STUDIA UNIVERSITATIS BABEŞ-BOLYAI
Engineering 67(1) 2022 DOI: 10.24193/subbeng.2022.1.22

# Study on the importance of upgrading public lighting systems

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***Abstract.*** *The paper presents a case study which advocates for the adoption of smart outdoor illumination installations that come with energy management systems. To analyse the energy efficiency we carried out measurements on: a) a classical outdoor lighting system, with sodium vapour sources, b) the same system after the sodium vapour light sources were replaced with LEDs, and c) the same system with LEDs augmented with an energy management system. Our analysis shows that replacing the outdoor light-sources with LEDs, in combination with an energy management system, results in a reduction of 40% in energy consumption. At the same time, the luminance coefficients of the LED lighting system are significantly higher than the luminance coefficients of sodium vapour sources.*

***Keywords***: *illumination, LED, management system, electric energy reduction.*

## 1. Introduction

By definition, street lighting is “a fixed lighting installation designed to provide, during night-time, good visibility to users of public outdoor traffic areas in order to support the safety and flow of traffic as well as public safety" [1]. This definition includes both lighting of roadways as well as pedestrian and bicycle paths.

Studies have shown that, worldwide, lighting sources make about 19% of total electricity consumption [2]. In the context of the global economic crisis, replacing outdated lighting sources with highly energy-efficient ones is being widely implemented. The current lightsources of choice are LED sources [3], which achieve significant electricity savings [4].

In order to increase the lighting systems energy efficiency and increase their sustainability, certain criteria must be followed, such as:

- the choice of technologies must meet environmental requirements and use recyclable materials;
- a life cycle analysis of the lighting system and all necessary components must be done beforehand;

- an analysis of the impact of the lighting system on users and the environment must be available.

To reduce electricity consumption various solutions can and are implemented. For example, it has been established on a university campus that by applying a lighting enhancement scenario, in 12 years approximately 1.3 million euros can be saved [5]. The scenario envisages the replacement of existing lighting sources (metal halide) with LED sources and the adoption of a programmed switch-off of lighting sources and dimming with dimming modules.

For street lighting systems, the dimming modules are complemented by a system that monitors the number of vehicles which causes the luminous flux to be automatically adjusted depending on the traffic participants [6]. These systems can be powered by photovoltaic panels, by means of a battery and a controller, which monitors the lighting level, battery capacity, avoiding excessive battery discharges [7].

Lately, trends in outdoor lighting make use of artificial intelligence algorithm. For example, a rule-based algorithm has 213 rules and considers feedback from sensor systems to efficiently manage a lighting system. During the tests, which lasted for one semester, an average electricity saving of 33% was achieved [8, 9].

In order to get an overview of the energy efficiency of lighting systems, it was proposed to approach the analysis strategy at component and system level. At the component level the aim is to replace inefficient sources with LED sources and to optimise the performance of LED drivers. At the system level, through control strategies, the aim is to obtain real-time information about energy consumption and provide data about the operation of complete lighting systems [10].

In order to ensure the lighting coefficients, established by current in-force standards, it is necessary to pay more attention to the optimal design, to the appropriate location of lighting poles and crutches, to the choice of lighting sources with an appropriate photometric curve [11-15].

It is a known fact that, as the duration of use of lighting sources increases, their luminous flux decreases. In order to establish the efficiency of the lighting source/system, it is necessary to carry out light measurements at a certain, regular, time intervals [16]. At the same time, periodically, it is necessary to carry out proper maintenance so that the entire system is always in working order, ensuring the necessary quality coefficients [17].

The efficiency and sustainability analysis of lighting systems must also take into account the rather high cost of luminaires equipped with LED sources, especially in the case of high-power LEDs [18]. According to the previously mentioned research [19] where the outdoor lighting systems on a university campus combined LED sources with Smart Grid technologies, the payback period was 4 years and 10 months.

With the intention to reduce pollution, it is necessary to reduce or even eliminate light pollution through a management architecture that uses IoT (Internet of Things) technologies [20].

As the existing lighting system on the main road in the municipality was to be upgraded, it was necessary to identify the lighting and energy performance before and after the system change.

In order to analyse the lighting system efficiency, both from a lighting and energy point of view, this paper presents the lighting coefficients measured on a boulevard section where the light sources installed were sodium vapour based lights. After replacing these sources with LEDs, we carried out again photometric measurements for various values of luminous flux (nominal flux and nominal flux with a dimming system). This case study shows the energy efficiency that can be achieved by replacing sodium vapour sources with LED sources, and by additionally combining LED sources with an energy management system.

## 2. Analysis of the Lighting System Before the LED Modernisation

The lighting system we analysed is located on a boulevard in a municipality city. The light measurements were carried out on two sections between three lighting poles [21].

The roadway where the measurements were done, consists of a 5 m wide sidewalk (including a 1.5 m wide bike lane), followed by a 1.5 m wide green space and two lanes for motorized vehicles, each 3.5 m wide, on the direction of travel. The other traffic direction is separated from the one just described by a 5 m wide green space, and also consists of two traffic lanes and an additional bike lane.

The lighting poles illuminating the carriageway and pavement are placed in the view space, 2 m from the traffic lane, with 40 m between them. The pole height is 12.4 m, each pole has 2 arms of 4 m on which sodium vapour lamps powered at 230V and a power of 171 W (including ballast), luminous flux 17,700 lm and a power factor of 0.92 are mounted.

The photometric measurements were made with a luminance-meter and a lux-meter. The measurements were done at 9 regular intervals between the lighting poles, which constitute the measuring points. The following locations were selected for the light measurements:

- on the pole axis, on the green space separating the traffic directions;
- on the longitudinal axis separating the two traffic lanes in each direction;
- on the pavement;
- on each traffic lane direction, two measuring points at equal distances.

This resulted in a matrix with 63 measurement points. Table 1 shows the measured illuminance values and Table 2 the luminance values for the non-modernised, or classic, illumination system. We computed, for each measurement point, the average illuminance, and the average luminance as the arithmetic mean of the measurements.

**Table 1.** Illuminance values for the classic (sodium vapor-based) lighting system ("R" stands for "Direction")

| Illuminance measurements for sodium vapor sources 171 W [lx] | | | | | | | | | | $E_{med}$ [lx] |
|---|---|---|---|---|---|---|---|---|---|---|
| Pole axis | 31.5 | 25.5 | 16.1 | 12.4 | 9.3 | 10.4 | 13.6 | 23.4 | 27.5 | 18.86 |
| Lane 1 R1 | 31.4 | 25.6 | 15.5 | 12.2 | 9.5 | 10.5 | 14.23 | 23 | 26.4 | 18.70 |
| Lane 1 R2 | 25.9 | 27.4 | 15.7 | 12 | 9 | 10.1 | 13.8 | 22.6 | 20.7 | 17.47 |
| Long. Axis | 27.6 | 26.6 | 15.4 | 12 | 9.4 | 10.4 | 13.2 | 21.9 | 22.5 | 17.67 |
| Lane 2 R1 | 25 | 22.2 | 15.6 | 11.5 | 9 | 8.5 | 11.8 | 19.6 | 23 | 16.24 |
| Lane 2 R2 | 21 | 20.3 | 14 | 11.3 | 8.5 | 7.9 | 10.6 | 15.7 | 20 | 14.37 |
| Side walk | 14 | 11.4 | 11.5 | 10.3 | 7.3 | 6.7 | 8 | 9.3 | 11 | 9.94 |

**Table 2.** Luminance values for the classic (sodium vapor-based) lighting system.

| Luminance measurements for sodium vapor sources 171 W [cd/m$^2$] | | | | | | | | | | $L_{med}$ [cd/m$^2$] |
|---|---|---|---|---|---|---|---|---|---|---|
| Lane 1 R1 | 1.74 | 1.49 | 0.89 | 0.65 | 0.52 | 0.79 | 1.05 | 1.78 | 2.11 | 1.22 |
| Lane 1 R2 | 1.41 | 1.18 | 0.67 | 0.50 | 0.46 | 0.57 | 0.4 | 1.51 | 1.65 | 0.93 |
| Long. Axis | 1.07 | 1.08 | 0.52 | 0.37 | 0.44 | 0.29 | 0.68 | 1.11 | 1.30 | 0.76 |
| Lane 2 R1 | 0.93 | 0.80 | 0.44 | 0.34 | 0.32 | 0.47 | 0.62 | 1.10 | 1.24 | 0.70 |
| Lane 2 R2 | 0.93 | 0.81 | 0.54 | 0.40 | 0.39 | 0.44 | 0.76 | 1.13 | 1.29 | 0.74 |

The average illuminance calculated on the road surface is:

$$E_{med\ road} = \frac{E_{medPoleaxis} + E_{medL1R1} + E_{medL1R2} + E_{medLongaxis} + E_{medL2R1} + E_{medL2R2}}{6} = \frac{18.86 + 18.70 + 17.47 + 17.67 + 16.24 + 14.37}{6} = 17.22 \ [lx] \quad (1)$$

and the average luminance is:

$$L_{med\ road} = \frac{L_{medL1R1} + L_{medL1R2} + L_{medLongaxis} + L_{medL2R1} + L_{medL2R2}}{5} = \frac{1.22 + 0.93 + 0.76 + 0.70 + 0.74}{5} = 0.87 \ \left[cd/m^2\right] \quad (2)$$

The overall illuminance and luminance uniformity coefficients, calculated as the ratio of the measured minimum value to the calculated average value [22-24], for pavement and roadway are:

$$U_0(E)_{\text{pavement}} = \frac{E_{\min}}{E_{med}} = \frac{6.7}{9.94} = 0.67 \quad (3)$$

$$U_0(E)_{road} = \frac{E_{\min}}{E_{med}} = \frac{7.9}{17.22} = 0.46 \quad (4)$$

$$U_0(L)_{road} = \frac{L_{\min}}{L_{med}} = \frac{0.29}{0.87} = 0.33 \quad (5)$$

The luminance longitudinal uniformity coefficient (on the road axis), computed as the ratio between the measured minimum illuminance and average value is:

$$U_1(L) = \frac{L_{\min 1}}{L_{\max 1}} = \frac{0.29}{1.3} = 0.22 \quad (6)$$

We found that the illuminance uniformity, the illuminance, and the average luminance are within the value ranges established by technical standards in force, but the overall and longitudinal luminance uniformity are not, as they are lower than the values in the standards (greater than 0.4 and 0.5 respectively).

Considering that a luminaire operates 10 hours a day, 30 days a month, the energy consumed by a luminaire in a month is:

$$W_{\text{luminaire}/month} = P_{\text{luminaire}} \cdot no\ hours \cdot no\ days = 171 \cdot 300 = 51.3 \ [kWh] \quad (7)$$

As there are 52 poles on the section of road we measured, each with two luminaires, the monthly energy consumed is:

$$W_{section/month} = W_{luminaire/month} \cdot No_{luminaire} = 51.3 \cdot 52 \cdot 2 = 5335.2 \ [kWh] \quad (8)$$

which is a substantial amount of energy consumed in the area analysed.

## 3. Analysis of the Upgraded Lighting System

The lighting system presented in Section 2 was upgrade by replacing the lighting fixtures with LEDs and installing an energy management system. The fixtures were placed on already existing street poles and positioned so that the central light flow falls perpendicular to the street surface, on the longitudinal axis separating the two traffic lanes.

The LEDs power is 140.5 W, they have a luminous flux of 12938 lm and have a power factor of 0.9. The LED sources are powered by a driver, monitoring the light installation is done through a communication and dimming module is used to monitor the lighting system. The street lighting system is divided into segments, controlled, and monitored by a segment controller. This controller transmits and receives information from the communication and dimming module and adjusts the light intensity from 10% to 100%.

After upgrading the lighting system, we took photometric at the same measurement points as previously established. The values of the measured illuminances are shown in Table 3 and of the luminances in Table 4.

**Table 3.** Illuminance values for LED system

| Illumination measurements for the 140.5 W LEDs [lx] | | | | | | | | | | $E_{med}$ [lx] |
|---|---|---|---|---|---|---|---|---|---|---|
| Pole axis | 32.6 | 31.5 | 24.6 | 20.5 | 18.1 | 21.5 | 26.6 | 28.2 | 33.6 | 26.36 |
| Lane 1 R1 | 30.1 | 31.2 | 22.3 | 17.8 | 16.3 | 17.7 | 25.1 | 34.3 | 35.5 | 25.59 |
| Lane 1 R2 | 26 | 32.9 | 24.5 | 18.5 | 18.2 | 18.7 | 28.2 | 35.2 | 35.6 | 26.42 |
| Long. Axis | 24.8 | 37.6 | 23.5 | 21.2 | 20.7 | 23.2 | 23.8 | 33.9 | 34.5 | 27.02 |
| Lane 2 R1 | 23.8 | 21.4 | 19.8 | 18.4 | 16.5 | 18.7 | 21.6 | 24.4 | 26.2 | 21.20 |
| Banda 2 R2 | 20.2 | 18.7 | 18.1 | 16.9 | 14.2 | 15.8 | 17.7 | 20.2 | 12.4 | 17.13 |
| Side-walk | 9.6 | 8.4 | 7.3 | 6.5 | 5.2 | 6.4 | 7.9 | 8.3 | 9.16 | 7.64 |

**Table 4.** Luminance values for the LED street lighting system

| Luminance measurements for the 140.5 W LEDs [cd/m$^2$] | | | | | | | | | | $L_{med}$ [cd/m$^2$] |
|---|---|---|---|---|---|---|---|---|---|---|
| Lane 1 R1 | 1.27 | 1.41 | 1.36 | 1.28 | 1.19 | 1.25 | 1.34 | 1.40 | 1.21 | 1.30 |
| Lane 1 R2 | 1.29 | 1.46 | 1.42 | 1.29 | 1.22 | 1.27 | 1.38 | 1.42 | 1.25 | 1.33 |
| Long. Axis | 1.31 | 1.48 | 1.45 | 1.36 | 1.25 | 1.30 | 1.44 | 1.47 | 1.32 | 1.38 |
| Lane 2 R1 | 1.25 | 1.37 | 1.23 | 1.21 | 1.17 | 1.21 | 1.31 | 1.45 | 1.24 | 1.27 |
| Lane 2 R2 | 1.02 | 1.13 | 1.06 | 1.01 | 0.95 | 1.05 | 1.22 | 1.36 | 1.15 | 1.11 |

The average illuminance and luminance calculated for the road surface are:

$$E_{med\ road} = \frac{26.36+25.59+26.42+27.02+21.20+17.13}{6} = 23.95\ [lx] \quad (9)$$

$$L_{med\ road} = \frac{1.30+1.33+1.37+1.27+1.11}{5} = 1.28\ \left[cd/m^2\right] \quad (10)$$

The overall illuminance and luminance uniformity coefficients for the pavement and road surface are:

$$U_0(E)_{pavement} = \frac{5.2}{7.64} = 0.68 \quad (11)$$

$$U_0(E)_{road} = \frac{12.4}{23.954} = 0.52 \quad (12)$$

$$U_0(L)_{road} = \frac{1.01}{1.277} = 0.79 \quad (13)$$

The luminance longitudinal uniformity coefficient is:

$$U_1(L) = \frac{1.25}{1.48} = 0.85 \quad (14)$$

Our analysis shows that all the quality coefficients of the lighting system analysed fall within the range set by the standards currently in force.

For the same length of time analysed in Section 2, the monthly electricity consumed by one luminaire and the electricity consumed by all luminaires in the area analysed are calculated by:

$$W_{lu\min aire/month} = 140.5 \cdot 10 \cdot 30 = 42.150 \quad [kWh] \tag{15}$$

$$W_{section/month} = 42.15 \cdot 104 = 4383.6 \quad [kWh] \tag{16}$$

which is 17.84% less than with sodium vapour lighting.

In order to determine whether the lighting system also meets the quality conditions for dimming, measurements were made under the same operating conditions and at the same measuring points for a dimming that considers the luminous flux reduction at 66% and 50% [21]. We present in this paper the photometric measurements made at a 50% dimming (Tables 5 and 6).

**Table 5.** Illuminance values for system with LED sources and 50% dimming

| Illuminance measurements for the 140.5 W and dimmed LEDs [lx] | | | | | | | | | | $E_{med}$ [lx] |
|---|---|---|---|---|---|---|---|---|---|---|
| Pole axis | 22.8 | 23.6 | 16.7 | 13.3 | 10.7 | 14.1 | 16.4 | 19.2 | 24.7 | 17.94 |
| Lane 1 R1 | 20.6 | 21.7 | 17.8 | 13.9 | 11.9 | 12.4 | 17.5 | 21.8 | 21.5 | 17.38 |
| Lane 1 R2 | 20.4 | 22.2 | 18.8 | 14.5 | 12.5 | 13.5 | 18.8 | 24.6 | 25.3 | 18.96 |
| Long. Axis | 18.2 | 22.9 | 19.1 | 15.2 | 13 | 16.1 | 19 | 25 | 25.6 | 19.34 |
| Lane 2 R1 | 17.5 | 19.4 | 17.6 | 15 | 12.6 | 15.3 | 18 | 21.5 | 21.4 | 17.59 |
| Lane 2 R2 | 13.6 | 14.8 | 15.5 | 10.3 | 8.8 | 10.5 | 12.6 | 13.2 | 14.4 | 12.63 |
| Side walk | 7.1 | 6.2 | 5.6 | 4.5 | 3.7 | 4.6 | 5.2 | 5.8 | 6.9 | 5.51 |

**Table 6.** Luminance values for a LED lighting system, 50% dimmed

| Luminance measurements for 140.5 W LEDs [cd/m$^2$] dimmed | | | | | | | | | | $L_{med}$ [cd/m$^2$] |
|---|---|---|---|---|---|---|---|---|---|---|
| Lane 1 R1 | 0.98 | 1.05 | 0.85 | 0.68 | 0.51 | 0.63 | 0.88 | 1.04 | 0.89 | 0.83 |
| Lane 1 R2 | 1.07 | 1.17 | 0.96 | 0.75 | 0.67 | 0.71 | 0.93 | 1.14 | 0.,98 | 0.93 |
| Long. Axis | 1.12 | 1.21 | 1.04 | 0.78 | 0.77 | 0.82 | 1.01 | 1.23 | 1.07 | 1.001 |
| Lane 2 R1 | 1.09 | 1.11 | 0.97 | 0.67 | 0.51 | 0.64 | 0.86 | 0.95 | 0.88 | 0.85 |
| Lane 2 R2 | 0.89 | 0.93 | 0.72 | 0.51 | 0.44 | 0.47 | 0.56 | 0.77 | 0.62 | 0.66 |

The average luminance and illuminance values for this lighting system are then:

$$E_{med\ road} = \frac{17.94+17.68+18.96+19.34+17.59+12.63}{6} = 17.36\ \left[lx\right] \quad (17)$$

$$L_{med\ road} = \frac{0.83+0.93+1.01+0.85+0.66}{5} = 0.86\ \left[cd/m^2\right] \quad (18)$$

The general illuminance and luminance uniformity coefficients for the side walk and roadway and the longitudinal luminance uniformity coefficients are:

$$U_0\left(E\right)_{pavement} = \frac{3.7}{5.51} = 0.67 \quad (19)$$

$$U_0\left(E\right)_{road} = \frac{8.8}{17.36} = 0.51 \quad (20)$$

$$U_0\left(L\right)_{road} = \frac{0.44}{0.86} = 0.51 \quad (21)$$

$$U_1\left(L\right) = \frac{0.77}{1.23} = 0.63 \quad (22)$$

It is found that, even at 50 % dimming, the illumination uniformity on the roadway is superior to the situation where the lighting system had the sodium vapour sources and was operating at 100 % luminous flux. Additionally, the values of the lighting coefficients are higher than those required by the standards.

If we consider that the analysed lighting system operates according to a pre-set schedule (3 hours without dimming, 2 hours with a 66% reduction of luminous flux and 5 hours with a 50% reduction of luminous flux) for one luminaire, the energy consumed by it in one month at an operation of 10 hours/day is:

$$\begin{aligned} &W_{lu\min aire/lmonth(100\%)} = P_{lu\min aore(100\%)} \cdot no\ hours \cdot no\ days = \\ &= 140.5 \cdot 3 \cdot 30 = 12.645\left[kWh\right] \end{aligned} \quad (23)$$

$$\begin{aligned} &W_{lu\min aire/lmonth(66\%)} = P_{lu\min aire(66\%)} \cdot no\ hours \cdot no\ days = \\ &140.5 \cdot 0.66 \cdot 2 \cdot 30 = 5.564\left[kWh\right] \end{aligned} \quad (24)$$

$$\begin{aligned} &W_{lu\min aire/month(50\%)} = P_{lu\min aire(50\%)} \cdot no\ hours \cdot no\ days = \\ &140.5 \cdot 0.5 \cdot 5 \cdot 30 = 10.5275\left[kWh\right] \end{aligned} \quad (25)$$

$$\begin{aligned} &W_{lu\min aire/month} = W_{lu\min aire/lmonth(100\%)} + W_{lu\min aire/lmonth(66\%)} + W_{lu\min aire/month(50\%)} = \\ &= 12.645 + 5.564 + 10.5275 = 28.7365\left[kWh\right] \end{aligned} \quad (26)$$

which is 43.983% less than the energy consumed by conventional sources and 31.82% less than the case where the LED sources are operating non-dimmed.

The total energy consumed in one month, in the area analysed, when running with the previously mentioned schedule is:

$$W_{section/month} = W_{luminaire/month} \cdot No_{luminaire} = 28.7365 \cdot 104 = 2998.596 \ \left[kWh\right] \quad (27)$$

### 4. Comparative Analysis of the Two Lighting Systems

We compared the classic lighting system with the LED lighting at 100% flux and scheduled operation. We looked at the quality parameters and at the energy consumed by the lighting system in these three scenarios, the results are shown in Table 7.

**Table 7.** Illuminance values for the LED system and 50% dimming

| Coefficient / measure | Standard reference value | Value for 171 W light sources | Value for 140.5 W LEDs | Value for 140.5 W LEDs and 50% dimming |
|---|---|---|---|---|
| $E_{med}$ [lx] | 15.0 | 17.22 | 23.95 | 17.36 |
| $L_{med}$[cd/m$^2$] | 0.75 | 0.87 | 1.28 | 0.86 |
| $U_0(E)_{road}$ | > 0.4 | 0.46 | 0.52 | 0.51 |
| $U_0(L)_{road}$ | > 0.4 | 0.33 | 0.79 | 0.51 |
| $U_1(L)_{road}$ | > 0.5 | 0.22 | 0.85 | 0.63 |
| $W_{luminaire/month}$ [kWh] | - | 51.3 | 42.15 | 28.736 |
| $W_{section/month}$ [kWh] | - | 5335.2 | 4383.6 | 2998.596 |

Figure 1 shows a graph of the electricity consumption of the analysed luminaires for an operation of 10 hours/day, 30 days/month. The analysis shows that, for all three scenarios examined in this work, the average illuminances and luminances correspond to the values required by the standards. At the same time, we found that the average illuminance for the operation using LED sources and 50% dimming is 0.8% higher than the average illuminance with sodium vapour sources.

With regard to the uniformity coefficient of the illuminance, in all three analysed cases, its value corresponds to the requirements of the in-force standards. At the same time, it was found that at a dimming of 50%, the uniformity coefficient is 10.46% higher than the coefficient computed for the installation using sodium vapour light sources.

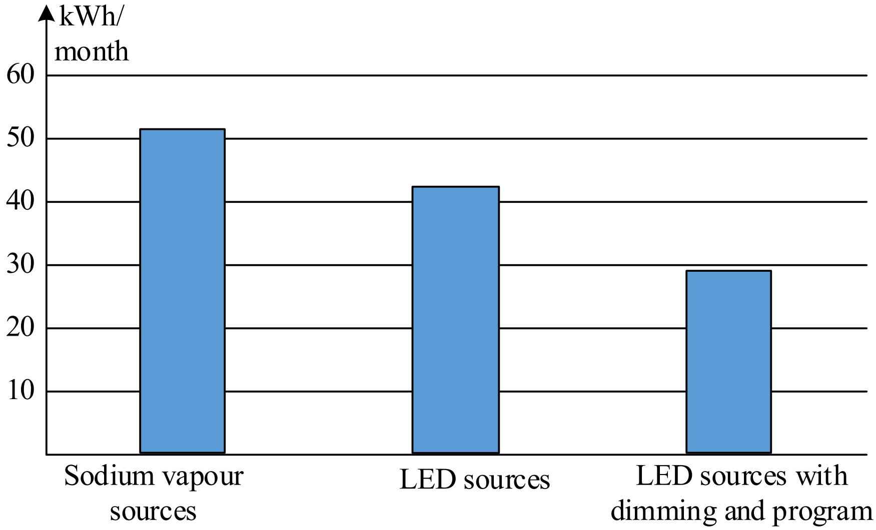


**Figure 1.** Monthly energy consumption for the examined lighting installations.

Our analysis shows that, for sodium vapour sources, the luminance uniformity coefficient and the luminance longitudinal uniformity coefficient are 16.75% lower and 55.4% lower than the values requested by the current technical standards in force, respectively. After replacing the lighting sources with modern LEDs, these coefficients are higher than the minimum required values, so even at a dimming of 50% the coefficients are 28.5% respectively 25.2% higher.

Regarding the electricity consumption, compared to the use of sodium vapour sources, LED sources bring a 17.84% reduction in electricity consumption. When an energy management system is used and the lighting system is operated on predefined schedules, the electricity reduction is of 43.98%.

## 4. Conclusion

The analysis we carried out emphasizes the need to modernize street lighting systems, by replacing energy inefficient sources and appliances with LED sources and high-performance lighting appliances that ensure the correct distribution of the light flow. Furthermore, the modernisation of lighting systems through the use of an energy management system allows the creation of different operating scenarios, which contribute to a substantial reduction in electricity consumption. At the same time, the management system allows remote control and monitoring, as well as providing information on the operating status of the installation.

In the context of the current energy crisis, the modernisation of lighting systems is a necessity, which must be supported by various government, European and global programmes.

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