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Critical analysis of the energy performance indicators for road lighting systems in historical towns of central Italy

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ABSTRACT

Energy demand represents a global challenge that calls for innovative energy solutions. Road lighting contributes in a small part to the overall worldwide electricity consumption, however the possibilities for energy saving are numerous. The road lighting should provide the required lighting quality, in the most energy efficient way as possible.

In this paper the Authors analyze, compare and discuss the numerical indicators currently used to evaluate the lighting and the energy performance of new-designed and existing road lighting systems. To support the discussion, the use of the case study of road lighting of the historic town center of Pisa is proposed. For the case study the Authors have chosen a significant sample of 20 roads representative of 80 similar roads located in the historic town center. For the sample, geometric surveys, luminance and illuminance measurements, calculation of the national and international energy performance indicators have been carry out. The considerations made by the Authors, obtained with an investigation procedure of general validity, are useful to point out strengths and weaknesses of each indicator and to provide suggestions on the use of the appropriate indicators during the design stage of road lighting systems.

1. Introduction

Energy demand represents a global issue that calls for innovative local energy solutions, such as the ones generally proposed in Sustainable Action Plans (SEAP) [1]. By the end of May 2016 more than 6700 cities around Europe (3100 in Italy), that involve 211,610,834 inhabitants, started to working on their SEAPs [2]. Public lighting (predominantly on roads) contributes for 2.3% to the global worldwide electricity consumption; thus, energy-efficient programs in this field are very welcome, since the possibilities for energy saving in road lighting are numerous and sometimes even enable reductions in electricity consumptions of more than 30% [3,4]. In 2005, in Europe, road lighting consumed a notable amount of energy: approximately 35 TWh [5]. In 2010, in the Netherlands, about 0.8 TWh per year were used by municipalities for public lighting, accounting for 60% of the local government's energy consumption [6]. In the same year, in Italy, the national consumption for lighting was about 50.8 TWh per year and, of this amount, 6.1 TWh per year were used for public lighting [7].

Currently, towns throughout the world are engaged in road lighting refurbishment, carried out with the changeover to more efficient luminaires, in some cases at the end of the economic life of the existing ones, in others before the end. Several studies have shown that urban interventions on lighting can lead to positive results [8–12], since public lighting is an essential element of urban environments [13]. Public lighting should: provide good visibility conditions, reduce potential hazards by illuminating objects in and along the roadways [14–16], influence the emotions of the observers.

With increasing consideration of pollution and energy conservation, the needs to introduce new recommendations for energy efficient lighting and new indicators to evaluate the energy performance of lighting systems are arisen. At the beginning, the attention was paid to the indoor lighting systems [17–22], nowadays new efforts are focused on the energy consumptions of public lighting systems [8,11,25] and some energy performance indicators have been proposed at international level to compare the performance of these systems [23].

In Europe, only few countries have provisions addressing the energy efficiency of the road lighting systems. In Ref. [8], useful suggestions for preparing such provisions were supplied, identifying a set of the most important recommendations regarding the

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influencing factors for energy savings in road lighting. However the suggestions were mainly qualitative and there was no systematic use of energy-based and lighting-based parameters for the comparison of different road lighting systems. In the Netherlands an energy efficiency A-G label were developed for road lighting systems, based on the Street Lighting Energy Efficiency Criterion (SLEEC), which is a whole system indicator taking into account efficiency of the lamp, ballast and luminaires [24]. In Ref. [25] a multi-objective evolutionary algorithms was presented with the aim to use it for planning efficient public lighting. The approach adopted in Ref. [25] was SLEEC-based, but no result about other performance indicators were shown, thus the work does not contribute to a critical comparison between the different performance indicators proposed at international level. In Italy, the legislative power in matter of light pollution, design and management of public lighting belongs to the Regions that can enact laws applicable in its territory [26,27]. In Ref. [11] a new interesting methodology for the evaluation of the cost-benefit ratio, for energy saving interventions on the road lighting, was proposed by using the case study of the Comiso Municipality (Italy). In the case study, a comparison between 2 different scenarios (providing specific energy efficiency measures) was made, but also in this work the techno-economic analysis does not use the performance indicators proposed at international level. In this context, it is clear the importance to critically discuss and compare the energy performance indicators for road lighting systems, currently available at international and national (Italian) level.

In this paper the Authors propose a critical analysis of the most significant numeric indicators for the evaluation of lighting and energy performance of both new-designed and existing (whose refurbishment is to be planned) road lighting systems. The comparison of energy performance indicator takes into consideration the types of lighting systems (new-designed or existing under refurbishment) and it is aimed to:

- define strengths and weaknesses of each indicator,
- provide suggestions on the use of the appropriate indicators during the design stage of road lighting systems.

These aspects are not sufficiently clarified by the technical standards and nor by the scientific literature. To support the discussion, the use of the case study of the road lighting of the historical old town center of Pisa is proposed. In order to analyze the current state of the road lighting systems of the case study, the Authors have defined an investigation procedure that has been applied to a sample of 20 roads, representative of 80 similar roads. The use of the case study is not be intended as a limitation of the performed research, but as an application example of the investigation procedure defined by the Authors, useful in highlighting the critical issues about the evaluation of energy performance indicators, especially for existing public lighting systems. The same approach followed by the Authors, in fact, could be used in any other town. Moreover, being the state of the art of public lighting in the historical towns of central Italy (often characterized by similar lighting infrastructure, similar lamps and luminaires typologies), the use of Pisa as case study town can be considered representative for a large number of historical towns located in that geographical area.

2. Energy performance indicators for road lighting

Recently, with the aim to quantify the potential savings obtainable from the improvement of the energy performance of the road lighting systems, some numerical indicators have been introduced on European and Italian levels. The most important energy performance indicators for road lighting systems are summarized in Table 1, and briefly discussed in the Annex B.

In the European standard [23], the Power Density Indicator and the Annual Energy Consumption Indicator have been defined. The Power Density Indicator (D_P) states the power needed for a road lighting system to meet the lighting requirements set out in Ref. [28]. The D_P (W/m^{2}lx) is defined as the value of the electrical power divided by the value of the product of the surface area to be lit and the maintained average illuminance value on this area (see Table 1) according to [29]. The Annual Energy Consumption Indicator (D_E) states the electrical energy consumption for a road lighting system during the year, also taking into account specific night-time or seasonal lighting performance (i.e. possible variations to absorbed grid power due to different operation profiles at night-time or during certain seasons of the year). The D_E (Wh/m^2) is defined as the electrical energy consumed by a lighting system throughout the year divided by the surface area to be lit (see Table 1). These indicators could be used to easily compare the energy performance of lighting systems obtained with different solutions and technologies for a single road. The comparison of the energy performance of lighting systems installed in roads with different features should be done with caution, because these indicators are function of the area to be lit and the lighting requirements [28–30].

In Italy, specifically in the regulations of the Emilia Romagna region [31], two indicators have been introduced with the aim to promote energy savings in outdoor public and private lighting: a Luminaire Energy Efficiency Indicator and a Lighting System Energy Efficiency Indicator. The Luminaire Energy Efficiency Indicator (IPEA) is useful to provide an objective overall assessment of the luminaire, disregarding aspects of lighting design and luminaire operation. The IPEA is the ratio between the luminous efficacy and the standard luminous efficacy related to the best technology available on the market (see Table 1). Starting from the IPEA calculated value, an energy class to the analyzed luminaire can be assigned. The Lighting systems Energy Efficiency Indicator (IPEI) has been introduced on the basis of the SLEEC [24], with the aim to enable the assessment of the overall energy performance of a particular lighting system. The calculation of IPEI (see Table 1) is based on the illuminance or on the luminance values ($IPEI_E$ and $IPEI_L$, respectively). Considering the assumption that the road surface is a Lambert source, using the relation $E_m = \pi \cdot L_m / r$ where r is the luminous reflection coefficient of the road surface, the illuminance based IPEI ($IPEI_E$) and the luminance based IPEI ($IPEI_L$) should produce the same results. Starting from the IPEI calculated value, an energy class to the analyzed luminaire can be assigned. The IPEA and IPEI can be used to evaluate both new-designed and existing road lighting systems.

2.1. Determination of the energy class for luminaires and lighting systems

The energy class for a luminaire is determined by comparing the obtained IPEA value with the labelling scheme [31] shown in Table 2. The energy class for a lighting system is likewise determined by using the obtained IPEI value [31] (see Table 2). In Italy, the Emilia Romagna region has established that, starting from 2013, for all new lighting systems (except for outdoor lighting systems with fewer than ten luminaires) the minimum acceptable class for the IPEA indicator shall be Class C (IPEA>0.93) and the minimum acceptable class for the IPEI indicator shall be Class B (IPEI<1.09). Regarding the refurbishment of existing lighting systems, the region of Emilia Romagna requires that at least one of the two indicators has to be improved with respect to the initial conditions (proven through the energy and lighting calculations).