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Energy efficiency indicators in road lighting: critical evaluation in a case study

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Abstract. Road lighting is a fundamental public service for the safety of pedestrians and drivers. Due to the global energy crisis and climate change, energy conservation has become a priority in any country. Road lighting should provide the required quality and quantity of illumination in the most efficient manner possible. In this work, a study of lighting conditions was carried out in an Argentinian city, and energy efficiency was evaluated based on three methods. The results and conclusions of the work provide an objective critique of the advantages and disadvantages of applying each method to measure the efficiency of an installation.

Key words: energy efficiency; energy efficiency indicator; lighting standards; public lighting; road lighting.

1. INTRODUCTION

One of the biggest and most important global problems today is global warming. It is defined as the increase in the Earth's surface temperatures caused predominantly by human activities that increase the concentration of greenhouse gases (GHGs) in the atmosphere. One of these activities is the production of electricity using fossil fuels [1].

Road lighting systems consume electricity, so their rational and efficient use can bring significant benefits, mainly in reducing GHG emissions and thus reducing environmental impact.

Historically, the simple ratio of luminous flux to electrical power consumption (lm/W) known as luminous efficacy has provided a significant value to quantify the efficiency of a lighting system. However, over time, it has been observed that this metric is not enough to evaluate the energy efficiency of a complete road lighting installation. Nowadays, it is known that, in addition to efficacy, many other factors influence efficiency, such as the way the light is distributed over the road, the consumption of control gear, oversizing, light pollution, road geometry, the position of the luminaires, the reflectance of the pavement, and even the age of observers (drivers) [2].

For this reason, a lot of research has been conducted to find the most convenient way to measure the energy efficiency of an installation, but there is still no consensus on the subject.

sheredia@herrera.unt.edu.arIn recent years, Boyce *et al.* [3] pointed out the need for an accepted system to evaluate the energy efficiency of road lighting in terms of a metric such as kW/lx/km or kW/cd/m^2/km.

Kyba *et al.* [4] recommended three policies to reduce energy consumption for outdoor lighting. The first policy is the use of lighting only, when necessary, that is, to reduce the emission of light from luminaires during periods of low activity. The second recommendation is to establish maximum lighting levels. Finally, they propose defining the efficiency of the road lighting system in terms of kWh/km/year.

Gutierrez-Escolar *et al.* [5] proposed an energy efficiency label and a new method to assess energy efficiency for road lighting systems. Their proposal assesses five parameters: lamps, energy efficiency index, light pollution, renewable energy contribution, and dimming luminous flux.

Leccese *et al.* [6] analysed the indicators of the EN 13201-5 standard and two indicators of the Italian standard to promote energy savings in public lighting. They applied these indicators to a city in Italy and the result of this work was a list of pros and cons of using each indicator.

In the case study of Sanchez-Balvas *et al.* [7] in Barcelona, a new approach to evaluating energy efficiency based on a value function is proposed. This proposal includes the use of the CIE 191:2010 Recommended System for Mesopic Photometry and the evaluation of the operating hours of the system.

Pracki [8] presented another way to evaluate the energy efficiency of road lighting. His proposal consists of a table of normalised power density values that facilitates classifying road lighting installations into energy efficiency classes.

The Regulation on Energy Efficiency in Outdoor Lighting Installations [9] was one of the first regulations at the state level and was established by the Spanish Government to improve energy savings and efficiency and, consequently, reduce GHGs for road lighting systems.

In 2010, intending to achieve energy savings in road lighting, the Netherlands Agency NL (Ministry of Economic Affairs,

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Agriculture and Innovation) developed an energy efficiency label system (A to G) based on Street Lighting Energy Efficiency Criterion, SLEEC (ratio of power consumed to road illuminance or luminance and area) [10, 11]. Also, New Zealand and Australia accepted the SLEEC indicator as the basis for their energy rating scheme [12].

The European Union published in 2011 the Green Public Procurement [10] for the energy efficiency of road lighting systems, which were developed based on SLEEC values.

In 2015 the European Committee for Standardization (CEN) published recommendations for the use of energy performance indicators such as the Power Density Indicator (PDI) and Annual Energy Consumption Indicator (AECI) which are included in the new version of the European EN 13201-5 standard [13].

In Latin America, some countries have regulations that include energy efficiency indicators as well as recommendations to reduce energy consumption in road lighting [14, 15].

In Argentina, since 1995, the IRAM-AADL J 2022-2 [16] standard has recommended the use of minimum initial values for lighting parameters. However, in its recent modification of the year 2021, maximum allowed lighting values were added to avoid or decrease the oversizing of lighting installations, thus improving their efficiency.

This paper presents a study of the energy efficiency of road lighting in the downtown area of the San Miguel de Tucumán city, located in the northwest region of Argentina. A survey was conducted between the four main avenues of the city. This area represents the most densely populated area of the city and includes residential and commercial areas connected by important avenues.

This work aims to evaluate the energy efficiency of these road lighting installations based on three methods in order to study the local applicability and to know which one shows the best performance.

2. ENERGY EFFICIENCY EVALUATION METHODS

The Argentinian IRAM AADL J 2022-2 standard classifies roadways and establishes corresponding qualitative and quantitative parameters for their lighting design. The last version of this standard was released in 2021 and, for the first time, included upper limits to lighting levels, in addition to minimal requirements for illuminance and luminance.

This study considers three methods of energy efficiency that are applied in the evaluated area according to the classification of the Argentinian standard (Tables 1 and 2). Note that class C can be specified in terms of luminance or illuminance.

2.1. Handbook Energy Labelling for Public Lighting – Netherlands (N)

The Agency & Ministry of Economic Affairs, Agriculture and Innovation of the Netherlands developed a voluntary initiative that defines energy efficiency levels for road lighting installations.

This method uses an efficiency indicator called the Street Lighting Energy Efficiency Criterion (SLEEC). For illuminance-based road classes, this indicator is called SE and relates installed power (P) with roadway area (A) and the road illuminance (E):

$$SE = \frac{P}{A \cdot E}. \tag{1}$$

Table 3 shows the energy ranking based on the SLEEC indicator.

Table 1
Lighting requirements according to IRAM AADL J 2022-2 standard for A, B, and C road classes in terms of luminance

Class	Minimum luminance	Maximum luminance	Minimum uniformities		TI (%)	G
	Lmed (cd/m^2)	Lmed (cd/m^2)	U_0 (Lmin/Lmed)	U_1 (Lmin/Lmax)		
A	2.7	3.4	0.4	0.7	≤ 10	≥ 6
B1	2.0	2.5	0.4	0.6	≤ 20	≥ 5
B2	1.3	1.6	0.4	0.6	≤ 15	≥ 6
C	2.7	3.4	0.4	0.6	≤ 15	≥ 6

Table 2
Lighting requirements according to IRAM AADL J 2022-2 standard for C, D, E, and F road classes in terms of illuminance

Class	Minimum illuminance Emed (lx)	Maximum illuminance Emed (lx)	Minimum uniformities	
			U_0 (Emin/Emed)	U_1 (Emin/Emax)
C	40	50	1/2	1/4
D	27	34	1/3	1/6
E	16	20	1/4	1/8
F	10	13	1/4	1/8

Table 3
Energy label categories with target ranges for the SLEEC

Label	SE (W/(lux·m^2))
A	0.005–0.014
B	0.015–0.024
C	0.025–0.034
D	0.035–0.044
E	0.045–0.054
F	0.055–0.064
G	≥ 0.065

2.2. Pracki's proposal 2011 (PP)

Pracki's proposal [8] consists of two related indicators. The installed power density indicator (P_D) is the ratio between the installed power (P) for a given road lighting installation and the area of the road surface unit (A) to be evaluated:

$$P_D = \frac{P}{A}. \tag{2}$$

On the other hand, he also proposes a normalised power density indicator (P_N) that describes the installed power density (P_D) required to produce the reference luminance (L) of the road surface:

$$P_N = P_D \frac{1}{L}. \tag{3}$$

Based on this indicator, Pracki proposes an energy efficiency classification for road lighting (Table 4).

Table 4

The energy efficiency classification for road lighting based on the normalised power density P_N $\left(\frac{\text{W}}{\text{m}^2} \text{ per } \frac{\text{Cd}}{\text{m}^2}\right)$

Lighting energy efficiency class		P_N
A	The most energy-efficient	≤ 0.2
B	Very energy-efficient	$> 0.2-0.4$
C	Energy-efficient	$> 0.4-0.6$
D	Intermediate energy-efficient	$> 0.6-0.8$
E	Low energy-efficient	$> 0.8-1.0$
F	Very low energy-efficient	$> 1.0-1.2$
G	The least energy-efficient	> 1.2

This energy classification can be adapted to the particular lighting classes of a standard, i.e. it is possible to calculate ranges of power density to classify the energy efficiency of a road. This is done by multiplying the P_N values from Table 4 by the minimum required luminance for each lighting class in the standard.

Table 5 shows the energy classification that has been adapted to the IRAM AADL J 2022-2 lighting classes used in this work.

The columns show the roadway classification according to IRAM standards and the rows show the energy efficiency classes.

Table 5

Energy efficiency classification adapted to the IRAM AADL J 2022-2 lighting classes, based on the power density (W/m^2)

	C	D	E	F
A	≤ 0.54	≤ 0.38	≤ 0.22	≤ 0.14
B	$> 0.54-1.08$	$> 0.38-0.76$	$> 0.22-0.45$	$> 0.14-0.28$
C	$> 1.08-1.62$	$> 0.76-1.13$	$> 0.45-0.67$	$> 0.28-0.42$
D	$> 1.62-2.16$	$> 1.13-1.51$	$> 0.67-0.90$	$> 0.42-0.56$
E	$> 2.16-2.7$	$> 1.51-1.89$	$> 0.90-1.12$	$> 0.56-0.70$
F	$> 2.7-3.24$	$> 1.89-2.27$	$> 1.12-1.34$	$> 0.70-0.84$
G	> 3.24	> 2.27	> 1.34	> 0.84

2.3. European Standard – EN 13201-5 (EN)

This standard applies to all traffic areas defined in EN 13201-2 [17], which also specifies the accepted oversizing criteria.

The purpose of this European standard is to define energy performance indicators for road lighting installations. The method introduces two metrics, the power density indicator D_P and the annual energy consumption indicator D_E:

$$D_P = \frac{P}{\sum_{i=1}^{n} (E_i \cdot A_i)}, \tag{4}$$

where:

- D_P is the power density indicator, in W·lx^{-1}m^{-2}.
- P is the power of the lighting installation system in W.
- E_i is the average maintained horizontal illuminance of sub-area "i" in lx.
- A_i is the size of the illuminated sub-area "i" by the lighting installation, in m^2.
- n is the number of sub-areas to be illuminated.

$$D_E = \frac{\sum_{j=1}^{m} (P_j \cdot t_j)}{A}, \tag{5}$$

where:

- D_E is the annual energy consumption indicator for a road lighting installation, in Wh·m^{-2}.
- P_j is the operational power associated with the jth operating period, in W.
- t_j is the duration of the jth period of the operating profile when power P_j is consumed, over a year, in h.
- A is the size of the area illuminated by the same lighting arrangement, in m^2.
- m is the number of periods with different operational power P_j.

These indicators can be used to compare the energy efficiency of different solutions and technologies for the same lighting project. An important point emphasized by this method is that "energy performances of road lighting systems with different geometries or with different lighting requirements cannot be compared with each other directly, as the energy performances are influenced by both the geometry of the area to be illuminated, as well as the lighting requirements" [13]. Due to this consideration, this method does not establish required efficiency values for different lighting classes, as compared to other lighting standards or proposals such as those mentioned above.

From now on, for ease of reading, reference will be made to N, PP, and EN when referring to the three energy efficiency methods, respectively, and AR when referring to the Argentinian standard IRAM AADL J 2022-2.

3. METHODOLOGY

An area of the city downtown was selected, formed by the set of blocks delimited by four main avenues: Sáenz Peña-Avellaneda, Belgrano-Sarmiento, Colón-Ejército del Norte, and Gral. Roca.

Within the study area, 4892 luminaires were identified, and the lighting installations were classified according to the following criteria:

3.1. Geometry

Information was collected in the area about the installation design (Fig. 1): road width (w), pole spacing (s), luminaire mounting height (h), overhang (o), and tilt angle (δ). In addition, the different configurations in terms of luminaire location and luminaire types were identified.

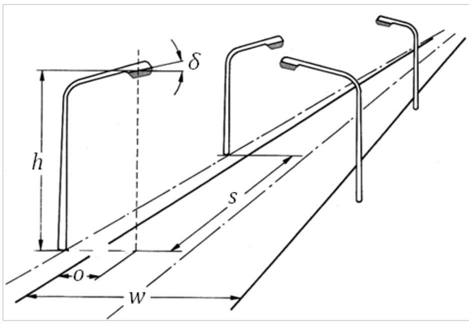

Fig. 1. Schematic diagram of a traffic lane for geometrical identification

It should be mentioned that, for this work, only functional road lighting was considered, so pedestrian roads, squares, parks, etc., are out of the scope of this study.

Based on the information provided by the municipality and verified by on-site measurements, three types of roads were identified according to their geometry (Fig. 2).

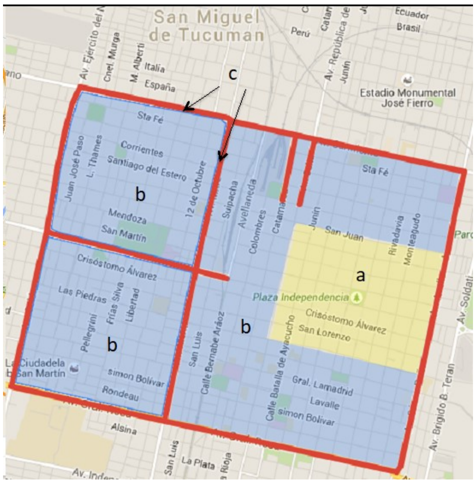

Fig. 2. Map of the surveyed area. Classification of traffic routes according to their geometry a – single carriageway, two lanes, lane width of 3.5 m, and sidewalk width of 2 m. b – single carriageway, three lanes, 3 m lane width, and 3.5 m sidewalk width. c – dual carriageway, three lanes per carriageway, 3 m lane width, 4 m sidewalk width, and 1 m central reservation

3.2. IRAM AADL J2022-2 standard (AR)

All standards establish road classes based on criteria such as traffic density, vehicle speed, presence of pedestrians, etc. Based on the factors established in AR, a classification of the road in the study area was made.

The roads that AR classifies as A and B were not found in the area of study because they correspond to highways and routes, respectively.

In general, four types of roads were distinguished:

- Main roads with speeds of up to 60 km/h. Type C class. The peripheral avenues in the area are a good example of this type of road. This type of road represents 31.2% of the total installed lighting power in the area under study.
- Roads with moderate to high vehicle traffic density and slow or congested speed. There is a significant presence of commercial and residential areas and a high pedestrian presence. Type D class. Roads with these characteristics account for 13.1% of the total installed lighting power in the area under study.
- Secondary or collector roads that connect traffic between main roads. They have high traffic density. Type E class. The installed lighting power for these roads reaches 33.3% of the total of the survey.
- Residential roads with moderate pedestrian presence and low to moderate vehicular traffic. Type F class. Roads with these characteristics account for 22.4% of the total installed lighting power in the survey.

3.3. Luminaire type

Eight different luminaire models were surveyed, including seven LED luminaires and one HPS (high-pressure sodium) luminaire (Table 6).

Table 6
Types of luminaires installed

Image	Power (W)	Flux (lm)	Luminous efficacy (lm/W)	Type
	50	6489	129.78	L1
	80	10873	135.91	L2
	117	17944	153.37	L3
	195	18414	94.43	L4
	83	6921	83.38	L5
	166	13842	83.38	L6
	70	9324	133.20	L7
	170	16033	94.31	L8

Based on these three classifications, 23 types of installations were identified within the surveyed area. Table 7 shows the characteristics of each type of installation.

Table 7
Types of roadway lighting and main characteristics

Lighting technology	Type of installation	Road geometry	Layout	AR classification of road	W (m)	s (m)	h (m)	o (m)	Luminaire	P luminaire (W)
LED	I	C	Twin central	C	9	28	11	2.5	L3	117
	II	C		C	9	28	6.5	3	L3	117
	III	C	Opposite	C	9	28	11	2.7	L6	166
	IV	C		C	9	28	13	2.7	L4	195
	V	C		C	9	32	13	2.7	L4	195
	VI	A	Single-sided	D	7	30	7	0	L5	83
	VII	A		D	7	30	7	0	L6	166
	VIII	B		D	9	30	7	1.6	L6	166
	IX	B		D	9	30	7	2.7	L6	166
	X	A		E	7	30	7	0	L5	83
	XI	B		E	9	30	7	2.7	L5	83
	XII	A		E	7	30	7	0	L6	166
	XIII	B		E	9	30	7	1.6	L5	83
	XIV	B		E	9	30	7	1.6	L6	166
	XV	B		E	9	30	7	2.7	L4	195
	XVI	B		E	9	30	7	2.7	L6	166
	XVII	B		E	9	30	7	2.7	L4	195
	XVIII	B		F	9	30	7	1.6	L2	80
	XIX	B		F	9	30	7	1.6	L1	50
	XX	B		F	9	30	7	1.6	L5	83
	XXI	B		F	9	30	7	1.6	L6	166
	XXII	B		F	9	30	7	1.6	L7	70
HPS	XXIII	B	Staggered	F	9	60	6	0	L8	170

Note: For type XXIII (staggered layout), 60 m is the distance between the closest luminaires on the same roadside

4. MATERIALS

The chosen energy efficiency methods were applied to the 23 types of lighting installations in the study area to compare which of the three regulations best assesses the energy efficiency of the installations.

The DIALux software was used to calculate the lighting parameters of the roads. This software requires as input data the geometry of the roads, the position of the luminaires, and the photometry of the luminaires. For the reflective properties of the road surface, class R3 was assumed in all cases for the asphalt concrete prevailing in the roads of San Miguel de Tucumán, as characterized by Kairuz [18].

Some luminaire characteristics were measured at the Photogoniometer Lab of the Lighting, Light and Vision Department of the University of Tucumán with an LMT GO-DS2000 photogoniometer model or taken from the catalogue according to the case.

The calculation of the indicators for all types of installations was done for one representative spacing as specified in [19]. Initial values of illuminance, i.e. maintenance factor equal to one, were calculated as this is how the lighting requirements are specified in AR [16]. Other considered indicators calculated for the analysis were: oversizing, luminous efficacy of the installation (defined as luminous flux reaching the evaluated area divided by the power installed), and utilance which is the ratio between the luminous efficacy of the installation and the luminous efficacy of the luminaire (Table 8).

5. RESULTS AND DISCUSSION

To apply the energy efficiency methods, the lighting conditions of the 23 types of installation were simulated (Table 8). The installations highlighted in red did not meet the minimum lighting requirements established in AR (Table 2), so they were not

Table 8
Results of the simulations and the application of the energy efficiency indicator

Type	Em (lux)	Oversizing (%)	Luminous efficacy of the luminaire (lm/W)	Luminous efficacy of the installation (lm/W)	Utilance	SLEEC		Pracki		EN	
						SE	Class	P_D	Class	D_P	D_E
I	49.0	23	153.37	105.5	0.69	0.009	A	0.46	A	0.009	5.57
II	59.3	48	153.37	127.1	0.83	0.008	A	0.46	A	0.008	5.57
III	38.0	–5	83.39	57.7	0.69	0.017	B	0.66	B	0.017	7.90
IV	50.0	25	94.62	64.7	0.68	0.015	B	0.77	B	0.015	9.27
V	38.0	–5	94.62	56.2	0.59	0.018	B	0.68	B	0.018	8.11
VI	18.9	–30	83.39	48.1	0.58	0.021	C	0.40	B	0.021	4.74
VII	34.2	27	83.39	43.2	0.52	0.023	C	0.79	C	0.023	9.49
VIII	31.4	16	83.39	51.1	0.61	0.020	C	0.61	B	0.020	7.38
IX	30.6	13	83.39	49.8	0.60	0.020	C	0.61	B	0.020	7.38
X	19.0	19	83.39	48.1	0.58	0.021	C	0.40	B	0.021	4.74
XI	14.9	–7	83.39	48.5	0.58	0.021	C	0.31	B	0.021	3.69
XII	34.2	114	83.39	43.2	0.52	0.023	C	0.79	D	0.023	9.49
XIII	17.0	6	83.39	55.3	0.66	0.018	B	0.31	B	0.018	3.69
XIV	31.0	94	83.39	50.4	0.60	0.020	B	0.61	C	0.020	7.38
XV	36.1	125	94.43	49.8	0.53	0.020	B	0.72	D	0.020	8.67
XVI	31.0	94	83.39	50.4	0.60	0.020	B	0.61	C	0.020	7.38
XVII	46.0	188	94.43	63.7	0.67	0.016	B	0.72	D	0.016	8.67
XVIII	22.0	120	135.91	74.3	0.55	0.013	B	0.30	C	0.013	3.56
XIX	13.3	33	129.78	71.8	0.55	0.014	B	0.19	B	0.014	2.22
XX	17.2	72	83.39	56.0	0.67	0.018	B	0.31	C	0.018	3.69
XXI	30.8	208	83.39	50.1	0.60	0.020	C	0.61	E	0.020	7.38
XXII	22.1	121	133.20	85.2	0.64	0.012	B	0.26	B	0.012	3.11
XXIII	9.8	–2	94.31	15.6	0.17	0.064	G	0.63	E	0.064	7.56

considered for energy evaluation. Installations III, V, and XXIII that also do not reach the required illuminance limit were considered within the analysis as the difference is very small, up to 5% below the level allowed.

To conduct a more precise analysis and compare the three efficiency methods, some specific cases will be examined in greater detail.

5.1. Type XIII and XIV installations

Type XIII and Type XIV installations are roads with the same geometry and lighting position (single-sided for both installations), and belong to the same road category (E) according to AR. The only difference between these two types of installations is the luminaire used (see Table 5, L5, and L6, respectively). According to the N method, both installations are energy-rated as B (Table 8), while according to the PP, Type XIII installation is rated as B and Type XIV as C. Analysing the equations of each indicator, it can be seen in equation (1) that SLEEC depends on the relationship between power density and lighting level. This means that the greater the power density, the lower the efficiency as long as the lighting level remains constant, however, if the lighting level increases in the same proportion as the power density, the indicator will be practically the same, as happens precisely in this case: luminaire L6 has double the power of L5 but also double the flux lumen output, so the SLEEC value in N is very similar. On the other hand, in PP, by using a power density indicator in which, at least directly, the lighting level does not influence, the result shows a lower rating for a lighting installation that consumes more energy, which seems more consistent.

In the case of the EN method, it can be observed that the D_P indicator (which is identical to SLEEC) in both installations is similar, however, the second indicator, D_E, clearly shows that Type XIII installation is more efficient.

5.2. Type VII and XII installations

Type VII and XII installations have the same road geometry, luminaires, and the same position on the road, so they have the same lighting level. However, according to AR, these roads belong to different classes: Type VII is class D and Type XII is class E. Obviously, for the N method, both roads have the same value of the SLEEC indicator, so they are rated with the same level of efficiency (B). On the other hand, according to PP, Type VII installation obtains a C rating, and Type XII installation is rated as D, that is, with lower efficiency. This might be thought to be strange because both installations are the same. However, Type XII installation has a lower required lighting level than Type VII installation. This means that PP considers the over-dimensioning of installations and punishes it. Finally, according to the EN method, it is not possible to compare the installations since they have different classifications.

5.3. Type VIII–XXII installations

Type XVIII, XIX, XX, XXI, and XXII installations belong to the same road class, and have the same geometry and luminaire install position but are from different types. Considering the results obtained using the N method (Table 8), these lighting installations all have a very similar value, which is indicated in their rating (B in all cases). In contrast, using PP, the ratings of these installations are much more diverse: two are rated as B, two as C, and one as E. These ratings correspond positively with the power of the installations, that is, the higher the installed power, the lower the rating.

For the EN method, the D_P indicator does not show significant differences, but it could be considered that the XXII and XVIII installations are the most efficient because they have the lowest values. However, when looking at the values of the D_E indicator, it is clear that the XIX installation is the most efficient.

5.4. Type XXI and XXIII installations

These two installations have the same geometry and correspond to class F according to AR. Their luminaires have almost the same power, but the XXI installation has an LED luminaire, and the XXIII installation has an HPS luminaire, both with very similar luminous efficacy. N penalizes more the low luminous efficacy of installation in XXIII because the photometric distribution of the L8 luminaire is so bad that it produces lower levels than those produced by the L6 luminaire in the XXI installation.

However, it can also be noted that the XXI installation has a high degree of oversizing (208%) which should mean a lower rating than C. On the other hand, PP rates them the same (E) because XXI has good utilance but oversizing, while XXIII has low utilance but no oversizing. In the end, both converge in the same rating for different reasons but rightly so. In the case of the evaluation with the EN method, both installations will have the same annual energy consumption (D_E), so it is difficult to say which installation is more convenient. The other indicator seems to show a better efficiency of the XXI installation; however, it does not consider the oversizing of the installation.

5.5. Discussion on results

The third column of Table 8 shows the oversizing of lighting installations. If any excess lighting beyond the minimum required is judged to be wasteful, then the oversizing of a lighting installation must be considered when evaluating efficiency. Installations XII, XIV-XVIII, XXI, and XXII present oversizing between 94% and 208%, meaning that in practical terms, they provide two or three times the lighting level required by AR. It is observed that the N method apparently does not consider this excess lighting, as all of these installations have been rated as B, a high level of efficiency. In contrast, for the PP energy rating proposal almost all of these installations are between efficiency levels C, D, and E. Only installation XXII is rated as B, possibly because this road has a luminaire with very high luminous efficacy (Table 8).

Analysing the luminous efficacy of luminaires (Table 8), it can be observed that method N does not reflect the energy rating result of using a luminaire with high or low efficacy either. There are installations with high luminous efficacy luminaires such as types XVIII, XIX, and XXII, which are rated as B, as well as installations with low efficacies such as installations XIII to XVII. In contrast to this situation, PP does show a relationship between energy rating and efficacy: installations with high efficacy as type XIX and XII receive a high rating (B), and on the other hand, installations XIV to XVII with low efficacies receive low ratings (C and D).

It is worth mentioning separately the case of type XIII and XVIII installations according to PP. Installation XIII has low efficacy but a high rating (B), this is probably due to the fact that this road shows very little oversizing (6%). The exact opposite situation occurs with installation XVIII: it has a luminaire with high luminous efficacy but is rated as C because it has a high degree of oversizing (120%), so in both cases, the rating seems appropriate.

Regarding EN, its indicators can only be applied to compare installations with the same geometric characteristics and lighting requirements. This is the case for installations XIII and XIV. Both installations have luminaires with the same luminous efficacy and a very similar D_P indicator; however, installation XIII has very little oversizing (6%) compared to installation XIV (94%). This is reflected in the value of the D_E indicator, which is much higher in the case of installation XIV.

6. CONCLUSIONS

Road lighting must meet the minimum requirements to reduce the risks of accidents associated with night-time driving of vehicles. In addition to this first requirement, it is desirable to consume the least amount of energy possible to achieve this purpose.

In road lighting, this statement essentially involves four aspects to consider: the luminous efficacy of the luminaires, the oversizing or excess lighting in the installations, the utilisation factor (utilance), and the possibility of reducing installation power consumption during lower vehicular traffic.

In this study, lighting installations in the downtown of the city of San Miguel de Tucumán were simulated to determine their lighting levels and evaluate their energy efficiency based on three energy efficiency methods.

The results show that the N method has poor performance in evaluating energy efficiency because it does not account for the oversizing in lighting installations. Looking at equation (1), it is easy to realize that SLEEC represents the amount of power consumed to generate a certain level of lighting, so this indicator can be low even when the installation is oversized.

The EN method has two indicators, the first of which, D_P, is identical to the SLEEC indicator, so it shows the same problems described in the previous paragraph. The second indicator, D_E, provides a much better idea of the efficiency of the installations because it is related to the power of the installations, that is, the higher the power, the greater the

energy consumption and the higher the value of D_E. This indicator also shows an indirect relationship with oversizing, the efficacy of the luminaires, and the usage time of the installations. The disadvantage of the EN method is the restriction on its use since it does not allow for the comparison of installations with different geometry and/or lighting classes, and therefore, an energy rating is not possible.

Finally, PP that uses a reference value table based on a power density indicator demonstrates the best performance in evaluating the energy efficiency of installations. It is observed that the ratings provided by this proposal adequately accompany the levels of oversizing of the installations and the efficacy of the luminaires. A major advantage of this proposal is that the power density reference values can be adapted to any lighting requirement.

Most of the road lighting in the city centre of San Miguel de Tucumán not only complies with the minimum lighting requirements established in the local regulation, but it is also over-lit, doubling, and in some cases tripling the minimum values. This indicates that, in the first instance, a norm that requires not only a minimum level of illumination but also a maximum level of illumination would avoid considering these lighting installations as efficient. However, this restriction could not be enough as shown in this work when analysing installation XXIII. For this reason, a method such as PP could produce better results in the Argentinian regulations and would also provide an energy rating for road lighting.

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REFERENCES

[1] World Meteorological Organization / United Nations Environment Program, “Climate Change – The IPCC Scientific Assessment,” 1990.

[2] O.U. Preciado and E.R. Manzano, “Spectral characteristics of road surfaces and eye transmittance: Effects on energy efficiency of road lighting at mesopic levels,” *Lighting Res. Technol.*, vol. 50, no. 6, pp. 842–861, Oct. 2018, doi: 10.1177/1477153517718227.

[3] P.R. Boyce, S. Fotios, and M. Richards, “Road lighting and energy saving,” *Lighting Res. Technol.*, vol. 41, no. 3, pp. 245–260, 2009, doi: 10.1177/1477153509338887.

[4] C.C.M. Kyba, A. Hänel, and F. Hölker, “Redefining efficiency for outdoor lighting,” *Energy Environ. Sci.*, vol. 7, no. 6, pp. 1806–1809, 2014.

[5] A. Gutierrez-Escolar, A. Castillo-Martinez, J.M. Gomez-Pulido, J.M. Gutierrez-Martinez, E.P.D. González-Seco, and Z. Stapic, “A review of energy efficiency label of street lighting systems,” *Energy Effic*, vol. 10, no. 2, pp. 265–282, Apr. 2017, doi: 10.1007/s12053-016-9454-7.

[6] F. Leccese, G. Salvadori, and M. Rocca, “Critical analysis of the energy performance indicators for road lighting systems in historical towns of central Italy,” *Energy*, vol. 138, pp. 616–628, 2017, doi: 10.1016/j.energy.2017.07.093.

[7] L.A. Sánchez-Balvás, J.J. de Felipe, J.M. Quintero, and A. de la Fuente, “An energy efficiency-based classification approach for street lighting by considering operational factors: a case study of Barcelona,” *Energy Effic*, vol. 14, no. 1, Jan. 2021, doi: 10.1007/s12053-020-09915-y.

[8] P. Pracki, “A proposal to classify road lighting energy efficiency,” *Lighting Res. Technol.*, vol. 43, no. 3, pp. 271–280, 2011, doi: 10.1177/1477153511407996.

[9] Documento BOE-A-2008-18634 – Ministerio de Industria, “Decreto Real 1890/2008 Reglamento de eficiencia energética en instalaciones de alumbrado exterior y sus Instrucciones técnicas complementarias EA-01 a EA-07,” *Agencia Estatal Boletín Oficial del Estado,* Nov. 2008.

[10] TBR and GPP, “Green Public Procurement Street Lighting and Traffic Lights Technical Background Report,” *Report for the European Commission – DG-Environment*, 2011.

[11] NSVV, *Energy Labeling Guide for Public Lighting*. Netherlands, 2009.

[12] Light Naturally, “Energy efficiency performance requirements for road lighting designs and luminaires,” South Australia, 2014. [Online]. Available: www.lightnaturally.com.au.

[13] CEN, “EN 13201-5; Road Lighting—Part 5: Energy performance indicators,” Brussels, Belgium, 2015. [Online]. Available: www.aenor.es.

[14] Ministerio de minas y energias de la Republica de Colombia, “Reglamento Técnico de Iluminación y Alumbrado – RETILAP – Resolución 180540,” 2010.

[15] Norma Oficial Mexicana, “NOM-013-ENER-2013: Eficiencia energética para sistemas de alumbrado en vialidades,” 2013.

[16] Instituto Argentino de Racionalización de Materiales, “IRAM-AADL J 2022-2, Alumbrado Público, Vías de Tránsito – Clasificación y Niveles de Iluminación,” Argentina, 2021.

[17] CEN, “EN 13201-2; Road Lighting – Part 2: Performance Requirements,” Brussels, Belgium, 2015.

[18] H. Kairuz, “Caracterización y medición de muestras de pavimentos en Argentina,” San Miguel de Tucumán, Argentina, 1987.

[19] P. Pracki and A.K. Jägerbrand, “Application of Road Lighting Energy Efficiency Evaluation System in Practice,” *CIE Centenary Conference “Towards a New Century of light”*, 2013.