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ORIGINAL RESEARCH ARTICLE

Energy-efficient light-emitting diode retrofit and advanced control in municipal street lighting: A case study from Bulgaria

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Abstract: Modernizing street lighting through light-emitting diode (LED) retrofits and advanced controls is recognized as an effective strategy for reducing energy use and costs. While numerous studies confirm these benefits in Western Europe, little is known about their performance in Eastern European municipalities. This study addresses this knowledge gap by presenting a case study of municipal street lighting in Bulgaria. It presents the methodology, implementation, and evaluation of an energy-efficient modernization project for municipal street lighting systems in the Bulgarian cities of Pavlikeni and Byala Cherkva. He project involved a complete transition from outdated lighting technologies (e.g., high-pressure sodium, compact fluorescent, and mercury vapor lamps) to high-efficiency LED luminaires, integrated with an intelligent control and monitoring system. An energy audit, conducted in accordance with national regulations and European standards (EN 13201), revealed that over 90% of luminaires had exceeded their operational lifespan and no longer complied with photometric and technical requirements. Lighting design classifications were applied in accordance with EN 13201:2016 to ensure compliance with the standard's requirements for luminance, uniformity, and glare control. An optimization problem was defined and solved using specialized software to determine the lowest luminaire power, minimum pole height, and smallest bracket tilt angle, with fixed pole spacing, while maintaining regulatory compliance. Using DIALux evo, multi-scenario photometric simulations and optimizations were performed, resulting in 47 optimized lighting models tailored to specific street segments. The upgraded system incorporates adaptive dimming features, enabling nighttime power reduction through pre-programmed driver settings. A centralized cloud-based management system was implemented for remote monitoring and control, enhancing reliability and reducing maintenance. Post-implementation analysis demonstrated 79.5% energy savings (549,082 kWh/year), along with carbon dioxide emission reductions of 1,349 t/year and a financial payback period of 6.2 years. This case study highlights the technical, economic, and ecological viability of large-scale LED retrofit projects with smart controls, offering a replicable model for municipalities across Central and Eastern Europe seeking improved energy efficiency and reduced environmental impact.

Keywords: Light-emitting diode street lighting; Street lighting audit; Street lighting modeling and optimization; Energy efficiency; Smart lighting control; Carbon dioxide emission reduction; Public lighting retrofit

1. Introduction

The judicious utilization of electrical energy in road lighting is regarded as a pivotal element for urban sustainability. Public street lighting typically contributes around 1–1.5% of a country's electricity consumption and can account for up to 30–50% of municipal energy expenditures, depending on the specific local circumstances.[1]

Conventional lighting technologies, such as high-pressure sodium (HPS) and mercury vapor lamps, present several drawbacks. These include low luminous efficacy (approximately 80–100 lm/W), limited operational life (approximately 12,000–24,000 h), and high maintenance demands.[2] Conversely, light-emitting diodes (LEDs) typically achieve luminous efficacies of at least 150 lm/W, provide service lifetimes of at least 50,000 h, and significantly reduce maintenance costs.[3,4]

In accordance with European standards, such as EN 13201, objective metrics—including power per length (PL [W/m]) and power per illuminated area (PA [W/m^2])—are employed to evaluate the performance of lighting systems.[5] Retrofit initiatives frequently yield energy savings of 50–70%, while intelligent control strategies, such as adaptive dimming, increase total savings to over 80%.[6]

A longitudinal monitoring study in Turin by Valetti *et al*.[3] documented a 51% annual energy reduction following LED retrofits, with photometric degradation being lower than predicted by standard models. Aghemo *et al*.[4] reported complementary findings across urban lighting installations. The carbon footprint of LED street lighting systems has been quantitatively assessed, with estimated reductions ranging from 0.4 to 0.7 kg CO_2/luminaire/year, depending on operational conditions and energy mix sources.[7] These findings highlight the substantial potential of LED-based lighting solutions to contribute significantly to climate mitigation.

Adaptive smart-city lighting projects—such as those integrating the Internet of Things and agent-based control—have demonstrated up to 35% additional energy savings over fixed-schedule designs. Smart dimming strategies linked to predictive traffic flows and environmental conditions further enhance performance.[8]

Large-scale municipal dimming experiments, such as the one conducted in Tucson involving approximately 20,000 luminaires, yielded approximately a 5% reduction in zenith sky brightness, corresponding to an overall street lighting contribution of around 14% to urban skyglow.[9] The adoption of warmer white or amber LEDs within spectral design frameworks has been demonstrated to simultaneously reduce ecological impacts while maintaining efficiency.[10]

Real-world case studies, including the retrofit of approximately 3,768 luminaires in Kraków, achieved notable reductions in energy consumption and carbon emissions, while also delivering improved economic performance through savings on emissions allowances.[11] Similar initiatives in European towns demonstrate consistent compliance with technical standards, safety, and environmental outcomes.[12]

The findings, when considered collectively, demonstrate that the implementation of LED-based public lighting, in conjunction with adaptive control strategies, has the potential to significantly contribute to the European Union's 55% greenhouse gas reduction target by 2030. This integration of lighting and control systems is expected to yield several key benefits, including enhanced operational cost-efficiency, improved road safety, and a reduction in environmental degradation.

The evolution of technologies in street lighting modernization in Bulgaria over the past three decades can be divided into two main periods[13]:

(i) Transition from mercury to HPS and compact fluorescent lamps (CFLs) (1995–2010).
(ii) Transition from HPS lamps and CFL to LEDs (2010–2015).

The approximate number of lamps of different types installed in outdoor luminaires in Bulgaria in 2010–2011 is shown in Table 1.[14]

The lamps used for outdoor lighting in Bulgarian municipalities at the end of the transition from mercury to sodium and CFL technologies (2010–2011) were as follows[15]:

(i) HPS lamps of 50W, 70W, 100W, 150W, 250W, and 400W.
(ii) CFLs of 11W, 13W, 36W, and 55W.
(iii) Metal halide lamps of 35W, 70W, 100W, 150W, and 250W.

Table 1. Distribution of luminaires by lamp type in Bulgaria (2010–2011)

Lamp type	Number	Share (%)
Sodium high pressure	450,000	53.0
Mercury vapor	136,000	16.0
Compact fluorescent	222,000	26.2
Metal halide	36,000	4.3
Light-emitting diode	4,500	0.5
Total	848,500	100

(iv) Mercury lamps of 80W, 125W, 250W, and 400W.
(v) LED modules of 20–150W.

This period marked the appearance of the first demonstration projects for outdoor LED lighting.

After 2010, the rapid increase in efficiency and reduction in the cost of LED technology coincided with the completion of the 15–20-year service life of the luminaries from the previous transition to sodium lamps. This convergence accelerated the widespread adoption of LED lights in outdoor lighting and initiated the transition from HPS and CFLs to LED light sources. The process was gradual, but all new street lighting systems were implemented with LED luminaires. The expansion of LED use in recent years has been highly dynamic across different Bulgarian cities, making it difficult to establish precise general data.

2. Methodology

This study presents the development, results, and the associated energy and environmental benefits of a project aimed at the energy-efficient modernization of street lighting systems in the Bulgarian municipality of Pavlikeni.

The research methodology consisted of the following stages:
(i) Conducting an energy audit of the existing street lighting systems.
(ii) Optimizing street lighting design through computational modeling using specialized software.
(iii) Implementing a modern street lighting management and control system.
(iv) Assessing energy efficiency, financial savings, and environmental benefits of the proposed modernization.

2.1. Energy audit of the existing street lighting systems

Conducting an energy audit of the existing street lighting systems is an important initial stage, as confirmed by several authoritative studies.[16-20]

The energy audit of the street lighting systems in the municipality of Pavlikeni was carried out in accordance with the applicable Bulgarian legislation, specifically Ordinance No. E-RD-04-05/04.10.2016 issued by the Ministry of Energy, which regulates the structure, content, and methodology for energy audits of industrial systems.[21] The audit also aligns with the principles and procedures outlined in EN 16247-2:2014,[22] which establishes the European standard for energy audits of buildings and technical systems, including outdoor lighting.[23] In compliance with these standards, the audit included an inventory of all lighting fixtures, measurements of installed and consumed power, nighttime observations of lighting quality, and verification of the system's conformity with applicable lighting design criteria.

The audit results revealed that over 90% of the existing luminaires equipped with HPS lamps had reached the end of their technical and operational life cycle. Common problems identified during the survey were mechanical failure of fixings, missing or damaged diffusers (Figure 1A-D), and a lack of moisture protection for the starting and control gear (Figure 1D). In some cases, LED and CFL lamps were installed in luminaires originally designed for HPS lamps (Figure 1C-F), leading to reduced luminance and illuminance levels on the roadway.

Steel street and park poles predominate in the central urban areas of the settlements, while reinforced concrete poles are mostly found in the outlying districts and villages. A significant proportion of luminaire cantilevers exhibit large tilt angles, ranging from 30° to 60°, which are inappropriate for the roadway widths, ranging from 4 to 9 m. These angles reduce the effective roadway coverage and illuminance while increasing glare and causing an unnecessarily large portion of the luminaire's light output to be directed onto the opposite sidewalks and building facades. In some cases, the luminaire bracket was misaligned, either rotated incorrectly around the horn axis or oriented in the opposite direction from the roadway.

Based on a detailed survey of the condition of the street and park lighting fixtures, the pole network, power lines, and the locations of the transformer substations and street lighting cassettes, a digital graphical model of the existing street lighting system in Pavlikeni was developed. This model integrates the survey data across separate map sheets, on which the collected information was plotted. Different types of luminaires, poles, power lines, and the positions of the control points and cabinets are indicated using appropriate graphic symbols. Figure 2 presents a section of one such map sheet from the digital graphical model, which was developed using AutoCAD (Autodesk Inc., USA). The graphic model is accompanied by detailed information about the existing lighting systems on all streets: The distances between the poles; the type and height of the poles; the length and angle of the bracket for mounting the luminaires; the type of luminaire and the technology; and the power of the light sources.

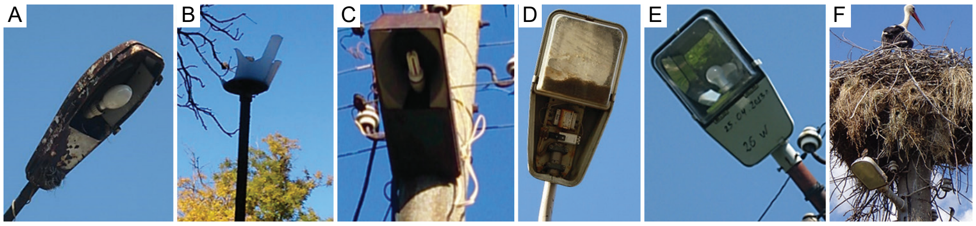


Figure 1. (A-F) Condition of depreciated street and park luminaires

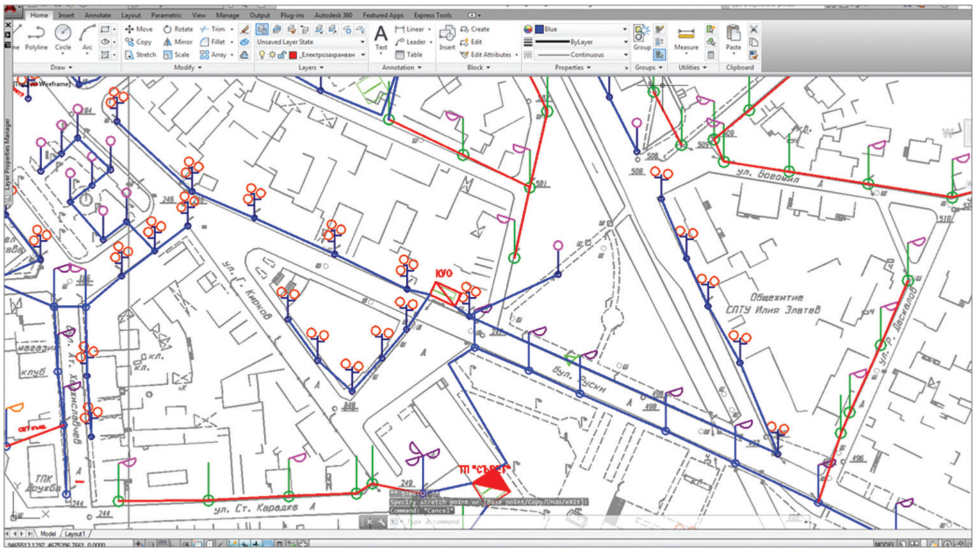


Figure 2. Section of a map sheet showing the plotted locations of the street lighting system in Pavlikeni

Figure 3 presents the distribution by type and power rating of the existing street and park luminaires in Pavlikeni. Street lighting accounts for 83.8% of the installed luminaires, while park lighting represents 16.2%. In the town of Pavlikeni, however, park luminaires constitute 48.3% of the total, whereas their share in the other settlements is negligible.

The predominant type of light source is HPS, representing 50.4% of all luminaires, followed by CFLs, which account for 36.5%. Street luminaires equipped with high-pressure mercury vapor lamps are outdated models, exceeding 25 years of service, and are significantly depreciated. In many cases, the lamps are missing, and only about 5% of the high-pressure mercury vapor luminaires remain operational.

In total, the street lighting system in Pavlikeni comprises 4,663 street luminaires and 901 park luminaires, resulting in a combined total of 5,564. In addition, there are 5,942 poles without luminaires—5,880 are reinforced concrete, 46 are steel, and 16 are wooden.

The total electrical power of the existing street and park lighting in all settlements in Pavlikeni is 280,153 W. Figure 4 illustrates the distribution of electrical power across the 20 settlements, while Figure 5 depicts the monthly electrical energy consumption for street and park lighting over the course of 1 year.

The municipality has a permanent population of 22,059, and the specific electricity consumption is calculated at 56 kWh/capita/year.

Based on the detailed survey analysis, the following energy-saving measures are proposed: Replacement of the existing street and park luminaires with new energy-efficient LED luminaires of lower installed power, implementation of an intelligent system for lighting control system, and optimization of the switching schedule.

2.2. Street lighting design optimization through computational modeling

2.2.1. Lighting classification and standardization

Based on a detailed audit of the geometric parameters of the street lighting installations in the individual settlements within the municipality of Pavlikeni, it was established that significant variability exists only in the two towns—Pavlikeni and Byala Cherkva—while the remaining settlements are small, relatively uniform villages. This finding justifies the need for detailed classification, standardization, and optimization

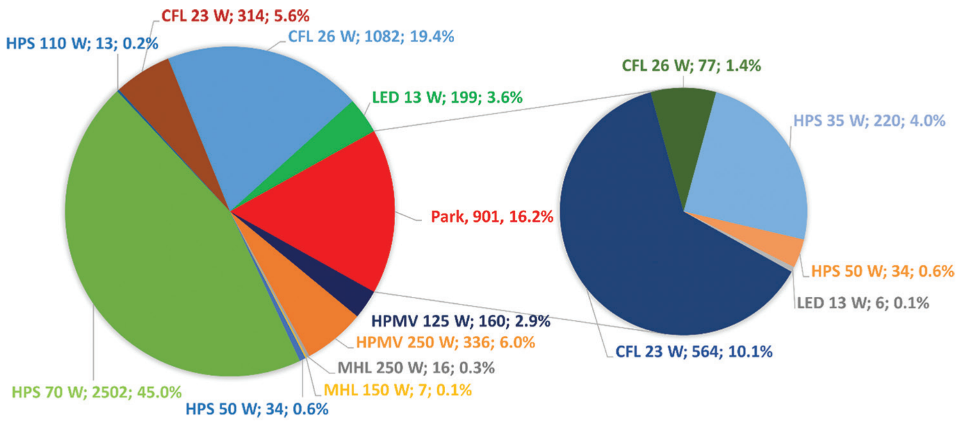


Figure 3. Distribution of the existing street and park luminaires by type and power rating (lamp type, number, and percentage share)

Abbreviations: CFL: Compact fluorescent lamp; HPMV: High-pressure mercury vapor; HPS: High-pressure sodium; LED: Light-emitting diode; MHL: Metal-halide lamp.

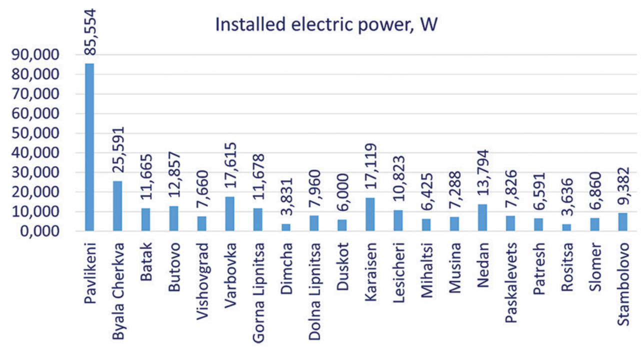


Figure 4. Installed electric power in existing street and park lighting systems in the settlements of the Pavlikeni municipality

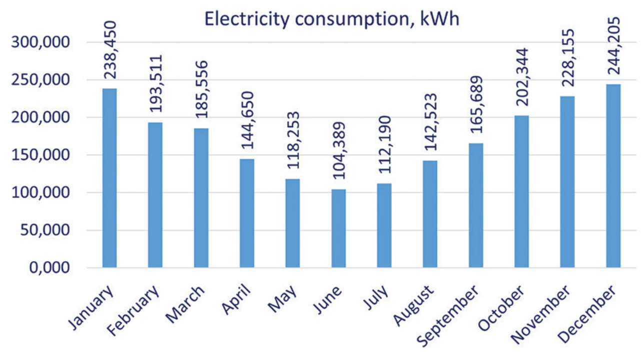


Figure 5. Monthly electricity consumption over 1 year for street and park lighting in the Pavlikeni municipality

calculations to be conducted specifically for these two urban areas within the municipality.

Before conducting lighting design calculations, the urban street network must be classified in accordance with current European standards. The standardization of the proposed street lighting designs in Pavlikeni and Byala Cherkva was carried out in accordance with the European street lighting standard BDS EN 13201:2016.[24] According to this standard, traffic on the streets in both towns primarily involves motorized vehicles, along with pedestrians and slow-moving vehicles, particularly on certain street types.

The lighting classification of the streets is defined as follows:

(i) M4: Regional arterial roads.
(ii) M5: Collector streets.
(iii) M6: Service (local residential) streets.
(iv) P6: Pedestrian streets, streets used by slow-moving vehicles, or short street segments unsuitable for luminance-based classification.

The lighting classification of the street network in Pavlikeni in accordance with BDS EN 13201:2016 is illustrated in Figure 6.

Table 2 presents the standard values for the quantitative and qualitative indicators of street lighting according to BDS EN 13201:2016. For classes M4, M5, and M6, the quantitative photometric parameter is the average road surface luminance (L_{avg}), while the qualitative parameters include overall uniformity (U_o), longitudinal uniformity (U_l), threshold increment (f_{TI}) as an indicator of glare, and the average horizontal illuminance of the surrounding area (R_{EI}).[24]

For streets and areas classified under lighting class P6, the standardized parameters are based on the average maintained illuminance (E_{avg}) and the minimum maintained illuminance (E_{min}), as shown in Table 3.[24]

Figure 6. Lighting classification of the street network in the town of Pavlikeni in accordance with EN 13201

Table 2. Standard lighting performance indicators for lighting classes M4, M5, and M6

Lighting class	Road surface luminance			Threshold increment	Surround ratio
	L_{avg}, cd/m^2	U_o	U_l	f_{TI}, %	R_{EI}
M4	≥0.75	≥0.40	≥0.60	≤15	≥0.30
M5	≥0.50	≥0.35	≥0.40	≤15	≥0.30
M6	≥0.30	≥0.35	≥0.40	≤20	≥0.30

Notes: f_{TI}: Glare index; L_{avg}: Average luminance; R_{EI}: Surround ratio; U_l: Longitudinal uniformity; U_o: Overall Uniformity.

2.2.2. Optimization of street lighting design

The energy efficiency of LED technology in lighting fixtures has steadily improved in recent years, reaching high yet variable performance levels. A wide range of luminaires with differing luminous flux outputs and light distribution characteristics is currently available on the market. In this study, two types of LED luminaires with luminous efficacy exceeding 120 lm/W and distinct light distribution characteristics were proposed, as required by the contract with the municipal street lighting maintenance company, as illustrated in Figures 7 and 8. The technical characteristics of the LED street luminaires, including the range of possible settings for electric power, luminous flux, and luminous efficacy, are presented in Table 4. These characteristics are utilized in the lighting calculations for Pavlikeni and Byala Cherkva.

Table 3. Standard lighting performance indicators for lighting class P6

Lighting class	Horizontal illuminance	
	E_{avg}, lx	E_{min}, lx
P6	≥2.00	≥0.40

Notes: E_{avg}: Average horizontal illuminance; E_{min}: Minimum horizontal illuminance.

According to the technical specifications prepared by the municipality of Pavlikeni, and to minimize investment costs in the modernization of street lighting, it was specified that the new LED lights should be installed only on existing poles. This requirement was supported by the findings of the comprehensive energy audit, which confirmed the satisfactory condition of the electrical supply network utilized for street lighting. The cost of implementing the project would be more than 10 times higher if the

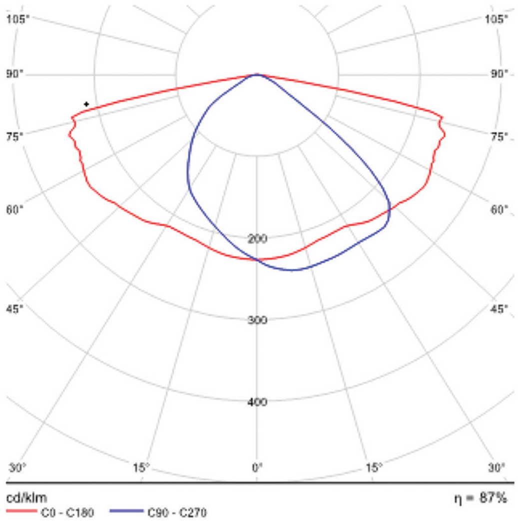


Figure 7. Light distribution of a street light-emitting diode luminaire, type 1

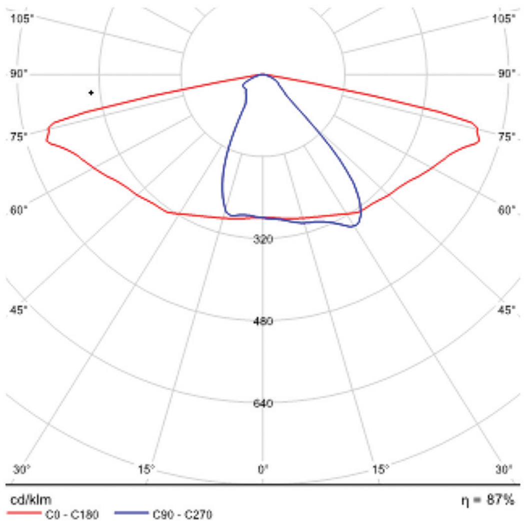


Figure 8. Light distribution of a street light-emitting diode luminaire, type 2

old poles were removed and replaced with new ones, together with a new electrical network. A further rationale for maintaining the existing poles is that a significant proportion of the reinforced concrete poles are owned by the electricity distribution company and are also used to provide electricity to domestic and small business consumers.

For standard optimization tasks involving completely new lighting systems, and in accordance with the two energy performance indicators introduced in EN 13201—power density (D_P [W/m^2]), and annual energy consumption per unit area (D_E [kWh/m^2/year])—the optimal solution from a technical and economic perspective was sought through a combination of the largest pole spacing, the smallest pole height, and the shortest bracket length and lowest slope angle, while ensuring compliance with the requirements of the given lighting class.

For the project in Pavlikeni and Byala Cherkva, where the spacing between poles (luminaire) is fixed, a non-standard optimization problem must be defined to determine the lowest luminaire power, combined with the lowest pole height and smallest bracket tilt angle that together satisfy the requirements of the designated lighting class.

The formulation of the optimization problem, where the pole spacing is fixed and the luminaire power, mounting height, and tilt angle are optimized to meet the requirements of a given M-class according to EN 13201, is as follows:

2.2.2.1. Given (parameters)

The listed parameters represent the key inputs for optimizing road lighting design: Road geometry defines the layout of the street lighting system, the EN 13201 lighting class specifies performance requirements (luminance, uniformity, glare, edge illumination), and the road surface R-table, together with luminaire photometry, provide the data required for accurate lighting calculations.

(i) Road geometry: Pole spacing, carriageway width, number of lanes, curbs, and medians.
(ii) Lighting class under EN 13201: M_k, with the required limits specified in Table 2—L_{req}, $U_{o,req}$, $U_{l,req}$, TI_{max}, and EIR_{req}.
(iii) Road surface type and R-table.
(iv) Luminaire photometry (Illuminating Engineering Society-format light distribution file).

2.2.2.2. Decision variables

The decision variables are calculated based on the following equation (Equation I):

$$x = (P, H, \theta) \tag{I}$$

where:

(i) P denotes the luminaire electrical power (equivalently, luminous flux/dimming level).
(ii) H signifies the mounting height.
(iii) θ represents the luminaire tilt angle.
(iv) Domain constraints are

$$P \in [P_{\min}, P_{\max}], \quad H \in [H_{\min}, H_{\max}], \quad \theta \in [\theta_{\min}, \theta_{\max}]$$

2.2.2.3. Objective function

To minimize installed power (or, equivalently, energy use per unit road length), the following equation is employed (Equation II):

$$\min_x f(x) = P \quad \text{(II)}$$

2.2.2.4. Constraints (EN 13201 class M_k)

Based on the photometric simulation, the design must meet the quantitative and qualitative criteria of street lighting according to EN 13201 for the relevant class Mk, including average luminance, overall and longitudinal uniformity, glare limitation (TI, accounting for veiling luminance Lv), edge illuminance ratio, and the geometric limits of the lighting system layout.

(i) Average road luminance: $L_{ave}(x) \geq L_{\text{req}}$ (III)

(ii) Overall uniformity: $U_o(x) = \dfrac{L_{\min}(x)}{L_{ave}(x)} \geq U_{o,\text{req}}$ (IV)

(iii) Longitudinal uniformity:

$$U_l(x) = \frac{L_{\text{min,along line}}(x)}{L_{\text{max,along line}}(x)} \geq U_{l,\text{req}} \quad \text{(V)}$$

(iv) Glare (threshold increment [*TI*]):

$$TI(x) = 65\,\frac{L_v(x)}{L_{ad}(x)^{0.8}} \leq TI_{\max} \quad \text{(VI)}$$

where L_v is veiling luminance from glare sources and $L_{ad} \approx L_{ave}$ for typical road viewing conditions.

(v) Edge illuminance ratio (if required):

$$EIR(x) = \frac{\bar{E}_{\text{outside edge lane}}(x)}{\bar{E}_{\text{inside edge lane}}(x)} \geq EIR_{\text{req}} \quad \text{(VII)}$$

(vi) Geometric limits:

$$H_{\min} \leq H \leq H_{\max}, \quad \theta_{\min} \leq \theta \leq \theta_{\max}, \quad S = \text{const} \quad \text{(VIII)}$$

2.2.2.5. Solving approach

Such lighting optimization tasks can be solved using specialized software tools, such as DIALux evo (DIAL GmbH, Germany). This software enables the solution of a constrained non-linear optimization problem, because the relationship between the decision variables (e.g., luminaire power, mounting height, tilt) and the objectives/constraints (e.g., L_{ave}, U_o, U_l, *TI*, and *EIR*) is non-linear. This problem can be classified as black-box optimization, as no analytical formulas are available for the objectives/constraints (e.g., L_{ave}, U_o)—they are obtained from the simulation software. In the simulation-based solution, the variables are restricted to discrete steps (e.g., height in 0.2 m increments, tilt in 1° increments), thereby forming a mixed-integer non-linear programming problem.

The constrained search approach includes the following steps:

(i) Use a global optimizer over (*P, H, θ*).
(ii) For each candidate:
(a) Set *P* via luminous flux.
(b) Set *H* and *θ*.
(c) Run the simulation → extract L_{ave}, U_o, U_l, *TI*, and *EIR*.
(d) Select the best feasible point with the lowest *P*.

Practical bounds and starting points used in the DIALux evo simulation are:

(i) *H*: 4–12 m (road dependent), step 0.2 m.
(ii) *θ*: 0–20° (per luminaire specification), step 1–2°.
(iii) *P*: From the minimum dimming level to nominal power (driver-specific steps from Table 4).

The process of modeling and optimization in DIALux evo for street lighting on a given street was carried out in the following sequence:

(i) Fix geometry, R-table, and pole spacing *S*.
(ii) Choose luminaire optics (fixed photometric file).
(iii) Run a coarse grid over (*H,θ*); for each pair, determine the minimum *P* that meets $L_{ave} \geq L_{req}$.
(iv) From the candidate solutions, check uniformities and *TI*; remove non-compliant cases.
(v) Fine-tune around the best points (local search) to obtain (*P, H, θ*) that satisfy all EN 13201 criteria.

In this study, and following the above-described methodology using DIALux evo (Figure 9), a multi-variant lighting modeling and optimization process was conducted for all streets with diverse geometrical characteristics in Pavlikeni and Byala Cherkva, involving the optimization of the power rating, mounting height, and tilt angle of the street LED luminaires.

For park lighting, the project included an LED luminaire with a rated power of 14.4 W, a luminous flux of 1,730 lm, and a luminous efficacy of 120.1 lm/W, with its light distribution shown in Figure 10. This luminaire is intended to replace the existing park fixtures mounted on 4.5-m-high poles in pedestrian zones in Pavlikeni, classified under lighting class P6.

A maintenance factor of *MF* = 0.81 was used in the lighting calculations, reflecting luminous flux depreciation to 90% of the initial value over the luminaire's lifetime (L90F10). If a luminaire with greater luminous flux depreciation is supplied, its electrical power must be proportionally increased. Conversely, for luminaires equipped with drivers that maintain constant luminous output over time (constant light output [CLO]), the required power may be reduced accordingly.

The LED street luminaires were mounted on existing poles made of tubular steel and reinforced concrete. The project included the replacement of existing park luminaires with new street-type LED luminaires on

Table 4. Main technical characteristics of light-emitting diode street luminaires used in optimized lighting calculations

	Dimming level steps of the luminaire electric power								
Electric power (W)	10.8	16.6	20.5	22.0	25.0	28.5	34.5	41.0	50.0
Luminous flux (lm)	1,401	2,167	2,601	3,061	3,503	3,941	4,681	6,130	7,282
Luminous efficacy (lm/W)	129.7	130.6	126.9	139.1	140.1	138.3	135.7	149.5	145.6

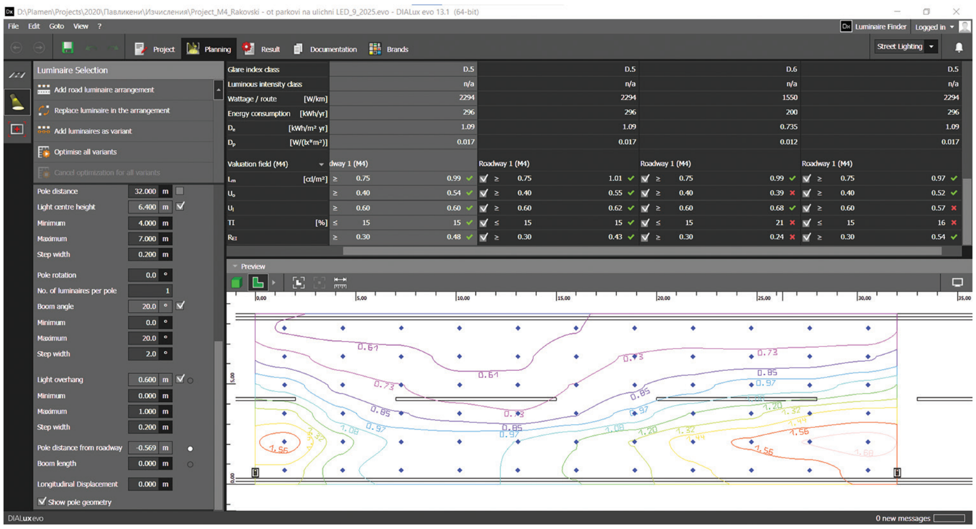


Figure 9. Multi-variant street lighting modeling and optimization in DIALux evo

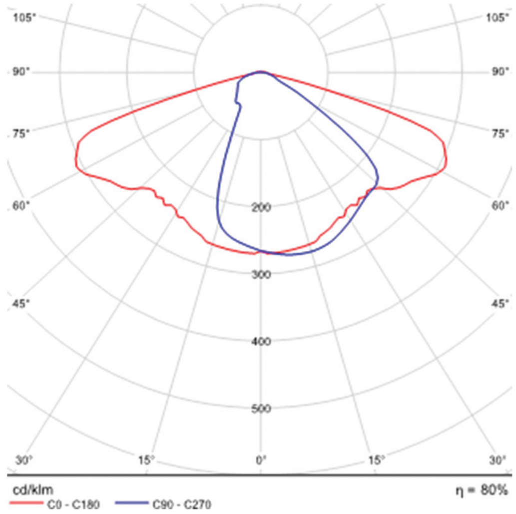


Figure 10. Light distribution of a park light-emitting diode luminaire

traffic streets of lighting classes M4, M5, and M6 in Pavlikeni.

Given that attempts to meet the regulatory requirements of the current European Union standard for traffic roads of lighting classes M4, M5, and M6 using park-type luminaires result in excessive glare beyond acceptable limits, this study proposed a technical solution involving the extension of the existing park poles and the installation of street-type LED luminaires (Figure 11). A maximum mounting height of 6.4 m was proposed when replacing park luminaires with new street LED luminaires on existing poles fitted with two- or three-arm brackets. A maximum mounting height of 5 m is proposed for poles without brackets. The pole extension details have been designed and specified in the Geometric Configuration columns of the tables presenting the results from the simulation calculations (Table 5).

Table 5 presents the achieved lighting performance indicators for a sample street of class M4 in Pavlikeni. The project includes detailed lighting calculations performed by specialized software[25,26]—DIALux evo—for all class M4 and M5 streets in Pavlikeni, M5-class streets in Byala Cherkva, as well as for the remaining M6- and P6-class streets based on generalized geometric configurations. The lighting calculations also incorporate two energy performance indicators introduced in BDS EN 13201—D_P and D_E. Table 5 is shown as an example, presenting the results from simulation calculations for all 32 streets and street groups with various geometric configurations and lighting classes.

Across multi-scenario optimization of lighting calculations using DIALux evo[27-29] for all streets in the two towns, the optimal luminaire types and rated power levels were determined for each individual street

Figure 11. Photographs illustrating the technical solution involving the extension of existing park poles and the installation of street-type light-emitting diode luminaires

segment. By updating the luminaire specifications and their respective power ratings in the graphical model developed during the energy audit, the accurate quantitative and energy performance parameters of the modernized lighting system were established.

A summary of the luminaire types, rated power, and quantities implemented in the modernized street lighting systems is provided in Table 6.

2.3. Implementation of a modern street lighting management and control system

Modern street lighting control systems use wireless[30] communication technologies based on global system for mobile communications (GSM)/general packet radio service (GPRS), Internet of Things,[31] and other smart systems for digital and cloud-based management.[32-34]

The control system was modernized by replacing the old power supply boxes (Figure 12) with new control and monitoring cabinets (CMCs) (Figure 13). These cabinets are equipped with the necessary protective, switching, and metering devices, as well as a GSM/GPRS controller-modem for communication with a centralized monitoring and control station running dedicated application software.

Communication between the CMCs and the centralized monitoring and control center is facilitated through the GSM network of a mobile operator, as illustrated in Figure 14.

The new street lighting control system must provide, at a minimum, the following functionalities:

(i) Remote switching of street lighting on and off from a central control (dispatcher) center.
(ii) Real-time (online) information on electricity consumption.
(iii) Alarm notifications in case of unauthorized connection to the street lighting network or unauthorized access to the lighting cabinet.
(iv) Information on non-functioning street luminaires, indicating the affected circuit branch and the number of defective units.
(v) Backup battery for autonomous emergency operation during prolonged power outages.
(vi) Archived data on the operational status of the street lighting system.

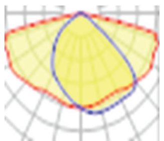
The system should also support the integration of additional functionalities, if needed, either through updates to the existing software modules, the addition of new ones, or by integrating new technical components. This would enable effective energy management for the street lighting system and facilitate planning and optimization of maintenance operations.

The project proposes dimming of the power and luminous flux of the LED luminaires, allowing for energy reduction through pre-programmed or remotely controlled LED drivers. This applies to streets of higher lighting classes, where luminaires can be dimmed to a certain percentage of their nominal power during nighttime periods with reduced traffic intensity. During these hours, the lighting class of the street is considered to temporarily shift to a lower class with less stringent requirements.

In the present project, dimming was implemented via pre-programmed drivers, reducing the luminaires' power output on streets of lighting classes M4 and M5 to 60% of their nominal power during the time period from 11 p.m. to 5 a.m.

The interface of the cloud-based control and monitoring software for the street lighting system in Pavlikeni is presented in Figure 15, and the power dimming process visualization module is shown in Figure 16.

Table 5. Achieved lighting performance indicators for a sample street of class M4 in the town of Pavlikeni

Street: "St. St. Cyril and Methodius" Town: Pavlikeni				**Geometric configuration**	**Standard lighting parameters for class M4 (BDS EN 13201:2016)**					**Energy performance indicators (BDS EN 13201:2016)**	
Lighting class: M4											
LED street luminaire parameters used in the lighting calculations					$L_m \geq 0.75$ cd/m^2	$U_o \geq 0.40$	$U_l \geq 0.60$	$f_{TI} \leq 15\%$	$R_{EI} \geq 0.30$		
Electric power (P), W	Luminous flux (Φ), lm	Efficacy (κ), lm/W	Light distribution type		Achieved lighting performance indicators (with maintenance factor=0.81)						
					Average luminance (L_{ave}), cd/m^2	Overall uniformity (U_o)	Longitudinal uniformity (U_l)	Threshold increment (glare index; f_{TI}), %	Surround ratio (R_{EI})	D_P, W/(lx.m^2)	D_E, kWh/m^2.г
50	7,282	145.6	 Type 1	• Roadway width: 8 m • Number of traffic lanes: 2 • Reflective road surface type: R3 • Pole spacing: 30 m • Luminaire arrangement: one-sided • Mounting height: 6.2 m • Tilt angle: 15° • Overhang: 0.5 m • Section length: 1,020 m	0.83	0.51	0.60	15	0.57	0.016	0.833

Abbreviation: LED: Light-emitting diode.

Table 6. Type, rated power, and number of luminaires in the modernized street lighting systems

Town	Flood-lights	Road type luminaires										Park type luminaires		Total number of street and park luminaires	Total installed electrical power, W
	LED power, W	LED power, W									Total number	CFL	LED		
	120	10.8	16.6	20.5	22	25	28.5	34.5	41	50		23	14.4		
Pavlikeni	16	78	807	113	36	61	77	59	50	28	1,325	-	52	1,377	29,221
Byala Cherkva	-	-	369	-	-	-	85	-	-	-	454	43	-	497	9,537
Total	16	78	1,176	113	36	61	162	59	50	28	1,779	43	52	1,874	38,758

Abbreviation: LED: Light-emitting diode.

Figure 12. Existing power supply box for street lighting with outdated protective and switching equipment

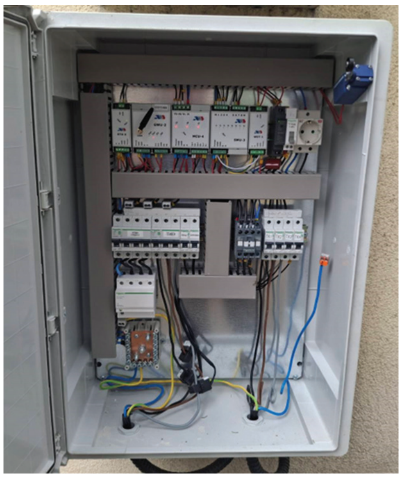


Figure 13. Modern control cabinet for street lighting with integrated global system for mobile communications/general packet radio service communication and monitoring

3. Evaluation of energy efficiency, financial savings, and environmental benefits of the proposed modernization

The calculations were prepared in connection with the main objective of the current investment working project—an application submitted by Pavlikeni municipality under the program "Renewable Energy, Energy Efficiency, Energy Security" of the European Economic Area Financial Mechanism 2014–2021, Procedure No. BGENERGY-2.001, titled "Rehabilitation and Modernization of Municipal Infrastructure—Systems for Outdoor Artificial Lighting in Municipalities." The calculated energy and economic indicators were comparable to those used in energy efficiency projects by leading researchers.[35-37]

In Bulgaria, the mandatory state regulation Ordinance No. E-RD-04-3 of May 4, 2016, titled "On eligible measures for the implementation of energy savings in final consumption, methods for demonstrating the energy savings achieved, requirements for assessment methodologies, and means of confirmation,"[23] is in force, according to which specialized methodologies, approved by the Bulgarian Sustainable Energy Development Agency, must be employed.

3.1. Energy and carbon dioxide savings calculations

The methodology for energy and CO_2 savings calculations, according to the national regulatory document[38], includes the sequential calculation of final energy savings at an end-user site (*FEStot*) (Equation IX), primary energy savings at an end-user site (*PEStot*) (Equation X), and CO_2 emission reductions (Equation XI).

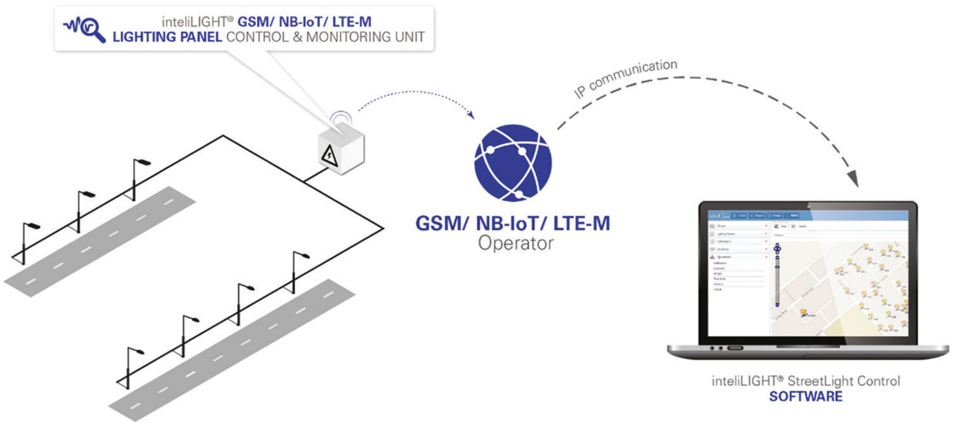


Figure 14. System architecture of centralized street lighting control via global system for mobile communications (GSM)/general packet radio service communication

Abbreviations: IoT: Internet of Things; LTE-M: Long-term evolution machine type communication.

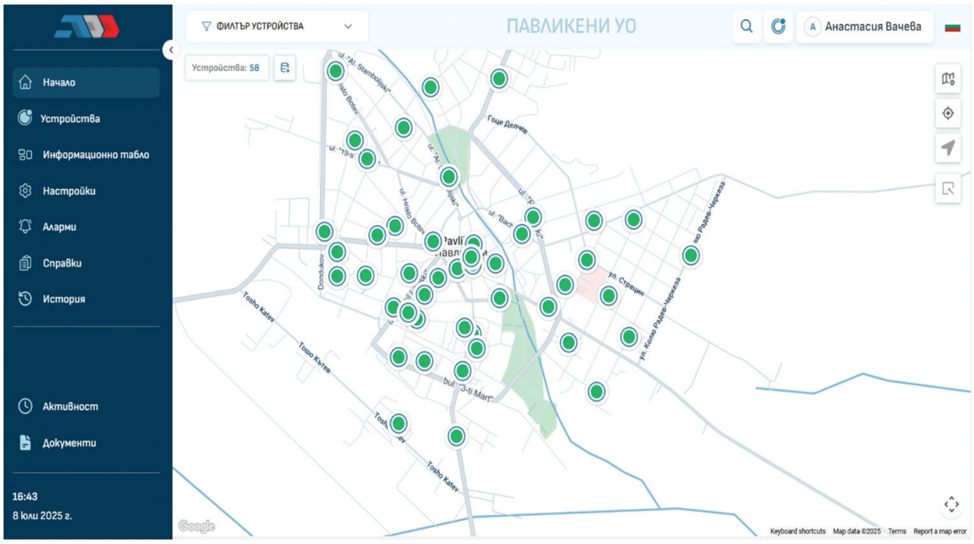


Figure 15. Interface of the cloud-based street lighting control and monitoring system in Pavlikeni

3.1.1. Energy savings at an end-user site

$$FEStot = \frac{(N_{ref,old}P_{old}\ k_{pra,old} - N_{ref,new}P_{new}k_{pra,new})T_{year}}{1000}, [MWh / year] \quad (IX)$$

where:

(i) *FEStot*: Energy savings at an end-user site (MWh/year).

(ii) N_{ref_old}, N_{ref_new}: Number of replaced luminaires in the existing installation and number of new luminaires replacing them, which meet the current normative lighting requirements.

(iii) P_{old}, P_{new}: Nominal power (kW) of the replaced luminaire and of the new luminaire, respectively, both satisfying the updated normative lighting requirements. The power of the new luminaire should reflect the actual operational values of its maintenance (operational) elements.

(iv) $k_{pra,\ old}$, $k_{pra,\ new}$: Coefficients accounting for losses in the control gear of the existing and replacement luminaires, respectively, including potential losses from CLO-type control devices.

(v) T_{year}: Annual operating time (utilization) of the lighting system (hours/year).

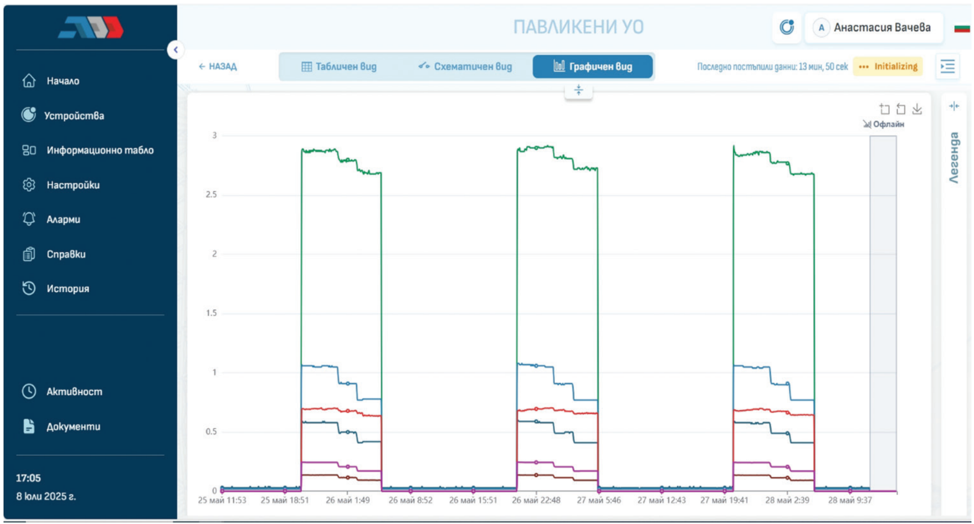


Figure 16. Visualization module for the luminaire power dimming process

3.1.2. Primary energy savings at an end-user site

$$PEStot = FEStot\ e_p, [MWh / year] \quad (X)$$

where:

(i) *PEStot*: Primary energy savings at an end-user site (MWh/year).
(ii) *FEStot*: Total final energy savings (MWh/year).
(iii) e_p: Primary energy factor from Table 7.

3.1.3. Carbon dioxide emission reductions

$$CO_2 = \frac{FEStot\ f_i}{1000}, [t\ CO_2 / year] \quad (XI)$$

where:

(i) CO_2: CO_2 emission reduction (t CO_2/year).
(ii) *FEStot*: Total final energy savings (kWh/year).
(iii) f_i: Ecological equivalent coefficient of energy (fuel) (g CO_2/kWh) from Table 7.

4. Energy, economic, and environmental impact assessment of the street lighting modernization project

Based on the energy efficiency measures and technical solutions proposed in the project—including the implementation of new LED lighting, optimized control and operational modes of the street lighting system, and the bill of quantities and costs—as well as the findings of the *Energy Efficiency Audit Report* for the outdoor artificial lighting systems in Pavlikeni and Byala Cherkva, calculations were performed to determine the achieved energy and economic performance indicators of the project. These indicators are summarized in Table 8. The approach is consistent with similar large-scale modernization initiatives aimed at reducing energy consumption and improving lighting infrastructure.[39-41]

Table 7. Reference values of the conversion factor, considering losses from extraction, production, and transmission of energy (including fuels), and reference values of the coefficient of ecological equivalent of energy

Type of energy resource/energy	Conversion factor from FES to PES, considering energy losses	Ecological equivalent coefficient
	e_p	f_i, gCO_2/kWh
Industrial gas oil, diesel	1.10	267
Fuel oil	1.10	279
Natural gas	1.10	202
Propane-butane	1.10	227
Black coal	1.20	341
Lignite/brown coal	1.20	364
Anthracite coal	1.20	354
Coal briquettes	1.25	351
Firewood, pellets	1.05	43
Heat from district heating	1.30	290
Electrical energy	3.00	819

Abbreviations: FES: Final energy saving; PES: Primary energy saving.

For the "Renewable Energy, Energy Efficiency, Energy Security" Program, Table 9 presents the

Table 8. Results of energy and economic calculations for the current investment project

Parameter	Unit	Town		Total
		Pavlikeni	Byala Cherkva	
Energy consumption before the project	kWh/year	C532,355	158,138	690,493
Energy consumption after the project	kWh/year	105,385	36,025	141,411
Investment (new luminaires)	BGN	354,452	113,257	467,709
Investment (control system, cabinets)	BGN	76,500	16,500	93,000
Investment (PV-powered luminaires)	BGN	7,200	-	7,200
Installation works	BGN	64,249	14,581	78,830
Total investment (+5% unforeseen costs)	BGN	528,282	151,733	680,015
Energy savings	kWh/year	426,970	122,113	549,082
Energy savings percentage	%	80.2	77.2	79.5
Average electricity price	BGN/kWh	0.1991	0.1991	0.1991
Cost savings	BGN/year	85,027	24,318	109,344
Payback period	years	6.21	6.24	6.22
CO_2 emissions saved	tCO_2/year	1,049	300	1,349
Investment efficiency	BGN/tCO_2	503.57	505.72	504.05

Abbreviations: CO_2: Carbon dioxide; PV: Photovoltaic.

Table 9. "Renewable Energy, Energy Efficiency, Energy Security" program indicators

Indicator	Unit	Pavlikeni	Byala Cherkva	Total
Estimated annual CO_2 reduction	tCO_2/year	1,049	300	1,349
Estimated annual energy savings	MWh/year	427	122	549
Estimated annual cost savings	EUR/year	43,474	12,433	55,907
People benefiting (men)	persons	4,569	820	5,389
People benefiting (women)	persons	4,893	849	5,742
Total beneficiaries	persons	9,462	1,669	11,131

Abbreviations: CO_2: Carbon dioxide; EUR: Euro.

indicators illustrating the contribution of the project to improved energy efficiency in buildings, industry, and municipalities.

The analysis of the results presented in Table 9 demonstrates that, through detailed project design and optimization of the energy-saving measures proposed in the *Energy Efficiency Audit Report*, the project implemented technical solutions that significantly improve the values of the technical, economic, and program-specific indicators defined by the "Renewable Energy, Energy Efficiency, Energy Security" program under the European Economic Area Financial Mechanism 2014–2021, Procedure No. BGENERGY-2.001, titled "Rehabilitation and Modernization of Municipal Infrastructure—Systems for Outdoor Artificial Lighting in Municipalities."

5. Conclusion

The LED retrofit project implemented in the municipalities of Pavlikeni and Byala Cherkva highlights the transformative potential of high-efficiency lighting technologies combined with intelligent control and management systems. Achieving over 79% energy savings, substantial CO_2 emission reductions, and a favorable economic payback period, the initiative exemplifies a holistic approach to sustainable public infrastructure. This study offers a replicable blueprint for municipalities across Central and Eastern Europe and holds relevance for urban planners and energy efficiency stakeholders worldwide seeking scalable solutions that align with contemporary environmental standards.

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Conflict of interest

The authors declare they have no competing interests.

Author contributions

Conceptualization: Plamen Tsankov
Formal analysis: Plamen Tsankov, Milko Yovchev
Investigation: All authors
Methodology: Plamen Tsankov
Writing – original draft: All authors
Writing – review & editing: Plamen Tsankov

Availability of data

Data are available from the corresponding author upon reasonable request.

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