energies

Article

Renovation of Public Lighting Systems in Cultural Landscapes: Lighting and Energy Performance and Their Impact on Nightscapes

Lodovica Valetti, Francesca Floris and Anna Pellegrino *

Department of Energy "Galileo Ferraris", Politecnico di Torino, 10129 Torino, Italy; lodovica.valetti@polito.it (L.V.); francesca.floris@studenti.polito.it (F.F.)
* Correspondence: anna.pellegrino@polito.it

Abstract: The technological innovation in the field of lighting and the need to reduce energy consumption connected to public lighting are leading many municipalities to undertake the renewal of public lighting systems, by replacing the existing luminaires with LED technologies. This renovation process is usually aimed at increasing energy efficiency and reducing maintenance costs, whist improving the lighting performance. To achieve these results, the new luminaires are often characterised by a luminous flux distribution much more downward oriented, which may remarkably influence and alter the perception of the night image of the sites. In this study the implications of the renovation of public lighting systems in terms of lighting and energy performance as well as the effects relating to the alteration of the night image, in historical contexts characterized by significant landscape value, are analysed. Results, along with demonstrating the positive effect that more sustainable and energy efficient lighting systems may have on the lighting performance and energy consumptions of public lighting systems, evidences the impact they may have on the alteration of the nocturnal image.

Keywords: public lighting; urban lighting; lighting retrofit; energy efficiency; nocturnal image; lightscape; cultural landscape

Citation: Valetti, L.; Floris, F.; Pellegrino, A. Renovation of Public Lighting Systems in Cultural Landscapes: Lighting and Energy Performances and Their Impact on Nightscapes. *Energies* **2021**, *14*, 509. https://doi.org/10.3390/en14020509

Received: 29 November 2020
Accepted: 15 January 2021
Published: 19 January 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

1. Introduction

In the last few decades, the concept of smart cities has promoted as a system aimed at increasing citizens' quality of life, safety and energy savings [1]. From an analysis of the literature it emerges that currently the meaning of a smart city is multi-faceted and characterized by many elements and dimensions [2]. The application of new technologies is one of the solutions adopted to obtain sustainable economic development, decrease energy consumption and improve the quality of life [3]. Within this frame in public policies, among the different contexts of intervention (buildings, mobility, etc.), the renewal of lighting systems has assumed a fundamental role. In fact, public lighting is an important service for cities and responds to specific needs: it has a key role for the security of citizens and prevention of criminal actions [4], as well as for their well-being. Moreover, public lighting has a fundamental role in defining the urban night-time panorama, improving the appearance and increasing the attractiveness of a city [5]. In fact, light is an element able to define the nocturnal image of urban spaces and to enhance monuments and architectures in the cities. However, it also represents a significant item of recurrent expenditure in the budget of municipal administrations [6], for energy and maintenance costs, and could have a significant impact in terms of energy consumption and light pollution [7].

As reported by Cellucci et al. in 2015 [8] in Europe in most cases urban and street lighting current systems are obsolete, inefficient, and not fulfil the standard requirements [9]. Therefore, they represent an opportunity to improve energy efficiency and reduce CO_2

emissions. A study conducted by the European Commission in 2004 [10] demonstrated that a savings of approximately between 30% and 50% of the electricity used for lighting could be achieved by investing in energy-efficient lighting systems. Such investments could be economically sensible with a good return on investment and sustainability, as well as improve lighting quality [11]. In Italy, the public lighting situation has been outlined in some studies conducted by the Italian research institute ENEA [12,13]. These studies showed that in 2015 street lighting was responsible for an energy consumption of 5.9 TWh/year and that about 2 million light points were still characterized by luminous efficiencies below 70 lm/W. Moreover, the lighting plants were mostly controlled by traditional switch systems. In general, results demonstrated that in Italy, on average, savings of approximately 30–40% could be achieved through public lighting renovation interventions.

The need of reducing costs and energy consumption connected to public lighting, combined with the important technological innovation that occurred in the field of lighting with the introduction of solid state lamps (SSL) and lighting control technologies, are leading many municipalities to undertake the renovation of public lighting systems. One of the most common measures is the substitution of luminaires using old light sources with more efficient lighting technologies (e.g., light emitting diode (LED) luminaires) and/or the introduction of smart lighting control systems. In fact, LED technology is currently a satisfactory solution due to its high luminous efficiency, long life, decreasing investment and maintenance costs and lower environmental impact [14–16].

Several studies have shown the effectiveness of interventions based on the renovation of the current lighting systems with more efficient ones. In 2019 Islam et al. [17] demonstrated the potential impact of the substitution of the energy-intensive lighting technologies mostly used currently in Kazakhstan with LED technology. In particular, in the study three subsectors were analysed: residential, commercial/industrial and outdoor illumination. Results demonstrated that the replacement of the current lighting system with lamps with LED sources could determine a significant increase in energy efficiency and favor investments. Djuretic and Kostic [18] estimated in 2018 potential energy savings of between 31% and 60% by using high-quality LED instead of high-quality high pressure sodium (HPS) luminaires in street lighting. In particular, the study demonstrated that significant savings could be achieved when applying multi-stage dimming scenarios and intelligent street lighting systems. Similar results were obtained by Yoomak et al. [19] who analysed the performance of LED luminaires and existing standard HPS luminaires in a roadway lighting system in Thailand. The two systems were compared in terms of lighting quality, energy savings, power quality, and investment. Results in terms of lighting performance showed that with the LED luminaires, minimum illuminances were maintained, while average illuminances were reduced, and uniformity was improved. The study highlighted a potential energy savings of 40% provided by the use of LED luminaire instead of the HPS luminaire. Moreover, in 2014 Escolar et al. [20] demonstrated the relevance of the application of adaptive control system. They enabled multiphase light sources to adapt their intensity based on the environment conditions to reach energy savings and sustainable goals.

From an economic point of view, Beccali et al. [21] analysed in 2015 the effects of the retrofit of a lighting system in Comiso, Italy. In the study a set of planning options to improve energy efficiency in street lighting systems were presented and the payback time considering three different scenarios was evaluated. The results demonstrated that the introduction of high efficient light sources such as LED allows one to significantly improve the lighting performance, as well as contain energy consumptions and expenditure. Carli et al. [22,23] proposed a multi-criteria decision-making tool in order to support the public decision maker in the selection of the optimal retrofit solutions in existing public street lighting systems. The aim of the study was the introduction of an operative tool designed to improve the energy and environment sustainability and maintain comfort, while ensuring an efficient use of public funds. The proposed method was applied and validated in a case study located in Bari, Italy. A comparison between different scenarios was made by Pagden et al. [24]. They performed an economic analysis to compare the feasibility for a case study located in UK of two different street lighting systems: LED lamps and 'part-night' lighting, assuming the return period of investment is twenty years. In fact, some city councils in UK adopt a 'part night' lighting system in order to achieve short-term energy savings. In particular, this solution is applied in residential areas, where lights of relatively lower importance (considering traffic accidents and crime rates) are dimmed or switched off at times during the night when they are least likely to be needed. The comparison between LED lamps and part-night lighting systems showed that electricity savings of 44% and 21%, respectively, could be achieved compared to current electricity usage patterns. The authors concluded that the 'part-night' lighting system could be beneficial in the short-term, however, the replacement of the existing lower efficiency lights with LED lamps is more cost-effective.

The reported works demonstrate that the renovation of public lighting systems with LED technologies can provide many benefits in terms of improvement of the lighting performance together with large energy and economic saving. However, in most cases different forms of financing support are needed, mainly because of the high investment costs and budget constraints of the municipalities. In Europe there are different forms of financing models and several organizations involved, such as European Union funds, public or private banks, energy services companies (ESCo), manufacturers of innovative lighting systems or institutional investors [25].

The renovation process of lighting systems is affecting both big cities and small urban centres. As an example, Cellucci et al. [8] presented in 2015 a study of smart lighting for a small town located on the Italian coast. The study analysed three different approaches and investigated their effects on the territory. In particular, the first level approach refers to the substitution of current luminaries with new ones selected for their technological characteristics, while the geometry of the lighting system (distance and height) remains unchanged. The second level involves the introduction of a new lighting system, characterized by a different layout and by a dynamic road lighting system able to adapt lighting conditions as needed. Finally, the third level approach adds to the second one a complete remote control, transforming the lighting system in a smart grid opportunity. The study demonstrated that the third approach achieves better results than both the two other approaches from an economic, social and environmental point of view. In general, results highlight a significant positive impact on annual energy costs and suggest applications of smart grid planning not only for metropolis and big cities, but also in smaller towns.

These kinds of interventions, based on the renewal of lighting systems, may reduce energy consumption and maintenance costs, whilst improving the lighting performance. Moreover, the new high efficient optics should avoid light pollution. On the other hand, the more controlled light output of the new luminaires may remarkably influence and alter the perception of the nocturnal image of single monuments, urban areas, and landscape in general. The implications on the nocturnal visual perception are currently less analysed in scientific research, but in fact play a fundamental role [26]. Indeed, valorisation strategies that consider all the hours of life of infrastructure, sites and settings, and which also pay attention to the nocturnal perception should be promoted [27]. Within this frame, artificial light could become one of the tools of the valorisation project [28,29]. In fact, it could give a significant contribution by enhancing a site and defining its nightscape, with positive effects on the economy, on touristic visibility and on the promotion of the territory (Figure 1). Some studies [30] demonstrated that projects based on nightscape strategies could increase night activities and the touristic attractiveness of a site, improving the user satisfaction and the cultural value of the territory. On the other hand, other studies focused on the potential impact of the nocturnal environment and of light and dark from a social-cultural perspective. In 2020 a study conducted by Kumar et al. [31] highlighted the importance of considering light, but also dark, in countryside environments. The study analysed how changes in lighting technologies and practices could affect different kinds of ordinary countryside. Within this frame, the study and the design of the nocturnal image should not only concern main cities or single buildings (historical buildings, monuments, etc.), but also small villages and countrysides. In particular in these contexts, it is necessary to carefully balance the use of light and dark, in order to enhance the perception of cities and territories, increasing the attractiveness of sites while preserving the social and cultural values.

(**a**) (**b**)

Figure 1. (**a**) Mont Saint Michel, France, day image. (Credits: Wikipedia—Luca Deboli—originally posted to Flickr as Lun de Miel 443, CC BY 2.0). (**b**) Mont Saint Michel, France, night image. Lighting project: Light Cibles, Louis et Emmanuel Clair, 2006. (Credits: Wikipedia—Benh Lieu Song—own work, CC BY 2.5).

Within this framework, the aim of the study presented in this paper is to evaluate the impact of the renovation of the public lighting system on the night image of settlements from both internal and external observation points. In particular, the implications of the renovation of public lighting systems in contexts characterized by cultural landscape and widespread settlements with historical values are analysed. A case study, composed of a historical village located in the Tuscany area of Maremma Grossetana, in Italy, was selected.

This kind of historical landscape strongly characterizes the European and the Italian territory. It is well known that the Italian identity is built in great part around the presence of numerous small historical settlements. As reported by Micelli et al. [32], the international and the national cultural debate, in the second part of the XXth century, focused on the country's historic centres and on the historical urban landscape. The aim was to define guidelines and development policies (for a critical review on the notion of historical urban landscapes see [33]). However, from the 1990s up to recent years, their social and economic attractiveness has progressively decreased, due to structural mutation in Italian society and in the country's economy. This trend is partially being reversed and, nowadays the small urban centres are becoming increasingly important from a cultural, social and economic point of view.

Like many other Italian villages, the municipality of the selected case study is considering the possibility to substitute the current urban lighting system with new, energy efficient lighting technologies. Within this study, the current lighting condition, produced by traditional lighting sources and luminaires, was compared, through simulation, to the lighting condition produced by the retrofit proposal of the current lighting system with LED luminaires typically employed in street and urban lighting retrofit. The effects in terms of lighting and energy performance were taken into consideration, as well as the implications relating to the alteration of the night image and night perception, considering both internal and external observation points of the settlements.

2. Case Study

The case study consisted of a medieval village, named Montepescali, located in the area of Maremma Grossetana, close to the city of Grosseto, in the Tuscany region of Italy. The case study was selected because of its interesting characteristics from both the point of view of the settlement, that is an historical village located in a prominent position, and the value of the surrounding landscape context.

Initially, a multidisciplinary analysis of the case study was carried out considering its morphological, perceptive, and functional aspects. Data related to the morphological conformation of the site, historical development phases, the presence of buildings of historical and architectural importance, as well as functional aspects and main access roads were analysed. The analysis was aimed at acquiring useful information for the evaluation of the night image. Furthermore, it was possible to identify significant observation points inside and outside the settlement from which to evaluate the night image of the site.

Montepescali is located in a strategic area, on the top of the hilly region of Maremma Grossetana. The prominent village position allows it to define privileged visibility and inter-relationship between the settlements, the viability system and the landscape context. Moreover, the area enjoys good tourist visibility and accessibility through the most important trade routes of the region. In fact, Montepescali is built along the historical Roman road called Aurelia (nowadays an highway), which leads from Grosseto to important Tuscan cities such as Livorno, Pisa and Siena (Figure 2a), and close to the Grosseto-Siena railway line, which is one of the main railway lines of the region (Figure 2b) [34].

(**a**) (**b**)

Figure 2. (**a**) View of Montepescali from the highway 1; (**b**) View of Montepescali from the Grosseto-Siena railway line. (Credits: Francesca Floris).

Montepescali is surrounded by towers and fortified walls and enjoys a well-preserved historical heritage. The village was founded during the Middle Ages (11th century) and its dimensions were expanded in several phases of construction during the following centuries [35]. Nowadays, the village plant has an ovoid shape divided in two levels, identified as the *upper plateau* and the *lower plateau*. The *upper plateau* corresponds to the original medieval core of the settlement (first expansion ring on Figure 3a) and is characterized by the presence of historical buildings such as the ancient castle (called *Cassero*) and the Saint Niccolò Church (Figure 3b). The *lower plateau* corresponds to the second expansion ring (Figure 3a) and includes the residential and service buildings, the Saints Stefano e Lorenzo Church and the historic village entrance (called Belvedere Tower), restored in the Renaissance period (Figure 3b) [36]. The village mobility is almost completely constituted by pedestrian streets except for a suburban road. The driveway leads to the main entrance of the village, located on the *lower plateau*, and surrounds Montepescali's external perimeter, allowing the access to the village from secondary entrances.

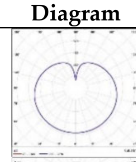
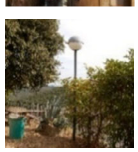
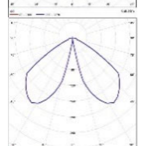
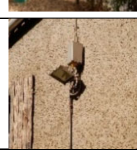
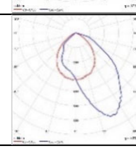
(**a**) (**b**)

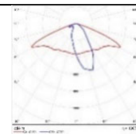
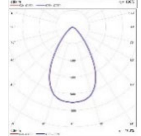
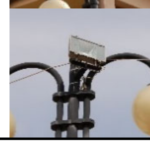
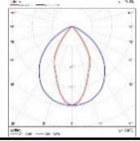
Figure 3. (**a**) Construction phases; (**b**) Identification of the main historical buildings.

2.1. Ex-Ante Lighting Systems

The existing lighting system of Montepescali village consisted of 259 luminaires. The entire stock of luminaires can be represented by the groups showed in Table 1. The abacus reports quantities and typology of luminaires, their photometric diagrams, lamp type, installed power, luminous flux and correlated colour temperature (CCT). In particular, three typologies of lighting systems are identified: *street lighting system*, *square lighting system* and *architectural lighting system*. The *street lighting system* (driveways and pedestrian streets) were composed by 228 diffusing globes (88% of the total luminaires) equipped with 65 W high-pressure sodium lamps (HPS) and two semi-diffusing globes (1% of total luminaires) equipped with 50 W HPS lamps. The street lighting systems were constituted, for all pedestrian streets, by one-sided disposition, with a constant inter-distance of 15 metres between the lighting poles. The driveway presented both a one-side lighting poles arrangements (inter-distance: 14 m) with a single luminaire per pole, and a one-side disposition (inter-distance: 23 m) with two luminaires per pole. The most important square in Montepescali, named Cassero Square, had a different lighting system (*square lighting system*) composed by 10 luminaires equipped with 150 W metal halide floodlights, installed on the façades of the surrounding buildings. Finally, 19 floodlights (7% of the total luminaires) with different powers and luminous fluxes were dedicated to the valorisation of buildings with particular historical and architectural value spread throughout the settlement (*architectural lighting system*). The current lighting system was automatically switched on and off and kept at full power for the whole night.

Table 1. Existing lighting system.

Description	N. of Luminaires	Luminaire Image	Photometric Diagram	Lamp Typology	Power [W]	Luminous Flux [lm]	CCT [K]
Street lighting luminaires	228			HPS	65 W	5300 lm	2000 K
	2			HPS	50 W	4400 lm	2000 K
Square lighting luminaires	10			MH	150 W	9370 lm	3000 K

Architectural lighting luminaires	3			F	85 W	1750 lm	3000 K
	8			MH	150 W [1] 230 W	13,500 lm 25,000 lm	3000 K
	8			MH	83 W	2500 lm	3000 K

[1] 6 lamps with an absorbed power of 150 W and a luminous flux of 13,500 lm and 2 lamps with an absorbed power of 230 W and a luminous flux of 25,000 lm.

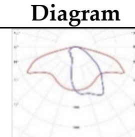
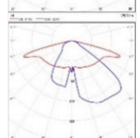
2.2. Ex-Post Lighting Systems

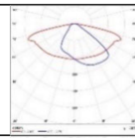
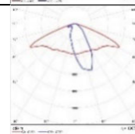
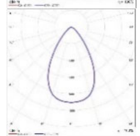
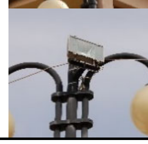
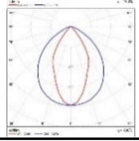
The existing street lighting system emitted light in almost all directions and, as a consequence, part of the light flux also reached the vertical surfaces of the surrounding buildings. However, the dispersion of light flux beyond the surfaces for which light is required (i.e., the carriage for street lighting) generated light pollution. Moreover, from an energy point of view, the flux dispersion and the adoption of traditional light sources determined a waste of energy and high operating costs. In order to improve energy sustainability and to address light pollution, in 2019 the administration of Montepescali commissioned the drafting of a new lighting plan for the municipality. The new lighting plan was drawn up by a professional lighting design studio and involved the replacement of almost all the existing luminaires with new ones chosen for their technological characteristics.

The proposed retrofit solution for Montepescali involved the substitution of the existing luminaires for *street lighting* and *square lighting* with LED technologies (Table 2). The *architectural lighting* system was not involved in the retrofitting and the geometry of the lighting system (distances and heights) remained the same. LED luminaires with shielded street optics and safety glass were proposed in place of the HPS diffusing globes (*street lighting system*), while LED floodlights with asymmetric light distribution (mounted parallel to the square surface) were proposed to substitute the MH floodlights (*square lighting*).

Furthermore, the retrofit proposal included a step dimming during night-time: the *street lighting system* and the *square lighting system* will be kept full power from the switching-on to 10 p.m. and 30% dimming (70% of nominal light flux) from 10 p.m. until switch-off. Instead, the *architectural lighting system* (not object of substitution) will be kept at full power and switched-off at midnight.

Table 2. Ex-post lighting luminaires.

Description	N. of Luminaires	Luminaire Image	Photometric Diagram	Lamp Typology	Power [W]	Luminous Flux [lm]	CCT [K]
Street lighting luminaires	228			LED	21 W	2500 lm	3000 K
	2			LED	13 W	2000 lm	3000 K

Square lighting luminaires	10			LED	58 W	10,000 lm	3000 K
Architectural lighting luminaires **NOT REPLACED**	3			F	85 W	1750 lm	3000 K
	8			MH	150 W [1] 230 W	13,500 lm 25,000 lm	3000 K
	8			MH	83 W	2500 lm	3000 K

[1] 6 lamps with an absorbed power of 150 W and a luminous flux of 13,500 lm and 2 lamps with an absorbed power of 230 W and a luminous flux of 25,000 lm.

The retrofit proposal for Montepescali was designed by a lighting design studio but has not yet been carried out. Therefore, in the present study the comparison between ex-ante and ex-post lighting conditions was performed by means of simulations.

3. Methods

In this section, the methodological approach adopted for evaluating the impacts of the renovation of the lighting system is presented. The comparison between ex-ante (current conditions) and ex-post (proposed lighting plan) conditions was made through simulations. A 3D model of the settlement with the ex-ante lighting system was initially created. Then the model was calibrated by comparing the results of the lighting simulation with the photometric data measured in field. The calibrated model was used in the study to simulate the ex-ante and ex-post lighting condition in order to assess the impact of the two solutions on the photometric and energy performance as well as on the nocturnal image of the settlement.

3.1. Identification of Significant Observation Points

In order to evaluate the night image of the site, some significant observation points located inside and outside the settlement were selected. Based on the information collected in the preliminary analysis of the case study (morphological, perceptive, and functional aspects), two external (E1 and E2 in Figure 4) and one internal (I1 in Figure 4) significant observation points were selected. In particular, the E1 viewpoint was located on the Highway 1 and the E2 viewpoint in a neighbouring village. The internal viewpoint I1 was located in the Cassero Square. Figures 5 and 6 show the diurnal and nocturnal photographs taken from the selected observation points.

Figure 4. Significant internal and external observation points.

(**a**) (**b**) (**c**) (**d**)

Figure 5. (**a**) day and (**b**) night photographs taken from the external point of view E1. (**c**) day and (**d**) night photographs taken from the external point of view E2. (Credits: Francesca Floris).

(a) (b)

Figure 6. (**a**) day and (**b**) night photographs taken from the internal point of view I1. (Credits: Francesca Floris).

3.2. Definition of the 3D Model, Measurement Campaing and Calibration of the Model

A 3D model of the case study was used for the lighting simulation of both the ex-ante and ex-post condition, carried out with the software DIALux Evo 8.2 (DIAL GmbH, Lüdenscheid, Germany). Based on the territorial and historical analysis, a 3D model including a significative portion of Montepascali village was created. The modelled area included parts of both the upper and the lower plateau, incorporating the parts of the village that are visible from the selected significant observation points. Moreover, the 3D model included all the different types of luminaires. In the 3D model the surfaces were characterized by attributing the corresponding reflection factors that were defined through an in-field survey.

In order to analyse the settlement image during night-time and to calibrate the model for the lighting simulations, an in situ measurement campaign was conducted. The measurement campaign was aimed measuring the luminance of the settlement's parts that are perceived from the selected internal and external points of view. Luminance is in fact the most representative photometric measurement of the brightness perceived when an object or a set of illuminated objects are observed [37]. The in situ measurement campaign was conducted by one of the authors during the month of September 2019. In this study, an "LMK Mobile" videophotometer (TechnoTeam Bildverarbeitung GmbH, Ilmenau, Germany) based on a EOS digital camera (Canon Inc., Ōta, Tokyo, Japan) positioned at eye level on a tripod was used to capture the luminance distribution of the considered areas from the different points of view. During the measurement campaign, the valid calibration ranges of the instrument were respected. All images were captured in RAW format. Different kinds of camera lens (focal length from 17 to 50 mm and from 70 mm to 200 mm) were used in order to take images of the entire settlement and detailed images of selected areas or relevant buildings. The associated TechnoTeam "LMK LabSoft" software was used to elaborate the captured images. Results were expressed as false colour images.

For the model calibration, the luminance values measured in-situ were compared with those obtained from the ex-ante lighting simulation. The calibration was done by comparing the measured luminance values and the simulated ones from both the external (Figure 7) and internal (Figure 8) observation points. Several elementary surfaces of the building façades with greater visibility from the viewpoints were selected for the comparison. For each elementary building's surface, the average luminance value was calculated, and the measured values were compared with the simulated ones (Tables 3 and 4). Furthermore, the relative differences (RD) between the ex-ante measured luminance values and simulated ones were calculated. The RD, expressed as a percentage, is calculated as:

$$RD = \frac{(x - x_{ref})}{x_{ref}} \quad (1)$$

where x_{ref}, in this study, corresponds to the values of the ex-ante condition. For the model calibration x is the simulated luminance value and x_{ref} is the ex-ante measured luminance value. The RD values obtained for all viewpoints were below 8%, a value that is acceptable for this study.

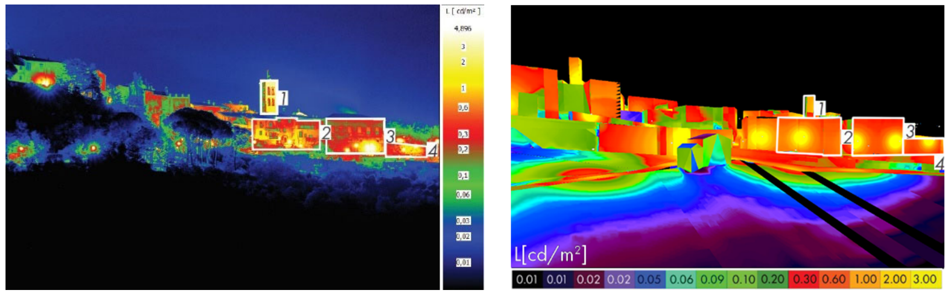


Figure 7. Comparison of the measured and simulated average luminance values from the external viewpoint **E1**. (**a**) Measured luminance distribution; (**b**) simulation output.

Table 3. Comparison of the measured and simulated average luminance values from the external viewpoint **E1**. (1) Bell tower (2) residential building (3) residential building (4) Historic wall.

	L_{av} (1) [cd/m²]	L_{av} (2) [cd/m²]	L_{av} (3) [cd/m²]	L_{av} (4) [cd/m²]
Ex-ante	1.26	0.65	0.61	0.78
Ex-post	1.25	0.70	0.65	0.77
RD	−0.79%	7.69%	6.56%	−1.28%

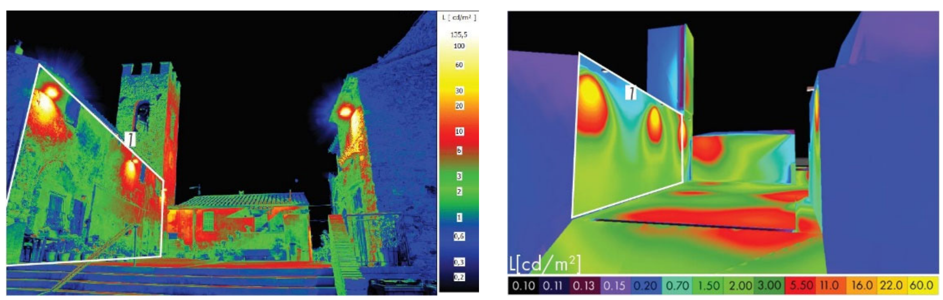


Figure 8. Comparison of the measured and simulated average luminance values from the internal viewpoint **I1**. (**a**) Measured luminance distribution; (**b**) simulation output.

Table 4. Comparison of the measured and simulated average luminance values from the internal viewpoint **I1**. (1) building façade.

<table>
<tr><th></th><th>Ex-Ante</th><th>Ex-Post</th></tr>
<tr><td>L_{av} (1) [cd/m²]</td><td>5.32</td><td>5.72</td></tr>
<tr><td>RD</td><td colspan="2">7.52%</td></tr>
</table>

3.3. Lighting Simulations and Analysis of the Results

The calibrated model was used to carry out the lighting simulations and results of the ex-ante and ex-post condition were compared. In order to simulate the lighting condition and to assess the lighting performance determined by the ex-ante lighting plants and the ex-post lighting design, an analysis of the roads' typologies and of the corresponding lighting classes was performed. According to the Standard UNI 11248:2016 Road Lighting—Selection of lighting classes [38], the roads were organized into categories based on their geometry and speed limit. The roads' typologies and the corresponding road lighting classes (defined according to the Standard) are shown in Figure 9. In particular, local urban pedestrian roads were identified with the P1 lighting class and the secondary suburban road (50 km/h speed limit) was identified with the M3 lighting class.

The ex-ante lighting classes were modified in the design phase conducted by the designers as a result of the risk analysis. The risk analysis, introduced by the Standard UNI 11248:2016 Road Lighting—Selection of lighting classes [38] is a mandatory phase in road lighting design. This involves the evaluation of the influence parameters in order to guarantee maximum efficiency of the lighting systems contribution to the safety of road users, while reducing energy consumption, installation and management costs, environmental impact and light pollution. According to the Standard, the project lighting category is defined by modifying the entrance lighting class (that depends on the type of road and the analysed area before any improvement) according to the risk analysis [39].

In this case, based on the risk analysis, the project lighting classes (ex-post) were increased by one class with respect to the entrance lighting class (ex-ante), decreasing the corresponding performance requirements. The P1 class was changed to P2 and the M3 to M4. The definition of the ex-post lighting classes allowed to establish the corresponding lighting requirements, according to the Standard EN 13201-2:2015 Road lighting—Part 2: Performance requirements [40].

Figure 9. Road lighting classes (ex-ante and ex-post).

In this study, a limited number of road sections, which were assumed to be representative of the totality of the road typologies of Montepescali village, were considered in the analysis of plants lighting performances and energy performances. In particular, the driveway (M3 lighting class) was characterized by two types of road sections: section M-S1 that was a one-way street and the carriage was 4 m wide, and section M-S2 that was a two-way traffic street and the carriage was 6 m wide. Instead, pedestrian roads (P1 lighting class) were characterized by three types of road sections: section P-S1 2.5 m wide; section P-S2 4 m wide and section P-S3 8 m wide.

Subsequently the ex-ante and ex-post condition were compared and results in terms of lighting performances, energy consumption and alteration of the night image and night perception were analysed. Concerning the lighting performances, the main metrics defined in the Standards as performance parameters for street lighting systems were calculated. The energy performances and the environmental impacts generated by the retrofit proposal were evaluated by comparing the energy demand of the ex-ante and ex-post systems. Moreover, some energy indexed were calculated, as requested by the European and Italian Standards. In particular, the power density indicator (D_P) and annual energy consumption indicator (D_E), introduced by the Standard EN 13201-5:2015 [41] as energy performance indicators for road lighting, were calculated. These indicators may be used to compare the energy performance of different road lighting solutions and technologies for the same road lighting project. In particular, the power density indicator (D_P) demonstrates the energy needed for a road lighting installation. The D_P of a lighting installation in a given state of operation is the value of the system power divided by the value of the product of the surface area to be lit and the calculated maintained average illuminance value on this area. According to the Standard [41], the D_P is calculated as:

$$D_P = \frac{P}{\sum_{i=1}^{n}(\bar{E_i} \cdot A_i)} \tag{2}$$

where D_P is the power density indicator [W·lx^{-1}·m^{-2}]; P is the system power of the lighting installation used to light the relevant areas [W]; $\bar{E_i}$ is the maintained average horizontal illuminance of the sub-area "i" [lx]; A_i is the size of the sub-area "i" lit by the lighting installation [m^2] and n is the number of sub-areas to be lit.

The annual energy consumption indicator (D_E) determines the energy consumption during the year and is calculated as the total electrical energy consumed by a lighting installation day and night throughout a specific year in proportion to the total area to be illuminated by the lighting installation. According to the Standard [41], the D_E is calculated as:

$$D_E = \frac{\sum_{j=1}^{m}(P_j \cdot t_j)}{A} \tag{3}$$

where D_E is the annual energy consumption indicator for a road lighting installation [Wh·m^{-2}]; P_j is the operational power associated with the j-th period of operation [W]; t_j is the duration of j-th period of operation profile when the power P_j is consumed, over a year [h]; A is the size of the area lit by the same lighting arrangement [m^2] and m is the number of periods with different operational power P_j.

Moreover, the parameterized index of lighting system efficiency (IPEI) for both the current and LED installations was calculated, as defined in the Italian Minimum Environmental Criteria [42], to define the corresponding energy class. According to the Standard [42] the *IPEI* index is calculated as:

$$IPEI = \frac{D_P}{D_{Pr}} \tag{4}$$

where *IPEI* is the annual energy consumption indicator for a road lighting installation [-]; D_P is the calculated power density indicator [W·lx^{-1}·m^{-2}] and is D_{Pr} is the reference power density indicator. The reference values are defined in the Italian Minimum Environmental Criteria [42], according to the road lighting class [W·lx^{-1}·m^{-2}].

Finally, the assessment of the nightscape was made by comparing the ex-ante and ex-post condition in terms of luminance values and luminance distributions on vertical surfaces (building façades). In addition, the luminance contrasts from the selected significant observation points were calculated. The luminance contrast is calculated as [43]:

$$C = \frac{L_t - L_b}{L_b} \tag{5}$$

where C is the luminance contrast; L_b is the luminance of the background and L_t is the luminance of the target

4. Results

In this section, results relative to the comparation between the ex-ante and ex-post lighting system, in terms of lighting performances, energy consumption and alteration of the night image and night perception are presented.

4.1. Lighting Performance

For both the ex-ante and ex-post lighting systems, the lighting performances were calculated and compared to the requirements of the Standard EN 13201-2:2015 Road lighting—Part 2: Performance requirements [40], according to corresponding lighting classes. The lighting performances were evaluated considering the representative road areas (M-S1, M-S2 for driveways and P-S1, P-S2, P-S3 for pedestrian roads) and the main pedestrian square of Montepescali (Cassero square).

The quantities calculated for the driveways (M-S1, M-S2) were: the average luminance (L_{av}), the overall uniformity (U_o), the Threshold Increment (TI) and the Edge Illuminance Ratio (EIR). Furthermore, the Relative Differences (RD) between the ex-ante and the ex-post performances were calculated.

In particular, according to the definitions of the Standard [40]:

- The average luminance (L_{av}) is the average value of the luminance calculated on the roadway.
- The overall uniformity (U_o) of the road surface luminance is the ratio between the minimum and the average value.
- the Threshold Increment (TI) is the parameter which expresses the disability glare as percentage increase in luminance contrast threshold (between object and background) that is required to make it visible in presence of disability glare generated by road lighting luminaires.
- the Edge Illuminance Ratio (EIR) is the ratio between the average horizontal illuminance on a strip nearby the carriageway and the average horizontal illuminance inside the carriageway, on a strip that have the width of one driving lane.

The results for the selected driveway areas are reported in Table 5.

Table 5. Lighting performances of the ex-ante and ex-post installations for the representative driveway areas.

		L_{av} [cd/m^2]	U_o	TI	EIR
Standard Requirement [1]		**>0.75**	**>0.40**	**<15%**	**>0.30**
M-S1	Ex-ante	0.43	0.40	74%	0.70
	Ex-post	0.88	0.54	12%	0.39
	RD	+52%	+26%	−83%	−45%
M-S2	Ex-ante	0.68	0.30	96%	0.56
	Ex-post	1.16	0.46	13%	0.37
	RD	+42	+35%	−87%	−34%

[1] EN 13201-2:2016 Standard (M4 class).

The quantities calculated for the three characteristic portions of the pedestrian streets (P-S1, P-S2, P-S3) and for the pedestrian Cassero square were: average illuminance (E_{av}), minimum illuminance (E_{min}), minimum semi-cylindrical illuminance ($E_{sc,min}$) and the minimum vertical illuminance ($E_{v,min}$). Furthermore, the Relative Differences (RD) between the ex-ante performance and ex-post performance were calculated.

In particular, according to the definitions of the Standard [40]:

- The average illuminance (E_{av}) is the horizontal illuminance averaged over a road area.
- The minimum illuminance (E_{min}) is the lowest illuminance on a road area.
- The minimum semi-cylindrical illuminance ($E_{sc,min}$) in a plane above a road area is the lowest semi-cylindrical illuminance on a plane at a specified height (in this case 1.50 m) above a road area.
- The minimum vertical illuminance ($E_{v,min}$) on a plane above a road area is the lowest vertical plane illuminance on a plane at a specified height (in this case 1.50 m) above the road area.

The results for the selected pedestrian areas are reported in Table 6 (pedestrian streets) and in Table 7 (Cassero square).

Table 6. Lighting performances of the ex-ante and ex-post installations for the pedestrian sections.

		E_{av} [lx]	E_{min} [lx]	$E_{sc, min}$ [lx]	$E_{v, min}$ [lx]
Standard Requirement [1]		**10 < E_{av} < 15**	**>2**	**>2**	**>3**
P-S1	Ex-ante	6.19	3.57	1.25	1.71
	Ex-post	14.26	8.53	1.42	0.70
	RD	+56%	+58%	+11%	−59%
P-S2	Ex-ante	5.70	3.24	1.37	1.67
	Ex-post	13.70	8.70	1.80	1.72
	RD	+58%	+62%	+23%	+2%
P-S3	Ex-ante	4.36	2.00	1.37	1.44
	Ex-post	10.41	3.60	0.95	1.09
	RD	+58%	+44%	−30%	−24%

[1] EN 13201-2:2016 Standard (P2 class).

Table 7. Lighting performances of the ex-ante and ex-post installations for the pedestrian square area (Cassero square).

		E_{av} [lx]	E_{min} [lx]	$E_{sc, min}$ [lx]	$E_{v, min}$ [lx]
Standard Requirement [1]		**10 < E_{av} < 15**	**>2**	**>2**	**>3**
P-S4	Ex-ante	94.35	60.89	11.41	4.77
	Ex-post	96.95	90.03	46.85	30.10
	RD	+3%	+33%	+76%	+75%

[1] EN 13201-2:2016 Standard (P2 class).

4.2. Energy Performance

The energy analyses allowed evaluation of the annual energy savings and the environmental impacts generated by the retrofit proposal. The evaluation of the energy performance was performed by considering the total absorbed power due to lamps, ballasts, and grid losses, and the equivalent hours of use. The equivalent hours of use resulted from the step dimming program planned for the new plants: the street lighting system and the square lighting system was kept full power from the switching-on to 10 p.m. and dimmed to 70% from 10 p.m. until switch-off. The architectural lighting system (not object of the substitution scheme) was kept at full power and switched-off at midnight. In Table 8 the input data for the energy analysis are reported.

Table 8. Total installed power and equivalent hours of use of the ex-ante and ex-post installations for the street lighting system and the square lighting system and for the architectural lighting system.

	Street and Square Lighting		**Arch. Lighting**	
	Total Power [W]	**Equivalent Hours [h]**	**Total Power [W]**	**Equivalent Hours [h]**
Ex-ante	17,560	4200	2439	4200
Ex-post	6714	3351	2439	2100
RD	−62%		0%	

The energy demand of the ex-ante and ex-post systems were calculated. Two scenarios in particular were considered in the analysis. Initially the energy demand of the ex-ante and ex-post systems considering only the substitution of the luminaires, without the introduction of dimming strategies during night-time, was calculated (Table 9). Subsequently, the energy demand of the ex-ante and ex-post systems also considering the step-dimming scenario was calculated (Table 10).

Table 9. Energy demand of the ex-ante and ex-post installations considering only the substitution of luminaires.

	Energy Demand (No Step-Dimming) [kWh]			
	Street Lighting	**Square Lighting**	**Arch. Lighting**	**Total**
Ex-ante	81,448	7607	12,446	101,501
Ex-post	27,051	2558	10,756	38,475
RD	−66.8%	−66.4%	−28.8%	−62.1%

Table 10. Energy demand of the ex-ante and ex-post installations.

	Energy Demands (with Step-Dimming) [kWh]			
	Street Lighting	**Square Lighting**	**Arch. Lighting**	**Total**
Ex-ante	81,448	7607	12,446	101,501
Ex-post	21,583	2041	6223	29,847
RD	−73.5%	−73.2%	−50%	−70.6%

Moreover, the environmental impacts generated by the retrofit of the lighting system were calculated in terms of tons of oil equivalent (TOE) and tons of annual carbon dioxide (CO_2). The relative differences (RD), corresponding to the energy savings, between the current system and the LED system were calculated and results are reported in Table 11.

Table 11. Tons of oil equivalent (TOE) and tons of annual carbon dioxide (CO_2) of the ex-ante and ex-post installations.

	TOE	CO_2
Ex-ante	18.98	32.88
Ex-post	5.58	9.67
RD	−70%	−70%

In order to assess the lighting installations energy performance, as defined by the European Standard EN 13201-5: 2015 *Road lighting—Part 5: Energy performance indicators* [41], the Power Density Indicator (D_P) and Annual Energy Consumption Indicator (D_E) were calculated for both the ex-ante and ex-post installations. Table 12 shows the calculated values for the driveway's areas (M-S1 and M-S2), Table 13 for the pedestrian areas (P-S1, P-S2 and P-S3) and Table 14 the pedestrian Cassero square area. Moreover, the Parameterized index of lighting system efficiency (IPEI) for both the current and LED installations was calculated, as defined in the Italian Minimum Environmental Criteria [42], to define the corresponding energy class.

Table 12. Energy performance indicators for ex-ante and ex-post installations of driveway areas.

		D_{Pr}	D_P	D_E	IPEI	Energy Class
M-S1	Ex-ante	0.040	0.28	11.26	7.00	G
	Ex-post	0.042	0.02	1.40	0.54	A3+
	RD	-	−92%	−88%	−92%	-
M-S2	Ex-ante	0.040	0.06	2.13	1.37	D
	Ex-post	0.042	0.01	0.50	0.19	A6+
	RD	-	−85%	−77%	−86%	-

Table 13. Energy performance indicators for ex-ante and ex-post installations of pedestrian areas.

		D_{Pr}	D_P	D_E	IPEI	Energy Class
P-S1	Ex-ante	0.048	0.53	21.13	11.04	G
	Ex-post	0.051	0.04	2.63	0.86	B
	RD	-	−92%	−88%	−92%	-
P-S2	Ex-ante	0.048	0.20	4.90	4.26	G
	Ex-post	0.051	0.027	1.17	0.50	A3+
	RD	-	−86%	−76%	−88%	-

P-S3	Ex-ante	0.048	0.13	2.45	2.78	F
	Ex-post	0.051	0.02	0.58	0.32	A5+
	RD	-	−88%	−76%	−88%	-

Table 14. Energy performance indicators for ex-ante and ex-post installations of the pedestrian square area (Cassero square).

		D_{Pr}	D_P	D_E	IPEI	Energy Class
P-S4	Ex-ante	0.048	0.09	42.22	1.82	E
	Ex-post	0.051	0.01	4.06	0.19	A6+
	RD	-	−89%	−90%	−90%	-

4.3. Visual Perception (Nightscape)

In this study, in addition to the lighting and energy analysis, the ex-ante and ex-post lighting solutions were also evaluated for the nightscape they determine for external and internal observation points.

The assessment of the nightscape of Montepescali was made through the calibrated model by comparing the ex-ante and ex-post condition in terms of luminance values, luminance distributions on vertical surfaces (building façades) and luminance contrasts from the selected external (E1 and E2) and internal (IM1) significant observation points.

As previously reported, the calibrated model included parts of both the upper and the lower plateau, incorporating the parts of the village that are visible from the selected observation points. In the study, the luminance values of the vertical façades in large part or completely visible from the selected points of view were analysed, including both the main historical landmarks (identified in the preliminary territorial analysis) and the residential buildings. The luminance distribution on the visible buildings' façades was evaluated and results relative to the ex-ante and ex-post conditions were compared. Figure 10 reports, for the observation point E1, the lighting condition (rendered image) and the luminance distribution (false colour image) obtained from the simulation for both the ex-ante and the ex-post installations. In this case, in particular, the visible portion of the *lower plateau* (residential buildings), the bell tower of the Santo Stefano and San Lorenzo Church and the Belvedere tower (historical landmarks) were analysed. Figure 11 shows the lighting condition (rendered image) and the luminance distribution (false colour image) from the E2 external point of view. In this case the visible façades of the *upper plateau* (residential buildings), the Cassero tower and the Belvedere tower (historical landmarks) were analysed. Figure 12 reports the lighting simulation results relative to the internal viewpoint I1 (Cassero Square).

For each observation point, the average luminance values (L_{av}) of the vertical surfaces corresponding to the façades of the visible building or monuments were calculated. Furthermore, the RD between the average luminance of the ex-ante and the ex-post installations were calculated (Tables 15–19).

Finally, for both ex-ante and ex-post solutions, luminance contrasts were calculated in order to quantify the visibility of a target relative to its immediate background. In this study the luminance contrasts between the average luminance values ($L_{av,t}$) of the main historical buildings that characterizes the village skyline (identified in the preliminary multidisciplinary analysis) and the average luminance values ($L_{av,b}$) of the background built context (residential buildings) were calculated. The calculated luminance contrasts are reported in the Tables 16–20.

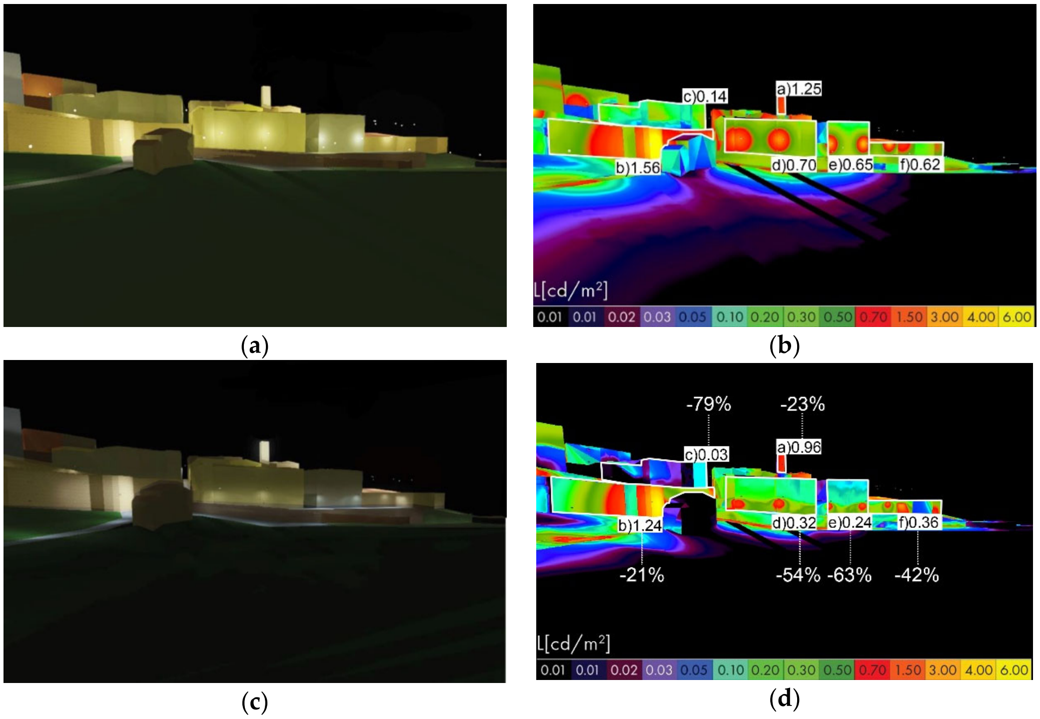


Figure 10. Observation point E1 (simulation performed using Dialux EVO software): (**a**) render of the ex-ante condition; (**b**) false colour render of the ex-ante luminance distribution. In evidence the analysed vertical surfaces and the corresponding average luminance values; (**c**) render of the ex-post condition; (**d**) false colour render of the ex-post luminance distribution. In evidence the analysed vertical surfaces, the corresponding average luminance values and the Relative Differences (RD) between the average luminance of the ex-ante and the ex-post installations.

Table 15. Observation point E1: (a) Bell tower, (b) Belvedere tower, (c) residential building, (d) residential building, (e) residential building, (f) Historic wall.

	L_{av} [cd/m²]					
	(a) [1]	**(b)** [1]	**(c)**	**(d)**	**(e)**	**(f)**
Ex-ante	1.25	1.56	0.14	0.70	0.65	0.62
Ex-post	0.96	1.24	0.03	0.32	0.24	0.36
RD	−23%	−21%	−79%	−54%	−63%	−42%

[1] Historic building illuminated by architectural lighting floodlights (not involved in the retrofit proposal).

Table 16. Observation point E1. Luminance contrasts.

	Luminance Contrast [–]	
	Bell Tower ǀ Context	**Belvedere Tower ǀ Context**
Ex-ante	1.37	1.96
Ex-post	3.04	4.22

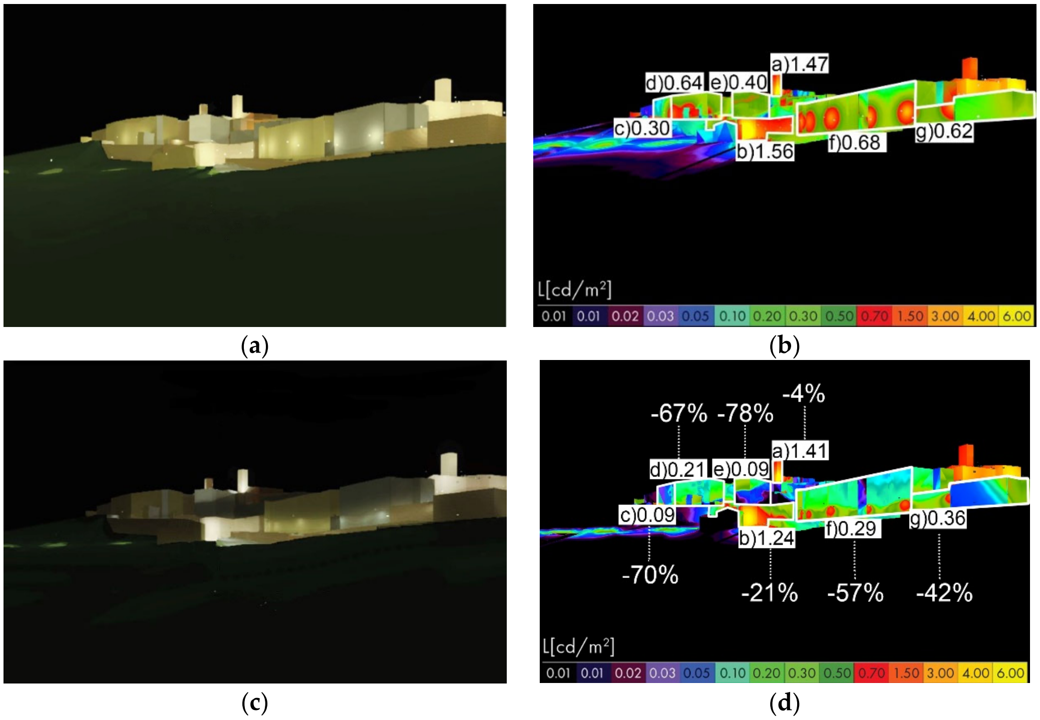


Figure 11. Observation point E2 (simulation performed using Dialux EVO software): (**a**) render of the ex-ante condition; (**b**) false colour render of the ex-ante luminance distribution. In evidence the analysed vertical surfaces and the corresponding average luminance values; (**c**) render of the ex-post condition; (**d**) false colour render of the ex-post luminance distribution. In evidence the analysed vertical surfaces, the corresponding average luminance values and the Relative Differences (RD) between the average luminance of the ex-ante and the ex-post installations.

Table 17. Observation point E2: (a) Cassero tower, (b) Belvedere tower, (c) residential building, (d) residential building, (e) residential building, (f) Historic wall.

	L_{av} [cd/m²]						
	(a) [1]	**(b)** [1]	**(c)**	**(d)**	**(e)**	**(f)**	**(g)**
Ex-ante	1.47	1.56	0.30	0.64	0.40	0.68	0.62
Ex-post	1.41	1.24	0.09	0.21	0.09	0.29	0.36
RD	−4%	−21%	−70%	−67%	−78%	−57%	−42%

[1] Historic building illuminated by architectural lighting floodlights (not involved in the retrofit proposal).

Table 18. Observation point E2. Luminance contrasts.

	Luminance Contrast [–]	
	Cassero Tower ǀ Context	**Belvedere Tower ǀ Context**
Ex-ante	1.78	1.95
Ex-post	5.78	4.96

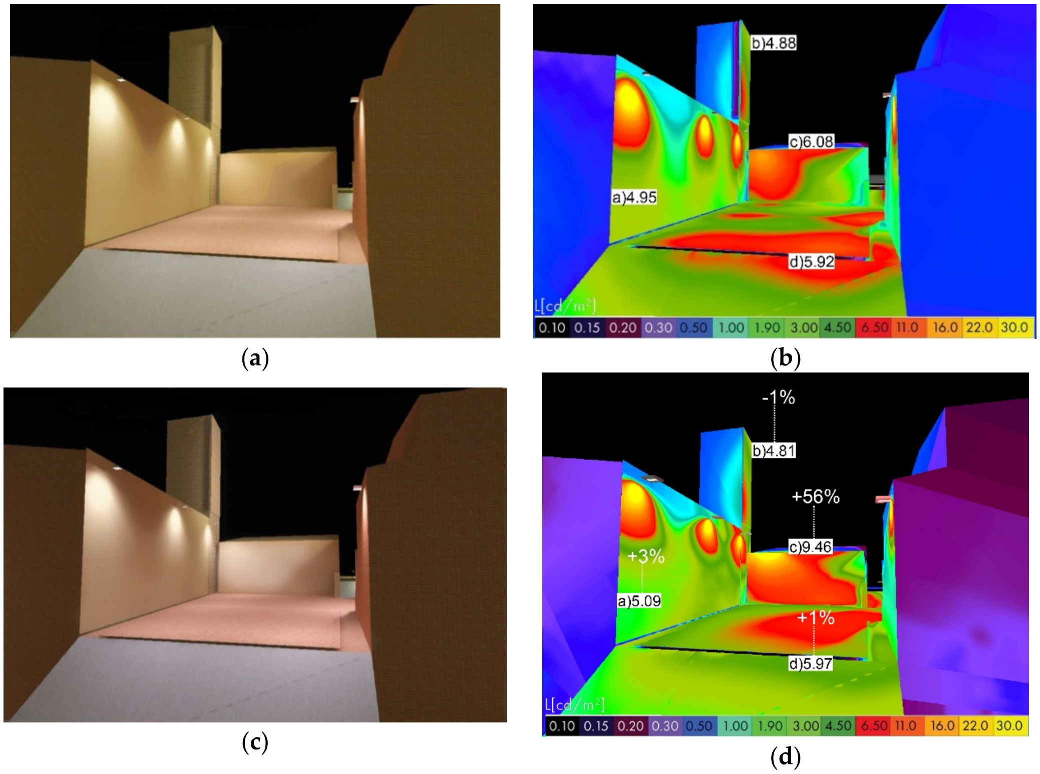


Figure 12. Observation point I1 (simulation performed using Dialux EVO software): (**a**) render of the ex-ante condition; (**b**) false colour render of the ex-ante luminance distribution. In evidence the analysed vertical surfaces and the corresponding average luminance values; (**c**) render of the ex-post condition; (**d**) false colour render of the ex-post luminance distribution. In evidence the analysed vertical surfaces, the corresponding average luminance values and the Relative Differences (RD) between the average luminance of the ex-ante and the ex-post installations.

Table 19. Observation point I1: (a) Cassero Façade, (b) Cassero tower, (c) residential building, (d) horizontal floor.

	L_{av} [cd/m²]			
	(a) [1]	**(b)** [1]	**(c)**	**(d)**
Ex-ante	4.95	4.88	6.08	5.92
Ex-post	5.09	4.81	9.46	5.97
RD	3%	−1%	56%	1%

[1] Historic building illuminated by architectural lighting floodlights (not involved in the retrofit proposal).

Table 20. Observation point I1. Luminance contrasts.

	Luminance Contrast [–]	
	Cassero Tower | Cassero Façade	**Cassero Tower | Façade (c)**
Ex-ante	−0.01	−0.20
Ex-post	−0.06	−0.49

5. Discussion

This study was aimed at assessing the impact of different lighting systems and control systems on the photometric and energy performances and on the nocturnal image of a small settlement located in a landscape context. In the paper, data and results relating to the case study of Montepescali were reported. Comparable results were obtained from an analogous study conducted by the same authors on the neighbouring village of Batignano.

As expected from the analysis of the literature, results confirmed the effectiveness of the retrofit proposal in terms of lighting and energy performances. In particular, the presented study showed that, even in the case of intervention in a small village, significant improvements in terms of lighting and energy performances could be achieved.

Concerning lighting performances, results confirmed the effectiveness of the diffusing globes retrofit with LED luminaires equipped with asymmetric optical systems. In fact, the analysis of the ex-ante lighting system showed that, in the driveway areas, the lighting performances did not comply with the Standard requirements in terms of average luminance values and threshold increment (TI) (due to the uncontrolled emission of luminous flux of the existing luminaires). The simulation of the ex-post solution showed that the average luminance values were increased by more than 42%, and the minimum requirement imposed by the Standard reference was respected. Moreover, the threshold increment (TI) was drastically reduced by more than 83%, solving the critical issue related to the disability glare. A different result was obtained for the pedestrian roads. The ex-post solution showed higher illuminance values on the horizontal surface with respect to the ex-ante condition, increasing the average illuminance values by more than 56% and respecting the Standard requirement. Instead, the semi-cylindrical and vertical illuminance values did not increase significantly in the ex-post solution and did not reach the Standard requirements. The reason for this result was that the new LED luminaires were characterized by high efficient optics, designed to decrease the dispersion of light flux towards the vertical surfaces.

Also for energy performances the results were in agreement with previous studies and demonstrated the positive potential of a retrofit intervention in terms of energy savings. Indeed, the comparison of the energy demand of the ex-ante and ex-post systems and the analysis of the environmental impacts generated by the retrofit of the lighting system (in terms of tons of oil equivalent (TOE) and tons of annual carbon dioxide (CO_2)) showed in both cases a reduction by more than 70%. Moreover, the calculation of energy performance indicators showed a significant potential of energy savings. On each analysed areas, the replacement of HPS lamps (70 W) with LED technologies (21 W) caused a reduction in the power density indicator (D_P) greater than 85% and of the annual energy consumption indicator (D_E) greater than 76%. Also the IPEI indexes of the different road areas were reduced significantly (relative differences between 86% and 92%) causing an improvement on the design energy classes.

The results of the study highlighted that with only the substitution of traditional lighting systems with LED luminaires, that is without the introduction of dimming strategies during night-time with further effects in the same direction, allows one to decrease the energy consumption of 62.1%. The introduction of lighting control systems, also in the case of a simple step-dimming program, could implement further total energy savings of 8.5% (from 62.1% to 70.6%). Within this frame, the introduction of an adaptive control system, as pursued in the smart cities approach, could further increase energy savings. Moreover, results demonstrate that the *architectural lighting system*, composed of metal halide lamps not replaced in the retrofit proposal, could also generate an energy savings of 50%. This result was only due to the efficiency of the power lines and the switch-off at midnight.

In this paper, in addition to the lighting and energy analysis, the ex-ante and the ex-post lighting solutions were evaluated for the nightscape they determine. In fact, in literature the implications on the alteration of the night image and night perception were generally not taken into account. In the present study the variation on nightscape was investigated and quantified. The nightscape was evaluated through simulations, analysing the average luminance distributions on the building façades observed from one internal and two external observation points and calculating luminance contrasts. Results showed a remarkable difference between the simulation of the ex-ante and ex-post lighting systems concerning the visual perception of the urban context.

From the external points of view, the simulation of the ex-post solution showed a reduction in buildings' average luminance values and a different luminance distribution on vertical surfaces. A decrease between 41% and 79% of average luminance values was obtained on the façades of common residential buildings, while a lower decrease (between 4% and 23%) was calculated on the façades of historical buildings (i.e., the bell tower, the Belvedere tower, etc.). Different results for historical buildings and residential buildings emerged. In fact, the ambient lighting of the settlement in the ex-ante condition was the result of the diffusion of the light beam from street lighting luminaires. Instead, the historic buildings were enlightened by the dedicated *architectural lighting system*, not included in the retrofit intervention, causing a lower alteration in their night perception. Moreover, the analysis of the luminance contrasts showed that the calculated luminance contrasts between the average luminance values of the historical buildings and the average luminance values of the visible parts of the surrounding residential buildings was higher in ex-post solution. In fact, the luminance contrasts increased respectively from 1.37 to 3.04 (bell tower) and from 1.96 and 4.22 (Belvedere tower) from the E1 point of view and from 1.78 to 5.78 (Cassero tower) and from 1.95 to 4.96 (Belvedere tower) from the E2 point of view. Also, in this case the reason was that the façades of the historic buildings, illuminated by the not replaced architectural lighting system, preserved high luminance values also in the retrofit solution. Instead, the replacement of the other lighting systems caused a significant decrease of the luminance values on the façades of the surrounding urban context, due to the more controlled light output of the new LED luminaires.

As a general comment, a significant variation in the luminance values and luminance distributions comparing the ex-ante and ex-post conditions emerged. In fact, the current lighting systems emits light in almost all directions and, as a consequence, part of the light flux reaches also the vertical surfaces of the surrounding buildings. However, the unnecessary dispersion of light flux generates energy waste and light pollution. The substitution with LED luminaires with high efficient optics, allow to reduce energy consumption and to minimize obtrusive light and light pollution. However, the limitation of the luminous flux emitted towards the building façades, significantly modified the nocturnal image and the perception of the urban context. In fact, results showed that the nocturnal visibility of residential buildings was significantly reduced in the ex-post condition, and consequently the luminance contrasts between the historical landmarks and the urban context increased. Results demonstrated that this design strategy allow to increase the visibility of the landmark elements. However, the excessive reduction of the visibility of the urban context could define a lack in the overall perception of the settlements. As a consequence, at night, only some elements, considered to be the most important, would be perceived from external points of observation. Within this frame, another study conducted by the authors [44] investigated the subjective perception of the nightscape perceived from observation points located outside settlements in prominent position and characterised by high historical and heritage value. The study demonstrated that when during night-time large parts of a settlement are not illuminated, and therefore not recognizable, the subjective pleasantness of the perceived nightscape is low. On the other hand, the subjective pleasantness rises when the overall or larger parts of the settlement can be perceived. The same study demonstrated that also excessive luminance contrasts could again reduce the perceived pleasantness of the nightscape. Within this frame, innovative strategies could be directed towards creating and controlling specific nocturnal lighting scenarios, considering also the visual aspects of the nightscape as a design criteria.

Different results were obtained in the analysis of the visual perception from the internal point of view. The replacement of existing luminaires (metal halide floodlights) with LED technologies in the Cassero square did not significantly change the existing visual perception. The reason is that the photometric diagrams of the current and new LED luminaires were similar and the installation in the upper part of the building façades allowed to homogenously illuminate the vertical surfaces in both ex-ante and ex-post conditions. In fact, the calculated luminance contrasts between the average luminance values of the vertical surfaces of the square were near-zero and without relevant differences between the ex-ante and ex-post conditions. As a comment, in this case the total absence of luminance contrasts could compromise the valorisation of the main buildings and the creation of a visual hierarchy able to enhance the architectures and their cultural values.

From the simulation of a retrofit intervention of a lighting system it was possible to demonstrate that the replacement of existing luminaires with LED technologies could improve the energy efficiency and the lighting performances. On the other hand, it may remarkably influence the perception of the nocturnal image of the monuments and of the urban context. Within this frame, the absence of a design strategy able to connect the different elements of the settlement in a coordinate system could compromise the overall perception of the settlements and of the context perceived from external points of view. On the other hand, the absence of a luminance hierarchy and an excessive uniformity could compromise the perception of the nocturnal image from internal observation points. For these reasons, in order to enhance the nightscape from both internal and external points, the introduction of new attentions and indications should be considered.

6. Conclusions

The renewal of public lighting systems, replacing the existing luminaires with LED technologies, is a policy that many municipalities are adopting to reduce their expenditure budget, as well as to increase the city environmental sustainability. Moreover, the introduction of innovative and flexible systems could be a first step toward the smart cities approach. In fact, the renovation of public lighting systems may increase the energy efficiency, reduce the maintenance costs and the CO_2 emissions, while improving the lighting performance. On the other hand, it may remarkably influence and alter the night image and night perception of the sites.

In this paper the possible implications of the retrofit of public lighting systems in small villages characterized by prominent position, landscape context and widespread heritage are analysed. The current lighting condition, produced by traditional luminaires, and the lighting condition produced by a retrofit proposal with LED sources of a case study located in the Tuscany area of Maremma Grossetana are evaluated. The ex-ante and ex-post lighting solutions are compared through simulations. The effects in terms of lighting and energy performance are analysed, as well as the implications on the alteration of the nightscape, considering both internal and external significant observation points.

Results confirm the positive effect that more sustainable and energy efficient lighting systems may have on the lighting performance and energy consumptions. On the other hand, a significant variation in the nightscape emerges, in particular considering the visual perception from external observation points. In fact, results demonstrate the high impact that retrofit interventions could have on the perceived visual image of a site. As a general comment, the need of introducing also the visual aspects as a design criteria of the nightscape emerged. Within this frame, future research will be devoted to defining new design indications. As an example, to allow a general perception of the settlement, design strategies based on the definition of a coordinated nocturnal image, considering both the main elements of the urban scene and the surrounding context should be developed. To this end, the definition of luminance hierarchies considering the entire settlement should be an effectiveness solution, as also recommended in [27]. Moreover, in order to avoid excessive luminance contrasts or, in contrast, an excessive uniformity in the perceived nocturnal image, design indications should be introduced in order to suggest specific range of luminance contrasts.

In conclusion, the introduction of a new approach based on a systemic vision should be considered. The definition of new design indications should be the premises to re-think the public lighting of urban settlements with cultural heritage value and to enhance the nightscape from both internal and external observation points. The final goal should be the promotion of both energy saving policies (economic and environmental sustainability) and valorisation of places and landscapes, respecting the socio-cultural values of the sites.

Author Contributions: Conceptualization, A.P.; methodology, L.V., A.P.; investigation, F.F.; data curation, L.V., F.F.; writing—original draft preparation, L.V., F.F.; writing—review and editing, L.V., A.P.; supervision, L.V, A.P.; project administration, A.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: the authors acknowledge the Studio Associato GMS (Milan) for the provided materials on the existing lighting systems and the new lighting plan for the municipality of Montepescali.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Bonomolo, M.; Beccali, M.; Galatioto, A.; Pulvirenti, E. A smart lighting network design for urban rehabilitation and environmental sustainability: A case study of Bagheria. In Proceedings of the 9th Conference on Sustainable Development of Energy, Water and Environment Systems, Venice, Italy/Istanbul, Turkey, 20–27 September 2014; pp. 1–19.
2. Albino, V.; Berardi, U.; Dangelico, R.M. Smart Cities: Definitions, Dimensions, Performance, and Initiatives. *J. Urban Technol.* **2015**, *22*, 3–21, doi:10.1080/10630732.2014.942092.
3. De Paz, J.F.; Bajo, J.; Rodríguez-González, S.; González, G.V.; Corchado, J. Intelligent system for lighting control in smart cities. *Inf. Sci.* **2016**, *372*, 241–255, doi:10.1016/j.ins.2016.08.045.
4. Peña-García, A.; Hurtado, A.; Aguilar-Luzón, M.C. Impact of public lighting on pedestrians' perception of safety and well-being. *Saf. Sci.* **2015**, *78*, 142–148, doi:10.1016/j.ssci.2015.04.009.
5. Seshadri, K. City Beautification at Night. *J. Illum. Eng. Inst. Jpn.* **1997**, *81*, 139–140, doi:10.2150/jieij1980.81.Appendix_139.
6. Radulovic, D.; Skok, S.; Kirincic, V. Energy efficiency public lighting management in the cities. *Energy* **2011**, *36*, 1908–1915, doi:10.1016/j.energy.2010.10.016.
7. Leccese, F.; Tuoni, G. On the environmental pollution and energy waste due to urban lighting. *WIT Trans. Ecol. Environ.* **2003**, *63*, 285–297. Available online: www.witpress.com (accessed on 23 October 2020).
8. Cellucci, L.; Burattini, C.; Drakou, D.; Gugliermetti, F.; Bisegna, F.; Vollaro, A.D.L.; Salata, F.; Golasi, I. Urban Lighting Project for a Small Town: Comparing Citizens and Authority Benefits. *Sustainability* **2015**, *7*, 14230–14244, doi:10.3390/su71014230.
9. Kostic, M.; Djokic, L. Recommendations for energy efficient and visually acceptable street lighting. *Energy* **2009**, *34*, 1565–1572, doi:10.1016/j.energy.2009.06.056.
10. European Commission. *Eurelectric, Electricity for More Efficiency: Electric Technologies and Their Energy Savings Potential*; European Commission: Brussels, Belgium, 2004.
11. Gil-De-Castro, A.; Moreno-Munoz, A.; Larsson, A.; De La Rosa, J.J.G.; Bollen, M.H.J. LED street lighting: A power quality comparison among street light technologies. *Light. Res. Technol.* **2013**, *45*, 710–728, doi:10.1177/1477153512450866.
12. Annunziato, M.; Giuliani, G.; Gozo, N.; Consonni, C.H.; Frascone, A.; Bucci, F.; Lo Bue, B. Progetto Lumière: Efficienza Energetica nell'Illuminazione Pubblica. Percorso e Metodologia di Sviluppo. ENEA Report RdS/2011/275; 2011. Available online: https://www.enea.it/it/Ricerca_sviluppo/documenti/ricerca-di-sistema-elettrico/illuminazione-pubblica/18-lumiere.pdf (accessed on 20 January 2020).
13. Gozo, N.; Blaso, L.; Caiaffa, E.; Fumagalli, S.; Giuliani, G.; Leonardi, G.; Novelli, C.; Pizzuti, S.; Zini, P.; Marino, F. Metodologia, Progettazione Macrofunzionale e Casi D'uso di una Infrastruttura Pubblica Energivora. ENEA Report RdS/PAR2015/001; 2015. Available online: www.enea.it/it/Ricerca_sviluppo/documenti/ricerca-di-sistema-elettrico/adp-mise-enea-2015-2017/illuminazione/rds_par2015-001.pdf (accessed on 20 January 2020).
14. Beccali, M.; Bonomolo, M.; Lo Brano, V.; Ciulla, G.; Di Dio, V.; Massaro, F.; Favuzza, S. Energy saving and user satisfaction for a new advanced public lighting system. *Energy Convers. Manag.* **2019**, *195*, 943–957, doi:10.1016/j.enconman.2019.05.070.
15. Pattison, P.M.; Hansen, M.; Tsao, J.Y. LED lighting efficacy: Status and directions. *Comptes Rendus Phys.* **2018**, *19*, 134–145, doi:10.1016/j.crhy.2017.10.013.
16. Tähkämö, L.; Halonen, L. Life cycle assessment of road lighting luminaires—Comparison of light-emitting diode and high-pressure sodium technologies. *J. Clean. Prod.* **2015**, *93*, 234–242, doi:10.1016/j.jclepro.2015.01.025.
17. Islam, G.; Darbayeva, E.; Rymbayev, Z.; Dikhanbayeva, D.; Rojas-Solórzano, L.R. Switching-off conventional lighting system and turning-on LED lamps in Kazakhstan: A techno-economic assessment. *Sustain. Cities Soc.* **2019**, *51*, 101790, doi:10.1016/j.scs.2019.101790.
18. Djuretic, A.; Kostic, M. Actual energy savings when replacing high-pressure sodium with LED luminaires in street lighting. *Energy* **2018**, *157*, 367–378, doi:10.1016/j.energy.2018.05.179.
19. Yoomak, S.; Jettanasen, C.; Ngaopitakkul, A.; Bunjongjit, S.; Leelajindakrairerk, M. Comparative study of lighting quality and power quality for LED and HPS luminaires in a roadway lighting system. *Energy Build.* **2018**, *159*, 542–557, doi:10.1016/j.enbuild.2017.11.060.
20. Escolar, S.; Carretero, J.; Marinescu, M.-C.; Chessa, S. Estimating Energy Savings in Smart Street Lighting by Using an Adaptive Control System. *Int. J. Distrib. Sens. Netw.* **2014**, *10*, 10, doi:10.1155/2014/971587.

21. Beccali, M.; Bonomolo, M.; Ciulla, G.; Galatioto, A.; Lo Brano, V.L. 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.
22. Carli, R.; Dotoli, M.; Pellegrino, R. ICT and optimization for the energy management of smart cities: The street lighting decision panel. In Proceedings of the 2015 IEEE 20th Conference on Emerging Technologies & Factory Automation (ETFA), Luxembourg, 8–11 September 2015; pp. 1–6, doi:10.1109/ETFA.2015.7301435.
23. Carli, R.; Dotoli, M.; Pellegrino, R. A decision-making tool for energy efficiency optimization of street lighting. *Comput. Oper. Res.* **2018**, *96*, 223–235, doi:10.1016/j.cor.2017.11.016.
24. Pagden, M.; Ngahane, K.; Amin, S.R. Changing the colour of night on urban streets—LED vs. part-night lighting system. *Socio-Econ. Plan. Sci.* **2020**, *69*, 100692, doi:10.1016/j.seps.2019.02.007.
25. Novikova, A.; Stamo, I.; Stelmakh, K.; Hessling, M. Guideline on Finding a Suitable Financing Model for Public Lighting Investment. Interreg Central Europe, Dynamic Light Project; 2017. Available online: http://www.interreg-central.eu/Content.Node/Dynamic-Light/Dynamic-Light-D.T2.3.2-Novikova-et-al.-2017-Financing-Model-.pdf (accessed on 22 October 2020).
26. Achsani, R.A.; Wonorahardjo, S. Studies on Visual Environment Phenomena of Urban Areas: A Systematic Review. In *IOP Conference Series: Earth and Environmental Science*; IOP Publishing: Bristol, UK, 2020; Volume 532, p. 012016, doi:10.1088/1755-1315/532/1/012016
27. Sozen, M.S.; Baskan, T.; Pollard, N.; Schwarcz, P.; Tammes, A. *CIE 234:2019: A Guide to Urban Lighting Masterplanning*; CIE Technical Report; CIE Central Bureau: Wien, Austria, 2019. doi:10.25039/TR.234.2019.
28. Valetti, L.; Pellegrino, A.; Aghemo, C. Cultural landscape: Towards the design of a nocturnal lightscape. *J. Cult. Herit.* **2020**, *42*, 181–190, doi:10.1016/j.culher.2019.07.023.
29. Valetti, L.; Pellegrino, A. Analysis and design approach for a nocturnal image of the cultural landscape. In Proceedings of the 29th CIE SESSION, Washington, DC, USA, 14–22 June 2019; pp. 811–822, doi:10.25039/x46.2019.PP27.
30. Guo, Q.; Lin, M.; Meng, J.-H.; Zhao, J.-L. The development of urban night tourism based on the nightscape lighting projects—A case study of Guangzhou. *Energy Procedia* **2011**, *5*, 477–481, doi:10.1016/j.egypro.2011.03.083.
31. Kumar, A.; Shaw, R. Transforming rural light and dark under planetary urbanisation: Comparing ordinary countrysides in India and the UK. *Trans. Inst. Br. Geogr.* **2020**, *45*, 155–167, doi:10.1111/tran.12342.
32. Micelli, E.; Pellegrini, P. Wasting heritage. The slow abandonment of the Italian Historic Centers. *J. Cult. Herit.* **2018**, *31*, 180–188, doi:10.1016/j.culher.2017.11.011.
33. Santander, A.A.; Azkarate, A.; Arana, A.D.L.F. Historic Urban Landscapes: A Review on Trends and Methodologies in the Urban Context of the 21st Century. *Sustainability* **2018**, *10*, 2603, doi:10.3390/su10082603.
34. Provincia di Grosseto, Piano Territoriale di Coordinamento della Provincia di Grosseto. La Qualità del Paesaggio [Territorial Plan, Province of Grosseto. The Landcsape Quality]. 2010. Available online: https://www.regione.toscana.it/documents/10180/70960/Grosseto/6020ff20-7997-4aa0-a3fe-223a5626cf82;jsessionid=F1C7EB3A7B903C93826901776DCB6785.web-rt-as01-p2?version=1.0 (accessed on 20 January 2020)
35. Citter, C. L'assetto urbanistico del castello di Montepescali nel Medioevo [The urban structure of the castle of Montepescali in the Middle Ages]. In *Progetto Montepescali*; Portici Editore: Grosseto, Italy, 1997; pp. 31–52.
36. Citter, C. *L'edilizia Storica di tre Castelli Medievali. Batignano, Istia d'Ombrone, Montepescali [The Historical Structure of Three Medieval Castles. Batignano, Istia d'Ombrone, Montepescali]*; Portici Editore: Grosseto, Italy, 1995.
37. Kruisselbrink, T.; Dangol, R.; Rosemann, A. Photometric measurements of lighting quality: An overview. *Build. Environ.* **2018**, *138*, 42–52, doi:10.1016/j.buildenv.2018.04.028.
38. Ente Nazionale Italiano di Unificazione. *UNI 11248:2016 Road Lighting—Selection of Lighting Classes*; Ente Nazionale Italiano di Unificazione: Milan, Italy, 2016.
39. Petritoli, E.; Leccese, F.; Pizzuti, S.; Pieroni, F. Smart lighting as basic building block of smart city: An energy performance comparative case study. *Meas. J. Int. Meas. Confed.* **2019**, *136*, 466–477, doi:10.1016/j.measurement.2018.12.095.
40. European Committee for Standardization (CEN). *EN 13201-2:2015 Road Lighting—Part 2: Performance Requirements*; CEN: Brussels, Belgium, 2015.
41. European Committee for Standardization (CEN). *EN 13201-5: 2015 Road Lighting—Part 5: Energy Performance Indicators*; CEN: Brussels, Belgium, 2015.
42. DM 27 September 2017. Criteri Ambientali Minimi per L'acquisizione di Sorgenti Luminose per Illuminazione Pubblica, L'acquisizione di Apparecchi per Illuminazione Pubblica, L'affidamento del Servizio di Progettazione di Impianti per Illuminazione Pubblica [Minimum Environmental Criteria for Public Procurement of Lamps, Luminaries and Design Entrustment for Public Lighting]. Integrated with DM 28 March 2018 "Criteri Ambientali Minimi per l'Affidamento del Servizio di Illuminazione Pubblica"; Update of CAM Adopted with DM 23 December 2013 (in G.U. n.18 23 January 2014) [Minimum Environmental Criteria for the Entrustment of Public Lighting Series]. Available online: https://www.minambiente.it/sites/default/files/archivio/allegati/GPP/GU_244_Illuminazione_Pubblica.pdf and https://www.gazzettaufficiale.it/atto/serie_generale/caricaDettaglioAtto/originario?atto.dataPubblicazioneGazzetta=2018-04-28&atto.codiceRedazionale=18A02943&elenco30giorni=true (accessed on 23 October 2020)

43. Boyce, P. *Human Factors in Lighting*, 3rd ed.; CRC Press: Boca Raton, FL, USA, 2014.
44. Valetti, L. Luce e Paesaggio Culturale: Proposta per una Metodologia di Analisi per il Progetto Dell'immagine Notturna di un Patrimonio Diffuso [Light and Cultural Landscape: Proposal for an Analysis Methodology for the Design of the Nocturnal Image of a Widespread Heritage]. Ph.D. Thesis, Politecnico di Torino, Turin, Italy, 2020. Available online: http://hdl.handle.net/11583/2842517 (accessed on 20 January 2020).