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.

Keywords: Road lighting; Public lighting; Energy performance indicators; Lighting requirements; Electrical energy consumption; Energy performance.

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 [8], useful suggestions for preparing such provisions were supplied, identifying a set of the most important recommendations regarding the 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 [25] a multi-objective evolutionary algorithms was presented with the aim to use it for planning efficient public lighting. The approach adopted in [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 [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 [28]. The D_P (W/m^2lx) 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 Tab. 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 Tab. 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 Tab. 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 Tab. 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 Tab. 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).
Moreover, it should be noticed that the determination of the energy classes, for luminaires and road lighting systems, makes sense only if the requirements fixed by the standards (in terms of luminance or illuminance) are fulfilled. On the contrary, before proceeding to the classification, the analysis and the resolution of non-compliances of the lighting requirements is strongly recommended.

3. Analysis of the energy performance of urban lighting systems: the case study of Pisa

The city of Pisa originated as an Etruscan river port around the middle of the sixth century, even though the presence of definite clusters of dwellings was documented around the ninth century [32,33]. Pisa is located few kilometers from the Arno river mouth on the Tyrrhenian Sea and is considered to be one of the most important art cities in Europe [33]. The city covers an area of 185.2 km^2; the oldest part of Pisa lies within its

Medieval walls and is centrally located, whereas modern buildings and industrial plants have developed on the outskirts around the historical center [32].
The Municipal Authority of Pisa joined in 2010 the Covenant Major [1] and it has scheduled in 2015 an extensive plan for replacing approximately 13,000 existing luminaires with new generation LED-source luminaires. Such plan involves an investment of approximately 18 million Euro and includes the replacement of the luminaires by the end of 2018, the management and the maintenance of the lighting systems for ten years.
Public lighting in Pisa is currently composed of approximately 14,000 luminaires (of varying types) having lamps with different characteristics (i.e. electrical power, luminous flux, color temperature, color rendition, luminous efficacy). Specifically there are historical luminaires (e.g. wall and lamp post lanterns in the historical center and along the roads that run alongside the Arno river), luminaires for road lighting (e.g. projectors on lamp posts or mounted on catenaries) and luminaires for lighting parks and gardens (e.g. artistic luminaires mounted on lamp posts not taller than 4 meters). There are also special luminaires for architectural lighting of squares and monuments, which are not considered in the current analysis. Data from 2009 indicated the annual consumption of electrical energy due to public lighting to be about 9 GWh/year corresponding to an annual cost of 18 €/inhabitant and 122 €/luminaire. These values closely match those processed for the major Italian cities [7,34].
In order to analyze the energy performance of the existing urban lighting systems in the city of Pisa, the Authors have carried out a systematic procedure based on in-field measurement of the current lighting performance and on post processing activities of the results, necessary to calculate the energy performance indicators [23,28,35,36]. The various phases of the activity can be listed as follows:

- Step 1) Identification of a representative sample of roads;
- Step 2) Survey of the geometric characteristics of each road;
- Step 3) Determination of the lighting class of each road;
- Step 4) Survey of the main characteristics of the lighting system (i.e. type and size of the support structures, photometric characteristics of lamps and devices) for each road;
- Step 5) Identification of the typical span, on which to carry out in situ lighting measurements, for each road;
- Step 6) In situ lighting measurement activity (i.e. horizontal, vertical and semi-cylindrical illuminance, luminance, color temperature and color rendering index of the installed lamps);
- Step 7) Post processing of the measurement results (in order to calculate lighting parameters and energy efficiency indicators).

It is important to note that the step 1 is performed only once at the beginning of the procedure, the steps from 2 to 7 are repeated for all the roads belonging to the sample.

3.1 Identification of a representative sample of roads

The identification of a representative sample of roads is undoubtedly the most delicate operation, since an unsuitable choice of the sample could produce incorrect results. In this phase, all the different types of roads in the territory need to be considered, in order to select a sample having an adequate number of roads to allow the extension of the results to a significant part of the town. Additionally, the choice of the roads has to take into account the types of traffic and the operation time profiles in order to guide the measurement activities.
In the current case study an appropriate selection was made of 20 roads, distributed within the municipal territory (Fig. 1), in representation of 80 roads. The sample of 20 road has been identified by considering in particular the following characteristics: arrangements and types of lighting system, lighting classes of the roads. The roads inserted in the sample have different characteristics to cover the largest case present in the center of Pisa. The differences between the roads can be detected by observing the last four columns of Table 3, where all combinations (Arr, Type, Lighting class) are different, except for the roads 19 and 20 which

have the same combinations of the roads 4 and 16 respectively. However, the road 19 has a different installation height of the luminaires compared to the road 4 (10 m instead of 8.5 m), the road 20 has a different luminaires interdistance compared to the road 16 (27.5 m instead of 23 m). Each of the 80 roads represented by the sample has similar characteristics to at least one of the roads contained in the sample. The sample of 20 roads has a total length of 12 km and is constituted by a total of 600 luminaires within a whole lit area of 153,000 m^2. The sample extended to the 80 roads is constituted by a total of 2600 luminaires within a whole lit area of 660,000 m^2, it develops along an overall road length of 75 km and it includes the 19% of the luminaires of the municipal territory and the almost totality of the luminaires of the city-center.

3.2 Survey of the geometric characteristics of each road

The following characteristics have been measured for each road belonging to the sample: the total length (L), the carriageway width (W_2) and sidewalks widths (W_1, W_3), the height of luminaire system (H), the luminaire interdistance (d) intended as the distance between the luminaires on the same side of the road, the number of the luminaires (No) located on the road, and the arrangement (Arr) of the luminaires. The survey results of the geometric characteristics are shown in Table 3 for the examined roads. For the sake of completeness, in Table 3 the types of luminaire and lamps (Type) as identified in Table 4 are also shown, together with the lighting classes assigned to the carriageway (M) and to the sidewalks (P).

It should be noted that most of the analyzed roads have sidewalks on both sides, except the road 1 (which is completely pedestrian) and the roads 11, 16, and 17 (which have a sidewalk on one side only). Despite the presence of sidewalks on both sides of the carriageway, the luminaires are often located on one side only (Arr=O, Tab. 3). In some cases, between the sidewalk and carriageway, there is a car parking lane. The luminaire system height usually coincides with the pole height and in each road the luminaires are ~~all~~ mounted at the same height. In some cases the luminaires are mounted as a suspended catenary, for example in the roads 9, 11, and 17. The lengths of the analyzed roads vary between approximately 200 m and 2 km. The luminaire interdistance (d), in relation to the luminaires arrangement, has been considered as shown in Figure 2.

3.3 Identification of the lighting class of each road

The road lighting classification has been carried out using the selection procedure presented in [35]. This classification is based on different lighting situations (i.e. motorized traffic areas, conflict areas, pedestrian and low speed areas) and on several parameters that include the design speed, the traffic volume and the traffic composition, the function and the overall layout of the road, the environmental conditions. The classification, which is based on European technical standards, is aligned to the classification of the roads according to the traffic laws in Italy, which are based on the type of road and the maximum vehicle speed allowed [37,38].

The results of the lighting classification, evaluated for the 20 analyzed roads, are shown in Table 3. Note that for the aims of the surveys undertaken in this study, in the case of one-sided arrangement of the luminaires (Arr=O, Tab. 3), a subscript value of 1 refers to the sidewalk on which the luminaires are located (in the graphical representations, the location is on the left).

3.4 Survey of the main characteristics of the lighting system

In this phase, ~~both~~ by visual inspection as well as by in situ measurements, the types of luminaires, and when distinguishable, the types and the powers of the installed lamps have been identified. The results of the survey have been verified with the installation data provided by the Municipal Authority of Pisa.

The obtained results have been used to conduct research in the luminaire manufacturer catalogues in order to identify the characteristics required to complete the analysis, in particular: photometric data, light output ratio of the luminaire (for determining *Dlor*), efficacy of the power supply (η_{supply}). The results of the survey regarding the lighting system are indicated in Table 4, where the following data are shown for each luminaire: photo of the luminaire, the type and the power of the installed lamp, the color temperature (CCT) and the color rendering index (Ra) of the lamp. The latter two characteristics have been measured in situ by using a Konica Minolta mod. CL-500A spectrophotometer in order to verify the installation data provided by the Municipal Authority of Pisa.

3.5 Identification of the typical span for each road

The identification of the typical span on which to carry out in situ lighting measurements constitutes a very important activity, in order to obtain significant and representative results for the entire length of the road. In this phase it is necessary to examine the entire road and assess the uniformity of the lighting system, the luminaire interdistance, the geometric dimensions of the road section, etc. It is very convenient to choose a typical span in which there are no parasitic light sources, for example: luminous signs, business activity windows (e.g. shops, banks, cafes, etc) that are lit at night time, curb parked vehicles that obscure the portion of sidewalk on which the measurements are carried out, pedestrian crossings or other areas that require appropriate evaluation. It must be stressed that such issues are very frequent and are at times difficult to handle; it is not always possible to identify a convenient typical span (consider, for example, business roads that have heavy traffic even at night time) and in such cases it might be appropriate to carry out the measurements several times at different hours and on different days of the week. Three example of typical spans for the roads in the analyzed sample are shown in Figure 3, with the illustrations of the arrangements of the luminaires and the associated photographic images.

3.6 In situ lighting measurement activities

The following activities have been carried out on each road in the sample: horizontal illuminance measurements on the sidewalks and the carriageways, luminance measurements on the carriageways in both directions, and vertical and semi-cylindrical illuminance measurements on each sidewalk in both directions. Altogether in this extensive series of measurements approximately 1300 lighting measurements have been carried out, subdivided as follows: 365 horizontal illuminance measurements, 370 vertical illuminance measurements, 370 semi-cylindrical illuminance measurements, and 190 luminance measurements, in addition to some control measurements. In this paper only the horizontal illuminance and luminance measurements are shown and discussed in so far as they are useful for assessing the energy performance of lighting systems.

In order to conduct a series of in situ lighting measurements it is necessary to set up an adequate measurement grid by identifying the minimum number of points in which to measure illuminance and luminance. For each typical span, 5 points have been identified for the horizontal illuminance measurements on each sidewalk (such points have been also used for the vertical and semi-cylindrical illuminance measurements in both directions), 9 points have been identified for the horizontal illuminance measurements on the carriageway, and 6 points have been identified for the luminance measurements on the carriageway. In Figure 4 examples of illuminance measurement points, for spans belonging to two of the analyzed roads, are shown. With the aim of verifying the repeatability of the measurements results, the horizontal illuminance and luminance measurements have been repeated 3 times for the 20% (randomly selected) of the total measured points, obtaining a maximum deviation between measures taken at the same point equal to 8%. This deviation, in relation to the type of measurements made (illuminance and luminance values due to road lighting systems), is such that no significant variations on the results obtained for the energy performance indicators were introduced.

The instruments utilized for carrying out the series of measurements are part of the instrumentation made available by the Laboratory of Lighting and Acoustics of the School of Engineering at the University of Pisa. The measurement instruments are compliant to the requirements indicated in [36]. Specifically for the illuminance measurements, the luxmeter PRC Krochmann model Radiolux 111 was used. The luxmeter was equipped with a probe for horizontal illuminance measurements. The luxmeter allows illuminance measurements in the range $1 \cdot 10^{-3} \div 3.6 \cdot 10^{5}$ lx, with maximum errors of 3% and 1.5% in the spectral sensitivity response and in the cosine response [39] respectively. For the luminance measurements, the luminancemeter Hagner model S4 was used. The luminancemeter was equipped with a silicon photodiode detector, it allows luminance measurements in the range $1\cdot10^{-2}\div2\cdot10^{5}$ cd/m^2 with a measuring angle of 1° and with maximum errors of 3% and 1.5% in the spectral sensitivity response and in the cosine response [39] respectively. The luxmeter and the luminancemeter are characterized by the maximum precision level on a three level scale compliant with [39]. The utilized measuring instruments were accompanied by calibration certificates, issued by accredited laboratories, that attested the regular operation according to the Italian standard for portable photometers [39].

3.7 Post processing and discussion of measurement results

For each analyzed road, the following activities have been carried out: the average values of illuminance have been calculated on the sidewalk and carriageway areas (E_m), the maximum and minimum values of illuminance (E_{min}, E_{max}) have been identified, and the average illuminance uniformity (U) has been calculated. For the carriageways the average luminance values (L_m) have been also calculated, the minimum luminance value (L_{min}) has been identified, and the overall (U_0) and longitudinal (U_L) luminance uniformities have been calculated. The measurements results are shown in Tables 5 and 6 for the 20 analyzed roads. In the measurement results the subscripts 1, 2, 3 match the notation used in Table 3. For the sake of completeness, in Tables 5 and 6 the minimum values required by the standards [28,30] are shown. It should be noted that the values of E_m required for the carriageways (see Table 6), which are unspecified in the technical standards, have been derived for the purpose of the present paper from the values required for L_m and using a mean reflection coefficient of the examined roads surfaces equal to 0.2 [30].

From the results of the illuminance measurements on the sidewalks (see Table 5) it can be observed an overall compliance with the standard requirements [28,30]. The major critical situations derive from the results of the horizontal illuminance measurements in roads with sidewalks on both sides with one-sided arrangement of the luminaires and without luminaires specifically dedicated to the pedestrian lanes. In such cases a large difference in the average illuminance values between the two sidewalks can be observed, for example, in the road 3 (Table 5) the average illuminance on the sidewalk where the luminaires are installed is E_m=32.6 lx whereas the average illuminance on the opposite sidewalk is E_m=4.7 lx, with a difference of 27.9 lx, i.e. a reduction of over 85% and a corresponding visual discomfort for walkers. Moreover, in some roads the average values of illuminance are totally unsatisfactory, with values equal to or less than 2 lx, for example roads 2, 10, and 18 (Table 5). In all the last three cases, the luminaire installation heights are inadequate with respect to the luminaire interdistances.

From the results of the illuminance measurements on the carriageways (Table 6), it can be observed that the average illuminance values are often higher than 10 lx, and the lower values has been obtained on the roads 10 and 18 with average illuminance values lower than 2 lx. From the results of the luminance measurements on the carriageways (Table 6) it can be observed an overall compliance with the standard requirements [28,30]. Clearly, due to the one-sided arrangement of the luminaires, compliance with carriageway longitudinal luminance uniformity is much more difficult to obtain. This is especially evident for the roads 2, 5, 13, 19, and 20 (Tab. 9), with U_L values ranging between 0.27 and 0.61.

4. Calculation and discussion of energy performance indicators

The energy performance indicators D_P and D_E specified in [23] and the energy performance indicators IPEA and IPEI specified in [31] have been calculated for the analyzed roads.

For calculating D_P it has been necessary to identify the areas which make up the chosen typical span (sidewalk and carriageway) and to refer to the calculated average illuminance (see Table 5 and 6). For calculating D_E an operating time of 4000 hours has been assumed with a single utilization profile in the absence of control systems for shutting off totally or partially the luminaires during the night-time.

In Table 7 for each road are shown: the luminaire lamp power (P_L), the absorbed power (P) including that used by auxiliary electrical components, the surface of the subareas that make up the typical span, and the calculated values of numerical indicators D_P and D_E. Furthermore the values of Annual Energy Consumption in the case of reduction of luminous flux of 50% for 1700 hours of the overall 4000 hours of annual use (corresponding, for example, to the time period 23:00-04:00) D_E* has been added. The results show a high discrepancy in the values calculated for the numerical indicators D_P and D_E: D_P varies from 17.7 mW/m^{2}lx for the road 13 to 197.1 mW/m^{2}lx for the road 3; D_E varies from 1.1 kWh/m^{2}y for the roads 8, and 18 to 5.6 kWh/m^{2}y for the road 3 (see Table 7). These results should not surprise, considering the evident high dissimilarity in the configurations (i.e. arrangement, installation height, type of lamp and luminaire) pertaining to the public lighting systems in the city of Pisa. Concerning the operating time, in the case of reduction of luminous flux of 50% for 1700 hours, the D_E* results 21% lower than the D_E obtained in the case of total power for all 4000 hours.

The calculation of IPEA has been carried out using the characteristics of the luminaires installed in the analyzed roads. The utilized luminaires are all old generation luminaires (about to be replaced with LED luminaires) and have IPEA values ranging from 0.39 to 0.93, between class D and class G (see Table 8). Clearly, all luminaires pertain to classes lower than class C (IPEA≥0.93, Table 2), which is the lowest acceptable class for implementing new lighting systems in the region of Emilia Romagna [31].

For calculating the IPEI, it has been necessary to compare the measured lighting values with those required by the reference technical standards [28] and to know the geometries that characterize roads and installations (i.e. carriageway width, and post inter-distance), see Table 9. As the luminaires located in the analyzed roads provide both carriageway as well as sidewalk lighting, it seems more appropriate to determine an IPEI value which takes into account the installation performance across the entire road section. It should be noted that in [31] the method for calculating the IPEI is not specified in the case of roads composed of both carriageway lanes as well as pedestrian sidewalks. The global indicator ($IPEI_w$) defined by the Authors is calculated as a weighted average on the areas of the indicators obtained for the various subareas that make up the analyzed typical span, because a different lighting requirement has to be met for each of the subareas, appropriate values of E_{mR} or L_{mR} need to be used each time. For the sake of completeness, in Table 9 the $IPEI_m$ values are additionally shown for all the analyzed roads. The $IPEI_m$ values were calculated as the arithmetic average of the values obtained for the subareas, in which each road can be divided into. For each IPEI value obtained separately for the sidewalks and the carriageways and for the corresponding arithmetic and weighted average values, energy classes have been determined and indicated in Table 9. Clearly, as expected from the previous results, both for the average illuminance and luminance values as well as for the numerical indicators D_P and D_E, the overall energy classes of the roads in the analyzed sample are very low. The best overall energy class $IPEI_w$=D was assigned to the roads 1,4,13, and 19, which, except for the pedestrian road 1, is always positively influenced by the high energy class obtained by the respective carriageways.

Summarizing the results obtained from the calculation of the four performance indices it is possible to put in evidence the following observations.

- Low D_P values (i.e. D_P <27 mW/lx·m^2) have been obtained for the roads 4,6,12,13,14,19. For these roads, with the exception of the road 12, the average illuminance values satisfy the limit values required by the technical standards. Although very high D_P values (i.e. D_P>120 mW/lx·m^2) have been obtained for the roads 2,3,10 and 18, for some of these roads (roads 10 and 18) very low illuminance levels were measured.
- Low D_E values (i.e. D_E=1.1 kWh/m^{2}y) have been obtained for the roads 8,18. These results, however, are influenced by the fact that these roads are so scarcely lit, so that at reduced energy consumption do not match adequate lighting performance (non-compliance with the lighting requirements fixed by the technical standards). The highest D_E values (i.e. D_E>3.0 kWh/m^{2}y) have been obtained for the roads 1,3,7,15 which satisfy, sometimes very largely, the lighting requirements fixed by the technical standards. Therefore, a high D_E value indicates an inadequate exploitation of the lighting system (e.g. lamps with too high luminous flux and electrical power, luminaires with unsuitable emission characteristics, etc.).

- The lower IPEI values (i.e. IPEI<2.0) have been obtained for the roads 1,4,6,12,13,19, in analogy with the D_P values (this result was easily predictable, given the relationship existing between IPEI and D_P, see Annex B). The highest IPEI values (i.e. IPEI>10) have been obtained for the roads 10 and 18, scarcely lit roads which correspond to very high D_P values.
- The lower IPEA values (and lower energy classes) have been obtained for the older luminaires. The highest energy class ("D" class) has been obtained for the luminaires identified with the codes $L1_B$ and L5 (see Table 4). For all the analyzed roads, the IPEA values, and the correlated energy classes, are lower than the minimum values required in [31].

5. Conclusive remarks

From the detailed analysis conducted on the different performance indicators and from their application to the case study of the historical town of Pisa, the following considerations can be outlined for each studied indicator. Although deducted from the case study of Pisa, the following considerations are obtained with an investigation procedure of general validity and they can be extended to other towns, with particular reference to the historical towns of central Italy, whose road and lighting configurations are similar to those of Pisa.

- The definition of the Power Density Indicator (D_P) is based on the illuminance values maintained on the different reference areas (e.g. carriageway, sidewalk, cycle path), this makes it a flexible indicator and applicable to roads consisting of different lanes with different uses characterized by different lighting requirements. Moreover from the D_P values can be pointed out the scarcely lit roads (high D_P values), as happens for the case study presented in this work. However, the D_P does not take into account the limit values fixed by the technical standards and of any other benchmark values by which the quality of road lighting can be assessed. The D_P does not take into account even the road surface luminance, benchmark parameter used in the technical standards in the case of roadways travelled by motorized traffic.
- The Annual Energy Consumption Indicator (D_E) takes into account only the electrical power installed for lighting, the surface area to be lit and the duration of the operating time over a year. The D_E is useful in order to predict the energy consumptions of the lighting systems, especially when different operation profiles (e.g. total or partial switch-off of some luminaires in late night) are used, as it has been shown for the analyzed case study. The D_E is an indicator of immediate determination, however, it does not provide details on the lighting quality, since it does not take into account the illuminance and luminance values required by the technical standards. It should therefore be used only after the verification that the lighting system meets all the lighting requirements.
- The Lighting System Energy Efficiency Indicator (IPEI) takes into account both the illuminance levels and the luminance levels, depending on the analyzed area (motorized, pedestrian, conflict). In the definition of the IPEI is included a comparison with the limit values fixed by the technical standards and the IPEI is associated with an energy labelling system for the whole road lighting system. The calculation of this indicator is unclear in the case of roads composed of lanes with different limit values of the lighting parameters (i.e. sidewalks and carriageways) and lighted by a single type of luminaire, as happens for the case study and as often happens in the historical city centers.
- The Luminaire Energy Efficiency Indicator (IPEA) is a very useful indicator for the determination of the energy performance of a single luminaire, it takes into account the performance of lamps and of power suppliers, as well as the percentage of the luminous flux emitted downward (only portion of emitted flux that is useful in the case of road lighting). The IPEA is associated with a labelling system of energy performance, similar to that already introduced for the electrical appliances that enables immediate understanding of the performance of each analyzed luminaire. The IPEA does not take into account the operation of the lighting system as a whole and is linked to standard luminous efficacy, intended as the best technology on the market, this implies that the values of the standard luminous efficacy and the limit values of the different energy classes have to be periodically updated.

References

[1] Committee to local sustainable energy. Covenant of Majors: How to develop a Sustainable Energy Action Plan (SEAP). - Guidebook. Luxemburg. 2010.

[2] Cellucci L, Burattini C, Drakou D, Guglielmetti F, Bisegna F, De Lieto Vollaro A, Salata F, Golasi I. Urban lighting project for a small town: comparing citizens and authority benefits. Sustainability 2015; 10(7): 14230-14244. DOI:10.3390/su7101423.

[3] Lobao JA, Devezas T, Catalao JPS. Energy efficiency of lighting installations: Software application and experimental validation. Energy Reports 2015; 1: 110-115. DOI: 10.1016/j.egyr.2015.04.001.

[4] Mokey Coureaux IO, Manzano E. The energy impact of luminaire depreciation on urban lighting. Energy for Sustainable Development 2013; 17: 357-362. DOI:10.1016/j.esd.2013.03.006.

[5] Tahkamo L, Halonen L. Life cycle assessment of road lighting luminaires - Comparison of light-emitting diode and high-pressure sodium technologies. Journal of Cleaner production 2016; 21: 137-145. DOI:10.1016/s11367-015-1000-x.

[6] Haans A, de Kort YAW. Light distribution in dynamic street lighting: Two experimental studies on its effects on perceived safety. prospect. concealment. and escape. Journal of Environmental Psychology 2012; 32: 342-352. DOI: 10.1016/j.jenvp.2012.05.006.

[7] Giuliani G., Gozo N., Honorati Consonni C., Meloni C., Pollidori R., Annunziato M. "The Lumière Project", Project of Ministry of Economic Development and National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), September 2010, Rome (in italian).

[8] Kostic M, Djokic L. Reccomendations for energy efficient and visually acceptable street lighting. Energy 2009; 34: 1565-1572. DOI:10.1016/j.energy.2009.06.056.

[9] Onaygil S, Guler O, Erkin E. Cost Analyses of LED luminaires in road lighting. Light and Engineering 2012; 20(2): 39-45.

[10] De Bernardis P, Marchionni C, Capannolo L. The urban lighting in the rehabilitation of the minor historical centre. The design scenarios for the architectural valorisation and the energy efficiency improvement of the urban environment. Vitruvio International Journal of Architecture Technology and Sustainability 2015; 1: 27-43. DOI: 10.49957vitruvio-ijats.2015.4473.

[11] Beccali M, Bonomolo M, Ciulla G, Galatioto A, Lo Brano V. Improvement of energy efficiency and quality of street lighting in South Italy as an action of Sustainable Energy Action Plans. The case study of Comiso (RG). Energy 2015; 92: 394-408. DOI: 10.1016/j.energy.2015.05.003.

[12] Radulovic D, Skok S, Kirinic V. Energy efficiency public lighting management in the cities. Energy 2011; 36: 1908-1915. DOI:10.1016/j.energy.2010.10.016.

[13] Murray AT, Feng X. Public streetservice standard assessment and achievement. Socio-Economic Planning Sciences 2016; 53: 14-22. DOI: 10.1016/j.seps.2015.12.001.

[14] Navvab M, Bisegna F, Gugliermetti F. Dynamic roadways and in-vehicle lighting conditions for determining mesopic adaptation luminance. 15th International Conference on Environmental and Electrical Engineering. EEEIC 2015 - Conference Proceedings. 2005-2010. DOI:10.1109/EEEIC.2015.7165482.

[15] La Malva F, Lo Verso VRM, Astolfi A. Livingscape: a multi-sensor approach to improve the quality of urban spaces. Energy Procedia 2015; 78: 37-42.

[16] Ekrias A, Eloholma M, Halonen L, Song XJ, Zhang X, Wen Y. Road lighting and headlights: luminance measurements and automobile lighting simulations. Building and Environment 2008; 43(4): 530-536. DOI:10.1016/j.buildenv.2007.01.017.

[17] Aghemo C, Virgone J, Fracastoro GV, Pellegrino A, Blaso L, Savoyrat J, Johannes K. Managment and monitoring of public buildings through ICT based systems: Controls rules for energy saving with lighting and HVAC services. Frontiers of Architectural Research 2013; 2: 147-16. DOI: 10.1016/j.foar.2012.11.001.

[18] Ardente F, Beccali M, Cellura M, Mistretta M. Energy Environmental benefits in public buildings as a result of retrofit actions. Renewable and Sustainable Energy Reviews 2011; 15: 460-470. DOI:10.1016/j.rser.2010.09.022.

[19] Lo Verso VRM, Pellegrino A, Pellerey F. A multivariate non-linear regression model to predict the energy demand for lighting in rooms with different architectural features and lighting control systems. Energy and Buildings 2014; 76: 151-163. DOI: 10.1016/j.enbuild.2014.02.063.

[20] Salvadori G, Fantozzi F, Rocca M,. Leccese F. The energy audit activity focused on the lighting systems in historical buildings. Energies 2016, 9(12): 998; DOI:10.3390/en9120998.

[21] Fantozzi F, Leccese F, Salvadori G, Rocca M, Garofalo M. LED Lighting for indoor sports facilities: Can its use be considered as sustainable solution from a techno-economic standpoint?. Sustainability 2016; 8 (7): 1-13. DOI: 10.3390/su8070618

[22] European Committee for Standardization. EN 15193. Energy performance of buildings - Energy requirements for lighting. Brussels. 2010.

[23] European Committee for Standardization. EN 13201-5. Light and Lighting. Road lighting - Part 5: Energy performance indicators. Brussels. 2015.

[24] Directorate-General for Environment, Department of European Commission. Green Public Procurement. Street Lighting and Traffic Lights. Technical Background Report. Brussels. 2011.

[25] Rabaza O, Pena-Garcia A, Perez-Ocon F, Gomez-Lorente D. A simple method for designing efficient public lighting. based on new parameters relationships. Expert Systems with Applications 2013; 40: 7305-7315. DOI:10.1016/j.eswa.2013.07.037.

[26] Leccese F., Tuoni G. On the environmental pollution and energy waste due to urban lighting. Advanced in Ecological Sciences 2003; 18: 285-297.

[27] Leccese F, Tuoni G. Lighting Requirements and the other Energy Safety Aspects in Urban Areas. 2005 LUX EUROPA - 10th European Lighting Conference on lighting for humans.

[28] European Committee for Standardization. EN 13201-2. Light and Lighting. Road lighting - Part 2: Performance requirements. Brussels. 2015.

[29] European Committee for Standardization. EN 13201-3. Light and Lighting. Road lighting - Part 3: Calculation of performance. Brussels. 2015.

[30] International Commission of Illumination. CIE 115. Lighting of Roads for Motor and Pedestrian Traffic. Vienna. 2010.

[31] Regional Council of Emilia Romagna. Directive No. 1732 of the November 12, 2015. Third directive for the application of the article 2 of Regional Law no. 19/2003 – "Standards on reduction of light pollution and energy saving" (in italian).

[32] Cutini V. The revenge of the urban space. The configurational approach to the study and the analysis of City Center (in italian). Pisa, Italy: Pisa University Press, 2010.

[33] Tolaini E. Forma Pisarum. Issues and research for urban history of the city of Pisa (in italian). 2nd ed. Pisa, Italy: Nitri-Lischi Editori 1992.

[34] Agency for the control and the quality of local public services of the City of Rome, "Annual report on local public services and activities (in italian), 2009.

[35] European Committee for Standardization. CEN/TR 13201-1. Light and Lighting. Road lighting - Part 1: Guidelines on selection of lighting classes. Brussels. 2014.

[36] European Committee for Standardization. EN 13201-4. Light and Lighting. Road lighting - Part 4: Methods of measuring lighting performance. Brussels. 2015.

[37] Ente Nazionale Italiano di Unificazione. UNI 11248. Light and Lighting. Road lighting - Selection of lighting classes. Milano. 2013.

[38] Italian Ministry of Infrastructure and Transport, Legislative Decree No. 285 of the April 30, 1992, and subsequent amendments. Traffic laws. in force since January 1, 1993.

[39] Italian Committee for Standardization. UNI 11142. Light and Lighting. Portable Photometers: performance Characteristics (in Italian). Milano. 2004.

ANNEX A – LIGHTING CLASSES FOR ROAD AREAS

The lighting requirements for road areas are related to the visual tasks of the road users. In the European Standard [29] the road areas are divided (in relation to the expected type of traffic) in: *Motorized* (M) that are intended for drivers of motorized vehicles on traffic routes, and in some countries also on residential roads, allowing moderate to high driving speeds; *Conflict areas* (C) that are intended for use on conflict areas on traffic routes where the traffic composition is mainly motorized; *Pedestrian and low speed areas* (P) that are intended predominantly for pedestrians and cyclists for use on footways and cycle ways, and drivers of motorized vehicles at low speed on residential road.

For the motorized roads (M) are defined 6 lighting classes (from M1 to M6) and for each lighting class the limit values of the average road surface luminance (L), the overall uniformity of the luminance (U_0), the longitudinal uniformity of the luminance (U_L) are provided. Note that U_0 is defined as ratio of the lowest to the average road surface luminance found in the whole carriageway, and U_L is defined as the ratio of the lowest to the highest road surface luminance found in a line in the center along each driving lane which compose the carriageway.

For the conflict areas (C) are defined 6 lighting classes (from C0 to C5) and for each class the limit values of the average value of the horizontal illuminance (E), and the overall uniformity of the horizontal illuminance (U) are provided. Note that U is defined as ratio of the lowest to the average horizontal illuminance.

For the pedestrian and low speed areas (P) are defined 7 lighting classes (from P1 to P7) and for each class the limit values of horizontal illuminance (E), the overall uniformity of the horizontal illuminance (U), the vertical plane illuminance (E_v), and the semi-cylindrical illuminance (E_{sc}) are provided.

Obviously in the real cases, it is very common to find spans with motorized lanes, sidewalks on one or both sides, and various conflict areas (e.g. pedestrian crossings, traffic roundabouts) for each of these areas it is necessary to evaluate the satisfaction of the related limit values based on the reference lighting classes.

ANNEX B – DISCUSSION OF ENERGY PERFORMANCE INDICATORS

The indicators defined in previous sections (see Table 1) may be utilized for comparing energy performances of different types of lighting systems along an examined road. More specifically, they can be considerably useful to the lighting system management authority in order to obtain a forecast of the energy consumption for new lighting system, and the energy savings due to the refurbishment for an existing lighting system. It is interesting to note that the indicators introduced at an international level [23] match those introduced in Italy [28]. For example, in the simplest of cases (but widespread in real situations) in which the surface area to be lit is not divided into subareas D_P is equivalent to SE and it can be obtained the following:

$$IPEI_E = k_E \cdot D_P / SE_R \tag{1}$$

In the case that there is only one operation profile, a simple and useful relation between D_E and D_P can be obtained:

$$D_E = D_P \cdot E_m \cdot t \tag{2}$$

In Table B1, the values of D_E for pedestrian lanes are shown, they are calculated for different lighting classes and for different values of IPEI,. The table has been obtained by combining the Eqs. (1) and (2), assuming that each lighting system fully complies with the lighting requirement (E_m=$E_{m,R}$) which is set as a function of the lighting class and considering an annual operating time of 4000 h. As an example, for a P4 lighting class pedestrian lane using a class C lighting system (see Table 2), the lighting system management authority can estimate a maximum annual electrical energy consumption of 2.97 kWh/m^{2}year. If the same road were to be lit utilizing a class A++ lighting system, the estimated maximum annual electrical energy consumption would be equal to 1.65 kWh/m^{2}year with an energy saving of 45%.
In the Table B2, the values of D_E for roads are shown, they are calculated for different lighting classes and for different values of IPEI. The table has been obtained in a way similar to that done for pedestrian lanes, assuming that each lighting system fully complies with the lighting requirement (L_m=$L_{m,R}$) which is set as a function of the lighting class and considering an annual operating time of 4000 h. In this case, as the lighting requirement is relative to the road surface luminance, the value of E_m to use in Eq. (2) has been calculated in the assumption that the road surface is a Lambert source. Such assumption is useful when the lit area in not observed by a small angle or when the directional reflection coefficient is unknown (is known only the diffuse reflection coefficient). In the case of both the reflection coefficients are unknown, the diffuse reflection coefficient can be assumed equal to 0.30 [30,31]. As an example, if a lighting class M4 road is considered, utilizing a class C lighting system (see Table 2), management authority can estimate a maximum annual electrical energy consumption of 2.35 kWh/m^{2}year. If the same road is lit utilizing a class A++ lighting system, the estimated maximum annual electrical energy consumption is 1.31 kWh/m^{2}year with an energy saving of 45%.

Table B1. Value of D_E obtained for pedestrian road in relation to the IPEI and the lighting class.

IPEI	Lighting class					
	P1 ($E_{m,R}$=15 lx)	**P2** ($E_{m,R}$=10 lx)	**P3** ($E_{m,R}$=7.5 lx)	**P4** ($E_{m,R}$=5 lx)	**P5** ($E_{m,R}$=3 lx)	**P6** ($E_{m,R}$=2 lx)
0.75	3.15	2.40	2.03	1.65	1.26	1.02
0.82	3.44	2.62	2.21	1.80	1.38	1.12
0.91	3.82	2.91	2.46	2.00	1.53	1.24
1.09	4.58	3.49	2.94	2.40	1.83	1.48
1.35	5.67	4.32	3.65	2.97	2.27	1.84
1.79	7.52	5.73	4.83	3.94	3.01	2.43
2.63	11.05	8.42	7.10	5.79	4.42	3.58
3.10	13.02	9.92	8.37	6.82	5.21	4.22

Table B2. Value of D_E obtained for motorized traffic road in relation to the IPEI and the lighting class.

IPEI	**Lighting class**					
	M1 ($L_{m,R}$=2.00 cd/m^2)	**M2** ($L_{m,R}$=1.50 cd/m^2)	**M3** ($L_{m,R}$=1.00 cd/m^2)	**M4** ($L_{m,R}$=0.75 cd/m^2)	**M5** ($L_{m,R}$=0.50 cd/m^2)	**M6** ($L_{m,R}$=0.30 cd/m^2)
0.75	2.94	2.30	1.65	1.31	0.90	0.59
0.82	3.21	2.51	1.80	1.43	0.98	0.64
0.91	3.57	2.78	2.00	1.58	1.09	0.71
1.09	4.27	3.34	2.40	1.90	1.31	0.85
1.35	5.29	4.13	2.97	2.35	1.62	1.05
1.79	7.02	5.48	3.94	3.11	2.15	1.40
2.63	10.31	8.05	5.79	4.58	3.16	2.05
3.10	12.15	9.49	6.82	5.39	3.72	2.42