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Assessing the Potential of Smart Lighting for Sustainable Urban Development: A Case Study of Marshal Tito Street, Sarajevo

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Abstract

Smart lighting integrates various technologies such as LEDs (Light Emitting Diodes), motion sensors, and IoT (Internet of Things) to achieve energy efficiency, improve safety, and support various urban services. Beyond simple illumination, it serves as a conduit for deploying information and communication technologies to enhance efficiency and mitigate environmental impact. This paper analyzes the technical and economic feasibility of smart lighting compared to traditional lighting systems through a case study and mathematical model on the busiest street in Sarajevo, Marshal Tito street. It underscores the transformative potential of smart lighting, not only as a technical solution but also as a strategic instrument for urban development and sustainable growth. By introducing LED lighting with motion sensors, significant savings in electricity consumption and maintenance costs have been achieved, indicating the potential of smart lighting to transform urban spaces into sustainable and functional environments. Overall, this paper emphasizes the critical role of smart lighting in shaping the cities of the future, fostering efficiency, and sustainability in urban environments.

Keywords: *Smart Lighting, Light Emitting Diodes, Energy Efficiency, Sustainable Development, Internet of Things.*

1. Introduction

Smart lighting is an important element of energy management as part of the smart city concept. It encompasses a heterogeneous area of lighting management, offering the possibility of integrating a wide range of techniques and technologies with developmental concepts. It is no longer just lighting connected to a street lamp, but a device that enables the installation and use of information and communication technologies to achieve better efficiency and reduce negative environmental impact. A smart lighting network provides access to additional real-time data. In this sense, it is possible to discuss individual elements, such as air pollution, traffic monitoring, and network power, which employ a holistic approach, including management and monitoring of the entire urban ecosystem. [1].

The multifunctionality of smart lighting enables the integration and utilization of resources such as light sources, relays, weather stations, air pollution monitors, or electric vehicle chargers. Modern luminaires have electronic systems that allow control and monitoring of various processes [2] to support urban smart services. Currently, technological advancements in solutions using LEDs (Light Emitting Diodes) not only enable energy savings due to the technology of the light source itself but also promote the development, integration, and use of advanced lighting systems and functions. Thus, it enables high efficiency and responsible use of infrastructure.

Smart lighting creates intelligent functions and interfaces for lighting solutions for management in ambient, commercial, and public domains using the Internet of Things (IoT) [3]. The advent of IoT technologies opens avenues for developing new applications, such as automating smart lighting solutions [4]. LED smart lighting can be a significant catalyst for the evolution of IoT, supporting the rapid development of the smart city concept on a global scale. Systems for data monitoring, storage, processing, and analysis enable comprehensive optimization of the entire installation and monitoring of municipal lighting systems based on various parameters. Contemporary management of outdoor lighting systems is possible from a single central point, and technological solutions allow for the management of the entire system and each luminaire or lighting fixture individually [5].

This paper focuses on the significance of smart lighting within the framework of energy management in

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smart city initiatives. The main objectives are summarized as follows:

- To propose a mathematical model for evaluating the technical and economic feasibility of smart lighting systems compared to traditional lighting systems.
- To presents a case study of Marshal Tito street in Sarajevo, analyzing the potential benefits of replacing existing luminaires with LED lighting equipped with motion sensors.

The rest of the paper is structured as follows: The second chapter provides review of existing literature on smart lighting. The third chapter proposes a mathematical model for evaluating the technical and economic feasibility of smart lighting systems compared to traditional lighting systems. The fourth presents detailed data and analysis regarding the potential savings and benefits of implementing smart lighting on Marshal Tito street in Sarajevo. The fifth chapter contains conclusions.

2. Literature Review

Smart lighting integrates smart functions and interfaces at four levels that complement each other [3, 6]:

- The first level or levels are embedded in the light engine or the light source itself.
- The second level or levels are in the electrical system of luminaires and lighting systems.
- The network level or levels involve managing light from beginning to end and monitoring energy sources, power plants, and municipal services in real-time along with distribution facilities.
- The fourth level or levels of communication and detection consist of incomplete light technologies along with applications and programs for monitoring, controlling, and management.

Such a system requires appropriate optimization. Among other things, it relies on designing with the aim of finding the most efficient technical parameters and their combinations to achieve the best results. Parameters influencing these factors may include the height of lighting units, their tilt, or the spacing between poles [7, 8]. This system is very useful due to the location, density, and availability of lighting fixtures. LED lighting can be used as a platform for smart urban services. If they are part of a smart city, this allows them to:

- Reduce energy costs and maintain infrastructure,
- Increase public safety through a better, more efficient, and dynamic street lighting system adapted to external conditions,
- Provide safer mobility, better risk prediction,
- Protect the environment due to lower emissions of harmful substances into the atmosphere,
- Ensure the right amount of light, at the right time and in the right place,
- Utilize infrastructure for mobile communication,
- Control traffic lights,
- Support intelligent parking solutions,
- Aid in traffic management,
- Serve as electric vehicle (EV) charging stations,
- Register seismic changes in the event of earthquakes,
- Install emergency phone booths,
- Ensure a longer lifespan for this type of luminaire.

There is a wealth of research in the literature on street lighting that focuses on operational and strategic levels. The functional level allows real-time representation of ways to improve the efficiency of implemented systems (including management and luminaire control methods) [9], adaptive energy street lighting controlled on demand and, for example, traffic forecasts [10] all the way up to actions at the strategic level, which involve integrating smart lighting with traffic management within a smart urban platform [11] or diversifying electrical energy and using renewable energy sources. At the strategic level, including in smart cities, LED street lighting programs are combined with a central management system (CMS), utilizing IT networks and communication technologies. With all these functions, city lighting can be managed much more efficiently and wisely. Decisions are not made based on estimates but on specific data continuously fed into the system from smart sensors embedded in each luminaire.

One of the first cities to extensively use LED lights was Los Angeles. The city has replaced 180,000 streetlights with LED fixtures to date, resulting in energy savings of 65%, which translates to savings of €8.17 million annually [12]. The main factor behind the "smart city" initiative in Copenhagen was the installation of 20,000 connected LED lights in street lighting, leading to a 65% energy saving [13]. The new LED street lighting system in Manchester, with 56,000 LED fixtures, achieves a 60% efficiency saving compared to traditional lamps, allowing the city to save approximately £3m million annually on energy costs [14]. As part of London's (Canada) LED street lighting transition program, 35,000 luminaires will be replaced by 2022/23. The total cost of LED fixtures is around €11.98 million. The payback period is estimated to be less than 10 years [15]. Chicago launched its smart lighting program in 2017. It is expected to replace over 270,000 obsolete high-pressure sodium (HPS) lamps with LED bulbs [13].

3. Mathematical Evaluation Model

In this section, the possibility of developing smart lighting is analyzed from the perspective of the technical application of IoT technologies and the economic feasibility compared to traditional lighting systems. To conduct this analysis, it is necessary to define the technical and economic parameters of the luminaires, as well as to analyze profitability [16]. The mentioned elements of the analysis include the following:

1. Technical parameters of the luminaire:
   - For the existing luminaire: bulb power [W], electricity consumption [kWh], lifespan [hours]
   - For the replacement luminaire: bulb power [W], electricity consumption [kWh], lifespan [hours]
2. Economic parameters of the luminaire:
   - For the existing luminaire: electricity consumption [currency/year], maintenance costs [currency]
   - For the replacement luminaire: electricity consumption [currency/year], maintenance costs [currency]
3. Profitability analysis:
   - Difference in operation before and after replacement [currency]
   - Payback period [years]

We calculate the total installed power [17]:

$$\boldsymbol{P_u = \sum_{i=1}^{N} P_i \cdot n\ [kW]} \qquad (1)$$

where:

P_u – total power of lighting fixtures

P_i – installed power of individual luminaire

n – total number of luminaires of a certain power

N – number of different types of luminaires according to installed power.

The electricity consumption is calculated [17]:

$$\boldsymbol{W = P_u \cdot t\ [kWh]} \qquad (2)$$

where:

W – electricity consumption

t – operating time of public lighting

The electricity consumption in BAM (Bosnia and Herzegovina convertible mark) is calculated [17]:

$$\boldsymbol{C_W = W \cdot c\ [BAM]} \qquad (3)$$

where:

C_W – electricity consumption of public lighting in BAM

c – price of electricity in BAM/kWh

4. Case Study

The subject of research in this paper is the busiest street in the city of Sarajevo – Marshal Tito street (Figure 1). Initially, data was collected on the current number of streetlights, the type of luminaires used, and their power. Then, that number of streetlights was replaced with LED luminaires with the addition of motion sensors. It is important to note that the currently installed lighting in this area is nearly 20 years old, and exclusively high-pressure sodium lamps have been used.

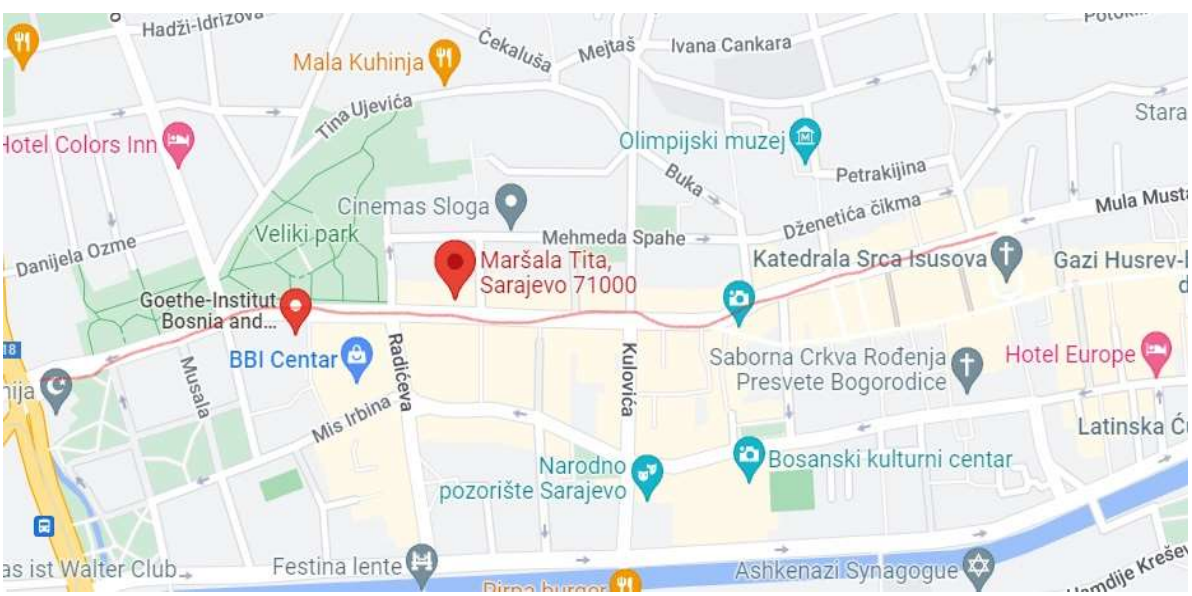

Figure 1. Research area: Marshal Tito street, Sarajevo.

Along Marshal Tito street, a total of 79 streetlights have been installed, predominantly consisting of high-pressure sodium lamps with powers of 70W and 150W [18]. The 70W luminaires are installed in the pedestrian walkway part of Marshal Tito Street, while the 150W luminaires are installed in the section where motor vehicles travel. Table 1 provides an overview of the lighting data for the mentioned street, which was used in the calculations. The recommendation is to replace the existing luminaires with LED lighting ranging from 60 to 80W [16]. The total power of the luminaires is calculated using formula (1).

Table 1. Comparison of the power between the currently installed public lighting and LED lighting.

Type of luminaire	Power of luminaire (W)	Number of luminaires	Total installed power (kW)
High-pressure sodium lamps 1 (HSL 1)	70	21	1,47
High-pressure sodium lamps 2 (HSL 2)	150	58	8,70
Total			10,17
LED	73	79	5,767

Smart lighting also involves the introduction of motion sensors and light sensors, which further save energy in three ways:

- They enable turning on only those luminaires where motion is detected.
- They allow for adjusting the shorter duration of the light being on (e.g., 30 seconds instead of 1-3 minutes).
- They prevent turning on the lighting if there is sufficient natural light in the area.

Depending on the configuration of the lighting in the street, i.e., how the luminaires are distributed, sensor lighting will activate an average of 55% of the luminaires. In other words, it will contribute to additional energy savings of 45%. [19]. Table 2 presents the technical parameters and displays the difference in the lifespan between the currently installed lighting and LED lighting. Data used for calculation are:

- Operating time of the public lighting system during one year is 4128 hours [17],
- Price of electricity for public lighting is 0.189 KM/kWh.

The electricity consumption (kWh) is calculated using formula (2):

$$W_{HSL1} = P_{HSL1} \cdot t = 1{,}47 \cdot 4128 = 6.068{,}16\ kWh$$

$$W_{HSL2} = P_{HSL2} \cdot t = 8{,}70 \cdot 4128 = 35.913{,}6\ kWh$$

$$W_{LED} = P_{LED} \cdot t = 5{,}767 \cdot 4128 = 23.806{,}18\ kWh$$

Considering that the lifespan of a quality high-pressure sodium lamp is around 30,000 hours, it means that for a 10-year lifespan of the public lighting system, with the assumed operating hours, it is sufficient to change one luminaire per pole. The cost of luminaires (two pieces) and their replacement per luminaire is 120.00 KM for its lifespan [17]. Considering that the lifespan of quality LED lighting is 50,000 to 90,000 hours [16], it means that for a 10-year lifespan of the public lighting system of this type, with the assumed operating hours, there is no need for maintenance investment.

In addition to the difference in lifespan, Figure 2 illustrates the difference in electricity consumption expressed in kW. Reducing electricity consumption automatically implies lower monetary expenses. Figure 3 illustrates the savings of smart lighting, noting that in the calculation for LED lighting, losses from the ballast were not considered, which are even lower than with other types of lighting, meaning that the savings are even greater.

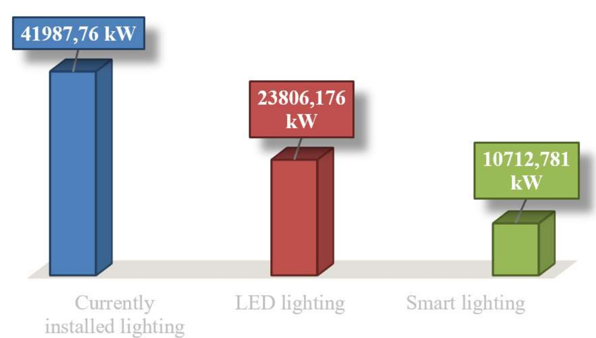

Figure 2. Difference in electricity consumption between currently installed lighting and smart lighting.

Table 3 summarize maintenance costs, as well as other economic parameters related to electricity consumption in KM for one year as well as for a period of 10 years. The electricity consumption in BAM is calculated using formula (3). The electricity consumption using traditional public and LED lighting expressed in BAM:

$$C_{W1} = W_{NVP1} \cdot c = 6.068{,}16 \cdot 0{,}189 = 1.146{,}88\ BAM$$

$$C_{W2} = W_{NVP2} \cdot c = 35.913{,}6 \cdot 0{,}189 = 6.787{,}67\ BAM$$

$$C_{W3} = W_{LED} \cdot c = 23.806{,}176 \cdot 0{,}189 = 4.499{,}37\ BAM$$

Table 2. Comparison of technical parameters between currently installed public lighting and LED lighting.

Type of luminaire	Power (W)	Total consumption (kWh)	Lifespan (h)	Replacement period
HSL 1	70	6.068,16	28000	6y4m
HSL 2	150	35.913,6	32000	7y3m
LED	73	23.806,176	50000	11y5m
Difference in lifespan: Lifespan of LED 73W compared to HPS 70W = 44% Lifespan of LED 73W compared to HPS 150W = 36%				

Table 3. Profitability analysis of replacing existing public lighting.

Type of luminaire	Number of luminaires	Power (W)	Total consumption (kWh)	Electricity consumption in BAM	Electricity consumption in BAM for 10 years	Maintenance costs (BAM)
HSL 1	21	70	6.068,16	1.146,88	11.468,8	2520
HSL 2	58	150	35.913,6	6.787,67	67.876,7	6960
Total			41.981,76	7.934,55	79.345,526	9480
LED	79	73	23.806,176	4.499,37	44.993,67	0
Savings in public lighting consumption in KM for a period of 10 years: 43.295% Savings in maintenance costs by introducing LED lighting: 100%						

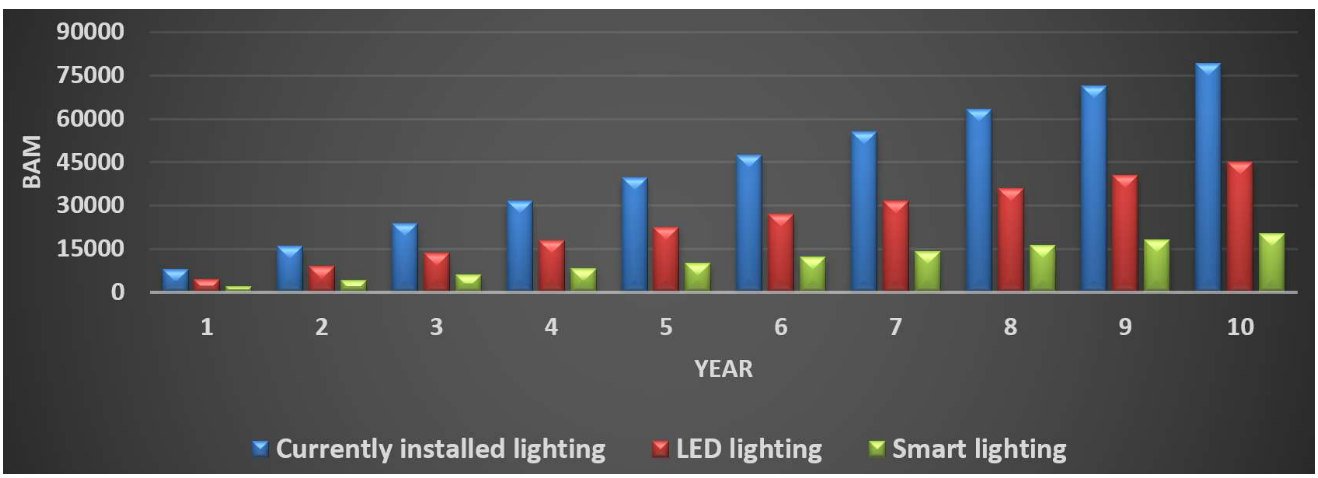

Figure 3. Comparison of electricity consumption over a period of 10 years.

Based on the conducted technical and economic analysis, we can conclude that installing a smart lighting system offers many advantages. Firstly, the introduction of smart street lighting impacts sustainability and economic viability. Additionally, such a system consumes much less energy, and the luminaires last longer than their traditional counterparts such as incandescent or fluorescent lamps. LED luminaires are energy-efficient because they emit very little heat, requiring much less energy to emit the same amount of light as their conventional equivalents. These advantages imply that the introduction of IoT technologies makes public lighting infrastructure more efficient, versatile, and flexible.

5. Conclusion

This research provides insight into the complexity and potential of smart lighting in the context of urban planning and sustainable development. Smart lighting is not just a technical solution for illuminating public spaces; it represents a fundamental component of the smart city concept, which aims for integrated and efficient resource and infrastructure management.

Smart lighting encompasses various aspects such as LED technology, motion sensors, IoT, and management systems. This holistic approach enables integration with other smart systems and services, creating a complex yet highly functional urban ecosystem. Through the application of LED technology, lighting becomes energy-efficient, reducing energy consumption and maintenance costs. Additionally, the integration of motion sensors allows for dynamic adjustment of lighting according to real-time needs and environmental conditions, contributing to efficiency and safety. Moreover, smart lighting opens doors to various smart services and applications in the urban environment. From traffic monitoring to security systems, from parking management to support for electric vehicles, these functions not only improve the quality of life for citizens but also provide additional economic benefits and contribute to environmental protection.

Overall, this research shows that smart lighting is not just a technological solution but also a strategic tool for transforming urban spaces into smart, sustainable, and functional environments. Its comprehensive and integrated operation can have a significant impact on urban infrastructure, the economy, and the environment. Therefore, investing in smart lighting is a step towards building the cities of the future.

Competing Interest Statement

The authors declare no known competing interests or personal relationships that could have influenced the work reported in this paper.

Data and Materials Accessibility

All data generated or analyzed during this study are included in this article.

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