efficiency. Considering only a photopic-only approach in SL may be a limitation when LED lamps are used, because it enhances the opportunity to change and tune SPD in order to improve visual perception.

On the other hand, there are two principal features of SL in determining how much lighting to provide without causing needless energy consumption: light level and spectral power distribution (SPD) (Yang 2014). Previous section exposes the empirical recommendations considering the SPD of the lamp to improve visual performance in mesopic vison.

Moreover, several studies have investigated the potential of reduction in energy consumption in SL by considering mesopic design. The effect of mesopic dimensioning on energy consumption and life cycle cost of the LED installation was formerly studied by (Ylinen et al. 2011), which concluded in that energy can be saved as much as 70% when mesopic dimensioning is applied to SL design.

Kostic and others (A. Kostic et al. 2012) compared the use of light-emitting diode (LED) and conventional luminaires in street and roadway lighting regarding to electricity consumption by considering mesopic effects. It was found that when using LED instead of Metal Halide (MH) luminaires, the energy savings were 33% and, if mesopic effects were taken into account, the decrease of electricity consumption amounted up to 43% (A. Kostic et al. 2012).

Fotios *et.al.* proved in (S. Fotios and Cheal 2011) that lighting using lamps of higher S/P ratio (LED, MH, FL) will produce greater brightness perception than others with lower SP/ratio (HPS) at the reference illuminance of 5 lx. Improve of maintain brightness by manipulating SPD without changing the quantity of light consequently maintaining the same level of energy.

Third, some researcher suggested a quantification system for measuring energy efficiency that incorporates all the elements that affect the overall efficiency of the installation with respect to time (Kyba et al. 2014; Loe 2003; San Martín Páramo 2011), because *time* has been given little attention in the EPI and ECS existing.

There is a consensus on that energy efficiency of SL lies in optimizing the use of energy while guaranteeing the amount of luminous flux necessary to carry out activities at night and, at the same time, preserving comfort, high perception of security and adequate visibility for safe movement. This consensus highlights two important concepts: use of energy and luminous flux. The former is related to the average power (P) used in an installation during a certain time (t), the latter being related to the quantity of light (E_m) directed to a specific area (A). This results in the energy efficiency indicator (EE) referred in (Mockey-Coureaux and Manzano 2011) and expressed in (Eq.1).

$$EE = \frac{P \cdot t}{E_m \cdot A} \qquad Eq. 1$$

On the one hand, energy efficiency can be achieved either by minimizing P or t, where power (P) is intrinsic to the lighting installations (lamps, luminaires, ballast, gears, auxiliary devices) and time (t) is related with the use that is made for it. On the other hand, energy efficiency also can be achieved by reducing average illuminance level (E_m), but this implies other components that deserves further investigation[5].

Little attention has been given to time (t) parameter. Lighting researchers such as (Kyba et al. 2014) suggest a new definition of efficiency in urban SL by considering kWh/year as a measure for reporting energy efficiency. In the same way, in (Loe 2003) calls for a quantification system to measure energy efficiency that incorporates all the elements that affect the overall efficiency of the installation with respect to time. San

[5] The reduction of illuminance level is allowed depending of the Color Rendering Index (CRI) of the lamp and the recommendations and standards used in each country. For example, in the UK it is allowed the reduction of illuminance level for lamps with a CRI greater than or equal to 60 (British Standards Institution (BSI) 2003), and the average luminance and horizontal illuminance in road lighting recommendations and standards used in UK, USA, Japan, Australia and New Zealand is depending of the criteria of SL for each country (Boyce et al. 2009). Additionally, the quantity of light needed to lit a road surface, in terms of illuminance (E) or luminance (L), could be minimized by tuning the lamp, luminaria and road surface to each other (van Bommel 2015e).

Martín, 2011 (San Martín Páramo 2011) considers that the use of a time factor in the energy efficiency indicators will allow improvements of the management of luminous flux in a SL installation.

2.4 A VALUE FUNCTION FOR ASSESSING ENERGY EFFICIENCY

The multi-criteria decision making (MCDM) methodologies are useful to help policy makers handle complex decision-making situations in which many variables are taking into consideration. These variables are aimed at providing a framework that allows preferences to be quantified. The VF approach is one of the most widely accepted frameworks to standardize different units and magnitudes that reflects the preferences of the decision maker in a clear and easily applied way (Alarcon et al. 2011).

In the SL sector, many authors have been analyzed SL systems in a more complex manner by adopting MCDM methods that considers some variables such as lighting, energy, environment and economic criteria, aiming at supporting administrations, lighting designers or lighting tenders, to find optimal solutions that reduce energy consumption, while maintained the highest standards of quality.

Among the most recent studies, a multi-criteria assessment approach for outdoor lighting at the design step was recently proposed by Pracki and Skarzynski (2020), using criteria related to lighting requirements, light pollution and energy efficiency to find the best and most sustainable lighting solution for any outdoor situation. An algorithm has been presented for the assessment of any outdoor lighting solution. This involves (1) the road or area of interest, (2) design requirements of visual task and activities, light pollution and lighting energy efficiency.

A supporting tool for selecting the optimum retrofit for existing SL systems in urban areas has been proposed (Carli et al. 2017, 2018). The main performance criteria used in this tool was energy consumption, light pollution and the color rendering index. The aim was to reduce energy consumption and optimize the distribution of actions in subsystems, while ensuring an efficient use of public funds, protect the environment and maintain comfort. The decision-making tool was applied to the energy retrofit of the SL system of Bari for 316 lighting fixtures.

Similar studies advice the use of energy performance indicators (EPI), for instance, Power Density Indicator (PDI) and Annual Energy Consumption Indicator (AECI) found in the new version of European regulations EN 13201-5:2015 (European Committee for Standardization 2015a) as design criteria, which can be evaluation criteria in a lighting tender (Doulos et al. 2019). The aim was a) to present the significance of using these indicators through a decision tool, capable to evaluate several lighting designs in lighting tender and b) to propose an evaluation method as part of a future energy policy including environmental criteria. The different lighting designs were assessed with the PROMETHEE (Preference Ranking Organization Methods for Enrichment Evaluations) method to evaluate the ranking of the corresponding offers.

Some studies have been payed attention to the design of new street lighting systems and to the refurbishment of existing ones. According to (Lozano-Miralles et al. 2020), it is important to implement SL designs that fulfil lighting requirements, avoiding energy waste and eco-efficiency and, at the same time, result in sustainability for municipalities. One example given in (Hermoso-Orzáez et al. 2019) a methodological proposal was established by using the techniques of multiple decision-making criteria for the selection of bidding companies for public lighting outdoor lighting competitions. The PROMETHEE method multi-criteria analysis was used for the application of the most commonly used criteria for the luminaire LED selection process, including an environmental impact assessment with LCA techniques. This will allow the contest evaluator of public tenders to facilitate the choice of an LED luminaire that best suits the technical, light quality, savings and environmental sustainability requirements.

Another tool was presented in Silva *et. al.* (Silva et al. 2010) which can assess street lighting performance in the energy efficiency context. The tool uses a multi-criteria approach based on a hierarchical tree structure, where a set of lower-level criteria contributes to the assessment of the next higher-level criteria or dimension. Three indicators were developed: one to evaluate lighting performance criteria (Luminaire coverage and average illumination level) and two others to evaluate energy performance criteria (Luminaire coverage and efficiency, and lighting control devices). These three indicators were quantified and combined according to weighting and aggregation procedures, resulting in a synthetic score for the street lighting design from 0 to 1. According to (Gutierrez-Escolar et al. 2015), this simple tool has the shortcoming related to the score used for lighting control devices in which is used only two values (zero and one) depending on whether the SL installation has (one) or does not have (zero) these devices.

All the assessed methods used in the examples before mentioned embrace the most required characteristics of decision-making techniques with different qualities. Nevertheless, any of them have used the value function (VF) approach as a method to transform the different magnitudes and units for the indicators into a dimensionless parameter. Therefore, VF is presented as an alternative tool to standardize and quantify preferences for different quantitative measurement variables (indicators) and transform them into a value between 0 to 1 (Alarcon et al. 2011), where the minimum value of 0 represent the worst solution, therefore less grade of satisfaction; and the maximum value 1 represent the best solution, therefore more grade of satisfaction. In terms of the SL, the less energy is consumed the more grade of satisfaction.

The VF has been used in the MIVES method (Integrated Value Model for Sustainability Assessment), which has been originally developed for the assessment of sustainability in construction (Aguado et al. 2012; Pons and Aguado 2012; Pons and de la Fuente 2013) and engineering applications (Del Caño et al. 2015). Consequently, it has been validated in homogenous alternatives such as post-disaster temporary housing options (Hosseini et al. 2018; Hosseini, Pons, et al. 2020; Hosseini, Yazdani, et al. 2020), public investment projects (Pujadas et al. 2017), architectural applications (Gilani et al. 2017; Habibi et al. 2020; Pons et al. 2016), concrete type and reinforcement configurations for segmental linings of tunnel boring machine (de la Fuente et al. 2017) and the energy sector (Cartelle Barros et al. 2015).

According to Alarcón *et. al.* (2011), VFs need four aspects to be defined: (1) tendency (increase/decrease), (2) points corresponding to the minimum (value 0) and maximum (value 1) satisfaction, (3) shape (linear, concave, convex, S-shaped) and (4) constitutive parameters of the functions.

Increasing or decreasing tendency in VFs depends on the nature to the indicator to be evaluated (Alarcon et al. 2011). A concave shape is used when small changes around the point that generate minimum satisfaction are highly valuated. A convex function is used when is hardly to increase the satisfaction tendency making small changes in the indicator. If satisfaction increases or decreases steadily, a linear function is used.

Finally, an S-shaped function is used when significant increases in satisfaction are detected in central values. In Figure 2.6 these patterns are depicted.

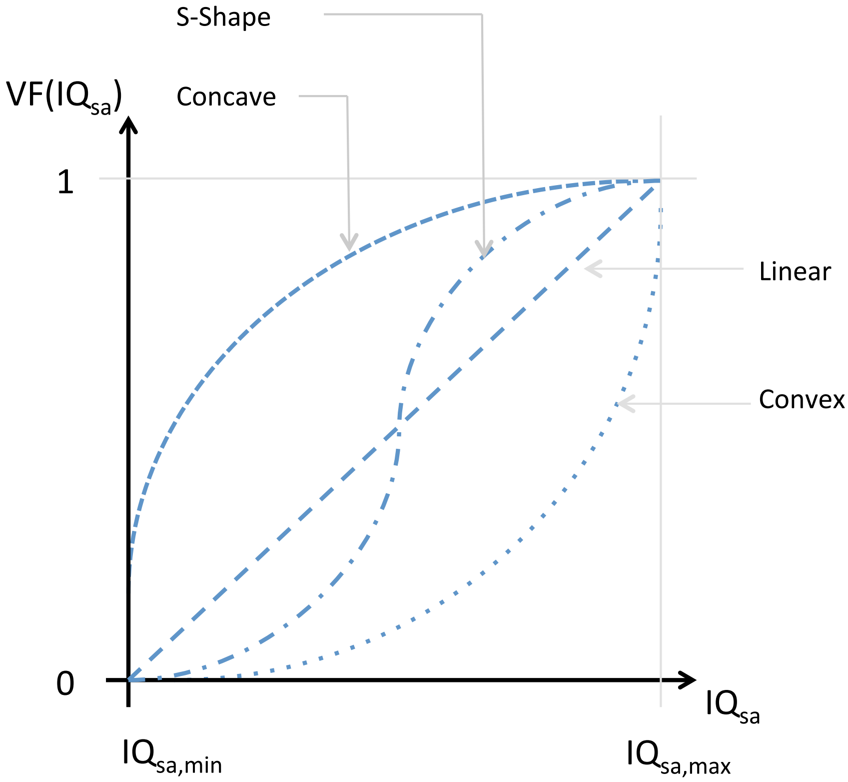


Figure 2.6 Value functions type.

The points of minimum ($IQ_{sa,min}$) and maximum ($IQ_{sa,max}$) satisfaction define the limits of the value function on the x-axis. These points are usually established by existing rules and regulations and, experience with previous projects.

Eqs. (2) and (3) allow assessing the satisfaction value for a given IQ_{sa}. P_i is a shape factor for concave ($P_i<1$), convex ($P_i>1$), linear ($P_i=1$) or S-shaped ($P_i>1$) functions. C_i and K_i are the coordinate and ordinate, respectively, of the inflection point. B_i (Eq. (3)) is the factor (normalizer) that allows the function to vary within the range of 0 to 1.

$$VF(IQ_{sa}) = B_i * \left[1 - e^{\left(-k_i * \left(\frac{|IQ_{sa} - IQ_{sa,max}|}{C_i}\right)^{P_i}\right)}\right] \qquad Eq. 2$$

$$B_i = \frac{1}{\left[1 - e^{\left(-k_i * \left(\frac{|IQ_{sa,max} - IQ_{sa,min}|}{C_i}\right)^{P_i}\right)}\right]} \qquad Eq. 3$$

2.5 SUMMARY

SL is a feature of urban areas and it has defined the modern city, in extending the visibility of its public spaces, inhabitants and itinerants beyond the hours of natural light. The main purpose of SL is to improve visibility, to improve safety, and to improve the feeling of safety for drivers and pedestrians at night. However, the expanding use of light at night, along with an inappropriate design, has led a large energy consumption and light pollution.

There is a growing body of literature that recognizes the importance of considering light pollution as a true atmospheric, environmental and health problem and its consequences should be studied. Forms of light pollution can be seen as the brightness of the night sky above cities (sky glow), the uncomfortable brightness of a light source (glare) or the unwanted light shining in a window (light trespass). The negative impacts have had consequences in the night sky, the ecology, the human health and socio-economics aspects.

To mitigate side-effects of a lighting installation it is necessary to provide light where needs to be lit using the minimum level required. For that, SL standards and practical recommendations play an important role. Standards for SL such as EN 13201-2-2015 (Europe) and the energy classification systems such as I_ε (Spain), SLEEC (Netherlands) and IPEI/IPEA (Italy) provide the quantitative value of the parameters needed to improve visual performance at night, while practical recommendations are qualitative recommendations useful to support administrations and designers to achieve the optimal energy performance in a SL installation.

With increasing consideration in light pollution, energy consumption and human health, new challenges are facing the SL sector. On the one hand, recent advances of lighting technologies (e.g. light sources, control systems and luminaires) and developments in science (Mesopic vision). On the other hand, Sustainability that demands balancing social, economic and environment aspects in the SL sector.

Traditionally, the idea of sustainability in SL was related with economical savings and technical performance that could be achieved by introducing, for instance, high-technological lamps; however, several studies and recommendations agree that SL is more that economic and energetic aspects: SL is for people's security and safety perception, especially for young women, is for preserving visual comfort for elderly people, is for the environment's protection by reducing the use of pollutants in light sources, materials non-renewables, waste of energy and do not disturbing wild life. Moreover, SL is for economics' affordability by reducing cost and contributing to the attractiveness of commercial areas.

There is a vast number of literatures on energy-efficiency approach in SL systems, since the growth of interest in global warming, light pollution and impact on human and the natural environment, as well as for decreasing the bills of electricity in municipalities.

On the one hand, the lighting industry sector has improved the energy efficiency and life-cycle cost of lighting in recent years. The technological advances for LED lamps, control system and luminaires enhance the approaches of SL that can be used for reducing energy consumption in any of the phases (design, operational or strategy) and moving forward into smart and sustainable SL. On the other hand, recommendations for energy efficient lighting and indicators to assess the energy performance of SL system have arisen.

EPI in SL installation are based basically on parameters of installed power and luminance or Illuminance, which have an influence in energy reduction through the lighting equipment and regulate the light levels entering the eye. However, given the recent advances in mesopic vision and its influence in energy reduction and vision performance, there is an ongoing need to introduce new parameters into the analysis of energy efficiency such as S/P ratio in which, along the photopic luminance level, helps to obtain the effective mesopic luminance level. Lighting is not for vision anymore, and the indicators and energy classifications to assess energy efficiency in a SL lighting should not be. Moreover, the parameter *time* has been given little attention in the current EPI and ECS, even some researcher suggested a quantification system for measuring energy efficiency that incorporates all the elements that affect the overall efficiency of the installation with respect to time.

The research outlined in this thesis, intents to fill these gaps by integrating both parameters that affect overall efficiency of a SL system and parameters disregarded into a proposed ECS. The value function approach is a validated method useful to standardize an indicator within a value scale ranging from 0-1. Using the VF approach to develop the proposed ECS, offers possibilities to objectivize the energy efficiency value of a SL installation.

3 DESIGN OF ENERGY EFFICIENCY CLASSIFICATION

This chapter develops the research structure explained in the previous section. This part is divided in Design Principles and Data collection of the case study. Design principles section explains all the components required to develop the alternative EPI (IQ_{sa}) with its corresponding ECS ($VF\ IQ_{sa}$) and the use of the Value Function (VF) method to standardize IQ_{sa} values. The second part involves the collection data of the experimental program comprises of 13 representative streets of the Eixample District of Barcelona.

3.1 DESIGN PRINCIPLES

3.1.1 Defining the energy consumption indicator (IQ_{sa})

An equation for measuring energy consumption, based on the Spanish lighting standard (Royal Decree 1890/2008 2008), was proposed. This involves two innovate features: Luminous Flux control factor (f_{cf}) and mesopic correction factor (f_{cm}). The latter takes into account the improvement of visual performance by correcting the standard photometry system (photopic) by the recommended system (mesopic) in the (Commission Internationale de L'Eclairage 2010).

According to (Royal Decree 1890/2008 2008), the energy efficiency can be calculated by means of the Eq. (4) or Eq. (5), before defined in Table 2.9.

$$\varepsilon = \frac{(A \cdot E_m)}{P} \qquad Eq.4$$

$$\varepsilon = \varepsilon_L \cdot f_m \cdot f_u \qquad \text{Eq. 5}$$

From Eqs. (4) and (5), the installed power demand (P) can be derived (see Eq. (6)). This equation describes the relation between the product of average illuminance (E_m) and the area illuminated (A) with the luminous efficacy of the lighting installation.

$$P = \frac{A \cdot E_m}{\varepsilon_L \cdot f_m \cdot f_u} \qquad Eq.6$$

The installed power density for the SL installation (P_D) relates the installed power demand *(P)* relating to the street surface illuminated *(A)* (Eq. (7)).

$$P_D = \frac{P}{A} = \frac{E_m}{\varepsilon_L \cdot f_m \cdot f_u} \qquad Eq.7$$

Notice that the luminous efficacy of the lamp (ε_L) is the product of the efficiency of auxiliary elements (W/W) and the nominal efficacy of lamps (lm/W) as shown in Eq. (8).

$$\varepsilon_L = \eta_{aux} \cdot K_{nl} \qquad Eq.8$$

The global energy consumption (Q'_{sa}), Eq. (9), can be obtained by multiplying the installed power density (P_D) by the number of hours that the light system is turned on (t_{ua}) and using Eq. (8) to replace ε_L.

$$Q'_{sa} = \left(\frac{E_m \cdot t_{ua}}{\eta_{aux} \cdot K_{nl} \cdot f_m \cdot f_u}\right)\frac{1}{1000} \qquad Eq. 9$$

Where E_m - Average illuminance level (lx); t_{ua} - Annual time operation of the lighting installation (h); η_{aux} - Efficiency of auxiliary elements (W/W); K_{nl} - Nominal efficacy of lamps (lm/W); f_m - Maintenance factor; f_u - Utilization factor; *1/1000* – conversion factor from W to kW.

From Eq. (9), it can be inferred that a reduction of the energy consumption, in practical terms, can be achieved in two ways, first is reducing the annual operation time of the lamp (t_{ua}), second is improving the luminous efficacy of the lamp (K_{nl}). To quantify these potential reductions, two factors were introduced in Eq. (9): luminous flux control factor (f_{cf}) and mesopic correction factor (f_{cm}).

The luminous flux control factor (f_{cf}) is calculated as the percentage of the area covered by the profile control flux as shown below in Figure 3.1. All the luminous flux profiles described, assumes the nominal voltage and stationary operation condition. That is, the luminous flux control derived from double flow ballast or electronic ballast.

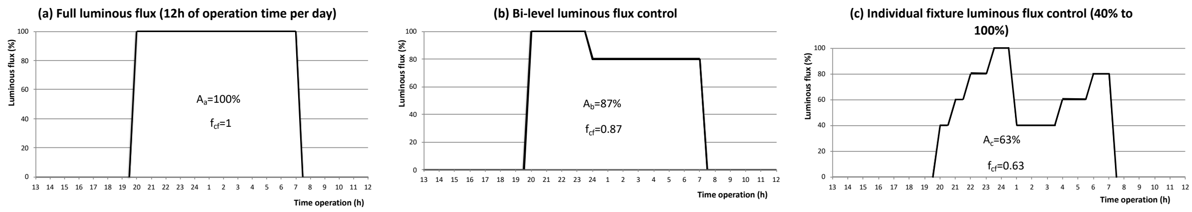


Figure 3.1 (a) Control profile for a non-reduction of luminous flux, (b) Bi-power profile and (c) multilevel control profile of the luminous flux.

While mesopic correction factor (f_{cm}) are associated to the improvement of the user's visual performance in the mesopic region. Table 3.1 provides the correction factors to be applied in order to obtain the equivalent mesopic luminance level. These values depend on photopic luminance level and the S/P ratio of the lamp and are based on the recommended system CIE photometric system (Commission Internationale de L'Eclairage 2010).

Table 3.1 Correction factors for mesopic photometry.

HPS S/P= 0.65		MH S/P= 1.85		LED S/P= 2.25		FL S/P= 2.45	
L_p (cd/m^2)	f_{cm}	L_p (cd/m^2)	f_{cm}	L_p (cd/m^2)	f_{cm}	L_p (cd/m^2)	f_{cm}
0.50	0.94	0.50	1.13	0.50	1.19	0.50	1.22
0.75	0.95	0.75	1.11	0.75	1.15	0.75	1.20
1.00	0.96	1.00	1.09	1.00	1.12	1.00	1.14
1.50	0.97	1.50	1.06	1.50	1.09	1.50	1.10
2.00	0.98	2.00	1.05	2.00	1.07	2.00	1.08

Source: Table 11 from the Recommendation CIE 191:2010, pp. 68. (L_p: luminance value in the photopic region).

Using the recommended system for mesopic photometry to calculate the effective luminance of the lamp, instead of the photopic spectral luminous efficiency function that is currently used in SL systems, will result in a significant change in their apparent efficacy. For example, at a photopic luminance of 1 cd/m^2 the use of the recommended system results in a change of between -4% and +14% for lamps with S/P ratios between 0.65 and 2.45; at 0.5 cd/m^2 the change is between about -6% and +22%. It should be noted that lamps with a relatively high output in the short wavelength region (S/P ratio > 1) result in increased luminance values when measured using the recommended system, whereas lamps with relatively high output in the long wavelength region result in decreased luminance values.

Once the correction factors are introduced in Eq. (9), the Eq. (10) can be obtained to compute the total energy consumption during one year per unit of illuminated area (Q_{sa}).

$$Q_{sa} = \left(\frac{E_m \cdot (t_{ua} \cdot f_{cf})}{\eta_{aux} \cdot (K_{nl} \cdot f_{cm}) \cdot f_m \cdot f_u} \right) \frac{1}{1000} \qquad Eq. 10$$

Beside the new corrections factors before described, Q_{sa} (kWh/m^2) involves the following parameters:

- Street surface illuminance (E): Illuminance values (lx) depends on lighting class (determined by road lighting Standards); and lighting class depending on traffic participants, diary volume of traffic, maximum permissible vehicle speed, density of conjunctions, ambient brightness, etc. All streets are categorized into six streets lighting classes according to European standards (European Committee for Standardization 2015b).
- Time of use (t_{ua}): it refers to daily operation time of a particular lighting level. If luminaires operates at same lighting level (full luminous flux) during all night, the annual operation time will be 4000 h (European Committee for Standardization 2015b).
- Luminous efficacy ($\varepsilon_L = \eta_{aux} \cdot K_{nl}$): The luminous efficacy (lm/W) of the lamp and auxiliary equipment influences the energy efficiency of a SL installation to the greatest extent. Typical values of luminous efficacy of lamp cover a wide range of lamp power; from the lower values given by HPM [25-55 lm/W], through MH [55-105 lm/W] to the upper values LED's and HPS [55-160 lm/W] (Pracki, 2011).
- Utilization factor (f_u): it is defined as the relation between the luminous flux reaching the road surface and the luminous flux produced by the lamp. According to (Pracki 2011) typical values attainable in road lighting installations are in a range of 0,3 – 0,5; while values up to 0,6 are very difficult to achieve in current practice.
- Maintenance factor (f_m): a parameter showing the reduction of the luminaire luminous flux due to dirt pollution accumulated on the luminaires and depreciation of the lamp luminous flux (Djuretic and Kostic 2018). For calculating f_m is necessary data of Lamp Lumen Depreciation Factor (LLD), Lamp Survival Factor (LSF) and Luminaire Dirt-Depreciation Factor (LDF).

Since Eq. (10) takes into consideration the operational hours and mesopic design parameters, both disregarded by the most commonly used energy classification approaches as can be seen Table 2.9, this expression can be assumed as an innovate and more representative measurement of energy efficiency for SL.

In order to estimate the variation range of Q_{sa}, a wide range of possible technical scenarios for SL was established and assessed by applying the Eq. (10). For this purpose, a set of 8 road types with: (1) the corresponding lighting classes (M1, M2, M3, M4, C2, S1, S2, S3); (2) average illuminance levels according to the Spanish lighting standard, 5 types of lamps (HPS, high pressure mercury (HPM), MH, LED, FL); (3) 3 luminous flux control (full flux, bi-level and individual fixture) and (4) 2 types of photometry (photopic and mesopic) were defined.

Q_{sa} was calculated for each SL arrangement under the following assumptions and results are listed in Table 3.3.

- Illuminance (E_m): 30 – 20 – 15 – 10 – 7.5 (lx)
- Time of use (t_{ua}): 4000 h
- Luminous flux control (f_{cf}): C1 full flux (100%), C2 bi-level (87%), C3 individual fixture (63%) (Figure 3.1)
- Luminous efficacy (($\varepsilon_L = \eta_{aux} \cdot K_{nl}$): Values are listed in Table 3.2
- Mesopic correction factor (f_{cm}): S/P= 0.65 – 1.85 – 2.25 – 2.45 (see Table 3.1)
- Utilization factor (f_u): 0.4
- Maintenance factor (f_m): Values in Table 3.2 assume a 2-year luminance cleaning interval, group replacement after 8000 hours, the commonly used IP5X luminaires and high environmental pollution for vehicular street and low environmental pollution for pedestrian street. Maintenance factor values for LED are obtained from (IDAE 2012).

Table 3.2 Values of luminous efficacy of the lamp ($\boldsymbol{\varepsilon}_L$), utilization factor ($f_u$) maintenance factor ($f_m$) used to calculate Q_{sa}.

Lamp type	Luminous efficacy (lm/W)	f_m	f_u
HPS	125	0.74	0.4
HPM	47	0.58	0.4
MH	90	0.60	0,4
LED	162	0.85	0.4
FL	73	0.77	0.4

Note: The luminous efficacies values include the power losses in the auxiliary elements.

In this research, SL installations are proposed to be rated according to the energy consumption indicator (IQ_{sa}), see Eq. (11), and the results are listed in Table 3.4.

$$IQ_{sa} = \frac{Q_{sa}}{Q_{sa,R}} \qquad Eq.11$$

The reference value of energy consumption ($Q_{sa,R}$) for each lighting class was computed by assuming a typical installation consisting of HPS lamps, full luminous flux control, and photopic photometric (Table 3.3).

Table 3.3 Energy consumption (Q_{sa}) and reference values ($Q_{sa,R}$) for different SL arrangements.

Road class	Description road	Criteria		Lighting Class	E_m (lx)	Lamp	Q_{sa} C1 (kWh/m^2)		Q_{sa} C2 (kWh/m^2)		Q_{sa} C3 (kWh/m^2)	
		IMD	Velocity (km/h)				ph	mes	ph	mes	ph	mes
A	Motorway	IMD(1)	>60	M1	30	HPS	3.23	3.30	2.81	2.87	2.05	2.09
					30	HPM	11.04	-	9.60	-	7.01	-
					30	MH	5.55	5.29	4.83	4.60	3.53	3.36
					30	LED	2.18	2.04	1.90	1.77	1.38	1.29
A	Major road	IMD(2)	60	M2	20	HPS	2.16	2.23	1.87	1.94	1.37	1.42
					20	HPM	7.36	-	6.40	-	4.67	-
					20	MH	3.70	3.47	3.22	3.02	2.35	2.20
					20	LED	1.45	1.32	1.26	1.15	0.92	0.84
B-C	Collector street	IMD(3)	30 to 60	M3	15	HPS	1.62	1.68	1.41	1.46	1.03	1.07
					15	HPM	5.52	-	4.80	-	3.50	-
					15	MH	2.78	2.55	2.42	2.22	1.76	1.62
					15	LED	1.09	0.97	0.95	0.85	0.69	0.62
B-C-D-E	Local streets	IMD(4)	5 to 30	M4	10	HPS	1.08	1.15	0.94	1.00	0.68	0.73
					10	HPM	3.68	-	3.20	-	2.34	-
					10	MH	1.85	1.64	1.61	1.42	1.18	1.04
					10	LED	0.73	0.61	0.63	0.53	0.46	0.39
D-E	Historic centre area	high traffic	5 to 30	C2	20	HPS	2.66	2.76	2.32	2.40	1.69	1.75
					20	MH	4.48	4.19	3.89	3.65	2.84	2.66
					20	LED	1.45	1.32	1.26	1.15	0.92	0.84
					20	FL	4.50	4.05	3.92	3.52	2.86	2.57
C-D-E	Residential and comercial area	high traffic	5 to 30	S1	15	HPS	2.00	2.08	1.74	1.81	1.27	1.32
					15	MH	3.36	3.08	2.92	2.68	2.13	1.95
					15	LED	1.09	0.97	0.95	0.85	0.69	0.62
					15	FL	3.38	2.96	2.94	2.58	2.14	1.88
C-D-E	Residential area	low traffic	5 to 30	S2	10	HPS	1.33	1.42	1.16	1.23	0.85	0.90
					10	MH	2.24	1.98	1.95	1.72	1.42	1.26
					10	LED	0.73	0.61	0.63	0.53	0.46	0.39
					10	FL	2.25	1.85	1.96	1.61	1.43	1.17
C-D-E	Pedestrian area	low traffic	< 5	S3	7.5	HPS	1.00	1.06	0.87	0.92	0.63	0.67
					7.5	MH	1.68	1.49	1.46	1.29	1.07	0.94
					7.5	LED	0.54	0.46	0.47	0.40	0.35	0.29
					7.5	FL	1.69	1.38	1.47	1.20	1.07	0.88

Note: Q_{sa} values highlighted are the energy consumption value of reference ($Q_{sa,R}$) for each class lighting. *ph* – photopic; *mes* – mesopic; IMD - average daily traffic; IMD(1)= IMD>25,000; IMD(2)= 15,000 < IMD < 25,000; IMD(3)= 7,000 < IMD < 15,000; IMD(4)= IMD < 7,000.

Table 3.4 The Energy Consumption Indicator (IQ_{sa}) for different street lighting arrangements.

Road class	Description road	Criteria		Lighting Class	E_m (lx)	Lamp	IQ_{sa} C1		IQ_{sa} C2		IQ_{sa} C3	
		IMD	Velocity (km/h)				ph	mes	ph	mes	ph	mes
A	Motorway	IMD(1)	>60	M1	30	HPS	1.00	1.02	0.87	0.89	0.63	0.65
					30	HPM	3.41	-	2.97	-	2.17	-
					30	MH	1.72	1.64	1.49	1.42	1.09	1.04
					30	LED	0.67	0.63	0.59	0.55	0.43	0.40
A	Major road	IMD(2)	60	M2	20	HPS	1.00	1.04	0.87	0.90	0.63	0.66
					20	HPM	3.41	-	2.97	-	2.17	-
					20	MH	1.72	1.61	1.49	1.40	1.09	1.02
					20	LED	0.67	0.61	0.59	0.53	0.43	0.39
B-C	Collector street	IMD(3)	30 to 60	M3	15	HPS	1.00	1.04	0.87	0.91	0.63	0.66
					15	HPM	3.41	-	2.97	-	2.17	-
					15	MH	1.72	1.58	1.49	1.37	1.09	1.00
					15	LED	0.67	0.60	0.59	0.52	0.43	0.38
B-C-D-E	Local streets	IMD(4)	5 to 30	M4	10	HPS	1.00	1.06	0.87	0.93	0.63	0.68
					10	HPM	3.41	-	2.97	-	2.17	-
					10	MH	1.72	1.52	1.49	1.32	1.09	0.97
					10	LED	0.67	0.57	0.59	0.49	0.43	0.36
D-E	Historic centre area	high traffic	5 to 30	C2	20	HPS	1.00	1.04	0.87	0.90	0.63	0.66
					20	MH	1.68	1.57	1.46	1.37	1.07	1.00
					20	LED	0.55	0.50	0.47	0.43	0.35	0.31
					20	FL	1.69	1.52	1.47	1.32	1.07	0.96
C-D-E	Residential and comercial area	high traffic	5 to 30	S1	15	HPS	1.00	1.04	0.87	0.91	0.63	0.66
					15	MH	1.68	1.54	1.46	1.34	1.07	0.98
					15	LED	0.55	0.49	0.47	0.42	0.35	0.31
					15	FL	1.69	1.48	1.47	1.29	1.07	0.94
C-D-E	Residential area	low traffic	5 to 30	S2	10	HPS	1.00	1.06	0.87	0.93	0.63	0.68
					10	MH	1.68	1.49	1.46	1.29	1.07	0.94
					10	LED	0.55	0.46	0.47	0.40	0.35	0.29
					10	FL	1.69	1.39	1.47	1.20	1.07	0.88
C-D-E	Pedestrian area	low traffic	< 5	S3	7.5	HPS	1.00	1.06	0.87	0.93	0.63	0.68
					7.5	MH	1.68	1.49	1.46	1.29	1.07	0.94
					7.5	LED	0.55	0.46	0.47	0.40	0.35	0.29
					7.5	FL	1.69	1.39	1.47	1.20	1.07	0.88

ph – photopic; *mes* – mesopic; IMD - average daily traffic; IMD(1)= IMD>25,000; IMD(2)= 15,000 < IMD < 25,000; IMD(3)= 7,000 < IMD < 15,000; IMD(4)= IMD < 7,000.

3.1.1 Defining the energy classification system (VF IQ_{sa})

In order to standardize the indicator IQ_{sa} within a value scale ranging from 0-1, the VF approach was used. The VF approach allows assessing the energy efficiency (grade of satisfaction) associate to the IQ_{sa} indicator. VFs need four aspects to be defined: (1) tendency (increase/decrease), (2) points corresponding to the minimum (value 0) and maximum (value 1) satisfaction, (3) shape (linear, concave, convex, S-shaped) and (4) constitutive parameters of the functions.

The points of minimum (*$IQ_{sa,min}$*) and maximum (*$IQ_{sa,max}$*) satisfaction define the limits of the VF on the x-axis. These points are usually established by existing rules and regulations and, experience with previous projects. For this research, both *$IQ_{sa,min}$* and *$IQ_{sa,max}$* were obtained from calculating Eq. 10 and Eq.11 in the 8 sets of road types with the corresponding technically available lighting configurations (Table 3.4). The constitutive parameters for defining the VFs of IQ_{sa} are shown in Table 3.5 and depicted in Figure 3.2.

Table 3.5 Constitutive parameters for defining the value functions for each type.

	Convex	S-Shape	Concave	Linear
C_i	4.5	1.7	3.0	0.29
K_i	0.3	0.4	0.8	<0.01
P_i	2.8	4.0	0.9	1.0
$IQ_{sa,min}$	0.29	0.29	0.29	0.29
$IQ_{sa,max}$	3.41	3.41	3.41	3.41
B_i	9.78	1.00	1.77	19.13

The selection of the curve depends on the indicator, as suggested by Alarcon *et. al.* (2011), but also on the compliance of the SL requirements of each city. A decreasing convex curve was selected for this case study in Barcelona. As shown in Figure 3.2, this curve depicted in red, leads to a grade of satisfaction of 0.5 to a typical SL installation comprising HPS lamps. In comparison to the other curves, where the typical installation has a grade of satisfaction above 0.8, the curve selected is aimed at promoting energy efficient SL systems. In this sense, it is worth to be remarked that 63% of the lamps installed in Barcelona are HPS.

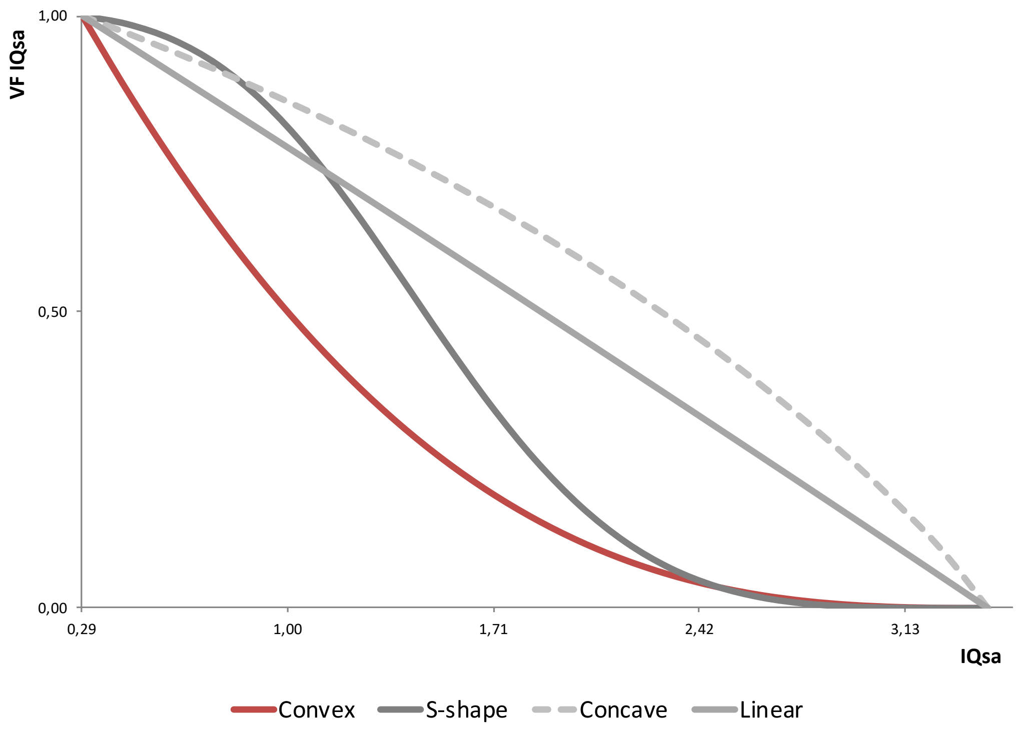


Figure 3.2 Different types of Value Functions applied to the Energy Efficiency Indicator IQ_{sa}.

Table 3.6 shows the proposed energy efficiency classification for SL based on VF of the energy consumption indicator (*IQ_{sa}*). The most energy efficient SL (class A) can be obtained by using the most efficient lamp (luminous efficacies of 150 lm/W or more) with a S/P ratio of 2.25 and using correction to the mesopic vison. It is expected that that this level can also be achieved using a very efficient luminaires (maintenance factor 0.8 - 0.85) with an appropriate layout (utilization factor up to 0.4), using the photopic vision but with a bi-level or multilevel luminous flux control profile. Energy efficiency class B can be obtained by using an efficient lamp with luminous efficacies up to 125 lm/W and with a bi-level or multilevel luminous flux control profile.

Table 3.6 The energy efficiency-based classification for SL based on the IQ_{sa} values.

Energy Efficiency Class	VF IQ_{sa}
A	1 – 0.84
B	0.83 – 0.70
C	0.69 - 0.56
D	0.55 – 0.42
E	0.41 – 0.28
F	0.27 – 0.14
G	0.13 – 0.00

Energy efficiency class C and D can be obtained by using a lamp with luminous efficacies of 80 lm/W and more and, with a bi-level luminous flux control although it might be possible to reach these levels using the most efficient lamps with a full luminous flux control. Energy efficiency class E would be obtained by using a lamp with luminous efficacies up to 70 lm/W and with a bi-level luminous flux control. Finally, classes F and G could be derived from using lamps with luminous efficacies lower than 70 lm/W and with a full luminous flux control.

3.2 BARCELONA CASE STUDY

The initial purpose of the SL in Barcelona was a function of security in both property and movement of pedestrians, its history can be summarized in two events: the evolution of lamp technologies and the continuous increase of points of lights in different parts of the city.

The public SL network of Barcelona began in the main streets of the city center, sponsored by a gas company during 1842-1874 and later with the electric network, were installed electric arc lamps on the Ramblas (1882-1898) (Magrinyà and Herce 2002). More details of the SL history can be found in appendix A.2 STREET LIGHTING TIMELINE OF BARCELONA. As the numbers of points of light increased, cities have also grown. In 1844 the SL of Barcelona consisted of 561 lanterns, 417 with a ledge and 144 with chandeliers. In 1861 the city had 1,957 gas lamps and 1,297 oil lamps. In 1901 the gas burners exceeded 13,000 units, 600 oil lamps and 152 electric lamps illuminated the Eixample of Barcelona (Muro Morales 2012).

Nowadays, according to the updated information to GENBA (Street Lighting Management of Barcelona), there are 149,307 luminaires and lamps of which 63% are HPS, 22% LED and 15% of the rest corresponding to MH, FL and HPM. The SL annual energy consumption per habitant is in average to 45 kWh and 71.3 GWh for the total consumption. This consumption represents 20% of the total energy consumption (Barcelona City Council 2020). In order to have an historical picture, the Figure 3.3 shows the annual energy consumption per habitant for SL from 2014 to 2018 corresponding in average to 50.7 kWh/hab and 81.7 GWh for the total energy consumption per year.

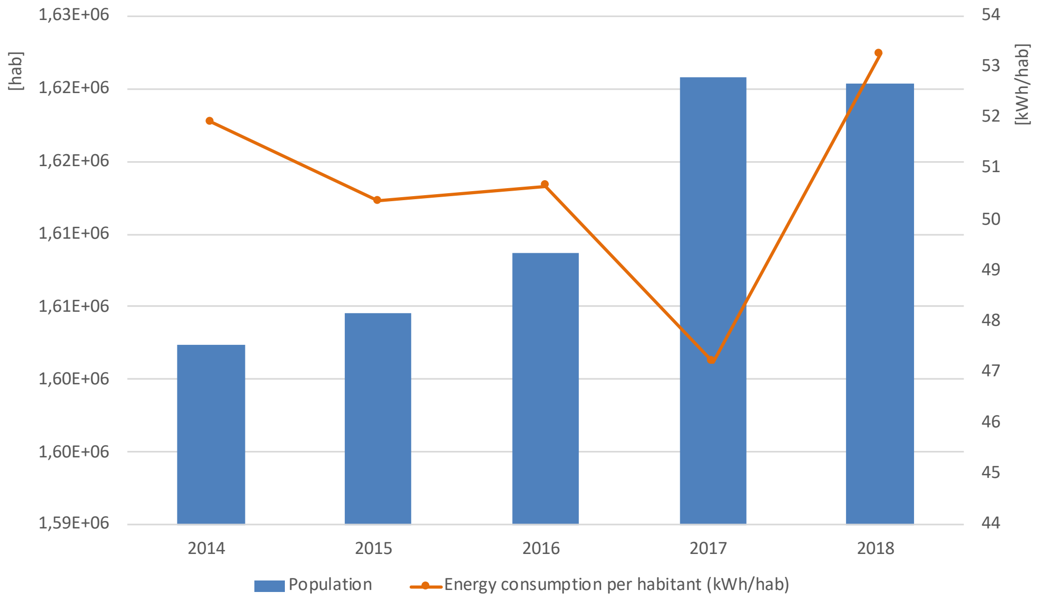


Figure 3.3 Annual energy consumption per habitant for the SL system in Barcelona. (Barcelona City Council 2019)

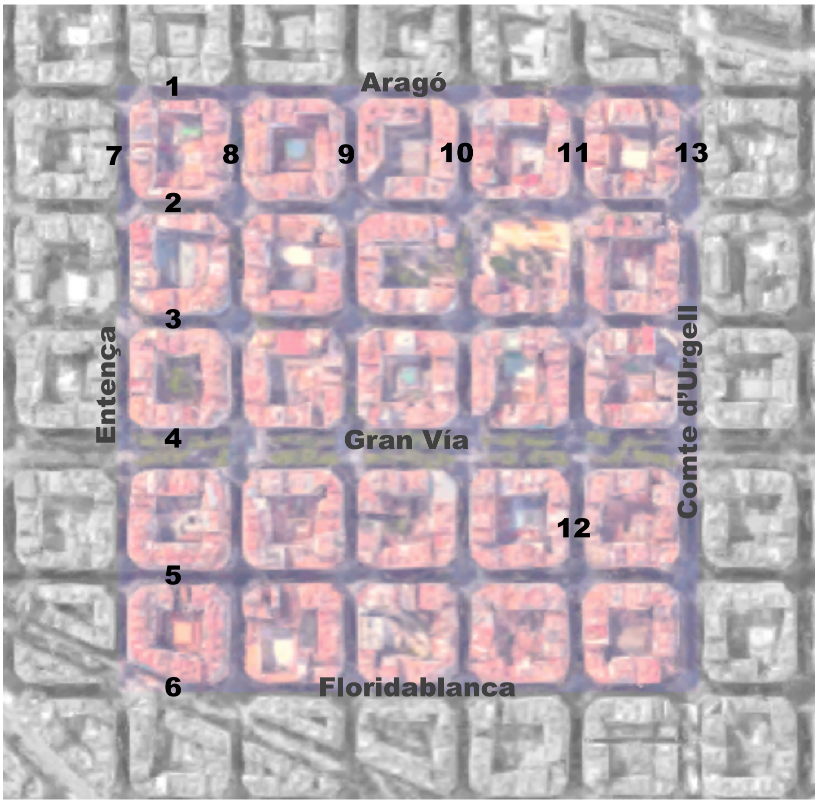
In this regard, Barcelona's council has an ambitious plan for replacing 10,000 existing luminaires with new LED-light luminaires over 200 streets in all city districts. This plan is meant to increase security, energy efficiency and smart management in the SL system by the end of 2020 (Barcelona City Council 2018).

3.2.1 Data collection

To analyze the energy performance of the existing SL system in a representative section of Barcelona, a systematic procedure was carried out by following the approach presented herein.

- Selection. Representative sample of streets.

The Eixample of Barcelona is a uniform grid of quadrangular blocks, that stands out amongst other cities, designed in 1859 by the Civil Engineer Ildefonso Cerdà (Centelles, December 23, 1815 – Caldas de Besaya, August 21, 1876). This urban layout with chamfered corners measures 133.3 m by side, and has regular streets of 20 m, 30 m or 50 m wide (Magrinyà et al. 2009). The selection of urban streets was done in representation of the Eixample District, with a sample of 13 streets divided into 6 horizontals and 7 verticals (Figure 3.4), which have a total length of 8.22 km and 974 luminaires within a whole lit area of 191.5 km^2. As a preliminary step in this case study, it was identified types of luminaires, lighting classes of the street, and type of traffic and street activity.



1	Aragó
2	Consell del Cent
3	Diputació
4	Gran Vía
5	Sepúlveda
6	Floridablanca
7	Entença
8	Rocafort
9	Calabria
10	Viladomat
11	Comte Borrell
12	Comte Borrell 2
13	Comte d'Urgell

Figure 3.4 Sample of the 13 streets analyzed in the Eixample District of Barcelona.

Note: For the sake of completeness Comte Borrell street has been divided into two sections because of it has a different configuration along the street as seen in Appendix A.3.

The Table 3.7 gathers the relevant information of each analyzed street in terms of street distribution and lighting class. From the sample, the percentage of the number of 20 m wide street is 84.6%, 30 m wide is 7.7% and 50 m is 7.7 %. From the streets with 20 m width, 15.4% are lighting class M1, 30.8% M2 and 38.5% M3. Streets 4 and 13 are the widest of the entire sample, 50 m and 30 m, respectively; therefore, these have the highest traffic street activity. The combinations of arrangement, interdistance and height of luminaires are similar between the streets due to the uniform grid layout of the Eixample, except the street 4 which has luminaires height of 5.0 m, 10.0 m and 11.0 m instead of 6.5 m or 9.0 m as other streets. It is noteworthy the variety of type of luminaires in the sample and introducing of LED's as a part of the renovation plan of the SL in Barcelona.

In order to provide more detail of the sample analyzed, in Appendix A.3 is presented the street configuration and the characteristics of lighting arrangement of one span for each street. The span of horizontal street comprises between Entença and Rocafort, and the span of vertical streets comprises between Aragó and Consell del cent.

- Shape. Geometrical characteristics of the streets.

Table 3.7 shows geometric characteristic for each street belonging to the case study. Topology such as the total length (*L*) the sidewalks widths (W_{sr} , W_{sl}), the carriageway width (W_c), the tree-lined street width (W_t) were measured. Data of the luminaires: height (*HL*), interdistance (*d*), arrangement (*Arg.*), and the luminaires' numbers (*#*) was kindly supplied by the GENBA. To enrich this information in each street, the type of luminaires (*Type*) was identified in situ and description is shown in Table 3.8. Lighting classes assigned to the carriageway (*Rd*) and to the sidewalks (*Pd*) were given according to Spanish standard (Royal Decree 1890/2008 2008). Note that most of the analyzed streets have sidewalks on both sides, the widths of these representing the 50% of the total street width; therefore, the pedestrian activity represents an important role in the Eixample of Barcelona. The luminaires are often located on both side of the carriageway with a two-sided staggered arrangement (*TS*), except in the street 4 where some luminaires are two-sided coupled (*TC*) and others are only one-sided (*OS*).

- Classification. Street lighting Classes.

The SL classification, based on the Spanish standard (Royal Decree 1890/2008 2008), is aligned to the classification of streets according to the daily volume of traffic in Barcelona (Security and Mobility Department 2011) according to the street type and the maximum vehicle allowed speed. In Table 3.7 the results of the lighting classification for the 13 analyzed streets are shown.

Table 3.7 Lighting classes and geometrical characteristics of the sample of streets.

No. Street	Lighting class Rd	Lighting class Pd	# Lanes	W_{sr} (m)	W_{sl} (m)	W_t (m)	W_c (m)	W_T (m)	L (m)	Luminaires Total	Luminaires #	Luminaires Type	HL (m)	d (m)	Arg.
1. Aragó	M1	S1	4	5	5	0	10	20	670	81	17	a4	9.0	24	TS
												a6	6.5		
											2	a2	9.0 6.5		
											7	b2	9.0		
											2	b3			
											5	b5	6.5		
											3	c3			
											5	d2	9.0		
											21	d3	7.5		
2. Consell del Cent	M2	S1	4	5	5	0	10	20	670	71	2	a2	9.0 6.5	24	TS
											14	b2	9.0		
											7	b3			
											7	b5	6.5		
											14	c3			
											4	d2	9.0		
											21	d3	7.5		
3. Diputació	M2	S1	4	5	5	0	10	20	670	72	2	a2	9.0 6.5	24	TS
											14	b2	9.0		
											4	b3			
											10	b5	6.5		
											14	c3			
											5	d2	9.0		
											21	d3	7.5		
4. Gran Vía de Les Corts	M1	S1	12	4	3	19	24	50	670	160	80	e3	5.0	14	OS
											9	f3	10		
											11	f2			
											60	g2	11	19	TC
5. Sepúlveda	M2	S2	4	5	5	0	10	20	670	73	18	b2	9	24	TS
												b4	6.5		
											35	c3			
											2	d1	9		
6.Floridablanca	M3	S2	4	5	5	0	10	20	670	70	15	b2	9	24	TS
												b4	6.5		
											28	c3			
											7	d3	7.5		
											3	d2	9		
											2	d1			

Table 3.7 (Continued).

No. Street	Lighting class Rd	Lighting class Pd	# Lanes	W_{sr} (m)	W_{sl} (m)	W_t (m)	W_c (m)	W_T (m)	L (m)	Luminaires Total	Luminaires #	Luminaires Type	HL (m)	d (m)	Arg.
7. Entença	M1	S1	4	5	5	0	10	20	700	70	14	b2	9	22	TS
											5	b3	6.5		
											4	b4			
											5	b5			
											36	c3			
											1	d2	9		
												d3	7.5		
											4	f2	10		OS
8. Rocafort	M3	S2	4	5	5	0	10	20	700	71	1	a4	9	24	TS
												a5	6.5		
											15	b2	9		
											7	b3	6.5	24.2	
											6	b4			
											2	b5			
											35	c3			
											4	f2	10		OS
9. Calabria	M3	S1	4	5	5	0	10	20	700	71	1	a1	9	24.2	TS
												a2	6.5		
											15	b1	9		
											2	b3	6.5		
											6	b4			
											7	b5			
											35	c3			
											3	f2	10		
											1	f3			
10. Viladomat	M2	S2	4	5	5	0	10	20	700	62	6	b2	9	23.8	TS
												b4	6.5	23.7	
											14	c3			
											11	d2	9	23.7	
											21	d3	7.5		
											4	f3	10		OS
11. Comte Borrell	M3	S1	2	7,5	7	0	5,5	20	350	43	10	b2	9	24.2	TS
												b5	6.5		
											21	c3			
											2	f3	10		OS
12. Comte Borrell 2	M3	S2	4	5	5	0	10	20	350	28	6	b2	9	24.2	TS
												b4	6.5		
											14	c3			
											2	f3	10		OS

Table 3.7 (Continued).

No. Street	Lighting class		# Lanes	W_{sr} (m)	W_{sl} (m)	W_t (m)	W_c (m)	W_T (m)	L (m)	Luminaires			HL (m)	d (m)	Arg.
	Rd	Pd								Total	#	Type			
											31	a2	9		
											10		6.5		TS
											21	a4			
13.Comte d'Urgell	M2	S1	5	7,5	7,5	0	15	30	700	102	4	f3	10	23.8	OS
											15	h2	12		
												h4	9		TS
											6	d1			

Rd: road; Pd: pedestrian; W_{sr}: sidewalk right side width; W_{sl}: sidewalk left side width; W_t: tree-lined street width; W_c: carriageway width; W_T: total width of the street; L: length; HL: height of luminaires; d: interdistance; Arg.: Arrangement: TS: two sided staggered; OS: one side; TC: two sided coupled.

- Lighting. Characteristics of the Lighting System.

The database of the lighting system of the area of study was obtained by the GENBA and by visual inspection *in situ* (Table 3.8). GENBA provided the average values of illuminance on the sidewalk and carriageway areas (E_m), Power (*W*) and type of the installed lamps (HPS, LED), among other data corresponding to arrangement, interdistance and height of luminaires. The luminaires were identified *in situ* while the technical data required for the calculation of energy indicators was extracted from the respective manufacturer catalogues. According to GENBA, E_m values are aligned to the diary volume of traffic for each street and it fully complies with the Spanish standard requirements.

Table 3.8 Luminaires installed in the analyzed streets.

Luminaire Image	Type	Lamp properties		Luminaire properties			
		Lamp	Power (W)	ε_L* (lm/W)	IP	ULOR	LOR
	a2- roura y mini	LED	250	125.71	IP66	<0.1%	94%
	a4- roura y mini	LED	100	125.71			
	a5- roura y mini	LED	70	117.14			
	a6- roura y mini	LED	50	117.14			
	b2- salvi conjunto venus	HPS	250	124.55	IP66	<0.1%	87%
	b3- salvi conjunto venus	HPS	150	121.05			
	b4- salvi conjunto venus	HPS	100	118.97			
	b5- salvi conjunto venus	HPS	70	115.00			
	c3- salvi venus	HPS	150	121.05	IP66	<0.1%	87%
	d1- hps (9m)	HPS	350	122.12	IP5X	-	70%
	d2- hps (9m)	HPS	250	124.55			
	d3- hps (7.5m)	HPS	150	121.05			
	e3- salvi - lira balmes	HPS	150	121.05	IP65	<0.1%	75%
	f2- reflector gran vía	HPS	250	124.55	IP5X	-	80%
	f3- reflector gran vía	HPS	150	121.05			
	g2- hps - gran vía	HPS	250	124.55	IP5X	-	70%
	h2 - hps - urgell	HPS	250	124.55	IP5X	-	70%
	h4 - hps - urgell	HPS	100	118.97			

ε_L* lamps+aux (lm/W), ULOR: upward light output ratio, LOR: light output ratio

4 RESULTS AND DISCUSSION

4.1 VALIDATION OF *VF IQ_{sa}*

The energy classification system *VF IQ_{sa}* has been designed taking into account sufficient lighting classes, a huge range of S/P ratios and luminous efficacy of the lamps, and most common light control systems, for allowing to include different lighting scenarios as far as possible.

The proposed *VF IQ_{sa}* was applied to the case study comprised of 13 road of the Eixample of Barcelona. Results are shown in Table 4.1 and depicted in Figure 4.1. Q_{sa} and IQ_{sa} was calculated according to the section 3.1.1.

For calculating Q_{sa}, an operation time of 4,375 h was calculated taking into account the sunrise and sunset data in Barcelona (National Institute of Geography 2017) with a full luminous flux profile in absence of control systems for turning off, totally or partially, the luminaires during the night. It should be noted that some streets of the sample are composed by LED and HPS lamps, therefore the ε_L , f_m and f_u for each street were assigned according to the weighted average of the percentage of types of lamps along the street, and consequently, the mesopic correction factor (f_{cm}) for each street was assigned according to the weighted average of the luminous efficacy of the lamp, because appropriate f_{cm} need to be used for each lamp.

Table 4.1 Value Function of IQ_{sa} and energy classes of the analyzed streets.

No. street	E_m (lx)	ε_L (lm/W)	f_m	f_u	f_{cm}	Q_{sa} (kWh/m^2)	IQ_{sa}	VF IQ_{sa}	Energy Class
1	30	121.4	0.81	0.68	1.02	1.93	0.60	0.76	B
2	20	121.4	0.78	0.58	0.97	1.63	0.76	0.65	C
3	20	121.2	0.78	0.58	0.97	1.64	0.76	0.65	C
4	30	122.6	0.77	0.52	0.98	2.72	0,84	0.59	C
5	20	121.4	0.79	0.56	0.97	1.70	0.79	0.63	C
6	15	121.5	0.78	0.54	0.96	1.33	0.82	0.61	C
7	30	121.4	0.78	0.55	0.98	2.54	0.79	0.63	C
8	15	121.7	0.79	0.56	0.96	1.26	0.78	0.63	C
9	15	121.2	0.79	0.56	0.96	1.27	0.78	0.63	C
10	20	121.8	0.77	0.48	0.97	2.02	0.94	0.54	D
11	15	120.5	0.79	0.55	0.96	1.32	0.81	0.61	C
12	15	121.4	0.78	0.51	0.96	1.42	0.88	0.57	C
13	20	121.6	0.81	0.76	1.05	1.10	0.51	0.82	B

As exposed in Table 4.1 street 1 and 13 achieved an energy efficiency classification B when the most efficient lamps and luminaires are installed with higher values of f_u; while streets with low f_u values resulted in an energy classification D even using efficient lamps. The f_u is the ratio of utilized lumen to the installed lumen and it is affected by some factors as mounting height of lamps and area to be illuminated. This factor is related to the SL layout and typical values attainable range within 0.3 – 0.5 (Pracki 2011). Therefore, it can be stated that there exists a strong relation between f_u and ε_L. Specifically, aspects as luminaire arrangement, road width, luminaire spacing, sidewalk width, etc., could be further explored.

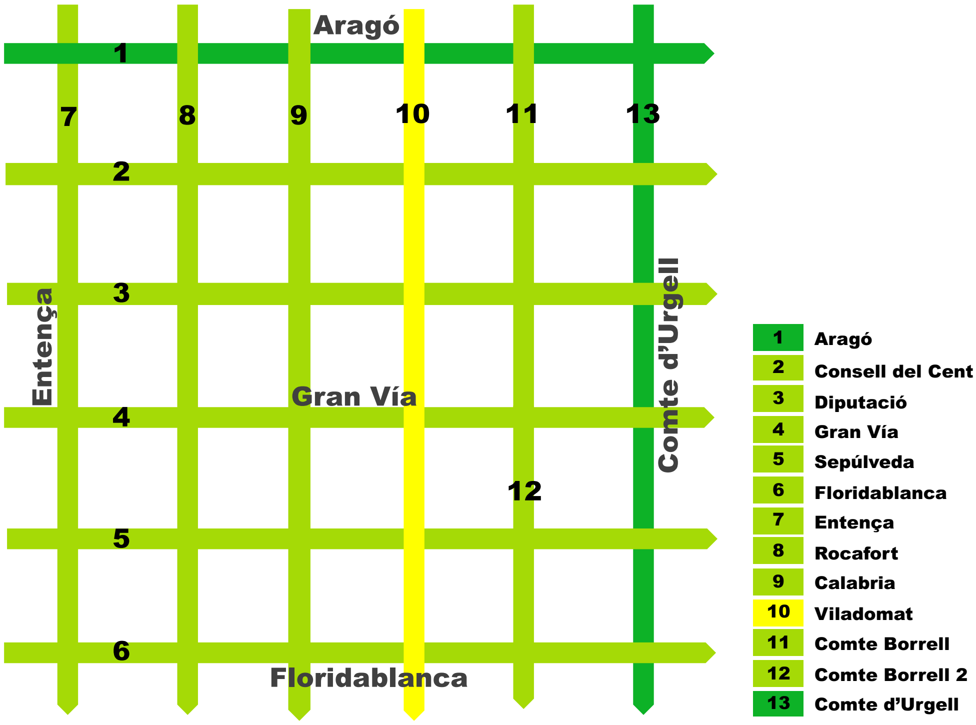


Figure 4.1 Results of the energy classification VF IQ_{sa} proposed of the analyzed streets.

The introduction of the mesopic correction factor f_{cm} into the proposed *VF* IQ_{sa} provided an indication of the luminous efficacy of the lamps used in the case study: HPS and LED. Streets with a large percentage of LED lamps in their composition have obtained a positive increment in the mesopic luminance that could be translated into an improvement in visual performance. On the other hand, streets completely compose of HPS lamps or with a large percentage of it, have obtained a negative increment in the mesopic luminance.

These results suggest two considerations. First, since the overall energy classes achieved were C, therefore it implies that streets of Barcelona have a wide potential of improvement in technological terms. Second, in order to achieve better energy class than C, an improvement of the luminous efficacy of the lamp should be necessary. That implies a replacement of HPS lamps by LED, however as suggested some authors, LED lamps emits more blue light of short wavelengths (S/P > 2.25) than HPS lamp. Blue rich lighting can increase the amount of sky glow between 10% - 20% (CEI 2017; IDA 2010; Jägerbrand 2015). Therefore, the proposed *VF* IQ_{sa} could be limited their use only in urban zones.

4.2 CORRELATIONS BETWEEN ENERGY EFFICIENCY CLASSIFICATIONS

The SL performance of the case study was assessed by applying the current indicators I_ε (Spain), SLEEC (Netherlands) and IPEA/IPEI (Italy). Consequently, the SL performance for each street was determined with its labeling scheme, obtaining the A-G energy classification. To this end, it was considered the total illuminated surface (*A*) including pedestrian and carriageway area and the total power (*P*) was calculated by considering all the luminaires contained along the street, including lamps and electrical auxiliary devices. The average illuminance (E_m) value was provided by GENBA and it complies with the Spanish standard requirements.

Results of the I_ε and its corresponding energy classification for each street analyzed are shown in Table 4.2. From this table, it can be remarked that I_ε varies from 0.61 (street 11) to 1.05 (street 1). This variation can be due to the dissimilarity in the configurations (i.e. type of lamp, luminaires) relating to the SL installations in the Eixample of Barcelona. Regarding the energy A-G classification obtained, streets 1 and 7 have the highest energy classification. In this regard, Figure 4.2 presents the relationship between I_ε and the energy A-G classification obtained for those streets analyzed.

Table 4.2 I_ε values and energy classes of the analyzed streets.

No. street	E_m (lx)	P (kW)	ε (m^2 lx/W)	I_ε	ICE	Energy Class
1	30	11.92	33.73	1.05	0.95	B
2	20	13.81	19.41	0.75	1.34	C
3	20	13.82	19.39	0.75	1.34	C
4	30	34.89	28.81	0.90	1.11	C
5	20	13.85	19.35	0.74	1.34	C
6	15	13.50	14.89	0.65	1.55	D
7	30	13.33	31.51	0.98	1.02	B
8	15	13.49	15.57	0.68	1.48	D
9	15	12.95	16.22	0.71	1.42	D
10	20	12.07	23.19	0.89	1.12	C
11	15	7.54	13.92	0.61	1.65	D
12	15	5.09	20.61	0.90	1.12	C
13	20	21.92	19.16	0.74	1.36	D

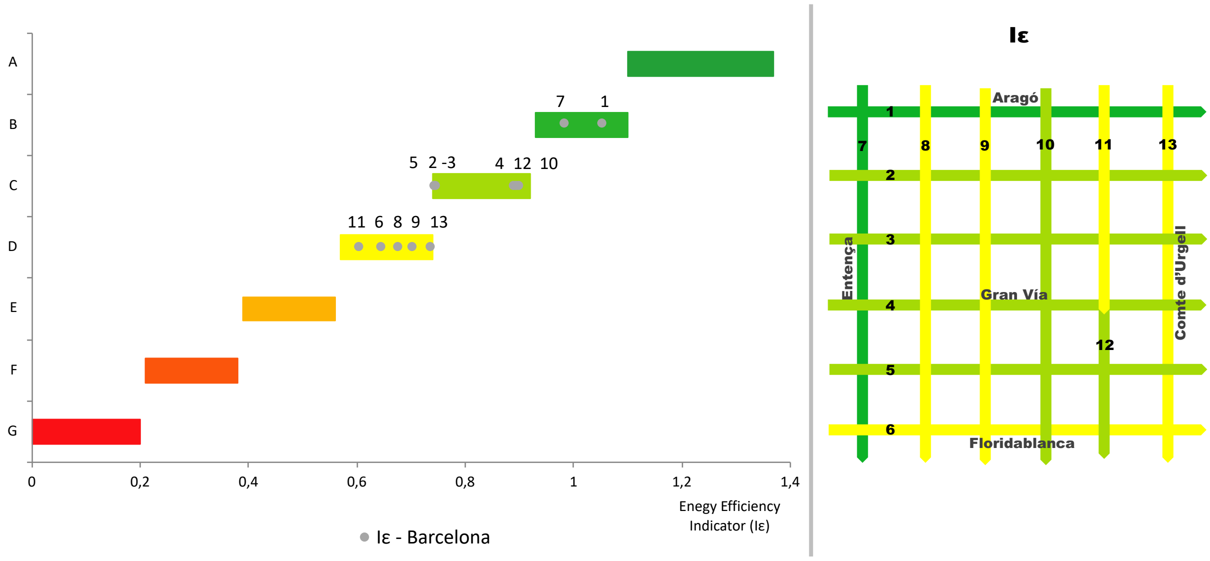


Figure 4.2 I_ε energy classification of the analyzed streets.

The SE values along with the SLEEC label were determined for each SL arrangement and the results shown that 5 of the 13 streets in the sample have obtained SLEEC= E, and the highest energy classification was obtained in the streets 1 and 7 with SLEEC= C (Table 4.3).

Table 4.3 SLEEC values of the analyzed streets.

No. street	E_m (lx)	P (kW)	SE (W/(lx·m^2))	SLEEC
1	30	11.92	0.030	C
2	20	13.81	0.052	E
3	20	13.82	0.052	E
4	30	34.89	0.035	D
5	20	13.85	0.052	E
6	15	13.50	0.067	G
7	30	13.33	0.032	C
8	15	13.49	0.064	F
9	15	12.95	0.062	F
10	20	12.07	0.043	D
11	15	7.54	0.072	G
12	15	5.09	0.049	E
13	20	21.92	0.052	E

The decreasing linear function shown in Figure 4.3 represents the SLEEC label. This reflects a steady decreasing pattern in the energy efficiency classification for increasing SE. There is a proportional relationship between SE values and the energy A-G classification. It is evident that noticeable improvements in the SL installations are required to achieve acceptable labels (higher than C) according to this classification approach.

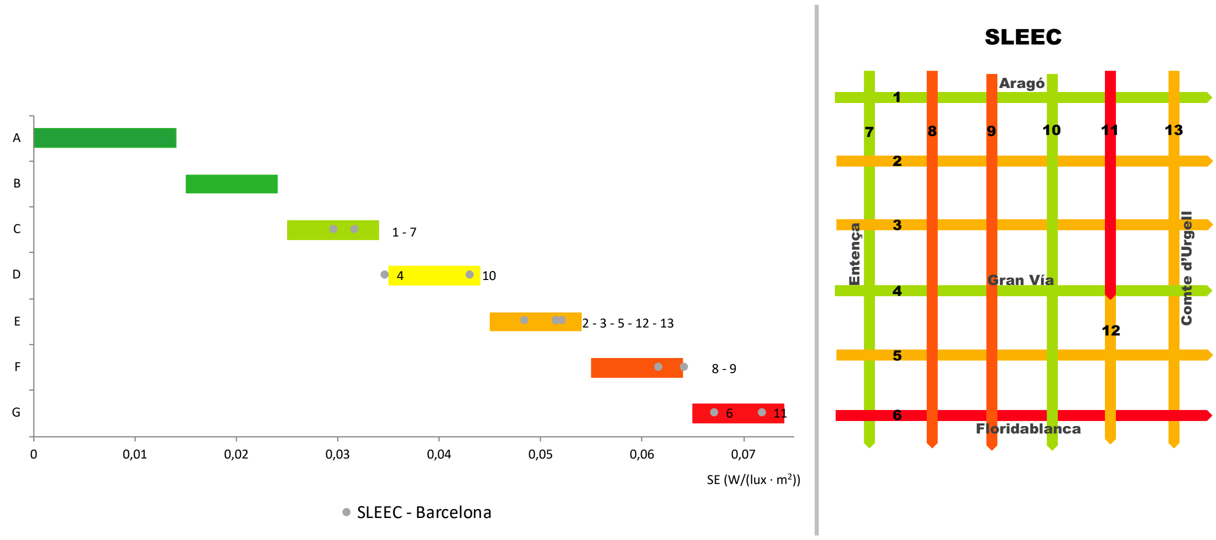


Figure 4.3 SLEEC energy classification of the analyzed streets.

The assessment of IPEA indicator was carried out using the characteristics of the luminaires installed in the analyzed streets (Table 3.8). From Table 4.4, it can be seen 12 types of luminaires at different heights, and according with IPEA indicator *a* (Roura) and *b* (Salvi) luminaires were the most efficient. These luminaires were implemented in the district of Eixample in the year 2000 to renovate obsolete equipment, these improving the energy efficiency of the installation and reducing light pollution.

IPEA values ranging from 0.94 to 1.93 between class A++ and class C (Table 4.4), and according to (Leccese et al. 2017; Regional Council of Emilia Romagna 2015) the class C is the lowest acceptable class for implementing new lighting systems.

Table 4.4 IPEA values and energy classes of luminaires installed in analyzed streets.

Type	P (W)	ε_L (lm/W)	Dlor	η_a (lm/W)	η_r (lm/W)	IPEA	Energy class
a4 (9.0m)	100	125.7	0.99	124.46	75	1.66	A++
a6 (6.5m)	50	117.1	0.99	115.97	60	1.93	A++
b2 (9.0m)	250	124.6	0.87	108.36	93	1.17	A++
b3 (6.5m)	150	121.1	0.87	105.32	81	1.30	A++
c3 (6.5m)	150	121.1	0.87	105.32	81	1.30	A++
d2 (9.0m)	250	124.6	0.70	87.18	93	0.94	C
d3 (7.5m)	150	121.1	0.70	84.74	81	1.05	B
e3 (5.0m)	150	121.1	0.75	90.79	81	1.12	A+
f2 (10.0m)	250	124.6	0.80	99.64	93	1.07	A
g2 (11.0m)	250	124.6	0.70	87.18	93	0.94	C
h2 (12.0m)	250	124.6	0.70	87.18	93	0.94	C
h4 (9.0m)	100	119.0	0.70	83.28	75	1.11	A+

A significant increase in energy class is detected in IPEA values >1, while few changes are presented in the minimum and maximum IPEA values (Figure 4.4).

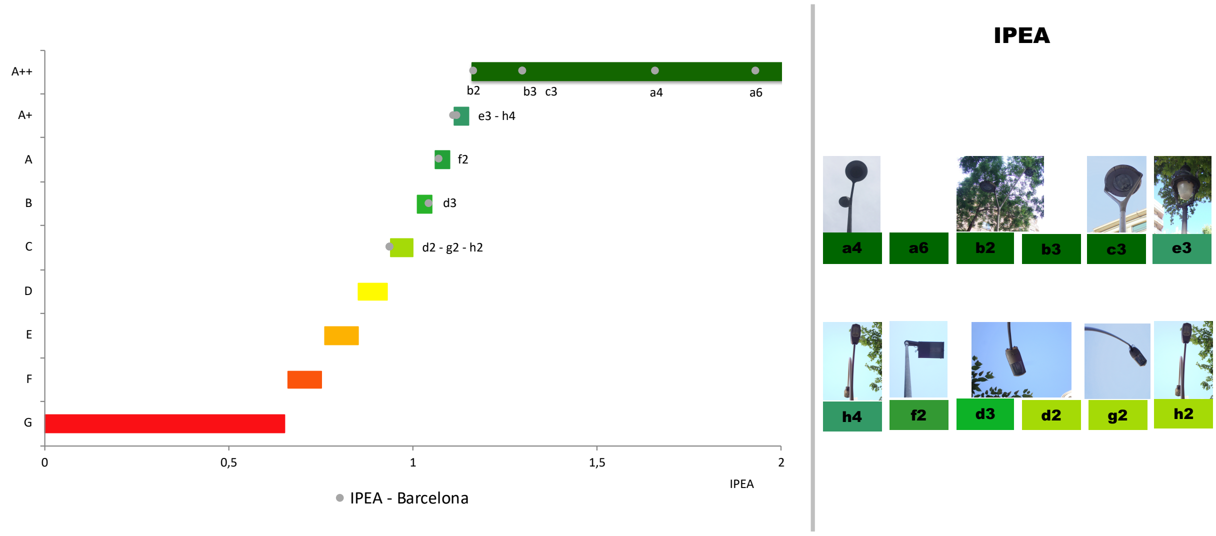


Figure 4.4 Graphic of the label scheme for luminaires in the streets analyzed based on IPEA values.

The IPEI indicator assessment was performed by comparing the lighting values provided by GENBA with those required by technical standard (Royal Decree 1890/2008 2008) considering the street geometries and lighting installations gathered in Table 3.7. In this sense, it should be emphasized that the methods for calculating the IPEI, $I\varepsilon$, SLEEC and VF IQ_{sa} do not specify the assessment for streets composed of both carriageways' lane and pedestrian sidewalks, such as the case of the sample in Eixample's streets. Therefore, within the framework of this research, an IPEI value which considers the installation performance across the entire street section ($IPEI_{Total}$) and another IPEI value ($IPEI_w$) calculated as a weighted average of the values obtained for the subareas, in which each street can be divided into, were considered. The latter was proposed in reference (Leccese et al. 2017) since different lighting requirements should be met for each of the subareas and, thus, appropriate values of $E_{m,r}$ or $L_{m,r}$ have to be used accordingly.

The overall energy classes of the analyzed streets resulted from applying the IPEI indicator resulted low (Table 4.5) and not acceptable, $IPEI_{Total}$= D being the best classification (assigned to the streets 1, 4 and 7).

An advantage of measuring the IPEI per street subareas is having an estimation of the individual energy consumption. This allows identifying areas where the system can be improved and, hence, increasing the global lighting performance if these are implemented. $IPEI_w$ values shown in Table 4.5 confirms a lighting overdesign in the subareas. Figure 4.5 represents the energy classification of each street analyzed according to the IPEI values obtained. The highest IPEI values were obtained for streets 9, 8, 6 and 11 whilst the lowest IPEI for streets 1, 7, and 4.

Table 4.5 IPEI values and energy classes of the analyzed streets.

No. street	P (kW)	$IPEI_{sr}$	Class	$IPEI_{sl}$	Class	$IPEI_t$	Class	$IPEI_c$	Class	$IPEI_{Total}$	Class	$IPEI_w$	Class
1	11.92	2.82	F	2.82	F			2.82	F	1.41	D	2.82	F
2	13.81	3.27	G	3.27	G			4.64	G	2.32	E	3.96	G
3	13.82	3.27	G	3.27	G			4.65	G	2.32	E	3.96	G
4	34.89	5.16	G	6.89	G	1.09	B	1.72	D	1.65	D	2.07	E
5	13.85	4.31	G	4.31	G			4.66	G	2.33	E	4.48	G
6	13.50	4.20	G	4.20	G			5.74	G	2.87	F	4.97	G
7	13.33	3.02	F	3.02	F			3.02	F	1.51	D	3.02	F
8	13.49	4.01	G	4.01	G			5.49	G	2.74	F	4.75	G
9	12.95	2.94	F	2.94	F			5.27	G	2.63	F	4.10	G
10	12.07	3.59	G	3.59	G			3.88	G	1.94	E	3.74	G
11	7.54	2.28	E	2.44	E			11.16	G	3.07	F	4.78	G
12	5.09	3.03	F	3.03	F			4.15	G	2.07	E	3.15	G
13	21.92	3.31	G	3.31	G			4.70	G	2.35	E	3.35	G

$IPEI_{sr}$ – sidewalk right side; $IPEI_{sl}$ - sidewalk left side; $IPEI_t$ - tree-lined street; $IPEI_c$ – carriageway.

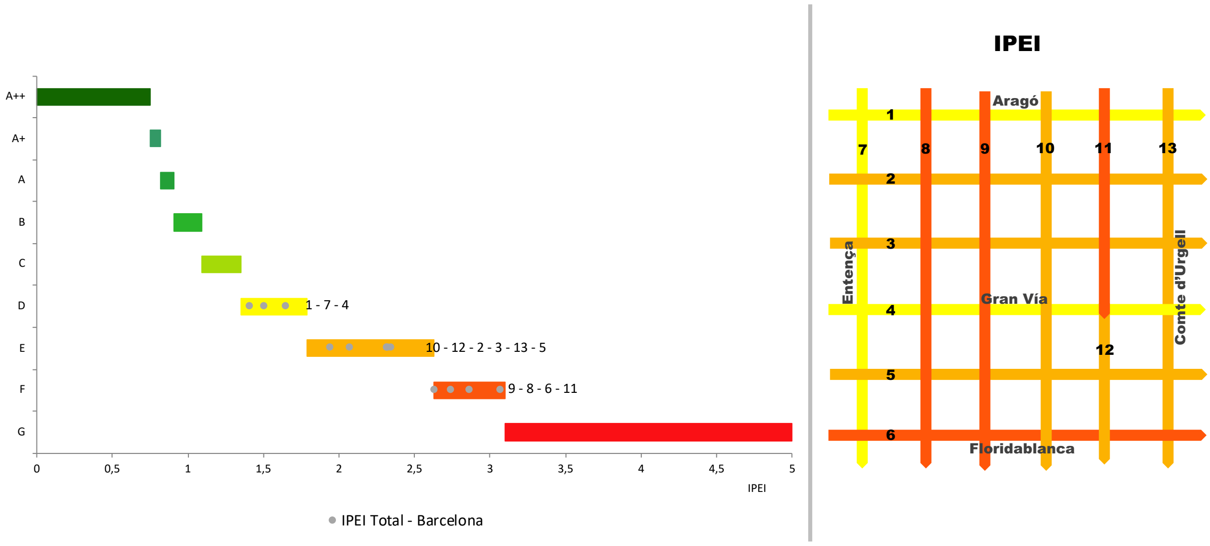
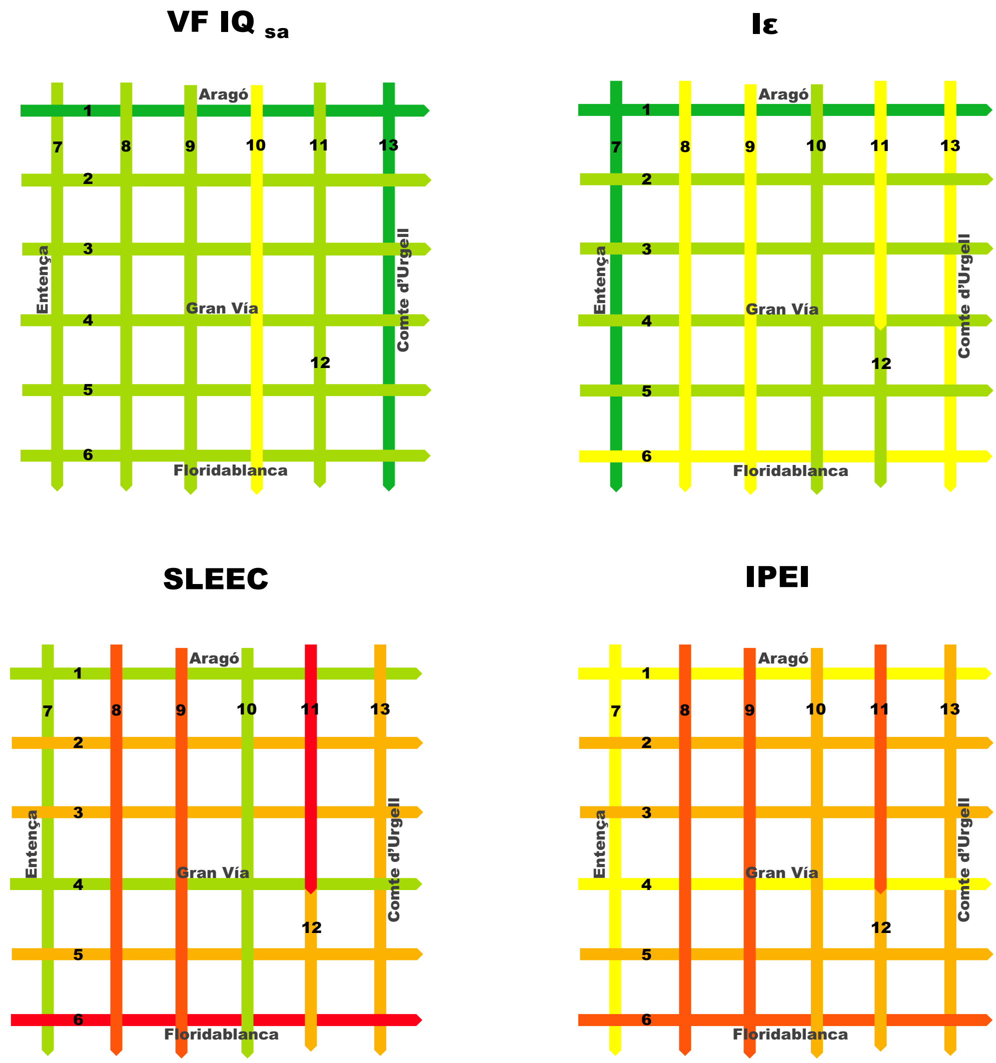


Figure 4.5 Graphic of the label scheme for the analyzed streets based on IPEI values.

4.3 DISCUSSION

The following considerations can be outlined from results obtained by applying each EPI's and its corresponding ECS to the case study of the streets on the Eixample neighbourhood of Barcelona.

Figure 4.6 gathers the classifications of each street according to the different approach considered. As expected from the previous results, the overall energy classes in the analyzed sample have differences. The reason for these differences is that: (1) each energy efficiency indicator accounts for different constitutive parameters and, (2), that the exigency levels of each energy classification (calibrated according to particular targets and lighting requirements) are also different.



VF IQ $_{sa}$	SLEEC	IPEI	Iε	
B	C	D	B	**1 Aragó**
C	E	E	C	**2 Consell del Cent**
C	E	E	C	**3 Diputació**
C	D	D	C	**4 Gran Vía**
C	E	E	C	**5 Sepúlveda**
C	G	F	D	**6 Floridablanca**
C	C	D	B	**7 Entença**
C	F	F	D	**8 Rocafort**
C	F	F	D	**9 Calabria**
D	D	E	C	**10 Viladomat**
C	G	F	D	**11 Comte Borrell**
C	E	E	C	**12 Comte Borrell 2**
B	E	E	D	**13 Comte d'Urgell**

Figure 4.6 Comparing energy performance indicators and its energy classification of the analyzed streets.

As mentioned in section 2.3, SLEEC is an indicator which relates the electrical power required to achieve the average illumination level in a certain surface to be illuminated. According to the results, this indicator presents a strong linkage with the power consumed by lamps and ballast of the system, therefore any improvement in the system, will be result in a better energy classification as can be seen in Figure 4.3.

Another important finding was the relationship with the lighting class of the streets. The average illumination level (E_m) of a street is given according to its lighting class. For those streets with higher E_m such as 1 and 7 the energy classification was C, higher than streets with the lowest values of illumination level (6, 8, 9 and 11). In this sense, by applying SLEEC could be misrepresent at increased the E_m for achieving a better rating, thus, another element should be incorporated into the indicator to penalize the score if the illumination average exceeds the lighting standard corresponding to the lighting class.

Unexpected result was given in street 4 (Gran vía). This street achieved SLEEC=D with biggest power value 34.89 kW and average illumination level 30 lx. That suggest that lighted surface parameter makes the difference, because it is the widest street in the sample of this case study.

The Energy Efficiency Indicator I_ε is based on the three parameters: total installed power, average illuminance and the lit-up surface, and likewise as the SLEEC indicator, the highest energy A-G classification achieved by applying the I_ε were obtained in the streets 1 and 7. However, the rest of the streets have obtained C and D energy classification. An explanation of these differences might be that the I_ε needs an energy efficiency value of reference, which is dependent of the illuminance average of the street.

The IPEI indicator calculation is based on SLEEC and, even though some streets have obtained the same energy classification value such as 2, 3, 4, 5, 8, 9, 12 and 13, the others have obtained worse value. These differences might be explained because of the reference value (SE_R *or* SL_R) and the correction factor (k_E or k_L) that are needed to calculate IPEI.

The SE_R or SL_R are intrinsically related with the lighting classification of each street, and the k_E or k_L compares the measured lighting values with those required by the reference technical standards. According to the data kindly proportionated by GENBA, all the streets in the case study fully complies with the average illuminance required by the RD 1890/2008, therefore, if this data is correct and fixed, the main parameter that influences the low rating obtained by applying IPEI indicator, might be the electrical power required to achieve the average illuminance level. This finding is contrary to the previous studied by Leccese *et. al.* (Leccese et al. 2017), because these results were linked with illuminance level rather than installed power, where the corresponding IPEI energy classification was penalized with very low illuminance levels.

The results obtained by applying $VF\ IQ_{sa}$ showed that there is a strong linkage between the utilization factor and the luminous efficacy of the lamp. Contrary to SLEEC, IPEI and I_ε, this new energy classification proposed herein is understood as a measure of the energy performance of lamps and power suppliers required to achieve the average illumination level in a certain time.

The higher levels of energy efficiency classification obtained with $VF\ IQ_{sa}$ can be corroborated by the results obtained with IPEA. This is because IPEA, likewise $VF\ IQ_{sa}$, is an indicator for measuring the energy performance of the luminaires. IPEA values obtained ranging between class A++ and class C, and consequently *VF* IQ_{sa} values are above of the C level.

Unlike the IPEA indicator, *VF* IQ_{sa} is based on the energy consumption indicator (Q_{sa}) which comprises other parameters, besides luminous efficacy of the lamps, such as Illuminance, time, maintenance factor, utilization factor, additionally, the correction factor of the mesopic photometry and operational hours. That allows incorporate other elements into discussion. For example, the results obtained by applying *VF* IQ_{sa} permit confirming that there is a strong linkage between the ratio of utilized lumen (f_u) and the luminous efficacy of the lamp. Therefore, this new energy classification proposed herein could be useful to design illumination SL project, as well as to evaluate existing lighting installation considering an A-G scale.

On the other hand, the use of the *VF* IQ_{sa} could be limited only for urban areas because LED lamps presents some restrictions that can affect the natural zones protected.

The result obtained by applying the value function (VF) approach to the energy performance indicator (IQ_{sa}) was an energy efficiency classification (VF IQ_{sa}) in a value scale between zero and one, and then an A-G scale was proposed. The original contribution by incorporating the VF approach to the method proposed herein are twofold. The former is related to the flexibility of VF by establishing the range of minimum ($IQ_{sa,min}$) and maximum ($IQ_{sa,max}$) values that it could increase or decrease a percentage, depending of the lighting project to be analyzed. Moreover, it allows adapting the SL requirements of each SL project through the election of the function type (convex, concave, S-shape, linear), therefore it could be adapted depending of the lighting requirements (i.e. by country, standards, etc.). The latter is related to the fact that this was the first time that the VF approach was applied for such a purpose in SL sector.

5 CONCLUSIONS

5.1 GENERAL CONCLUSIONS

This thesis presents an energy efficiency classification procedure based on the parameters that affect the energy consumption for street lighting (SL) as a new proposal to have more accurate and representative assessments. As a result of examining different EPI, an opportunity to incorporate two parameters disregarded by the most commonly used energy classification approaches in Europe appears: (1) the correction to the mesopic photometry, recommended within the CIE 191:2010, and (2), the operational hours of the SL system.

Incorporating these two parameters into the energy consumption indicator (IQ_{sa}) allows to include a wide range of SL solutions, expanding energy consumptions values in the range of minimum ($IQ_{sa,min}$) and maximum ($IQ_{sa,max}$). These values have defined the limits in the value function approach for the case study in Barcelona, which comprises 13 street in a reticular grid of the Eixample District.

From the results obtained by applying *VF* IQ_{sa} to the case study, it is possible to confirm that there is a strong linkage between the ratio of utilized lumen and the luminous efficacy of the lamp. Therefore, this new energy classification proposed herein is understood as a measure of the energy performance of lamps and power suppliers required to achieve the average illumination level in a certain time. Additionally, it could be useful to design illumination SL project, as well as to evaluate existing lighting installation considering an A-G scale.

Regarding to the value function method, this research shows that VF method is valid to standardize an indicator and also suited to be applied for measuring the preference or grade of satisfaction associate with the energy consumption in SL system. After applying VF for the first time in the streets of the case study of Barcelona, it can be concluded that it is a robust and flexible approach that could be useful for evaluation purposes.

It is flexible since the range of minimum ($IQ_{sa,min}$) and maximum ($IQ_{sa,max}$) and the shape of the value function can be adapted to the particular boundary conditions and requirements stablished by the stakeholders (ex., designers, police makers, public investors).

Nonetheless, as a future research, this energy classification system could be improved in two ways. On the one hand, by incorporating other social, economic and environmental indicators, besides energy efficiency, to advance on the assessment of an integrated sustainable system for SL. In this sense, insufficient research has been carried out to an integrate system for measuring sustainability on SL systems. On the other hand, by applying *VF* IQ_{sa} in case studies with luminous flux profiles.

The thesis has proven the hypothesis stated in the Introduction chapter: the analysis of the EPI and ECS used to measure energy efficiency in SL will provide the basis to propose an alternative energy efficiency classification that considers parameters disregarded, and the correlation of energy efficiency classification systems in a local case study will allow validation of the methodologies.

This thesis can contribute to change the paradigm that SL systems are based upon the implicit notion that sustainability deals with only to save energy by reducing installed power in the lighting system to achieve the lighting requirements. Many recommendations related to energy reductions, mesopic vision, circadian system and light pollution have been documented in many researches, but these concepts have not been implemented in the current energy efficiency classifications. For this reason, it was found necessary to scale all those researches to the practice, and this thesis have intended to contribute to that.

5.2 SPECIFIC CONCLUSIONS

From the detailed analysis conducted in Chapter 3 on the different ECS and its corresponding EPI, and from their application to the case study composed of 13 representative streets of the Eixample District of Barcelona, the following conclusions can be drawn:

- All the EPI analyzed have rewarded lighting installations in streets that have introduced the most efficient lamps.
- SLEEC, IPEI and I_{ε} comprises energy performance indicators which relate the electrical power required to achieve the average illumination level in a certain surface to be illuminated. Each indicator analyzed presents a different linkage with their parameters, for instance, SLEEC and IPEI indicators showed a strong linkage with the installed power parameter, while results of I_{ε} were found to be influenced by the Illuminance parameter.
- SLEEC penalizes streets with higher installed power using low illuminance levels, while IPEI penalizes the excessive installed power to achieve the average illuminance level required.
- IPEA is a very useful indicator for measuring energy performance of luminaires by considering the luminous efficacy, however, this does not take into account aspects of lighting design and luminaire operation.
- VF IQ_{sa} is linked to the luminous efficacy of the lamp, maintenance, and utilization factors of the SL installations, this implying that these values have to be periodically and carefully updated.
- VF IQ_{sa} results are clearly influenced positively by the energy performance of lamps and luminaires installed in the streets analyzed in Barcelona.
- *VF* IQ_{sa} could be limited their use only in urban zones.

Design principles section explained all the components required to develop the alternative EPI (IQ_{sa}) with its corresponding ECS (*VF* IQ_{sa}), the following conclusions can be outlined:

- Q_{sa} is an energy consumption-based indicator that comprises average illuminance, time, luminous efficacy, maintenance factor, utilization factor, additionally, two correction factors of the mesopic photometry and operational hours, respectively.
- Q_{sa} was calculated for a wide range of possible technical scenarios for SL. The results given by introducing these two factors to the global energy consumption equation show that major energy savings are achieved when is using lamps with S/P ratio >1.8, such as LED or MH, with individual luminous flux control. Another important finding was that HPS lamps had a negative energy performance when these are evaluated in the mesopic region.

Although this application focuses on energy savings by using different luminous flux controls and the correction for mesopic photometry, these findings have a significant implication for the understanding of how S/P ratio of the lamp influences in both the energy saving and the visual performance.

It is necessary to create public awareness about how SL can enhance to the quality of life of those using public spaces at night so all the actors involved in the SL design can respond, otherwise, it will continue measuring energy performance of a SL system based on the existing EPI and ECS. As explained in this thesis, indicators that takes into account the S/P ratio as a parameter not only to reduce energy consumption but also to improve visual performance and circadian system. It is unfortunate that this parameter is not being considered into the current EPI. In the same way, taking into account operational hours as a parameter in EPI can contribute to design luminous flux profiles according to the visual demands of pedestrians and drivers at night.

5.3 LIMITATIONS

Despite the reliability of the findings, there are limitations to be considered when analysing the results. One of the main limitations noticed in the case study application was the availability and accessibility of data. Most of the data needed was provided by the GENBA and by visual inspection in situ, however, some specific data for calculating utilization factor and maintenance factor was missed. Owing to this, it was necessary to use manufacture catalogues of luminaires to obtain such specific data.

The problem relies when some luminaires of the sample are outdated, so it was difficult to find information. Consequently, it had to be consulted a Spanish guideline for exterior lighting (CEI-IDAE 2002) for calculating the utilization factor. This guideline contains specified technical requirements and lighting levels to be met by the exterior lighting. On the other hand, to solve the lack of information for calculating the maintenance factor such as the local atmospheric contamination, the grade of protection of the luminaires and the total burning hours of the lamps, it was used the median values given in the Spanish lighting standard RD 1890/2008 (Royal Decree 1890/2008 2008) and to follow some recommendations given in (Mockey Coureaux and Manzano 2013).

Another limitation during the research, that does not directly affect the results, was the absence of instruments and technological tools to measure the amount of light (lx) and the SPD (S/P ratio) of the light sources, respectively. The former would have enriched the results when calculating the IPEI indicator, since it relates the illuminance value measured with the value established by the lighting standard. The latter would have helped to analyse deeply the results obtained by applying $VF\ IQ_{sa}$.

5.4 FUTURE PERSPECTIVES

Based on the findings of this thesis, some suggestions for future research work are listed below. These suggestions are meant to encourage the realization of truly sustainability-centred lighting, to advance on the assessment of an integrated smart and sustainable system for SL.

- Develop a method for analyzing the sustainability in SL systems based on multi-criteria techniques that allows incorporating other social, economic and environmental indicators, besides energy efficiency.
- Verify the current criteria that defines the SL sustainability and propose alternative criteria based on the rapid technological developments in exterior light sources (LED), the proliferation of intelligent infrastructures (IoT, data science), the recent advances in mesopic vision and its influence in health and vision performance, and the awareness of the light pollution as true atmospheric, environmental and health problem.
- Extend the data base of SL of Barcelona city, in order to compare SL performance in different neighborhoods.

Further research might explore the contribution of SL to the urban mobility post COVID-19 outbreak. During the lockdown, some cities have reorganized the urban mobility system as a response to contain the contagion and to allow the progressive reincorporation of activities into the "new normality". That is the introduction of new cycleways, widened sidewalks and pedestrian and cyclist priority streets (Cols 2020; Laker 2020; Reid 2020). The criteria for lighting should be changed if the principal user of the street are pedestrians and cyclists, therefore there will be a need to change the lighting requirements to improve visual performance while reducing energy consumption.

A APPENDIX

A.1 LIGHT POLLUTION PARAMETERS

- Upward Light Ratio (ULR):

$$URL = \frac{\phi_{lum\ up}}{\phi_{lum\ tot}}$$

where:

$Ø_{lum\ up}$ = luminous flux of a luminaire emitted at and above the horizontal (lm)

$Ø_{lum\ tot}$ = luminous flux of all installation emitted at and above the horizontal (lm).

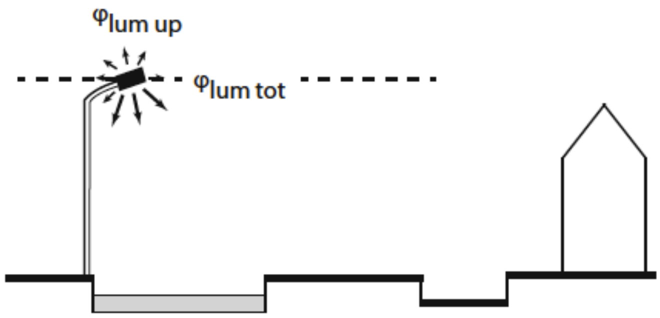


Figure A.1 The variables used in ULR road. (van Bommel 2015b)

- Upper Flux Ratio (UFR):

$$UFR = \frac{E_{av,initial}}{E_{av,maint}}\left\{1 + \frac{ULOR}{\rho_{area} * \mu} + \frac{\rho_{surrounds}}{\rho_{area}}\left(\frac{DLOR - \mu}{\mu}\right)\right\}$$

$$\rho_{area} = \frac{\rho_{carriageway} * w_{carriageway} + \rho_{adjacent} * w_{adjacent}}{w_{carriageway+adjacent}}$$

where:

$E_{av,initial}$ = The initial average illuminance of the area to be lit,

$E_{av,maint}$ = The required maintained illuminance of the area to be lit,

ULOR = Proportion of the upward flux to the total flux of the luminaires in their installed position,

DLOR = Proportion of the downward flux to the total flux of the luminaires in their installed position,

ρ_{area} = Reflectance of the area to be lit,

$\rho_{surrounds}$ = Reflectance of the surrounding surfaces,

μ = Utilization factor of the installation related to the area to be lit.

$\rho_{carriageway}$= reflectance of the area to be lit

$w_{carriageway}$= weighted average reflectance of carriageway

$\rho_{adjacent}$= reflectance of the adjacent areas

$w_{adjacent}$= weighted average reflectance of adjacent areas

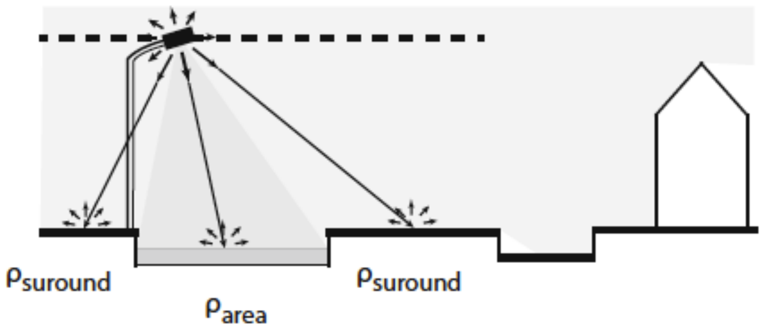


Figure A.2 The variables used in UFR. (van Bommel 2015b)

- Luminous intensities near the horizontal:

Light radiated near the horizontal in a zone between 90º and some 110º travels forward over a much greater distance than does light radiated at higher angles of elevation.

$$I_{90-110}$$

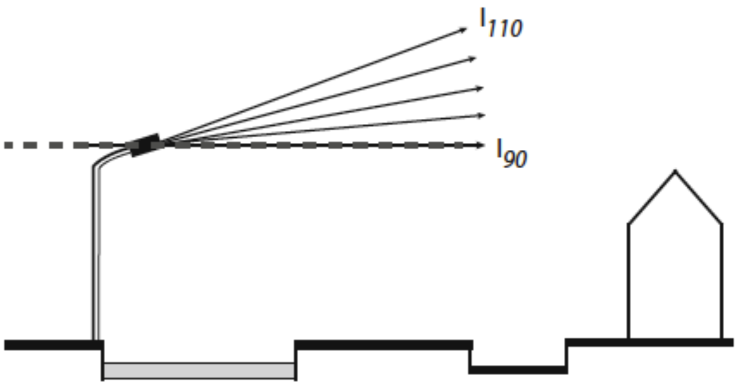


Figure A.3 Luminous intensities critical for sky glow at great distances. (van Bommel 2015b)

- Vertical illuminance on façades:

$$E_{vert,propert}$$

$E_{vert\ propert}$= vertical illuminance on the facades of properties outside the area being lighted.

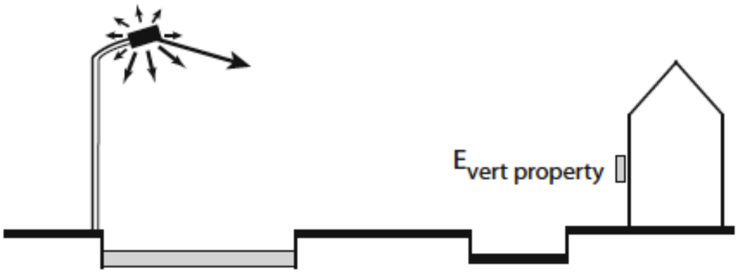


Figure A.4 Vertical illuminance on facades of neighboring property. (van Bommel 2015b)

- Luminous Intensity:

$$I_{property}$$

$I_{property}$= luminous intensity of luminaires in directions where views of bright parts of the luminaires are likely to be troublesome for residents in or around their property.

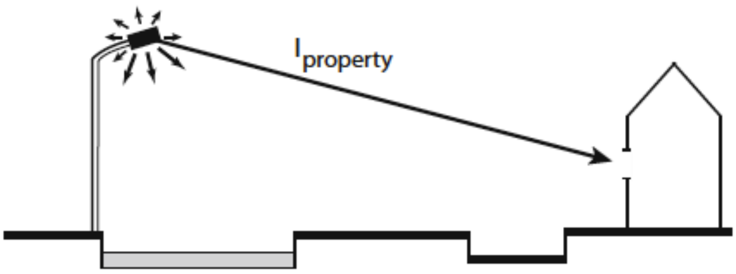


Figure A.5 Luminous intensity in the direction of neighboring property. (van Bommel 2015b)

- Façade Luminance:

$$L_{facade}$$

L_{facade} = luminance of the façade

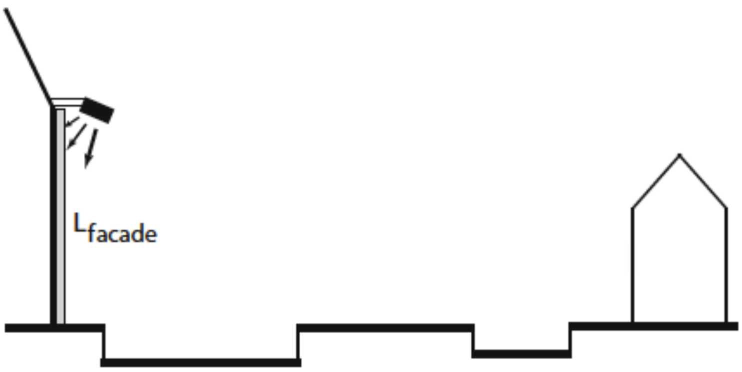


Figure A.6 Facade luminance as a measure to avoid over-lighting. (van Bommel 2015b)

- Veiling Luminance:

The disturbing effect of light pollution to road users is mainly that of increased glare on roads in the neighborhood of the installation responsible for the pollution.

$$L_{veil}$$

L_{veil} = veiling luminance

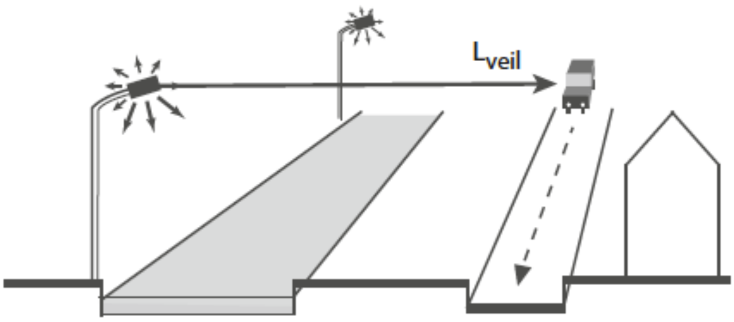


Figure A.7 Veiling luminance experienced by a motorist. (van Bommel 2015b)

A.2 STREET LIGHTING TIMELINE OF BARCELONA

In 1392, the "Consell de la ciutat" ordered to put that a lighted lantern was hung outside on the window along the street. Gas lamps were first used in London in 1807 (S. Fotios and Gibbons 2018), followed in 1841-1842 by Barcelona. Arc lamps were used to light public areas in Paris (1878), Cleveland (1879) and London (1880s) (S. Fotios and Gibbons 2018). In Barcelona, there is a register in 1852 installing the first electric lamps, but in 1881was installed the first electric network connecting 12 arc lamps (Table A.1).

There is not information about the introduction of discharge lamps into the SL installation in Barcelona, however the development of science and technology of these lamps are similar in all regions. In general, low pressure sodium (LPS) lamps were first installed in 1932, high pressure mercury vapor (HPM) in 1933, fluorescent in 1946 and high-pressure sodium (HPS) in 1966.

Table A.1 Street lighting timeline of Barcelona.

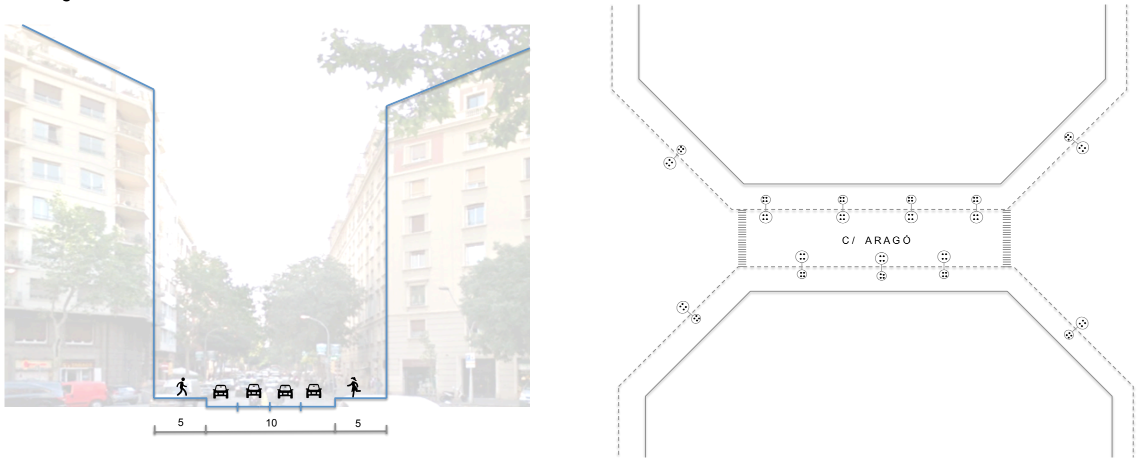
Year	Technology	Description	Source
XIV century	Torches	Gadgets fixed on the grid-shaped walls (Santa Maria del Mar).	
1392	Lighting lantern, candles.	City council urged the residents of the main streets to keep their lights on the windows of the houses at night, trying to improve the traffic of the citizen at very advanced hours.	
1599	First implementation of street lighting with a certain planning and guarantee of continuity, both in the lighting and in the maintenance of the lamps.	60 wrought iron grills were attached on the walls to burn resinous wood.	(Meca Acosta and Iranzo García 2010)
1752	Oil lamps	1,500 oil-lamps were installed in the streets and squares of Barcelona	
1777	Oil lamps	3000 oil-lamps were installed in the streets and squares of Barcelona	
1841	Gas lighting	Josep Roura obtained the first municipal permit to implement gas lighting in the city.	
1844	Street lighting of Barcelona based on gas lighting	Street lighting consisted of 561 lanterns, 417 with a ledge and 144 with chandeliers.	(Muro Morales 2012)
1852	Electric lighting	Barcelona starts to install few electric carbon arc lamps.	(Meca Acosta and Iranzo García 2010)
1852	Electric lighting	Barcelona starts to install few electric carbon arc lamps.	
1861	Street lighting of Barcelona based on gas lamps and oil lamps.	The city had 1,957 gas lamps and 1,297 oil lamps.	(Muro Morales 2012)
1881	Edison's lamp		(Meca Acosta and Iranzo García 2010)

Table A.2 (Continued).

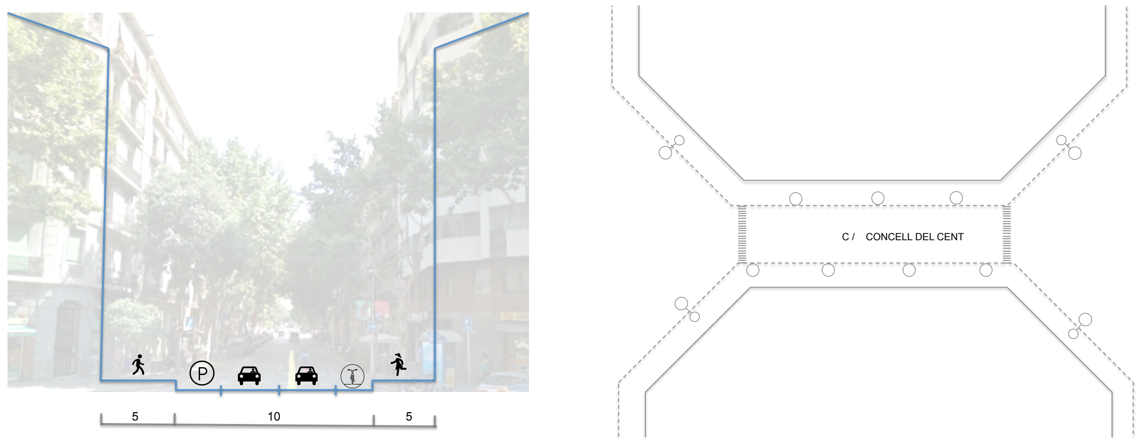
Year	Technology	Description	Source
1881	First electric network in the city	12 electric lamps with an intensity of 1,200 jail lighter, a unit of luminosity that allows comparison with gas lighting, supported by cast iron columns. They replaced 150 gas lamps.	
1887	Electric installation of the Rambla, Paseo de Isabel II, Plaza Palau and Paseo de la Aduana.	100 arc lamps of 2000 plugs.	(Muro Morales 2012)
1893	Electric lamps inventory	103 voltaic arc lamps and 120 jail system arc lamps	
1901	Street lighting inventory	13 000 gas lamps, 600 oil lamps, 152 electric lamps.	
1905	Electric lighting	711 oil light points, 13 079 gas lamps, 228 electricity lamps.	(Meca Acosta and Iranzo García 2010)
1915	Mix of street lighting: oil, gas and electricity	14,688 total lamps. 88% gas =12,900 gas lamp 830 electric lamps	
1922	-	In 1922, powerful 'lanterns' for public lighting were inaugurated by Barcelonesa in the Plaza de Catalunya. It was the intense and dazzling lights that helped develop electricity as an urban business and a well-lit city.	(Muro Morales 2012)
1967	Last gas lamp	Gas lamp turned off and the typical figure of the lamppost finished (lamplighters).	(Meca Acosta and Iranzo García 2010)

A.3 STREET CONFIGURATION AND LIGHTING ARRANGEMENT

1. Aragó



2. Consell del Cent



3. Diputació

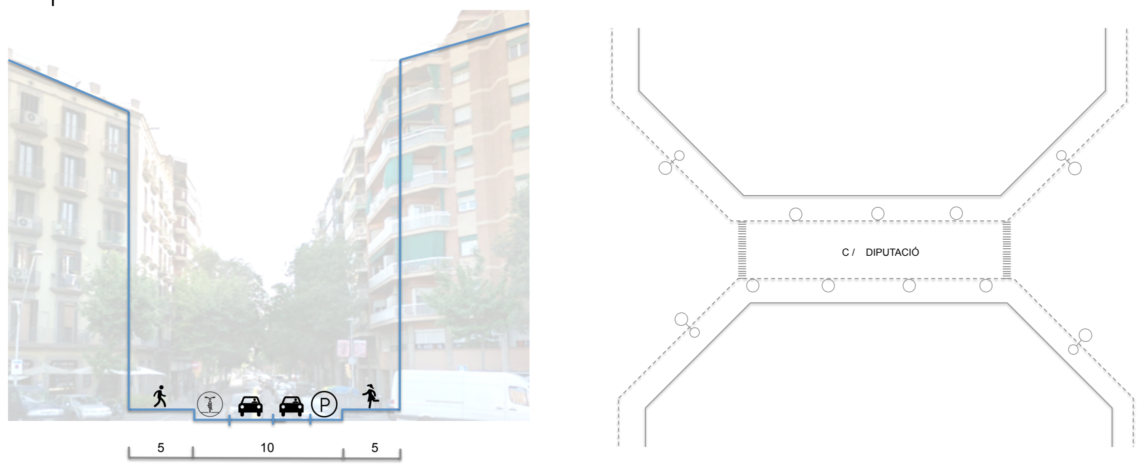
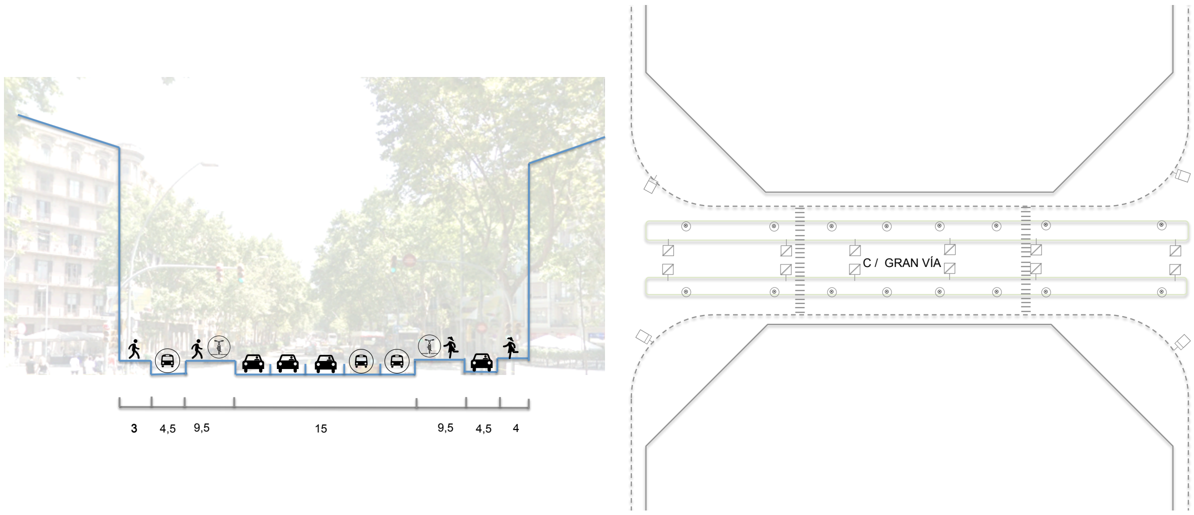
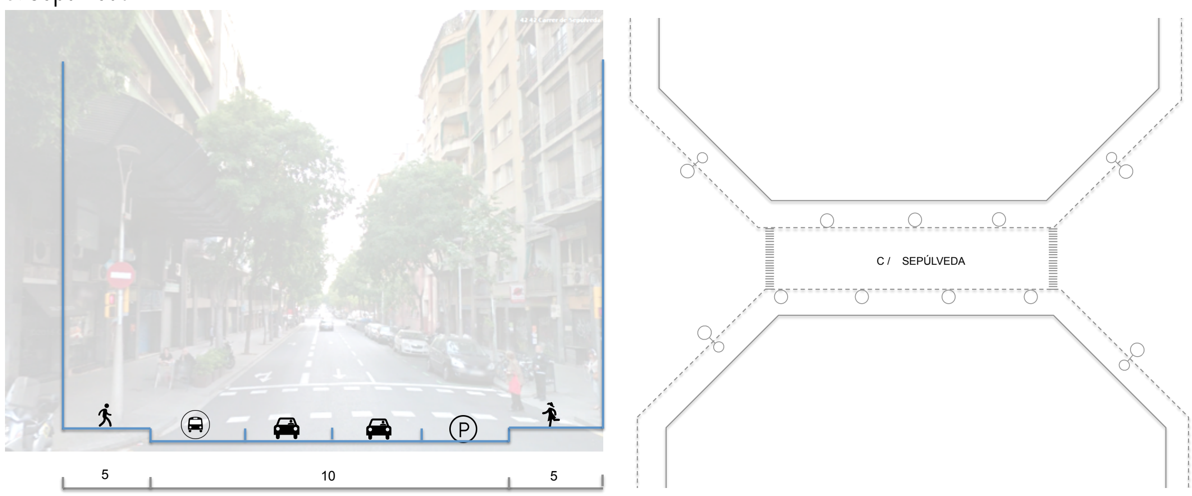


Figure A.8 Examples of one span for analyzed streets: street section (left), plans (right).

4. Gran Vía



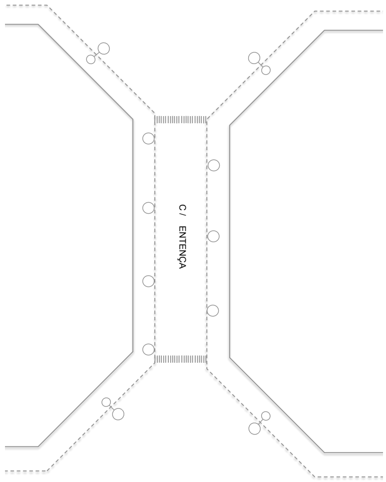
5. Sepúlveda



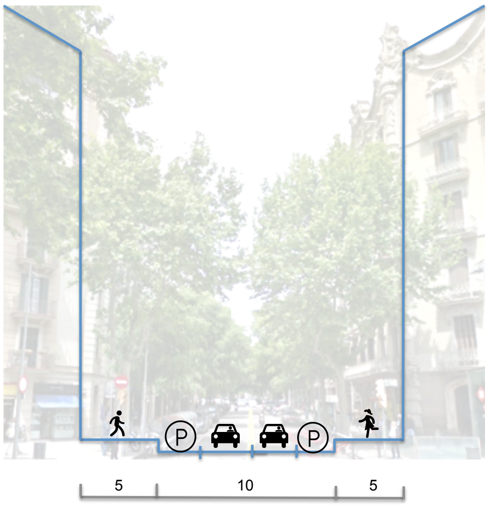
6. Floridablanca

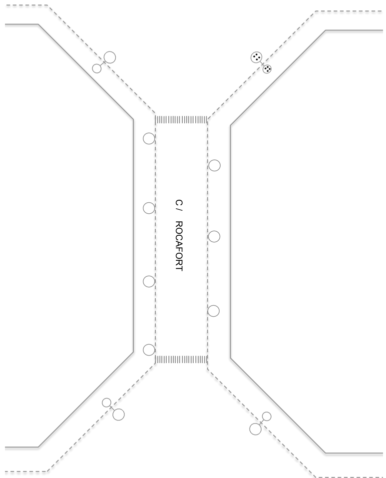
Figure A.8 (Continued).

7. Entença

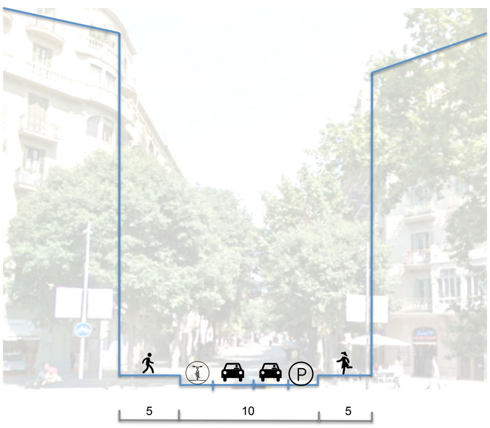


8. Rocafort





9. Calabria



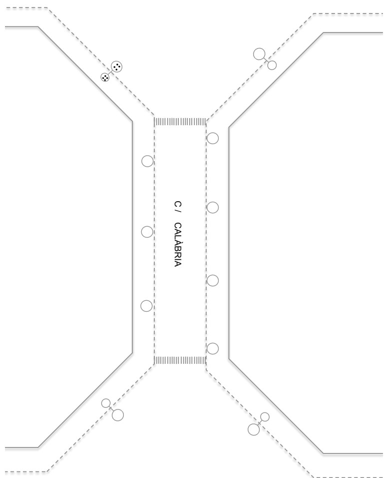
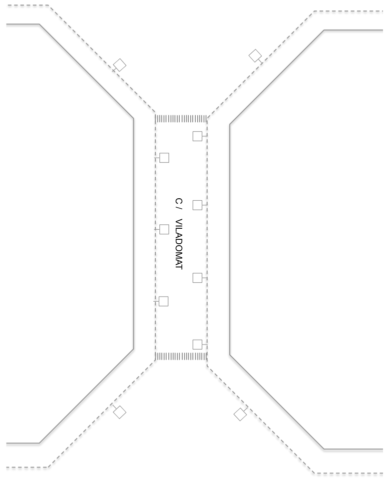
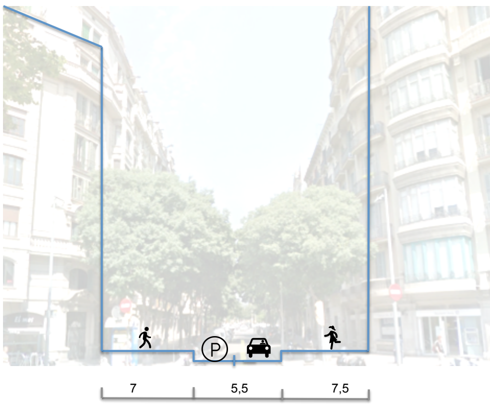


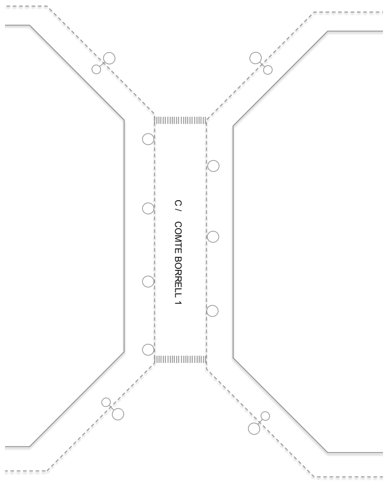
Figure A.8 (Continued).

10. Viladomat

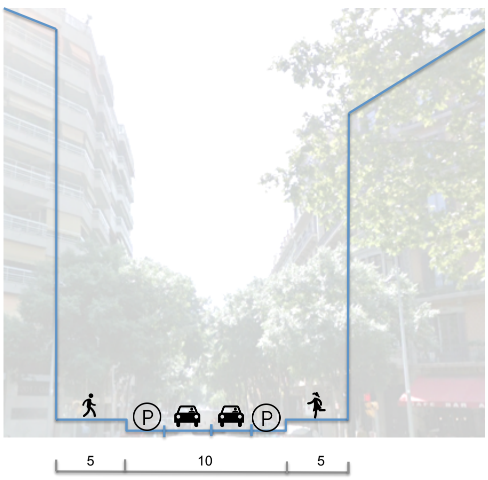


11. Comte Borrell 1





12. Comte Borrell 2



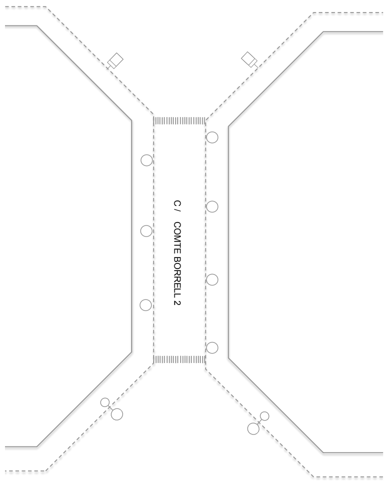
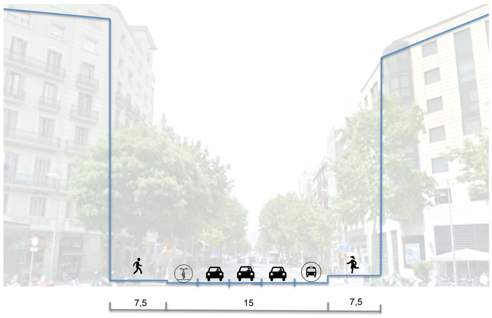
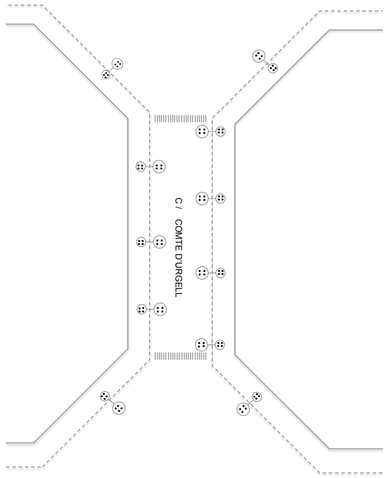


Figure A.8 (Continued).

13. Comte d'Urgell





🚶	Sidewalk	🚗	Traffic lane
🚌	Bus lane	Ⓟ	Parking/ Services
🚲	Cycle lane		

Figure A.8 (Continued).

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PUBLICATIONS

Peer-reviewed and proceedings publications, as well as research project participation are presented subsequently:

(Accepted) Sánchez-Balvás, L.; De Felipe, JJ.; Quintero, JM.; De la Fuente, A. An energy efficiency-based classification approach for street lighting by considering operational factors. Case of study of Barcelona. *Energy Efficiency*, 2020.

Sánchez-Balvás, L.A., Quintero, Jesús M., Sudrìa-Andreu, Antoni, De Felipe Blanch, José Juan and Carreras, Josep. Toward a new model of sustainable urban lighting. XI Iberoamerican Congress of Lighting. "*Proceedings of the XI Iberoamerican Congress of Lighting, Cartagena, Colombia. October 9, 10, 11 and 12, 2012*". National University of Colombia, 2012, p. 193-199.

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