A review of energy efficiency label of street lighting systems

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Abstract There are very few countries that have provisions addressing the energy efficiency of the whole street lighting system, such as Spain or the Netherlands. Nevertheless, there is not an agreement about how energy efficiency must be assessed. The Spanish Government contemplates it in the Royal Decree 1890/2008 with the goal of improving energy savings and efficiency. However, this has not obtained the expected results. Nowadays, energy efficiency of this kind of systems is assessed using a label. In the case of Spain, this label only assesses one magnitude. The contributions of this paper are two evaluation systems (kiviat diagram and pie chart) which assess five magnitudes: lamps, energy efficiency index, light pollution, renewable energy contribution, and harness of the luminous flux using dimming. After that, a survey was done to study several subjects: (1) if citizens are aware about the efficiency of street lighting systems, (2) whether the sample of colors used in the label is adequate, and (3) if our proposed systems could replace the current evaluation system. Finally, the paper finishes with the conclusions of the survey.

Keywords Energy efficiency index · Kiviat diagram · Lamp · Light pollution · Pie chart · Dimming luminous flux

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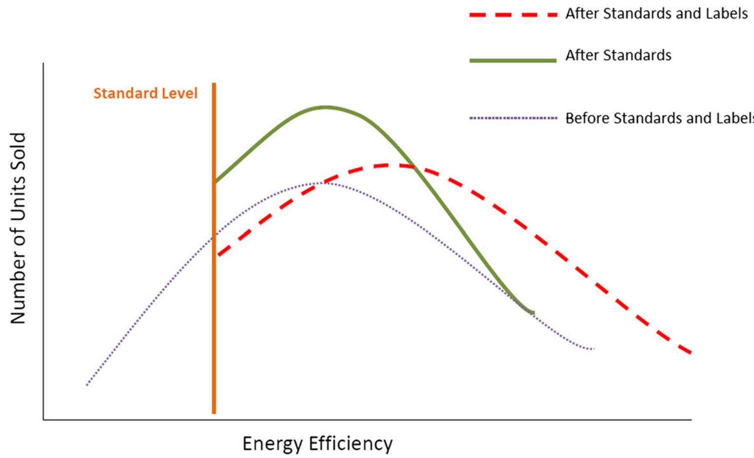
Introduction

At present, energy labeling is mandatory for appliances, equipment, lamps, buildings, and even street lighting systems depending on the country. Energy label is a measure which shows the purchaser of the product how economical, environmentally friendly, and/or energy saving that product is. In other words, labeling is a way of measuring and comparing energy consumption for a certain output rate (Ottens 2010).

Energy label has a significant effect on the choice of final product, possibly due to raised environmental awareness. Moreover, consumers prefer to pay more for energy efficiency in products used more frequently (Shen and Saijo 2009). Figure 1 shows the market transformation thanks to the energy label.

As it can be seen, energy efficiency labels can help a country to reduce electricity consumption. For instance, the estimation carried out by Meyers et al. (2004) indicates that it could reduce energy consumption in 2020 by 8 % compared to the levels expected without any standards. This estimation is for residential appliances, but until now no one has analyzed the consequences in

Fig. 1 Market transformation thanks to the energy label



the field of energy efficiency label for street lighting systems.

There are four types of energy labels (Saidur et al. 2006); (a) seal-of-approval programs, (b) single-attribute certification programs, (c) comparative, and (d) information-disclosure. These labels are summarized as below:

(a) Seal-of-approval programs (endorsement labels): These labels offer essentially a "seal of approval" that a product meets certain pre-specified criteria. Seal-of-approval programs award or license the use of a logo to products judged to be less environmentally harmful than other similar products. Figure 2 shows US endorsement label.

(b) Single-attribute certification programs: These certify that claims made for a single-attribute of a product meet a specified definition. Such programs define specific terms such as "recycled" or "biodegradable" and accept applications from marketers for verification that their product attributes meet the program definition. If the programs verify that the product attributes meets their definitions, the program awards the use of the logo to the marketer. Figure 3 shows EU ecolabel.

(c) Comparative labels: These labels allow the consumers to compare energy use among all available models in order to make an informed choice. Two subcategories of comparative labels have been developed around the world: one uses a categorical ranking system; the other uses a continuous scale or bar graph to show relative energy use. Figure 4a shows a continuous label, and Fig. 4b shows a categorical label.

(d) Information-disclosure: Information-disclosure labels provide information on the technical performance of the single-labeled product and offer no simple way to compare energy performance among products. These types of labels are generally not consumer-friendly because they contain only technical information. Figure 5 shows an example of information label.

Fig. 2 Example of endorsement label

Fig. 3 Example of single-attribute certification programs

(a) Example of continuous label **(b)** Example of categorical label

Fig. 4 Examples of label. **a** Example of continuous label and **b** example of categorical label

There are only very few countries that have provisions addressing the energy efficiency of the whole street lighting system (European Commission 2011), among them Spain and the Netherlands. The Royal Decree 1890/2008 (2008) was established by the Spanish Government with the goal of improving energy savings and efficiency, and, consequently, reducing greenhouse-effect gas emissions for street lighting systems. In this normative, it is defined how street lighting systems must be assessed regarding the energy efficiency. However, according to Sanchez de Miguel et al. (2014), who defined a procedure to estimate energy consumption in public electric lighting in Spain from 1992 to 2012, the most populated provinces appear to have begun to stabilize the growth of expenditure on public lighting. But this does not occur in the less populated provinces where this expense continues to rise in spite of the economic crisis. In general, this energy consumption in Spain has grown constantly over the last 18 years.

Hence, the Royal Decree has not obtained the expected results, as its goal is to reduce rather than stabilize. These unexpected results might be due to two reasons: (1) the unit measured may be inappropriate or (2) labeling does not take into account enough parameters.

This paper is focused on analyzing the current energy efficiency label for street lighting system through the proposal of two evaluation labels with reference to the Spanish regulation (Royal Decree 1890/2008). For this, this manuscript has been divided as follows: The first section shows a state of the art evaluation where the different units measured to assess the energy efficiency were studied. After that, two evaluation systems for the energy efficiency label are proposed (kiviat diagram and pie chart). The third part consists of a survey which was undertaken to check if citizens are aware of the existence of the energy efficiency label and if they would be willing to accept some of these new proposals. Finally, this manuscript finishes with the conclusions.

Fig. 5 Example of information label

State of the art

The first point that must be analyzed is the units measured used by different existing street lighting evaluation systems. Despite the fact that there are several ways to perform this evaluation, this section is split into two sections: standards adopted by different countries and other studies.

Standards adopted by countries and union of states

The European Union sets a standard called prEN 13201-5 (2013) which defines energy performance indicators for road lighting installations using a calculated power density (D), and a calculated annual energy consumption indicator (ECIy). These indicators may be used to compare energy performance of different road lighting solutions and technologies for the same road lighting project. This standard also gives the possibility of dimming the lighting level according to parameters such as the time of the day or weather conditions. It also contains equations for calculating the installation efficacy of road lighting schemes, to be adopted as a comparative tool. However, this standard does not set minimum performance levels. It is necessary to remember that prEN 13201-5 is based on CIE 115.

The energy efficiency performance standard developed by the Canadian Standards Association (CSA Group) (2013) establishes luminaire photometric performance efficiency with establishment of maximum unit power density (UPD) values in watts per area for typical applications. The standard includes a series of tables containing maximum UPD levels for each light source, luminaire type, class of roadway with subdivided levels for pedestrian areas, and number of lanes.

Spanish standard (Royal Decree 1890/2008) establishes energy efficiency limits according to installation type; functional road lighting facilities including motorways, highways, roads, and streets for moderate to high traffic speed (>30 km/h) and "ambient" street lighting that runs on low height (3–5 m) poles in urban areas, for pedestrian lighting, commercial streets, sidewalks, parks and gardens, historic districts, and paths with limited traffic speed (≤30 km/h).

The Netherlands NL Agency (Agency & Ministry of Economic Affairs, Agriculture and Innovation 2010) have developed a voluntary initiative that defines levels of energy efficiency for energy labels for public lighting installations with the intention of enabling objectives for saving energy to be achieved.

The aim of the standards for lighting of roads and public spaces in Australia and New Zealand Standards Australia Technical Committee (2010) AZ/NZS 1158 was to develop measures aimed at removing inefficient practices. The result was the development of a "design energy limit" which is characterized by the power consumption of the luminaire and the length of the road way.

The scope of the Bureau of Energy, Ministry of Economic Affairs of Chinese Taipei is for any streetlight product that is applying to receive the Energy Label certification. Unfortunately, the energy efficiency levels are luminaire specific only. This initiative does not include a requirement for efficiency in road lighting design (Bureau of Energy, Ministry of Economic Affairs of Chinese Taipei (Taiwan, 2012)).

The Slovenian Lighting Pollution Decree (Prelovšek et al. 2012) has enforced several changes in the fields of lighting design, installation, and maintenance. As to municipal lighting, the most far-reaching requirement is the maximum allowed annual lighting-energy consumption, which it is set at 44.5 kWh per inhabitant per year. The other and perhaps even more important condition is the requirement of zero upward light output ratio (ULOR).

The Lighting Research Center suggests that it should measure the luminaire efficacy through LSAE parameter (Luminaire System Application Efficacy) (ASSIST 2011). The LSAE metric involves three major steps: The first is to obtain an accurate measurement of the luminaire's intensity distribution in the format of an intensity distribution file. The second is to calculate the illuminance on the task area grid. The third step is to calculate LSAE based on the illuminance, percentage of conforming cells, and the input power of the system:

$$\mathrm{LSAE} = \frac{\left(\mathrm{ftask\_conforming}\left(\frac{N_{\mathrm{conforming}}}{N}\right)\right)}{P} \tag{1}$$

Where task_conforming is the luminous flux inside the target task plane that meets the lighting requirements, $N_{\mathrm{conforming}}/N$ is the ratio of conforming cells to the total number of cells in the calculation grid, and P is the total input power to the luminaire.

The calculated LSAE values is for one luminaire on one pole and will vary based on the mounting height. In terms of energy savings, a higher LSAE value will generally correlate to a lower lighting power density (Narendran et al. 2010). The advantage of this evaluation methodology is that it does not include the light output falling beyond the lit-up surface. In that way the luminaires that waste light by sending it outside the lit-up surface are penalized.

Other studies

The first evaluation analyzed was proposed by Herring (1999) and is mainly focused on the amount of lamp's lumens per watt, but there remains the problem of adjusting for quality of service, for example, color of light, comfort, or speed road. In addition, the same author (Herring 2006) supports carbon taxes and combined policies of "green" electricity (generated from renewable energy sources) and energy efficiency. Moreover, he indicates that the goal of efficiency should be less carbon dioxide emissions without a loss of energy use; ultimately, energy growth needs to be decoupled from CO2 emission. In our opinion, the incorporation of renewable energy contribution into energy efficiency could be very productive.

Another way was presented by Silva et al. (2010) who developed a tool which can assess street lighting performance in the context of energy efficiency. This tool uses three indicators; one to evaluate street lighting performance and two indicators to evaluate street lighting energy efficiency.

Street lighting performance is only evaluated on the basis of the target light levels, according to the class of area to be illuminated. However, street lighting performance does not take into account parameters such as uniformity or color rendering.

Regarding the street lighting energy efficiency, there are two factors of major importance: the efficacy of the lamps and the luminaire efficiency. The efficacy of a lamp, expressed in watts per luminous unit, represents the ratio between the luminous flux emitted by the lamp and its consumed power. The efficiency of a luminaire reflects the ratio between the luminous flux it emits and that produced by the lamp. The efficiency of a luminaire varies according to the type of luminaire and its photometry.

The research conducted by Pracki (2011) proposes a new classification systems based on the installed and normalized power densities of the whole street lighting system. This classification is very interesting because normalized power density depends on the following: sort of road surface; the luminous efficacy of the lighting system, which determines the energy efficiency of the lighting taking into account the watts per luminous unit (lm/W); the utilization factor, which can be expressed as a product of the light output ratio of luminaire and the road utilance; and the maintenance factor which depends on an environmental pollution conditions. In other words, this method takes into account several parameters and thus it can be used to compare the energy efficiency of design and the used of the whole street lighting systems.

Another possible option to measure the energy efficiency was proposed by Kyba et al. (2014) who established that the best way to assess street lightings is through the amount of energy consumption per kilometer per year (kWh / (km × year)).

After analyzing all the previous information, the absence of an agreement to measure the efficiency has attracted our attention. In addition, studying deeply the Spanish regulation we have realized that there are several parameters that seem too important to control, as light pollution, but they are not taken into account the

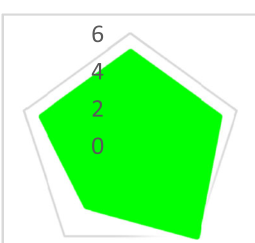


Fig. 6 Kiviat diagram

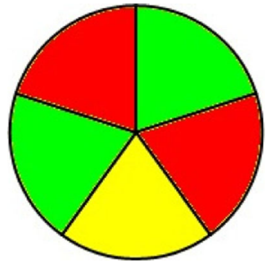


Fig. 7 Pie chart

Table 1 Levels regarding the luminous efficacy according to Pracki (2011) criteria

Level	Class	Luminous efficacy (lm/W)
6	A	lm/W > 150
5	B	150 > lm/W > 100
4	C	100 > lm/W > 75
3	D	75 > lm/W > 50
2	E	50 > lm/W > 25
1	F	lm/W ≤ 25

Table 2 Levels regarding the luminous efficacy satisfying the Royal Decree

Level	Class	Luminous efficacy (lm/W)
7	A	$\text{lm/W} \geq 150$
6	B	$150 \geq \text{lm/W} > 133$
5	C	$133 \geq \text{lm/W} > 116$
4	D	$116 \geq \text{lm/W} > 99$
3	E	$99 \geq \text{lm/W} > 82$
2	F	$82 \geq \text{lm/W} > 65$
1	G	$\text{lm/W} \leq 65$

setting of the energy efficiency. We want to suggest that it would be better if all parameters were included in the energy efficiency label, because in this way it is possible to analyze all the involved aspects.

New evaluation systems

Most of the previous evaluation systems only assess one parameter. Maybe, the energy efficiency would improve if the label showed more parameters, then lighting designers would be more careful when they designed this kind of installation.

Two different evaluation systems are proposed in this manuscript: the first label consists of a kiviat diagram. The second option is a pie chart with all the sections using the same percentage (20 %), but the color of each section depends on the classification. Both evaluation systems permit to compare different parameters using only one diagram. Figure 6 shows the kiviat diagram proposal.

We have considered that the kiviat diagram could be a good option to show the energy efficiency label because the values of each index are plotted on their individual axis. Moreover, this kind of diagram helps quick identification of performance evaluation (Keshtgary and Babaiyan 2012). By connecting the nodes, a distinct shape will be created which will give a global indicator that could be used during the project design to compare different solutions. Furthermore, this type of diagram has already been used to assess the performance for buildings (Schlueter and Thesseling 2009).

Table 3 Levels regarding the energy efficacy index

Level	Class	Iε
7	A	$I\varepsilon > 1.1$
6	B	$1.1 \geq I\varepsilon > 0.92$
5	C	$0.92 \geq I\varepsilon > 0.74$
4	D	$0.74 \geq I\varepsilon > 0.56$
3	E	$0.56 \geq I\varepsilon > 0.38$
2	F	$0.38 \geq I\varepsilon > 0.2$
1	G	$I\varepsilon \leq 0.2$

The second label proposed consists of a pie chart because we believe that this kind of diagram may be much clearer for citizens. Figure 7 shows one example.

From our point of view, the energy efficiency label must include as many parameters as possible. The parameters that should be considered to assess efficiency are five; lamps, energy efficiency index, light pollution, renewable energy contribution, and dimming luminous flux. The next describes how these parameters could be classified using the previous evaluation systems.

Lamps

There is no doubt that lamps are the most representative component of street lighting. There are several types of lamps which can be used on this kind of installation among which stand mercury vapor, high pressure sodium, low pressure sodium, high pressure ceramic metal halide, and led lamps. However, the second step of the EU directive 245/2009 (2009a, b), 347/2010 (2010) as well as the terms of the EU directive 2011/65 (2011) state that all mercury vapor lamps are no longer permitted to be placed on the market in the European Union. These kinds of lamps are traditionally used in town and street lighting, and still characterize the pattern of public lighting in many locations. Nevertheless, significantly more efficient and economic solutions are available that are also distinctly more sustainable.

Commission Delegated Regulation 874/2012 (2012) specifies how to estimate the energy labeling of lamps and luminaries. For this reason, we analyzed it to study the method used to make the classification. Energy efficiency class of lamps is determined on the basis of their energy efficiency index (EEI) which sets as Eq. 2.

$$\text{EEI} = \frac{P_{\text{cor}}}{P_{\text{ref}}} \tag{2}$$

Where P_{cor} is the power corrected for control gear losses and P_{ref} is the reference power obtained from the useful luminous flux by the following equations:

Table 4 Maximum percentage of ULOR for Spain and Croatia

	Croatian standard		Spanish standard	
Surrounding	Classification zone	Maximum ULOR (%)	Classification zone	Maximum ULOR (%)
Protected	EO	0	Not exist	0
Natural	E1	0	E1	1
Rural	E2	2.5	E2	5
Suburban	E3	5	E3	15
Urban	E4	15	E4	25

For lamp with $\varnothing < 1300$ lumen:

$$P_{ref} = 0.88\sqrt{\varnothing} + 0.049\,\varnothing \tag{3}$$

For lamps with $\varnothing \geq 1300$ lumen:

$$P_{ref} = 0.007341\,\varnothing \tag{4}$$

Analyzing this, we can appreciate that the method established by Pracki (2011) could be used for this new evaluation systems. Packri's criterion is based on the efficacy of the lamp, expressed in watts per luminous unit, because it represents the ratio between the luminous flux emitted by the lamp power. Table 1 shows the evaluation of this parameter following the classification established by Pracki (2011): (1) level class, where a high value represents a high level of energy efficiency; (2) a classification by a letter; and (3) the values of luminous efficacy of the lamp.

At first view, this classification could be considered as the best option. However, the Royal Decree 1890/2008 (2008) establishes that the minimum lumen output lamp shall be at least 65 lm/W. As can be appreciated in the Table 1, the classes E and F do not comply with the minimum requirement for Spain. Hence, we cannot propose the classification established by Pracki (2011) as such; we must modify the range of values. Table 2 shows the different classes regarding the efficacy of the lamp, taking into account the requirement of the Royal Decree.

Energy efficiency index

According to the Royal Decree 1890/2008 (2008), energy efficiency index (I) is the magnitude to give the energy efficiency class for street lighting systems. To know this magnitude, it is necessary first to calculate energy efficiency ( ) which sets as Eq. 5.

$$\varepsilon = \frac{S\,E_m}{P}\left(\frac{m^2 lux}{W}\right) \tag{5}$$

Where S is lit-up area, E_m is average illuminance, and P is active power. As can be appreciated, the current evaluation system assesses three parameters (S, E_m, and P). The value of energy efficiency must satisfy minimum requirements, depending of the speed limit of the road. Afterwards, I must be calculated following the Eq. 6.

$$I_\varepsilon = \frac{\varepsilon}{\varepsilon_R} \tag{6}$$

Where $_R$ is the energy efficiency reference which is established in the same Decree (2008). Table 3 shows the class regarding the energy efficiency index.

Table 5 Levels regarding the ULOR

Level	Class	ULOR (%)
7	A	ULOR < 5
6	B	5 ≤ ULOR < 9
5	C	9 ≤ ULOR < 13
4	D	13 ≤ ULOR < 17
3	E	17 ≤ ULOR < 21
2	F	21 ≤ ULOR < 25
1	G	ULOR ≥ 25

Table 6 Levels regarding the renewable energy contribution

Level	Class	Contribution (%)
7	A	% ≥ 25
6	B	21 ≤ % < 25
5	C	17 ≤ % < 21
4	D	13 ≤ % < 17
3	E	9 ≤ % < 13
2	F	5 ≤ % < 9
1	G	% < 5

Table 7 Levels regarding the dimming of luminous flux

Level	Class	Dimming (%)
7	A	$F \leq 50$
6	B	$40 \leq F < 50$
5	C	$30 \leq F < 40$
4	D	$20 \leq F < 30$
3	E	$10 \leq F < 20$
2	F	$5 \leq F < 10$
1	G	$F < 5$

Light pollution

This sort of pollution represents a loss. The light that is generated and disappears without having any use is a waste (Narisada and Schreuder 2004). Accordingly, poor lighting design contributes to increased carbon dioxide emissions and global warming (Gallaway et al. 2010). This magnitude should be considered to evaluate energy efficiency. To have a general idea of the wasted energy, at the end of 1990s, the amount of sky glow was equivalent to 15 million kWh of energy over Sapporo, Japan; 29 million kWh over London, UK; and 38 million kWh over Paris, France (Isobe and Hamamura 2000). The amount used for public street lighting in Helsinki, Finland, is roughly 170 million kWh, meaning that the light wasted in Paris over a 5-day period could illuminate the whole of Helsinki for 1 day. Light sent upward is estimated to produce economic losses worth billions of euros every year (Schwarz 2003). The wasted energy also means larger CO_2 emissions. In spite of the information showed for the previous researches, there is no energy efficiency label that light pollution takes into account.

New standards limit the percentage of a lamp's flux which can be directed above the horizontal plane passing through the light source in their operating positions. The upward waste light ratio (UWLR) is the proportion of the flux of a luminaire that is emitted above the horizontal when the luminaire is mounted in its position (Remande 2001). UWLR sets as Eq. 7:

$$\mathrm{UWLR}\ (\%) = \frac{\mathrm{ULOR}\ (\%)}{\mathrm{ULOR}\ (\%) + \mathrm{DLOR}\ (\%)} \tag{7}$$

Where upward light output ratio (ULOR) is the proportion of the flux of lamps of a luminaire that is emitted above the horizontal when the luminaire is mounted in its designed position and the downward light output ratio (DLOR) is the proportion of the flux of the lamps of a luminaire that is emitted below the horizontal.

Therefore, ULOR depends on the respective tilt angles, which allow improvement of the energy efficiency

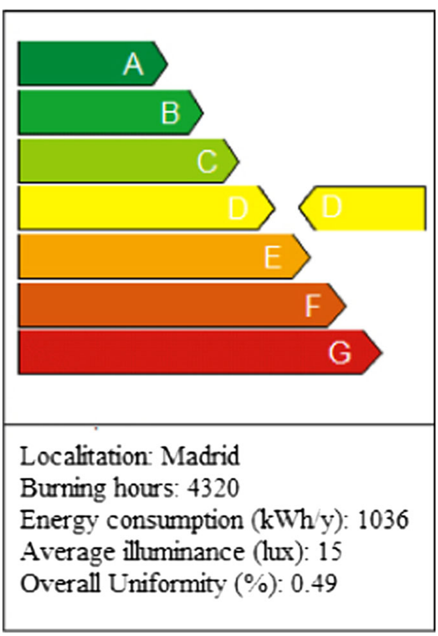


Fig. 8 Energy efficiency label of the example

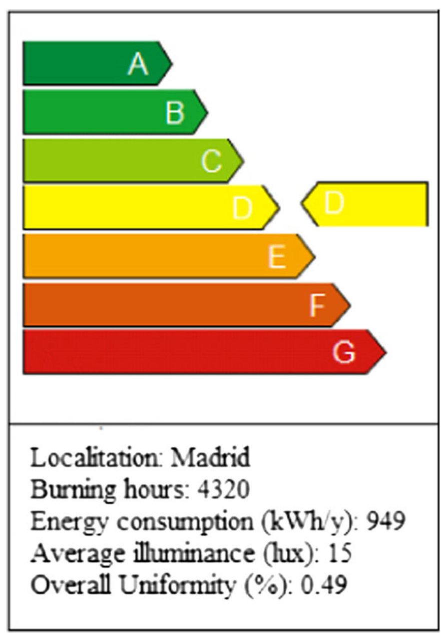


Fig. 9 Energy efficiency label (example with electronic ballast)

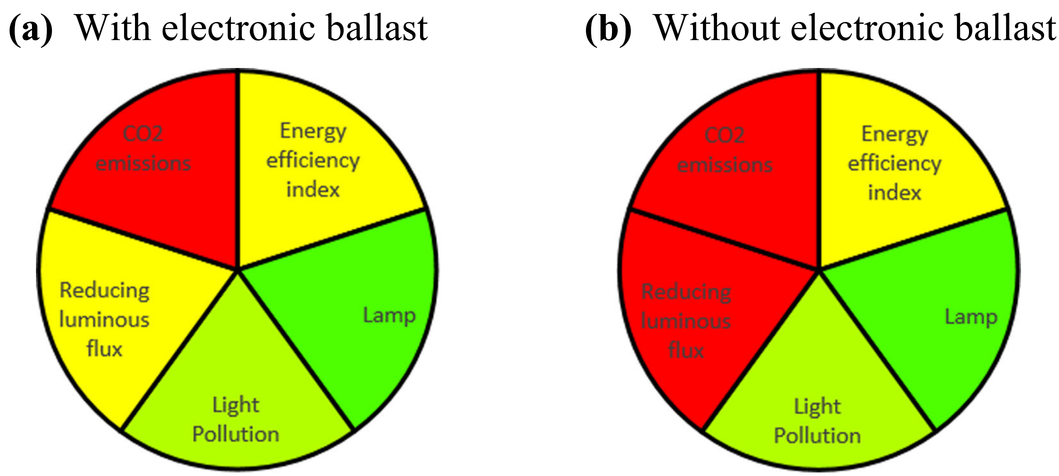


Fig. 10 Pie chart evaluation. **a** With electronic ballast and **b** without electronic ballast

of the installation. For example, in case of plain roads, a luminaire produces a 0 % ULOR at 0° of tilt but it will produce an ULOR of 2.5 % if the tilt angle is 10 % (Smarter Scotland 2007). Nevertheless, it must be taken into consideration that, in case of a steep road, any horizontal positioned lamp will decrease the efficiency of the system.

In this point, there is no agreement about the maximum level of this magnitude. The requirements are different, depending on the country. Table 4 shows the maximum values for Spain (Royal Decree 1890/2008) and Croatia (Croatian Ministry of Environmental and Nature Protection 2013).

Although the requirements of light pollution are included in the Royal Decree 1890/2008 (2008), this magnitude is not evaluated directly when assessing the energy efficiency. Lighting designers would be more rigorous regarding this aspect, if this parameter was considered within the energy efficiency label. Table 5 shows our proposal to assess ULOR.

Renewable energy contribution

The global need for energy savings requires the usage of renewable sources in many applications and street lighting systems are not an exception. Spain, owing to its location and climate, is one of the countries in Europe with the most abundant solar resources (Diez-Mediavilla et al. 2010). Global solar irradiation on a horizontal

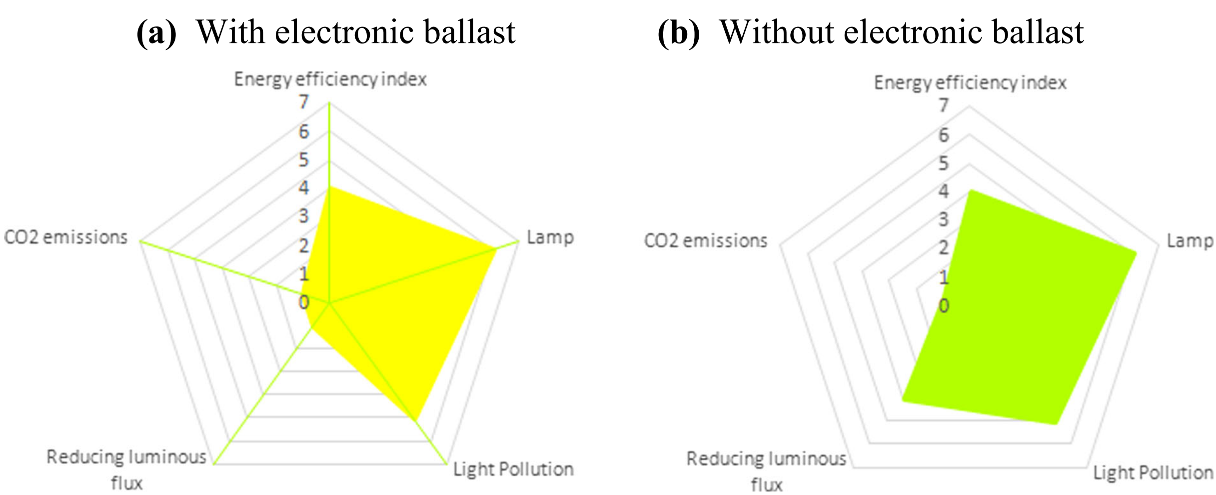


Fig. 11 Kiviat diagram evaluation. **a** With electronic ballast and **b** without electronic ballast

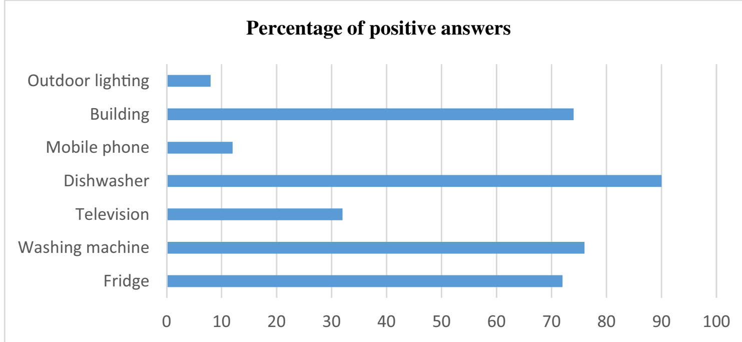


Fig. 12 Percentage of positive answers for the first question

plane is estimated as being between 1.48 and 3.56 kW/m^2 day in Spain.

Solar energy can be used for street lighting in cases of low consumption applications (Bouroussis and Topalis 2004). Maybe, the solar energy option is the best solution for autonomous street lighting systems because of its long life, easy installation, and modularity (Costa et al. 2009).

The solar energy is used to charge a self-contained battery during day time. Battery capacities are usually designed for power autonomy of 3–5 days to meet lighting loads under varying environmental conditions, and are often overdesigned (Chih-Chiang & Pi-Kuang 2005, Notton et al. 1996). Therefore, this kind of renewable energy reduces the CO_2 emissions considerably. A good example of the benefits of solar energy is the research carried out by Nunoo et al. (2010) in Ghana, achieving energy saving per day of 603 kWh. However, stand-alone street lighting systems based on the classical configuration coupling photovoltaic cells (PV) and battery cannot work all year round in regions that are far from the equator (Lagorse et al. 2009). To improve the classical system, the combination of some renewable energies is recommended.

Street lighting can also be supplied with other kinds of renewable sources or even the combination of several types of renewable sources like the research performed by Al-Fatlawi (2014) who combined solar and wind energy. Another example of this combination is the research performed by Georges and Slaoui (2011). In other words, street lighting systems which include photovoltaic systems and wind turbines typically include energy storage devices so that loads can be operated when solar energy is not available or when wind velocities are too low to generate power (Sperber et al. 2012).

However, there are not any evaluation systems that the benefits of renewable energy take directly into account. In our opinion, if the street lighting systems can reduce the CO_2 emissions through renewable energy, the energy efficiency label has to show it. The criteria followed to establish the class depends on the power contribution throughout the year. Table 6 shows our proposal to assess the contribution of renewable energy.

Dimming of luminous flux

There are three devices contemplated in the Spanish standard (Royal Decree 1890/2008) able to control

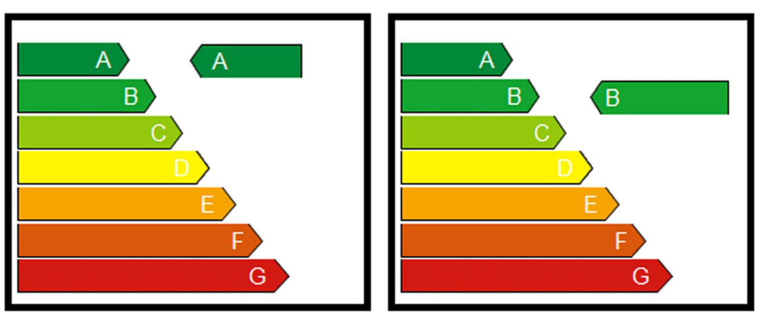
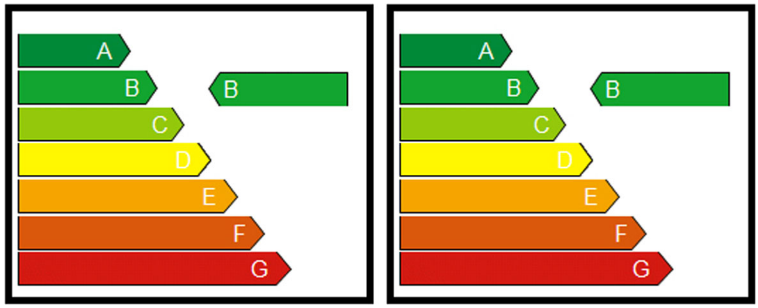


Fig. 13 First illustration of the second part

Fig. 14 Second illustration



luminous flux: series inductive type ballasts for dual power level, power controlled electronic ballasts, and regulators and stabilizers in the head of the line.

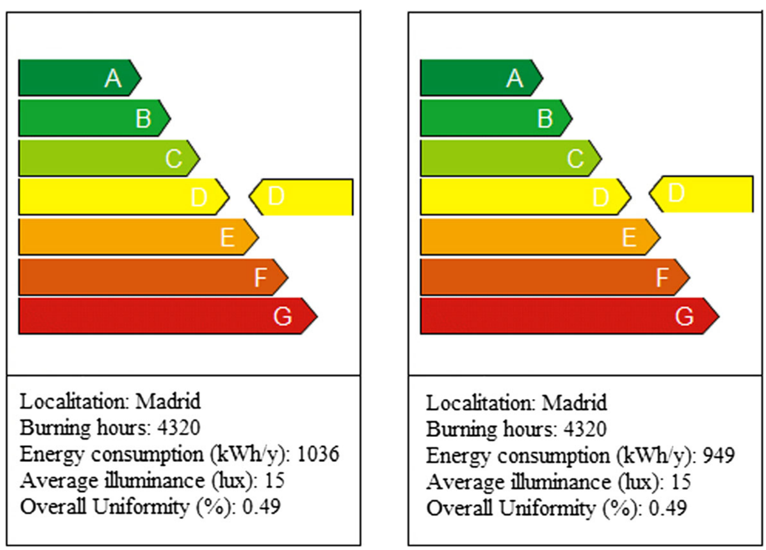
In order to comply with Spanish standard (Royal Decree 1890/2008), these devices can dim the luminous flux by up to 50 %, provided that overall uniformity is maintained. In addition, according to Bacelar (2005), this reduction is the maximum level allowed so as not to affect on visibility of pedestrian or driver. However, the previous research has a drawback, because the only kind of lamp studied was high pressure sodium (HPS) lamps.

The main problem of using ballasts for dual power levels is that these systems act locally, requiring an adjustment device attached to each of the individual charges and also a general control system (Blanquez et al. 2012). Regulators and stabilizers are able to control the voltage according to different parameters such as number of vehicles per hour (Moghadam and Mozayani 2011), weather conditions, or the presence of pedestrians (Zotos et al. 2012). Their operation consists of hanging the input mains voltage to a variable voltage within the range from 220 to 170 V (Yan et al. 2009). Those changes are accompanied by variations of luminous flux and lamp power.

A good example to understand the benefits of regulators and stabilizers is the research carried out by Blanquez et al. (2012) because the power consumption was reduced by 726 W, which represents, in its case, more than the 25 % of the total energy consumption. The samples of lamps were high pressure sodium lamps (HPS) (80 W) and metal halide lamps (MH) (70 W). HPS can achieve 50 % reduction in luminous flux if the lamp voltage decreased by 40.73 V; in other words, the power savings per lamp is 29.24 W per lamp, which means 33 % less of the power consumed. MH can reach a reduction of 50 % luminous flux if the lamp voltage decrease in 36.89 V; that is to say, the power savings per lamp is 30.89 W, which means 35 % less of the power consumed.

Although lighting level control devices permit a reduction of power consumed, Spanish standard (Royal Decree 1890/2008) does not specify when it

Fig. 15 Third illustration



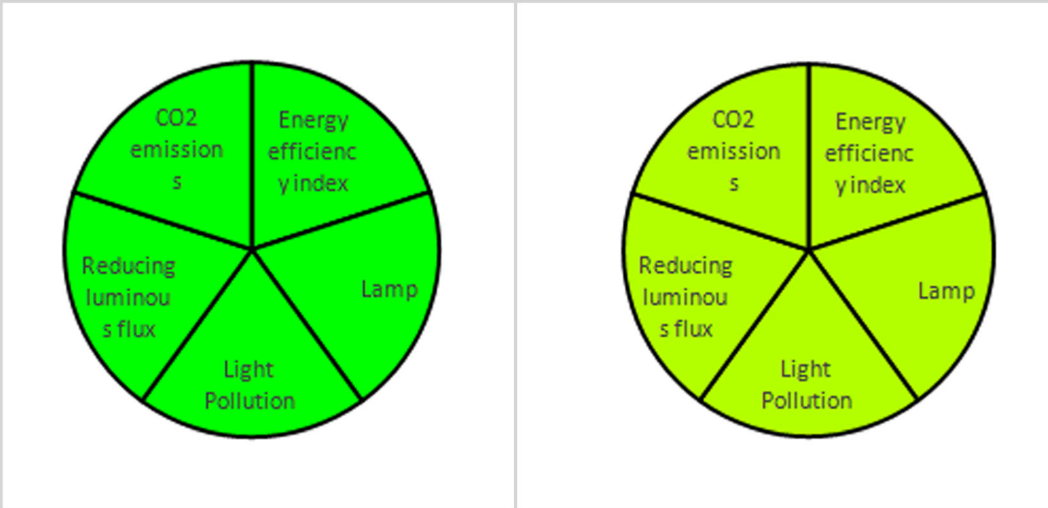


Fig. 16 Difference between A and B class

can be used. If we followed the recommendations of the Dutch ministry, dimmable road lighting systems could operate at 20 % when the density of traffic at night is low, at 100 % when the traffic density is high, and 200 % when there is a combination of high traffic density and exceptional conditions such as fog. The conclusions were that 20 % light level has no negative safety effects and is sufficient for low traffic density, but 200 % light level is not justified because the cost is high and the safety improvements are marginal at best (Van Hoek 1997). Another project (Collins et al. 2002) also investigated the effect of dimming. The lighting level setting was determined as follows; 100 % when there are more than 3000 vehicles per hour, 75 % when the range of vehicles is 3000–1500, and 50 % when the number of vehicles per hour is lower than 1500.

Following both projects and observing the behavior of Spanish roads (Dirección General de Carreteras), lighting level control devices can operate perfectly from 1:00 a.m. to 5:00 a.m., because the number of vehicles decreases considerably. In this aspect, the Croatian normative (NN 114/11 Official Gazette) specifies that, if the local government does not prescribe a schedule, the street lighting must be turned off or reduced by 50 % at least at 1:00 a.m.

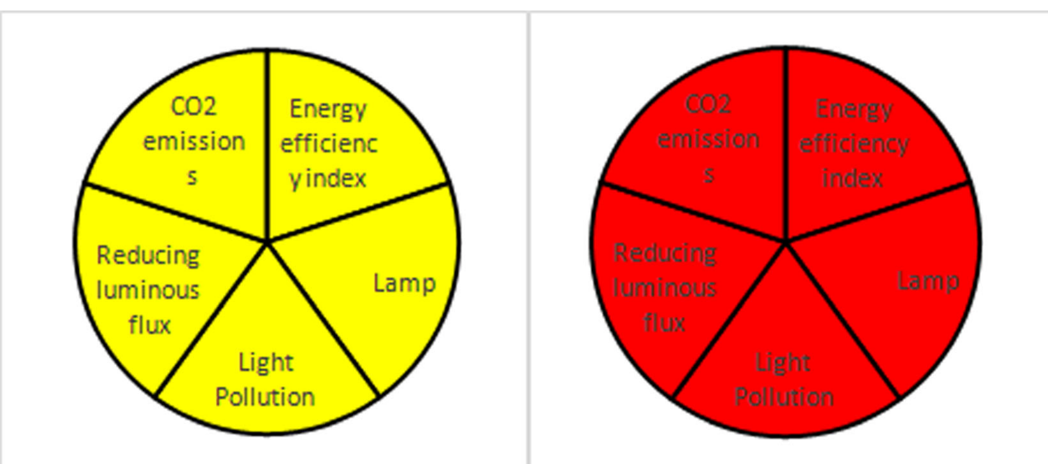


Fig. 17 Difference between level D and level G

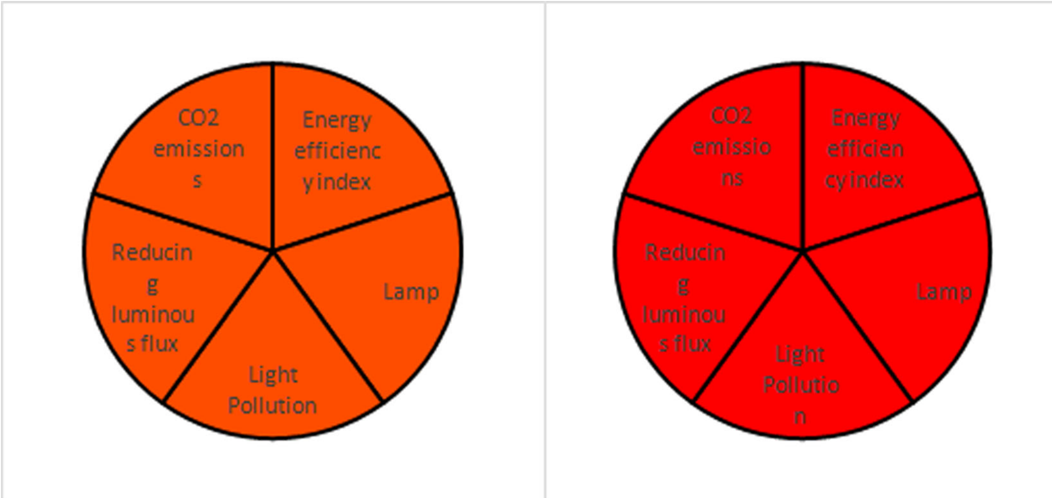


Fig. 18 Difference between level F and level G

There are a lot of examples that show the benefits of dimming of luminous flux. Nevertheless, there is not any evaluation system that directly keeps in mind this dimming when assessing the energy efficiency. Table 7 shows our suggestion to assess the class regarding the reduction of luminous flux.

Example

The best way to understand the working of these energy labels is with an example. First, it was analyzed two configurations with the current Spanish energy efficiency label and after that it was compared with our proposals to appreciate the differences.

The model of the luminary studied was BRS421 T15 1xECO113-2S/740 A (Philips). The lit-up surface was 240 square meters and the mounting height was 8.5 m. After using DIALux, the average illuminance was 15 lux. With the previous information, it is enough to develop the energy efficiency label using the current Spanish standard. The energy efficiency index was 0.7. As it can be seen in Table 3, the level would be D (Level 4). Figure 8 shows the energy efficiency label for the previous configuration.

As it can be noticed, lighting designers need few parameters to measure the energy efficiency of street lighting and they may omit some relevant parameter. On the other hand, our proposals need more information to assess the energy efficiency, for example,

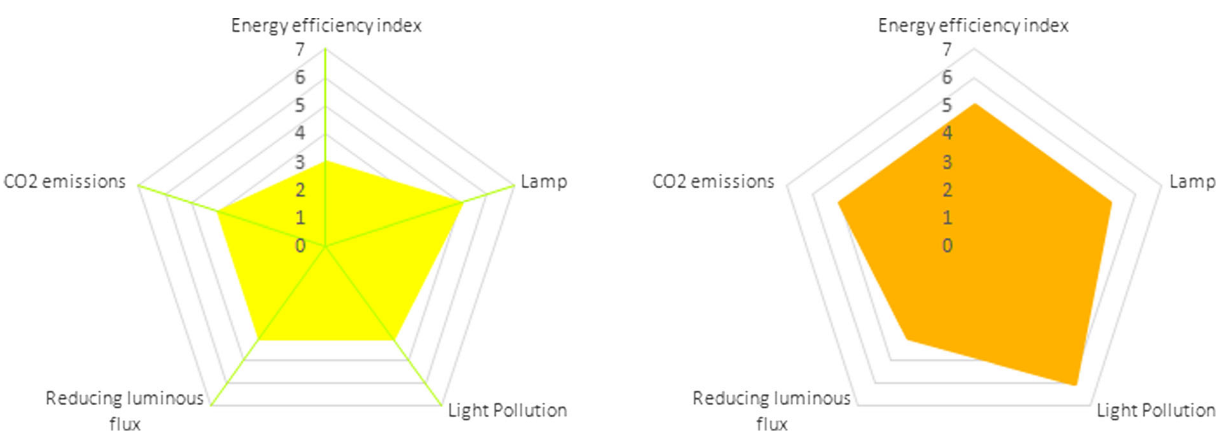


Fig. 19 Comparison between different kiviat diagrams

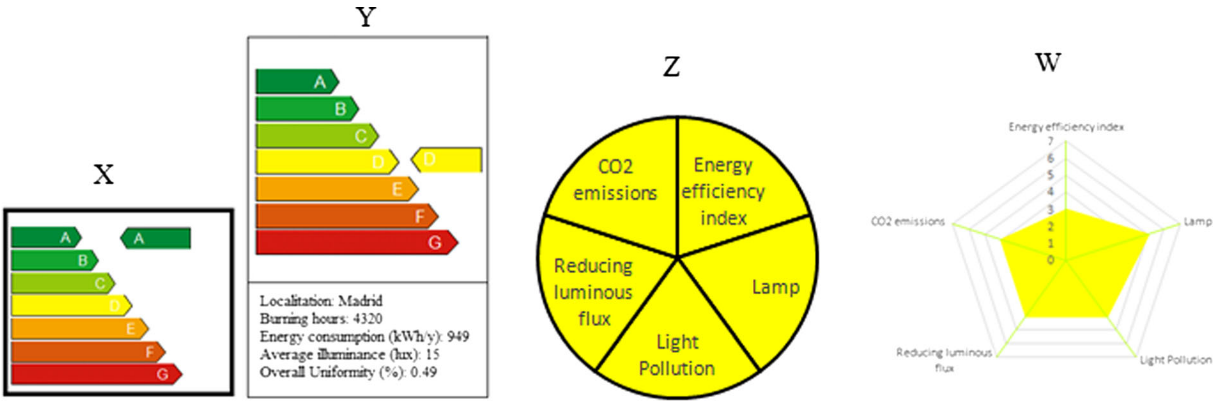


Fig. 20 Comparison among all energy efficiency labels used

renewable energy contribution, dimming of luminous flux, and light pollution.

In order to notice the difference with our proposal, it was analyzed how energy efficiency label would be if the previous configuration had electronic ballast. Unfortunately, with the current energy efficiency label would hardly change, because the unique parameter different would be the energy consumption. Figure 9 shows the energy efficiency label with electronic ballasts.

As it can be seen, it is difficult to see any difference between Figs. 8 and 9. On the other hand, our proposals take into account more parameters that allow appreciating the differences.

The first parameter of the evaluation is luminous efficacy. As the lamp power is 111 W and the total luminous flux is 11,329 lum. The luminous efficacy is 102 lm/W. This value is higher than 65 (minimum requirement). Therefore, using Table 2, the level of this lamp would be B (Level 6). This value is the same in both examples.

The evaluation of the second parameter, energy efficiency index, is the same than the current method, being in both cases a D level.

The third parameter of the evaluation is light pollution. This value was obtained from the simulations and it was 10 %. Thus, the level of this index in both cases would be C (Level 5).

The fourth parameter is renewable energy contribution. The examples analyzed do not have a renewable energy contribution. Therefore, the level of this index would be G (Level 1).

The last parameter is the percentage of dimming of luminous flux. The first example analyzed does not have any regulator nor stabilizer while the second case has a regulator and stabilizers which allows a dimming of the luminous flux of 25 % from 1:00 a.m. to 5:00 a.m. Thus, the level of this index would be G (Level 1) without dimming luminous flux and D (Level 4) in the second case.

As a result of the evaluation, and to show the differences between both evaluation systems proposed in this paper, Fig. 10 shows a pie chart for the two examples evaluated and Fig. 11 shows the same evaluation made with a kiviat diagram

In addition to the five indicators, the main contribution of kiviat diagram label is that the connection among

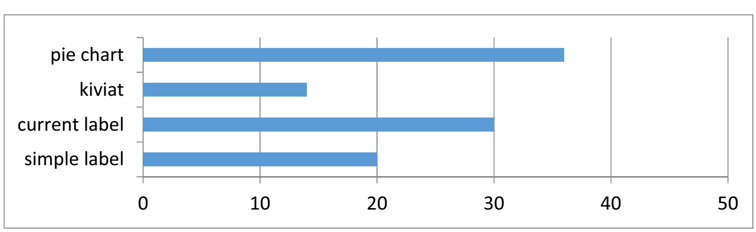


Fig. 21 Which energy label do you prefer to compare different street lighting systems?

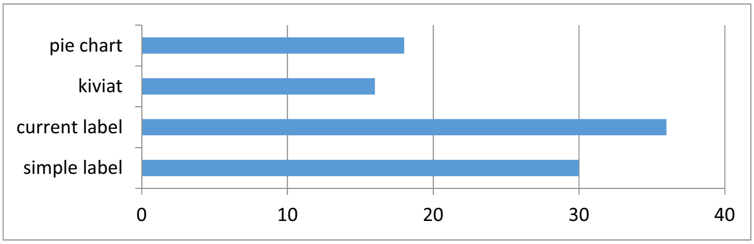


Fig. 22 Which energy label is the easiest to understand?

the five nodes gives a unique parameter which is very useful to compare different solutions.

Survey

We did a survey in Spain to check how prepared citizens are to accept these energy efficiency labels and if they are aware of the existence of an energy efficiency label for street lighting systems. The sample was composed of 50 people. The aim of the first question was to discover if citizens knew that there is an energy efficiency label for street lighting systems. We asked them if they knew which devices have an energy efficiency label. Figure 12 shows the percentage of positive answer.

Unfortunately, the percentage of citizens who knew that street lighting systems have an energy efficiency label was only 10 %. The survey respondents whose answer was positive for outdoor lighting were asked if they knew the unit used to measure the energy efficiency. They had three options: kWh, kWh/km^2 year, and (m^2 lux)/W. All of them chose kWh. This was noteworthy because the current unit in Spain is (m^2 lux)/W. In addition, awareness of energy efficiency labels on domestic appliances was high: dishwashers 90 %, washing machines 76 %, and fridges 72 %.

The objective of the second part of the questionnaire was to know if citizens assume that a better ranking means less energy consumption. This part is composed of three pictures, where two different systems for each energy label are shown and compared. Each comparison included two questions: Which street lighting systems is the most energy efficient? And which street lighting system consumes the least energy?

The first illustration had two simple labels with different ranks. Figure 13 shows the first picture of the second part. Surprisingly, 74 % of citizens assumed that an energy label which shows a better rank represents lower energy consumption than another label with lower rank. However, this is not the case because the traditional evaluation system only takes into account the lamp power and it does not take into account dimming of luminous flux or the contribution of renewable energy.

The second illustration had two simple labels with the same rank. Figure 14 shows the picture used for the second comparison. Ninety percent of citizens replied that both images were the same and they did not have enough information to answer the question. This means that the energy efficiency label needs to include more information. In that aspect, the label established by the Royal Decree is correct, because it includes information about the position, burning hours, energy consumption, average illuminance, and overall uniformity.

The third image had two current labels with the same rank, the difference regarding the previous illustration is that, this time, the energy labels include the information

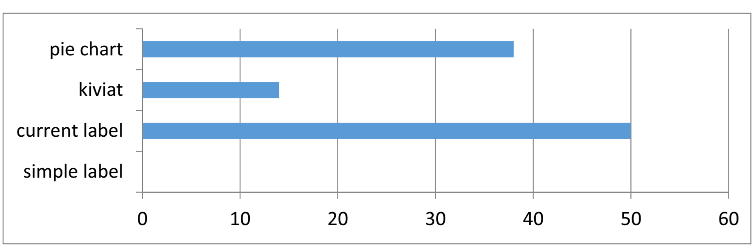


Fig. 23 Which energy label gives more detailed information?

required by the Royal Decree. Figure 15 shows the image used. One of them shows less consumption because the system has a device to reduce luminous flux. The results obtained again show that citizens assume that when a system consumes less energy, it is more efficient. Eighty percent of survey respondents said that the label displaying less energy consumption was the system more energy efficient, when both labels had the same rank.

The aim of the third part of the questionnaire was to confirm if citizens were able to easily differentiate the colors used on the energy efficiency label and if the difference between similar levels (for example level F and level G) is too subtle to distinguish clearly. This section consists of pie charts, and the survey respondents had to reply to two questions for each image: Which street lighting system is the most energy efficient? And which street lighting system consumes the least energy?

Using the first image (Fig. 16), we wanted to discover if people were able to see the difference between level A (0-255-0) (RGB) and level B (77-255-0) (RGB). Seventy-eight percent of respondents were able to see the difference.

With the second image (Fig. 17), we wanted to understand if survey respondents were able to distinguish between level D (255-255-0) (RGB) and level G (255-0-0) (RGB). Ninety-two percent of respondents were able to see the difference.

Through the third image (Fig. 18), we wanted to see if citizens were able to see the difference between level F (255-77-0) (RGB) and level G (255-0-0) (RGB). Eighty-four percent of respondents were able to see that difference.

The fourth part of the questionnaire used the kiviat diagram (Fig. 19). As this label has more parameters evaluated, we asked the following: Which street lighting system is the best regarding the energy efficiency index? Which street lighting system produces the least light pollution? Which street lighting system installation is the most energy efficient? Sixty percent of respondents were able to reply correctly to all the questions. This indicates that the kiviat diagram may be too complicated for citizens without technical knowledge. Maybe, it is a good option only for lighting designers.

The last part of sheet gathers all energy efficiency labels used in the survey. Figure 20 shows the picture used. We wanted to have an overall idea of which energy label is the best for citizens.

The questions were as follows: Which energy label do you prefer to compare different street lighting systems? Which energy label is the easiest to understand? Which energy label gives more detailed information? Which energy label should be used for street lighting systems? The next figures show the results obtained (Figs. 21, 22, 23, and 24).

As it can be appreciated, our assumption that the pie chart could be a good option was not wrong addressed because the pie chart and current label obtained similar percentage (36 and 30 %).

As it can be seen, citizens are used to seeing the typical label, because they understand better the traditional label than our proposals.

As it can be appreciated, the percentage of survey respondents who chose the simple label was 0 %. In addition, the numerical information of the current label was accepted with great popularity. On the other hand, we believe that the kiviat diagram was not accepted because it does not show data.

As it can be seen, the current label was considered as the best option followed by the pie chart. These results validate that the energy efficiency label established by the Royal Decree 1890/2008 (2008) is adequate for citizens, but we do not believe that it is adequate for lighting designers because it has been found that street lighting systems easily meet these values in the Netherlands (Ottens 2010).

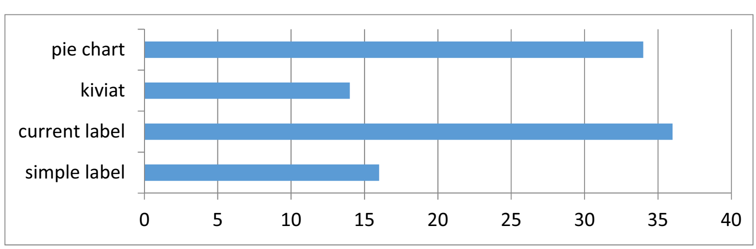


Fig. 24 Which energy label should be used for street lighting systems?

Conclusions

The results of this research are two new proposals for an energy efficiency label and a new method to assess energy efficiency for street lighting systems.

The main difference between the current evaluation system and these proposals is the number of parameters assessed. While the current evaluation system only assesses one parameter (energy efficiency index), our proposals assess five parameters: lamps, energy efficiency index, light pollution, renewable energy contribution, and dimming luminous flux.

Following the completion of this manuscript, the survey has revealed some aspects that we consider important to point out:

(1) Although the Royal Decree is mandatory from 2008, at present, only 10 % of survey respondents knew that street lighting systems must have an energy efficiency label. This means that those responsible of street lighting systems, for example, town councils, do not show the label. We propose that lamp posts would be a good place to display it. In addition, none of the respondents guessed the unit used to assess the energy efficiency correctly. They connect energy consumption with energy efficiency. In other words, they believe that energy consumption and energy efficiency is the same thing.

(2) The sample of colors used in the label is appropriate.

(3) Citizens prefer energy efficiency label with numerical data because it allows them to compare other products, systems, and so on.

(4) Finally, the current label is the best option for citizens because they do not need a lot of parameters to evaluate energy efficiency; they only need to obtain a general idea of performance. However, in our opinion, the kiviat diagram should be used for lighting designers so all aspects are taken into account at the design stage.

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