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Sustainability in Public Lighting: The Methodology for Identifying Environmentally Optimal Solutions in Replacement Planning—A Case Study

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Abstract: The urban public lighting system plays a fundamental role in enhancing safety and shaping the nocturnal identity of the city. Efficient lighting is also a key factor in reducing energy consumption and lowering atmospheric emissions. In the context of sustainable development goals, increasing attention is being directed towards the energy, social, economic, and environmental benefits associated with the adoption of LED lighting systems. This paper aims to assess the environmental impacts of two different public outdoor lighting replacement planning scenarios. The methodology employed in this study calculates the environmental impacts using a life cycle approach, incorporating data from the Environmental Product Declarations (EPDs) of the lighting systems. It involves a systematic census and categorization of lighting fixtures based on their installation year to determine both their quantity and average efficiency. This methodology, applied to a case study, demonstrates that it is possible to reduce the CO_2-equivalent emissions by approximately 7% depending on the technical and environmental performance of the fixtures and the timing of their replacements. These results provide a scientific foundation for supporting both the preparation of planning tools by governance entities and the technical and economic feasibility of designing and implementing interventions aimed at improving the environmental performance of public lighting. These efforts could contribute to achieving climate neutrality, conserving biodiversity, and mitigating the effects of climate change.

Keywords: lighting public system; energy efficiency; environmental product declaration; environmental cost-effectiveness

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1. Introduction

The global population continues to grow, as do cities. According to the *World Cities Report 2022*, the global population in 1950 was relatively small, with only 2.5 billion inhabitants, the majority of whom lived in rural areas. By 2020, however, the population had increased to 7.8 billion, with the majority residing in urban areas [1].

The widespread expansion of urban areas highlights the critical need to construct increasingly resilient and sustainable cities, equipped with modern, human-centred infrastructure designed to reduce energy consumption and the production of climate-altering gases [2].

Thus, city leaders are not only tasked with managing the challenges posed by urbanization but must also accomplish this in ways that align with long-term commitments to achieving net-zero emissions.

Energy efficiency in particular has become a central objective in national political agendas worldwide. The European Union, for example, set a precedent in 2021 by establishing ambitious targets to reduce net greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels, with the aim of becoming the first climate-neutral continent by 2050 [3]. As a result, there is a growing need for interventions focused on energy efficiency and demand-side management to reduce emissions, lower the energy intensity, and achieve cost savings within urban environments.

In urban environments, street lighting represents a significant share of cities' overall energy consumption, accounting for nearly 40% of the energy used by European municipalities [4–6]. According to a study conducted by the Italian National Agency for New Technologies, Energy, and Sustainable Economic Development (ENEA), Italy's total electricity consumption amounts to approximately 50.8 TWh per year, of which public lighting accounts for 6.1 TWh annually. Importantly, this study identifies a potential reduction in public lighting energy consumption ranging between 25% and 40% of the current levels [7].

This finding underscores the critical role that energy efficiency improvements in public lighting can play in reducing overall energy consumption, mitigating CO_2 emissions, and alleviating public financial burdens. While numerous solutions exist for lowering energy consumption and the associated management and maintenance costs—including the adoption of durable materials, solar-powered systems, technologies that integrate a data analysis [8], and Light-Emitting Diode (LED) technology [9]—a significant number of cities continue to rely on outdated and inefficient lighting systems [10].

The imperative of reducing energy consumption and emissions, coupled with rapid advancements in lighting technology, has driven many municipalities to modernize their public lighting infrastructure by replacing existing fixtures with LED technologies [11]. In alignment with this trend, the 2023 National Integrated Plan for Energy and Climate proposes a comprehensive set of measures to enhance energy efficiency and promote sustainable territorial development, including the widespread replacement of traditional lighting systems with LED solutions in public spaces [12].

The selection of appropriate lighting technologies is therefore critical from economic, environmental, and social perspectives. Numerous studies have highlighted the importance of upgrading existing public lighting systems and have provided robust evidence of the effectiveness of such interventions in achieving energy efficiency and sustainability goals [13,14].

Djuretic and Kostic [15] estimated potential energy savings ranging from 31% to 60% achievable through the replacement of existing high-pressure sodium (HPS) lamps with LEDs for street lighting.

A comparative study on the light quality and power quality for LED and HPS fixtures in a street lighting system conducted in Thailand demonstrated a reduction in the energy efficiency index of approximately 40% compared to that with an HPS fixture [16,17].

Jiang et al. [18] evaluated and compared the performance of LED fixtures with those of conventional HPS lamps both in roadside lighting and high-mast lighting, recommending LED lighting technologies.

Cucchiella et al. [19] emphasize the importance of LED lighting technology in achieving various Sustainable Development Goals outlined in the Agenda 2030, including target 7.3 "Double the global rate of improvement in energy efficiency by 2030", and also in reaching goals for reducing CO_2 emissions.

In 2017 and 2018, specific minimum environmental criteria (hereafter referred to as CAM IP) were introduced in Italy to increase the energy efficiency and environmental sustainability of public lighting [20]. These criteria are part of the Action Plan for Environmental Sustainability in Public Administration Consumption, namely the National Action

Plan on Green Public Procurement. They provide, in cases of designing new street lighting systems or replacing existing street lighting fixtures with new ones (for a total of at least 10 light points), an assessment of technologies that allow for, with an equal performance, lower management, maintenance, and environmental costs in the medium to long term.

Public administrations operate in highly diverse contexts and operational conditions, starting with the availability of information on the status of existing facilities and the financial resources for any refurbishment interventions; the same facilities can be in significantly different situations regarding their compliance with the regulations, technological updates, and levels of energy efficiency. Therefore, administrations must conduct a careful analysis of their needs and evaluate the actual consistency of their requirements based on the status of the facilities and the real needs in terms of citizen safety, quality of vision, visual comfort, and environmental sustainability.

In the context of environmental policy pursued at both the national and EU levels, interventions in the built environment objectively constitute a key sector, both for the role they play in the national economy and for the impact they have in social terms. Such impacts, albeit indirect, are highlighted by the fact that the built environment contributes to determining the "quality of life" and can foster interpersonal relationships and social cohesion. Moreover, it stimulates cultural and leisure activities, thereby generating additional employment prospects and ultimately contributing to economic advancement.

Translating sustainability into operationally concrete terms is not an entirely straightforward task, as it needs to be broken down into a wide array of specific sub/objectives. The number of these objectives naturally depends on the complexity of the issue at hand, and these objectives themselves vary for each individual intervention.

Typically, to conduct assessments of this kind, tools based on the life cycle thinking approach are employed, with specific regard to environmental aspects, employing the Life Cycle Assessment (LCA) procedure [21]. Life Cycle Assessment (LCA) is the most widely utilized method and is promoted by various environmental policies, voluntary technical standards, minimum environmental criteria, and Green Public Procurement (GPP). Notably, LCA analyses also serve as the foundation for Type III certifications, such as the Environmental Product Declaration (EPD) [22].

Guided by internationally recognized standards, EPDs enable the standardization and comparison of products, thereby fostering a market transition towards greener and more sustainable solutions. Following an LCA analysis conducted in accordance with the Product Category Rules (PCRs), manufacturers can request the issuance of an EPD, which certifies their commitment to environmental sustainability [23].

An EPD includes the technical characteristics of a product; the reference unit against which all the input and output data flows are normalized, referred to as the functional unit/Declared Unit; and the System Boundaries, which define the processes to be included or excluded within the Life Cycle Assessment. These boundaries must be defined consistently with the specifications outlined in BS EN 50693:2019 [24], *Product Category Rules for Life Cycle Assessments of Electronic and Electrical Products and Systems*.

Regarding the quality of the environmental data in an EPD, particular attention must be paid during the development of the Life Cycle Inventory, in accordance with ISO 14040:2006 [21].

The environmental data contained in an EPD pertain to all raw material and energy consumption, as well as all associated pollutant emissions, expressed in appropriate units of measurement, across the following stages: manufacturing, distribution, and installation; use; and end-of-life.

Specifically, for data related to the end-of-life phase (including waste management, transportation, recycling, disposal, and the benefits associated with potential reuse, recycling, and recovery), the data must be developed in accordance with the procedures specified in EN 15804:2012 + A2:2019 [25], with the Ecoinvent 3.8 database serving as the primary data source.

Specifically, for public lighting fixtures, a thorough investigation is necessary to evaluate their eco-compatibility. This is determined by their ability to maintain the initial "technical" performance required by the project over time, while minimizing—or ideally eliminating—impacts on human health and the environment throughout their entire life cycle.

The ability to sustain performance levels over time depends on various factors, including the durability certified by the manufacturers, design choices, installation methods, and scheduled maintenance interventions. Furthermore, the performance must comply with the safety, hygiene, comfort, appearance, health, and environmental requirements established by the European Regulation for Construction Products (CPR) No. 305, approved in 2011 [26].

Indeed, it is important to emphasize the critical role of public lighting in meeting safety requirements [27,28]. In full compliance with road safety standards, it is permissible to reduce the lighting class by two levels from the initial entry class, except in specific cases. EN 13201:2015 [29], on the other hand, addresses the performance requirements for road lighting, providing detailed guidelines for various lighting classes and specifying, from an illuminating engineering perspective, the minimum parameter values that must be considered during system design.

Studies on applying a life cycle analysis to public lighting systems, aimed at supporting the decision-making processes of public administrations, remain relatively scarce [30]. Consequently, Environmental Product Declarations (EPDs) for these systems are also regrettably underrepresented.

While most studies focus on comparing the impacts of two technologies without performing a comprehensive inventory of existing lamps [31–34], others are restricted to specific urban [35] or rural areas [36].

When, as mentioned earlier, the selection of appropriate lighting technologies has been made, the timing strategy for replacing fixtures becomes a significant factor. Generally, municipalities have tools for planning public outdoor lighting that are developed in alignment with urban and territorial planning instruments. In Italy, this tool is the *Municipal Lighting Master Plan* (*Piano Regolatore dell'Illuminazione Comunale*, PRIC), also referred to in some regions as the *Lighting Plan for the Reduction of Light Pollution* (*Piano dell'Illuminazione per il Contenimento dell'Inquinamento Luminoso*, PICIL) or the *Analysis Document for Outdoor Lighting* (*Documento di Analisi dell'Illuminazione Esterna*, DAIE). The plan includes an inventory of existing installations within the area and guidelines for regulating the installation of new systems, the replacement of old ones, and the scheduling of maintenance interventions. Additionally, it encompasses any calculations and simulations with an energy analysis comparing the consumption of the current state and the proposed design; economic estimates; a timeline for the implementation of interventions; and projections of the annual savings. Among its objectives, the PRIC aims to reduce light pollution, improve the energy efficiency of systems, and optimize the costs of installation, operation, and maintenance.

To achieve these objectives, in the current context, characterized by obsolete technologies in public lighting infrastructure, efficient technologies (such as smart lighting, LED relamping, multifunctional smart streetlights, etc.) and innovative approaches are needed to support public administrators in the preparation of the PRIC.

In this context, the methodology presented here aims to provide a standard procedure for the agile and accurate estimation of the environmental performance of public lighting. This procedure, which supports the planning, design, and long-term management of fixture replacement interventions, uses EPDs as the data source for the technical and environmental performance of the replacement fixtures. It also evaluates the CO_2-equivalent emissions in two scenarios for the temporal organization of replacements in order to answer the question(s) of *whether* and *when* to replace fixtures.

This study originates from a collaboration between a company specializing in energy supply and energy management services in Italy and the Inter-departmental Research Center for Territory, Building, Restoration, and Environment (CITERA) at Sapienza University of Rome, through the Department of Planning, Design, and Technology of Architecture. The focus is on innovation and sustainability in the energy sector.

The procedure—aimed at local administrations—to support initiatives and the preparation of the Municipal Public Lighting Master Plan (PRIC), will be verified in a real urban context (a case study). The results serve as foundational scientific analyses aiming towards climate neutrality, biodiversity protection, and the mitigation of climate change's effects.

Therefore, this paper is structured as follows: Section 2 describes the proposed methodology, Section 3 covers the application to the case study, the results are discussed in Section 4, and finally, the conclusions and future developments are formulated in Section 5.

2. Materials and Methods

As previously mentioned, within the framework of urban interventions, public lighting plays a significant role in reducing energy consumption and associated pollutant emissions while simultaneously being crucial to meeting road safety needs in urban areas. In this context, both the selection of new lighting fixtures to be installed and the temporal strategy and criteria for replacing existing fixtures are of particular importance, especially in cases where replacement occurs before the end of their useful life.

The methodological approach to achieving this goal encompasses the following phases (Figure 1):

1. *Identification of the territorial area* (urban, suburban) for intervention; consequently, determination of its governance, any ongoing initiatives, general guidelines, and objectives to be pursued, the reference regulations, and potential constraints; and, finally, verification of the availability of suitable partners and financial resources. This step requires an analysis of the public outdoor lighting planning tools for the area under intervention.
2. Definition of the type and sources of data to be acquired. This step requires the following:
    (a) A census of the lighting fixtures, both those installed and in use, categorized by the year of installation and type (decorative/artistic/porch/floodlight lamp, streetlight, pedestrian lighting fixtures). For each type, it is also necessary to record the number of gas-discharge lamps. The census uses data contained in the PRIC. The methodology is replicable, but the census requires an analysis of various documents (PRIC and documents related to both ordinary and extraordinary maintenance interventions) and sample checks.
    (b) Estimation of the key parameter in the analysis, the luminous efficiency of the surveyed fixtures, categorized by year of installation. The luminous efficiency is calculated using data contained in the technical specifications of the fixtures surveyed which were actually and truly installed in the reference year.
3. *Environmental impact analysis throughout the life cycle of the existing fixtures and replacement fixtures*. In this step, the impact category analyzed is the Global Warming Potential, expressed in kg CO_2eq emissions, calculated using the data contained in the EPD for the replacement fixture. The choice to use the EPD for the replacement fixture as the data source for the environmental analysis of all of the existing fixtures is necessary in urban contexts where there are typically numerous fixtures to be replaced

and for which corresponding EPDs often do not exist. For this reason, in the analysis performed, the kg CO_2eq emissions associated with the usage phase of the existing luminaires must be recalibrated, considering the percentage increase in the energy consumption of the existing fixtures compared to those of new installations relative to the usage data for the new luminaires. To quantify the higher energy consumption of the existing fixtures compared to the new product, as previously mentioned, a census and classification of the fixtures must be developed based on their year of installation. Regarding the production/transport/installation and end-of-life stages, the kg CO_2eq emissions for the existing fixtures are considered equal to those of newly manufactured fixtures. Regarding the use of EPD data in step 3 here, it is also important to note that it may be necessary to recalibrate the data reported in the EPD concerning the functional unit/Declared Unit. This is because in the case of lighting fixtures, the functional unit established by the Product Category Rules (PCRs) for electrical and electronic products and systems in the specific category of "Public Lighting" is represented by a single lighting fixture operating over a reference useful life of 40,000 working hours, powered by an LED. When applied to a real case, it will be essential to adjust the data to reflect the actual annual operating hours of the fixtures, as determined by each respective municipal administration and the prevailing regulations. In this regard, the annual operating duration of public lighting systems is generally estimated to be around 4000 h, corresponding to the nighttime hours when artificial lighting is required. This estimate, commonly used in the sector, is based on typical usage patterns and is widely accepted for calculations related to energy consumption and system lifespans [37].

Finally, environmental analyses must also include the following: the potential for reuse/relocation of replaced fixtures (prior to the end of their useful life) within the original urban context to replace less efficient fixtures, as well as the associated costs. In the environmental analyses, poles were not included because, as they do not consume energy during the use phase and are generally made of steel, they have high recycling rates, resulting in an environmental impact that is significantly lower compared to that of the fixtures [38].

Regarding the impact category considered in this study, it is important to note that the environmental assessment focuses on the impact that public lighting has on the environment in terms of greenhouse gas emissions, specifically the total quantity of carbon dioxide and other greenhouse gases associated with a product (a good or a service) throughout its entire life cycle. The impact category analyzed is the Global Warming Potential (GWP) over a 100-year period; thus, it expresses the contribution of a greenhouse gas (e.g., CH_4, N_2O, CFC, etc.) to the greenhouse effect relative to the effect of CO_2 emissions, with CO_2 having a reference potential equal to 1. The ultimate goal is to estimate the impacts caused by the increase in the average temperature on humans and ecosystems. The method for characterizing the impacts of greenhouse gases is based on the guidelines provided by the Intergovernmental Panel on Climate Change (IPCC) of the United Nations, which uses kilograms of CO_2 equivalent over a 100-year time horizon as the impact indicator. For the purpose of obtaining the EPD, the GWP must be determined as the sum of fossil GWP, biogenic GWP, and land use GWP according to the IPCC's 100-year baseline model (2013) and in accordance with the characterization factors and impact assessment methods specified in standard EN 15804:2012+A2:2019.

3.1 Regarding the criteria for the selection of the replacement fixture, it is essential (a) to identify the most prevalent type within the lighting fixture inventory of the municipality; then (b) to proceed with the possession of certifications attesting to the technical performance in compliance with the applicable regulatory standards; (c) to identify the distance in kilometers from the place of production; and finally (d) to select the replacement fixture based also on the availability of its EPD and the proximity of the production site to the project location.

4. *Development of lighting fixture replacement scenarios*. In the preparation of the scenarios, particular attention must be given to the parameters of luminous efficiency and the year of installation to decide whether and when to replace the fixtures. Upon the completion of the previous steps, we proceed with simulations for the replacement of the fixtures according to the following scenarios: Scenario (S1): Immediate replacement, within a single year, of all gas-discharge lamps and all LED fixtures installed from the earliest installation year, as traced from the previously conducted census, up to the installation year in which the luminous efficiency (calculated previously) is lower than that of the chosen replacement fixture. Scenario (S2): Replacement of all gas-discharge lamps and staggered replacement of all LED fixtures installed and in use over the predefined time horizon, based on the end of the useful life span of each fixture. The determination of the time horizon will depend on the local authority.
5. Recalibration of the municipal planning tool and development of the executive project.

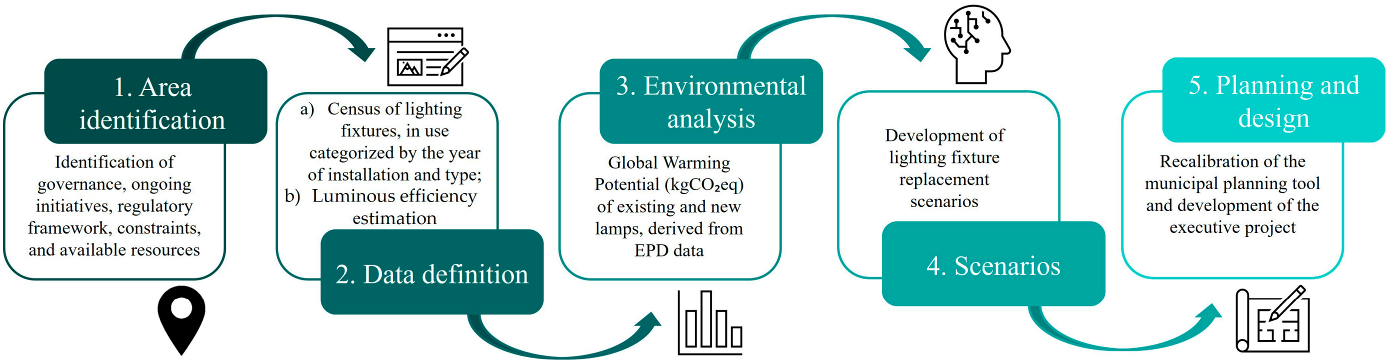

Figure 1. Schematic of the research methodology.

3. Case Study: Data Collection and LCA Model Development

The case study pertains to the outdoor public lighting system in the city of Bologna, located in Northern Italy, within the framework of a competition aimed at improving the energy efficiency of public lighting. In accordance with the proposed methodology, the PRIC was analyzed, the lamps were inventoried and classified, the constraints set forth by the plan were examined, the existing EPDs were verified, and the technical performance of the proposed lamps was assessed. Finally, based on the inventory and the constraints outlined in the PRIC, a time frame was determined to identify the number of lamps to include in the two scenarios. Following this, an environmental assessment was conducted, which informed the decisions on whether and when to proceed with the replacement of the fixtures. In detail, to quantify the higher energy consumption of the existing fixtures compared to that of the proposed new product, an inventory and classification of the fixtures were conducted based on the year of installation. Table 1 and Figure 2 present the inventory of existing lighting fixtures in Bologna. Each luminaire was assigned a specific luminous efficiency (lumen/Watt), as indicated in the respective technical data sheets (the table containing the existing lighting fixtures in Bologna, classified by year of installation, type, and luminous efficiency, is provided in Supplementary Materials Table S1).

Table 1. Census of existing lighting fixtures in Bologna.

Typology	**Decorative Lamp**
Year of installation	n. lighting fixtures
2015	1169
2016	1465
2017	1214
2018	1560
2019	666
2020	501
2021	525
2022	462
2023	3261
Gas-discharge lamps	377
Total number of lighting fixtures by type	**11,200**
Typology	**Artistic Lamp**
Year of installation	n. lighting fixtures
2016	46
2017	3
2018	39
2019	5
2021	19
2022	9
2023	408
Gas-discharge lamps	35
Total number of lighting fixtures by type	**564**
Typology	**Porch Lamp**
Year of installation	n. lighting fixtures
2015	52
2016	7
2017	97
2018	627
2019	45
2020	153
2021	1
2022	5
2023	2137
Gas-discharge lamps	1312
Total number of lighting fixtures by type	**4436**
Typology	**Floodlight**
Year of installation	n. lighting fixtures
2015	179
2016	303
2017	95
2018	45
2019	48
2020	277
2021	82
2022	72
2023	2279
Gas-discharge lamps	1208
Total number of lighting fixtures by type	**4588**

Table 1. *Cont.*

Typology	Streetlight
Year of installation	n. lighting fixtures
2015	3077
2016	5005
2017	5416
2018	4465
2019	3545
2020	2168
2021	802
2022	655
2023	4676
Gas-discharge lamps	177
Total number of lighting fixtures by type	**29,986**
Typology	**Pedestrian Lighting Fixtures**
Year of installation	n. lighting fixtures
2015	9
2016	9
2017	22
2018	16
2019	20
2020	44
2021	18
2022	5
2023	64
Gas-discharge lamps	1
Total number of lighting fixtures by type	**208**
Total number of lightings fixtures	**50,982**

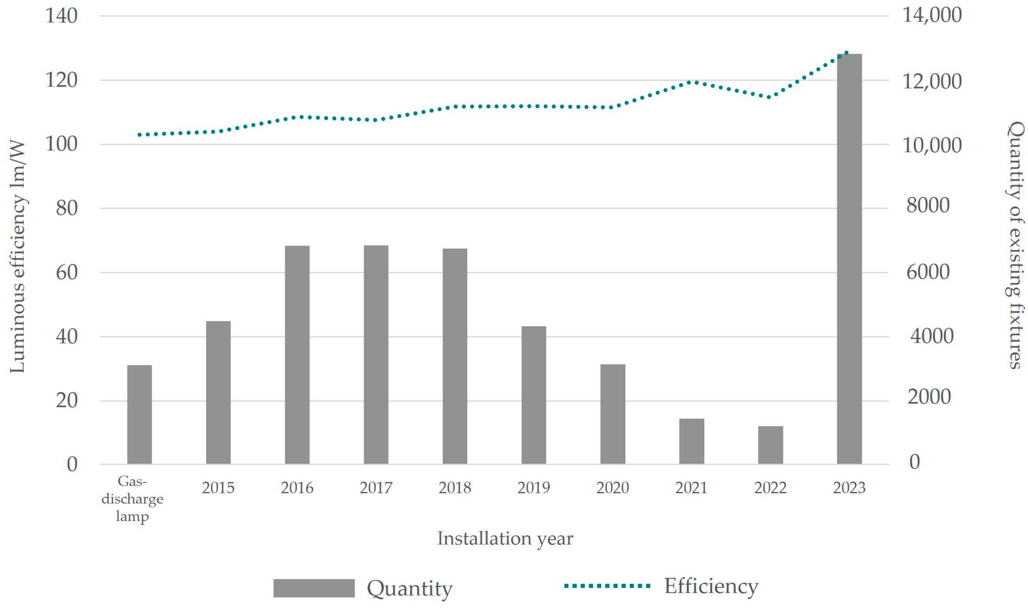

Figure 2. Classification of existing fixtures based on installation year and evaluation of luminous efficiency (luminous efficiency lm/W on the left and number of fixtures on the right).

The inventory reveals that the oldest fixtures were installed in 2015. The calculation of luminous efficiency shows that the new fixture is more efficient than all of those installed up to 2023. Nevertheless, the analysis of the PRIC indicates that only those installed between 2015 and 2019 can be replaced. It is worth noting that, as shown in Figure 2, the fixtures installed in 2022 have a slightly lower efficiency than expected, as fixtures with the "furnishing" functional type are less efficient than streetlights. For this reason, the installation years that can be included in the scenarios to be modeled refer to the comparison between replacing the fixtures in the first year and maintaining only the LED fixtures installed from 2015 to 2019.

The replacement or maintenance of the remaining existing fixtures is dictated and constrained by other needs, articulated as follows:

- For the existing discharge fixtures, replacement in the first year is planned for obvious energy efficiency reasons;
- For the existing LED fixtures installed between 2020 and 2022, maintenance is planned (without any initial requalification intervention in the first year), as their remaining useful life is largely compatible with the duration of the contract;
- For the existing LED fixtures installed in 2023 through specific tendering procedures (currently under completion) funded by the European funds "REACT EU ACTION 6.1.3—Completion of the LED transformation of installations" (intervention codes 6244, 6586, 6587, 6588), maintenance is planned (without any intervention in the first year), as their useful life is largely compatible with the contract duration and is also subject to maintenance constraints linked to the funding received.

Before the environmental impact analysis of the existing fixtures and replacement fixtures, referring to the impact category of Global Warming Potential (GWP), the replacement fixture was selected, and its EPD data were used. It was necessary to use the EPD of the replacement fixture as the data source for the environmental analysis of all the existing fixtures, as it was the only type of lamp that met the selection criteria defined in the methodology.

The lamp model chosen in this study for the environmental assessment is the "street" luminaire, which is the most representative type within the lighting fixture inventory of Bologna (accounting for approximately 30,000 units out of a total of about 50,000 luminaires). It meets the technical requirements, including possessing an Environmental Product Declaration and its production plant having the greatest proximity to the city of Bologna.

The environmental data source is the EPD for the replacement fixture, developed through an LCA in November 2022 by Greenwich Sustainability Consulting, following the guidelines outlined in the Product Category Rules (PCRs) EPDItaly020, Public Lighting, which are valid at the international level.

All data related to the activities at the lamp factory are primary data collected on site in 2021. For the phases associated with the supply and transportation of the raw materials, the data used are secondary data (revisions provided directly by the lamp factory). Regarding waste disposal scenarios, the data employed for the environmental analyses are secondary data sourced from Italian and European statistics, as well as from the scientific literature concerning the disposal of construction and demolition waste.

The technical characteristics of the product under study correspond to the reference type of lighting fixture with a power rating of 33.0 W, characterized by an energy consumption of 1,320,000 Wh over its entire useful life during the use phase. The functional unit/Declared Unit in the EPD was recalibrated based on the actual annual operating hours of the fixtures, set at 4000 h—equivalent to the nighttime hours requiring artificial lighting—and subsequently multiplied by the duration of the contract.

The input data used, summarized in Table 2, in the present comparative analysis refer to the GWP expressed in kgCO_2eq emitted during the following stages:

- Manufacturing, distribution and installation;
- Use;
- End-of-life.

Table 2. The Global Warming Potential in $kgCO_2eq$ for the reference light fixture with a power of 33.0 W.

Impact Category	Measurement Units	Manufacturing Stage	Distribution Stage	Installation Stage	Use Stage	End-of-Life Stage	Total
GWP	$kgCO_2eq$	4.33×10	9.52×10^{-1}	4.65	6.97×10^{2}	6.41	7.53×10^{2}

The existing light fixtures were subsequently categorized based on their installation year in order to determine their quantity and average luminous efficiency. Using these data, the increased energy consumption of the existing fixtures, in comparison to the average efficiency of the new lighting fixtures, was calculated for a period from 2015 to 2023, as illustrated in Figure 3. These data on increased consumption were then utilized for the environmental analyses. Concerning the production, transportation, installation, and end-of-life stages, the $kgCO_2eq$ emissions associated with the existing fixtures were considered to be equivalent to those of the newly manufactured fixtures.

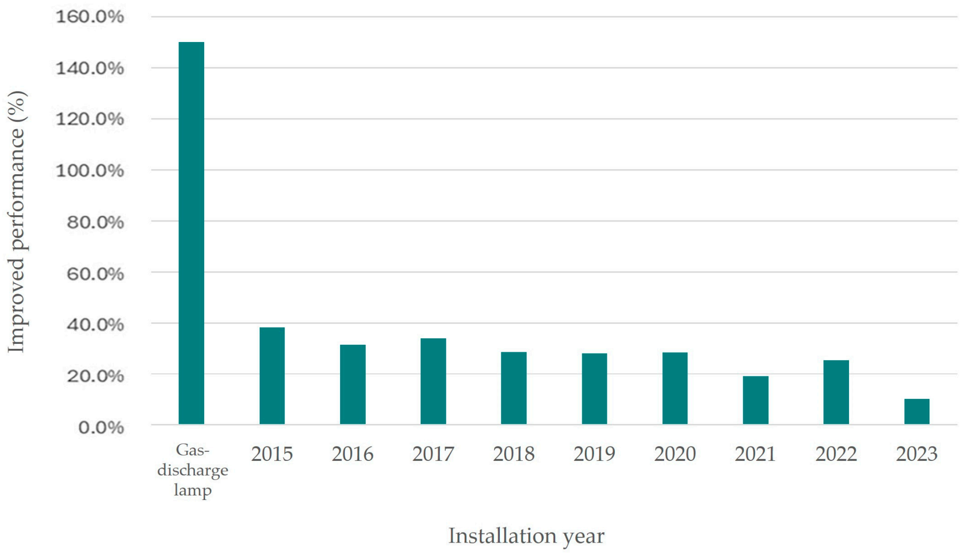

Figure 3. Improved performance through the replacement of existing fixtures.

In this context and with the aforementioned premises, the scenarios to be modeled were outlined as follows:

- *Scenario 1 (S1):* Replacement, during the first year of the contract, of all LED fixtures installed from 2015 to 2019 that are currently in use;
- *Scenario 2 (S2):* Gradual replacement, staggered over the 15-year duration of the contract, based on the end of the useful life of each fixture of all LED fixtures installed from 2015 to 2019 that are currently in use.

4. Results and Discussion

The results of the environmental impact assessment in terms of $kgCO_2eq$ emissions for the hypothesized scenarios, S1 and S2, are shown in Figure 4 below.

In *scenario S1*, which involves replacement of the fixtures in the first year, the total estimated emissions amount to 89,175,576 $kgCO_2eq$, while in scenario S2, which involves replacement at the end of their useful life, they amount to 96,200,997 $kgCO_2eq$. Between the two scenarios, there is a difference of 7.5%. This figure is derived from a combination of the improved performance efficiency of the fixtures and the energy mix of the Italian electricity grid powering them, updated to 2024, which recorded a renewable energy production of 43.9% [39]. The analysis of the two proposed scenarios, S1 and S2, revealed that proceeding with fixture replacement in the first year represents the most advantageous option, achieving a 7.5% reduction in CO_2eq emissions. This outcome is attributed to the superior technical performance of the new fixtures during the use phase compared to the existing fixtures (installed between 2015 and 2019). This improved performance ensures reductions in energy consumption that vary between 38% and 10%, depending on the production year of the fixtures being replaced. Regarding the life cycle phases of the proposed fixtures, the highest impacts on the Global Warming Potential (GWP) category are observed during the use phase (9.12%), followed by the production phase (6.88%), primarily due to the raw materials used in the fixtures. Approximately 62% of the fixtures' total weight of about 6 kg consists of recycled materials.

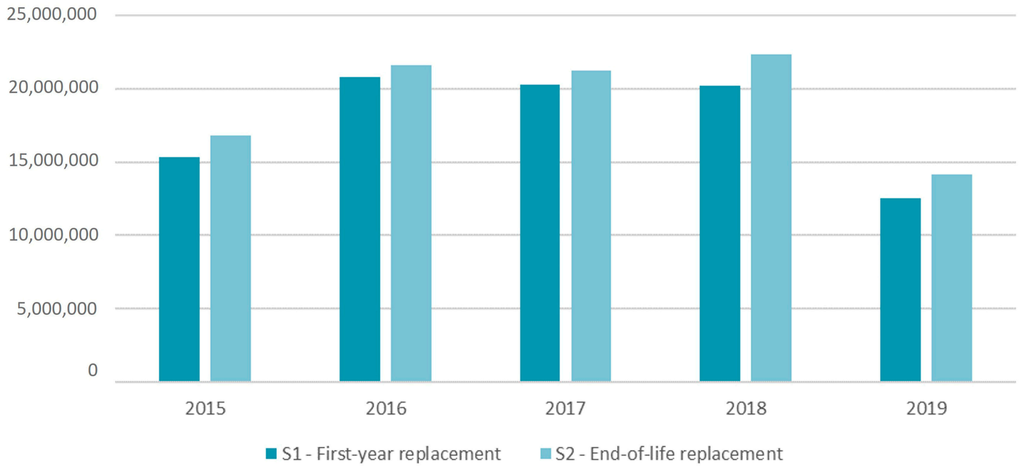

Figure 4. Comparison between the two scenarios S1 and S2 in terms of kgCO_2eq emitted.

For the fixtures installed between 2015 and 2019, which will be replaced before the end of their useful life, it is recommended to relocate them to other areas of the local urban fabric to replace less efficient fixtures.

5. Conclusions

In alignment with the objectives advocated by the United Nations, it is imperative to address the multifaceted challenges requiring urgent action in urban areas. These interventions are designed to promote resilient communities, inclusive and safe spaces, and environmentally sustainable practices, fostering solidarity. Such efforts aim to fulfill international commitments to decarbonization and digital transformation while simultaneously enhancing quality of life in tangible, everyday contexts.

To achieve these objectives, a range of policies, tools, funding mechanisms, and research initiatives—encompassing both public and private sectors—have been developed and promoted over several decades to empower governance as the cornerstone of sustainability. These efforts aim to enable the planning, design, and implementation of actions that effectively integrate economic, environmental, and social dimensions.

The findings of this study emphasize the importance of effective fixture management, which not only ensures adequate illumination levels but also contributes to a reduction in energy consumption and associated emissions. In the case study, replacement strategies involving more efficient fixtures lead to a 7.5% reduction in CO_2eq emissions. This outcome is a result of selecting appropriate lighting technologies, with the superior technical performance of the new fixtures during their operational phase compared to the existing fixtures (installed between 2015 and 2019). The decision to immediately replace, in the first year of the contract, all fixtures that, according to the PRIC, could be replaced demonstrates that when the performance of the fixtures is nearly equivalent, it is crucial to understand the optimal timing for replacement and whether it is advantageous to bring it forward in order to optimize the energy efficiency and reduce the overall environmental impact.

This improved performance ensures variable reductions in consumption ranging from 38% to 10% depending on the production year of the fixtures being replaced. The main limitations of this research are related to the lack of an assessment of the maintenance costs for the lighting fixtures. The analysis assumes that the same lighting class has been implemented and is currently in use on every street, which, in terms of changes to its function over the years, may not be entirely accurate. Furthermore, other potential energy-saving measures that a municipality could adopt, such as delaying the lighting system's activation time and advancing its deactivation time, are not considered. However, the proposed methodology, being flexible, allows for an easy update to the environmental analysis by incorporating these new parameters.

These results represent fundamental scientific analyses conducted in collaboration between the company and the university to support the decisions of the local authority.

The replacement of the existing fixtures in their current state remains environmentally beneficial even today. However, as we approach the year 2050, the effectiveness of this solution will diminish, as electricity production goals foresee the gradual phasing-out of fossil fuel sources. From an energy-saving perspective, future scenarios will include not only the improvement of lighting fixtures' efficiency but also the creation of intelligent management systems based on the development of digital twins aimed at predictive lighting and optimization of maintenance activities [40–42].

Digital twin technology enables the creation of a virtual replica of a physical system, facilitating real-time monitoring, analysis, and optimization [43–45]. By leveraging real-time data and advanced simulation models, digital twins can facilitate the prediction and optimization of public lighting systems' performance, minimizing downtime and enhancing the overall system efficiency.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/en18030535/s1. Table S1: Survey of lighting fixtures installed in Bologna from 2015 to 2023.

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