Analysis of the operation of solar-powered street lighting luminaires

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Abstract. Street lighting is a key element ensuring the safety of motorists and pedestrians. The development of LED light sources and their high luminous efficiency have meant that currently available LED luminaires, in addition to traditional power from the power grid, can be autonomously powered by solar energy, wind energy, or a combination of both. This article presents the results of simulation studies related to a one-year analysis of the operation of solar-powered street lighting luminaires. In the first stage of the study, the luminaires were selected with the power requirements of the EN 13201:2015 standard for the assumed lighting class. Next, simulation studies were conducted for an actual set consisting of a street lighting luminaire, photovoltaic panels, batteries, and a charge controller, related to the operating conditions of the LED luminaire. Individual months of the year in Poland were analyzed to assess the self-sufficiency of the energy generated to power the LED road luminaire, particularly during winter.

1 Introduction

Semiconductor light sources have revolutionized lighting technology in recent years, becoming the primary technology used in both indoor and outdoor lighting. These sources offer numerous advantages, including high luminous efficacy, which currently exceeds 200 lm/W, long lifespan, a wide range of color temperatures, and the ability to smoothly adjust the luminous flux, which is used in advanced lighting control systems. These features have led LEDs to rapidly replace previously used discharge light sources [1-7].

LED luminaires have also become the dominant technology in road lighting, replacing previously used luminaires, primarily those with sodium light sources. High energy efficiency, enabling significant reductions in energy costs, combined with available lighting control systems that further reduce energy consumption, means LED luminaires are being used on expressways, urban and local roads, and pedestrian crossings [8-13].

The vast majority of currently used solutions are LED luminaires powered by low-voltage power grids. An alternative to standard grid-powered luminaires are LED luminaires powered by solar energy, wind energy, or a combination of both. This solution is particularly useful in locations where power is unavailable from the grid or access to the grid is significantly limited. Solar-powered LED luminaires are also popular for lighting pedestrian crossings, recreational areas, and park paths [14-15]. It is worth noting that the above solution fits perfectly into the current trends related to limiting the use of fossil fuels and switching to alternative energy sources enabling the reduction of CO_2 emissions, which is particularly important in the context of new challenges and the energy policy implemented, among others, by the European Union member states[16-17].

In addition to the technological advances made in recent years in semiconductor light sources, the field of renewable energy sources, including solar-powered photovoltaic panel technology, is also experiencing dynamic growth. The gradual increase in power output per unit area, as well as increasingly higher efficiencies averaging over twenty percent, make photovoltaic panels a promising alternative energy source to high-efficiency semiconductor light sources [18-19]. At the same time, we are seeing significant progress in energy storage technology, including in electric car batteries. More and more advanced technologies are becoming available that enable us to increase maximum battery capacity, increase the total number of charge and discharge cycles, and extend the overall battery life [20-21]. Efficient energy storage and the ability to use it during the evening and night hours are crucial for the operation of solar-powered LED luminaires. Correct and efficient operation, as well as the self-sufficiency of the generated solar energy, will depend on several factors. The first is the power of the LED luminaire used, which depends on the roadway's lighting class. Another factor is the appropriate selection of the photovoltaic panel's power, the capacity of the battery used, and the controller that will manage its charging and discharging process. Location and atmospheric conditions, along with solar radiation throughout the

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year, are important considerations. LED road luminaires are characterized by the longest operating time during the autumn and winter seasons, when the sun's exposure above the horizon is shortest, while the luminaire operates the shortest in the summer, when the amount of solar energy obtained is greatest. The minimum and maximum ambient temperature are also important, significantly affecting, among other factors, the efficiency of the energy storage system. The factors mentioned above are important aspects of the correct operation of solar-powered LED road luminaires, which must be taken into account already at the stage of designing the lighting system.

This article presents the results of simulation studies of a solar-powered LED road lighting luminaire. The tests were conducted for two luminaire power ratings, meeting the requirements for lighting classes M6 and M4, as defined by the EN 13201:2015 standard [22]. The tests were based on actual parameters of photovoltaic panels and batteries used in commercial solutions available on the market. The tests were conducted for Polish conditions, analyzing the annual operating time of a solar-powered LED luminaire, with particular emphasis on the autumn and winter periods, which are characterized by the most critical operating conditions.

2 Autonomous LED luminaire powered by solar energy

Figure 1 shows the main components of an autonomous solar-powered road lighting system. These include: an LED road luminaire, a photovoltaic panel, a battery and a charge controller.

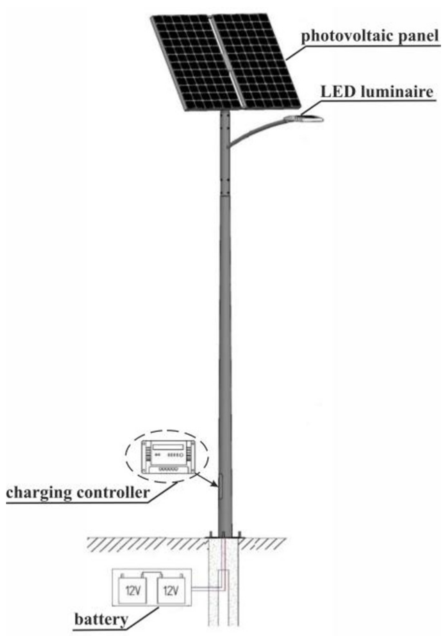


Fig. 1. Example structure of an autonomous road lighting system.

LED luminaires are powered by a battery, and the switching process is controlled by a charge controller, typically located in the lighting pole. Luminaires should feature the highest possible luminous efficacy of the semiconductor sources used to reduce the luminaire's final power consumption. The power of solar-powered LED luminaires typically ranges from a few to several dozen watts. Selecting the appropriate lens system is also crucial, ensuring the optimal light spot shape for the intended lighting conditions.

The next element is the energy source in the form of a photovoltaic panel. This panel is usually mounted on the top of a lighting pole and its orientation and tilt angle are adjusted to the most favorable solar radiation conditions for a given location. In most cases, monocrystalline panels with an efficiency above 20% are used, and their power typically ranges from 100 to 450 W [23-24].

Electricity generated by converting solar energy in a photovoltaic panel is stored in a battery. This component plays a key role in an autonomous lighting system, and its proper selection will determine the proper operation of the entire system. Currently, several solutions are available related to the design and material technology of batteries, influencing key parameters such as capacity, number of operating cycles, and charging and discharging temperature range.

The battery capacity will depend on, among other things, its construction, electrolyte temperature and load current and can be determined by the formula [25-26]:

$$C\,(I, T_e) = \frac{K_C C_0 (1+\frac{T_e}{-T_f})^{\varepsilon}}{1+(K_C-1)(\frac{I}{I_n})^{\delta}} \qquad (1)$$

where: K_C, ε, δ - constants determined based on battery design data, C_0 - battery capacity [Ah], T_e – electrolyte temperature [C°], T_f - electrolyte freezing point [C°], I - battery load current [A], I_n – rated battery current [A].

An important parameter is charging efficiency, which depends on the charging current, which is crucial in the context of the low currents drawn from photovoltaic panels. Efficiency is determined according to the formula below [25-26]:

$$\eta_{charge} = 1 - \exp\left[\frac{20{,}73}{\frac{I_{bat}}{I_{10}}+0{,}55}(SOC-1)\right] \qquad (2)$$

where: SOC – charge status [-], I_{bat} – battery charging current [A], I_{10} – rated battery current given by the manufacturer [A].

Among the latest battery technologies available, such as lithium iron phosphate (LFP) and nickel manganese cobalt (NMC) batteries, lead-acid gel batteries (AGM) are often used in automotive lighting systems. This solution is less expensive than LPF or NMC technologies, and the special VRLA technology used in these batteries improves their performance parameters, including a minimum charging temperature range of up to -10°C. Despite increased resistance to deep discharge (up to 80%), to extend battery life, discharge should be limited to 50% of its rated capacity.

The charging controller is the element that oversees battery operation. Its task is to monitor and protect the battery against excessive discharge and voltage drops in its cells, as well as to protect against excessive voltage increases, which can result in battery gassing.

3 Description of the simulation model

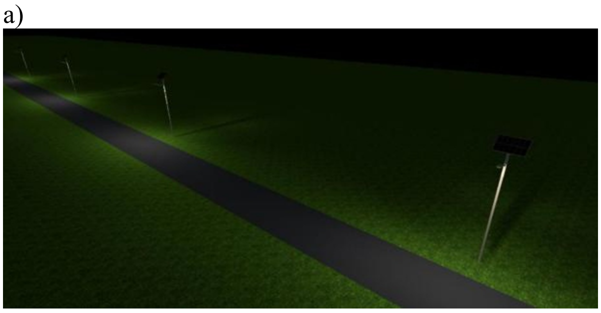
Modelling the operation of a solar-powered luminaire can be divided into two stages: the first involves selecting the luminaire power to meet the required lighting parameters. The second stage involves modelling the energy obtained from photovoltaic panels and stored in a battery, which serves as the power source for the street lighting luminaires.

3.1 Modelling road lighting conditions

Two types of roadways were used for the tests: the first was 5 m wide and had lighting class M6, the second was 7 m wide and had lighting class M4. The luminaire power and light distribution were selected to meet the requirements of EN 13 201:2015 regarding the average luminance value (L_m), overall uniformity (U_0) and longitudinal uniformity (U_l), glare index (TI) and roadside illumination index (R_{EI}). The luminaires were mounted at a height of 8 m, 40 m apart, and the distance from the edge of the road was 1 m. The mentioned geometry of the lighting luminaire installation made it possible to meet the requirements of the PN-EN 13:201 standard, and the adopted value of the distance between the luminaires, as well as the assumed height of the poles, is typical for street lighting using LED luminaires with lens systems. Simulation calculations were performed using Dialux Evo 13.2 software [27].

An example road rendering for the M6 lighting class and the luminance value in the measurement area are shown in Figure 2.

a)



b)

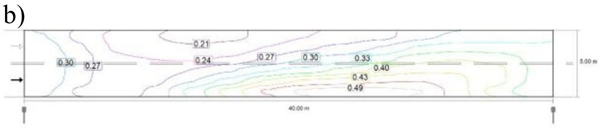


Fig. 2. Roadway 5 m wide and class M6: a) visualization of the illuminated roadway, b) luminance distribution in the measurement area. structure of an autonomous road lighting system.

The required and obtained parameter values for the adopted road lighting classes are listed in Table 1.

A 30 W luminaire was used to illuminate a 5 m wide roadway with lighting class M6, while a 70 W luminaire was used for a 7 m wide roadway with lighting class M4.

Table 1. List of required and achieved parameter values

Parameter	Road 5 m (class M6)		Road 7 m (class M4)	
	Require d values	***Values obtained***	***Required values***	***Values obtained***
L_m [cd/m^2]	≥ 0.30	0.32	≥ 0.75	0.76
U_0 [-]	≥ 0.35	0.59	≥ 0.40	0.55
U_l [-]	≥ 0.40	0.54	≥ 0.60	0.62
TI [%]	≤ 20	12	≤ 15	14
R_{EI} [-]	≥ 0.30	0.64	≥ 0.30	0.59

3.2 Modelling the operation of a solar-powered lighting luminaire

Figure 3 presents a simulation model for a year-long analysis of the operation of a solar-powered luminaire. Insel software, which enables the design of renewable energy sources based on block diagrams, was used for the simulation studies [28].

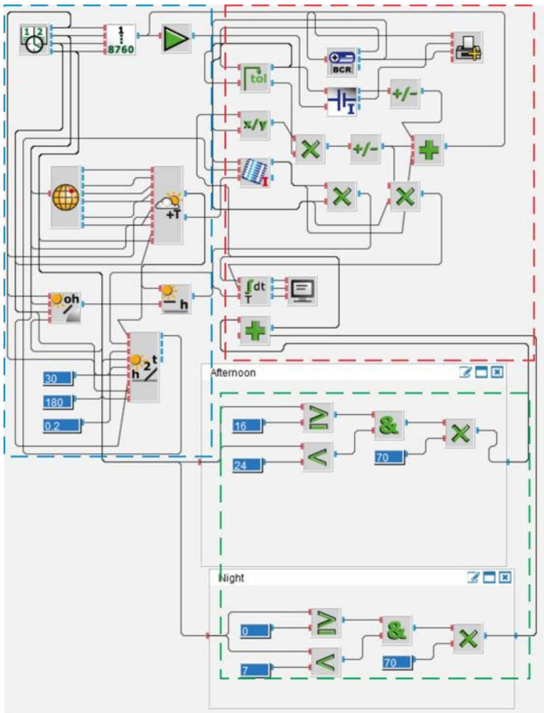


Fig. 3. Simulation model of an autonomous lighting system.

The presented simulation model can be divided into three distinct sections. The first, marked with a dashed blue line, contains blocks responsible for simulating incoming solar energy. For a given location and defined receiver position, the incident solar radiation intensity is determined. Simulation studies determined the annual solar radiation intensity for Polish conditions, specifically for Warsaw.

The second part of the model, marked with a dashed red line, contains models simulating the operation of the photovoltaic panel, battery, and charge controller. A monocrystalline photovoltaic panel with a nominal power of 450 W and an efficiency of 22% was used for simulation tests for both luminaire power variants. This panel power is currently one of the highest available powers used by manufacturers in solar-powered lighting solutions. A lead-acid AGM gel battery was modeled for energy storage. A 24 V battery with a capacity of 100 Ah was selected for the system with a 30 W luminaire, while a 24 V battery with a capacity of 200 Ah was selected for the system with a 70 W luminaire. These parameter values correspond to the parameters of batteries available in commercial solutions [23-24]. In the simulation model, the voltage at the battery terminals V during discharge is determined based on the Shepherd equation [29]:

$$V = V_{0d} - g_d \mathrm{H} + \rho_d \frac{I}{Q_n} \left(1 + M_d \frac{H}{C_d - H}\right) \quad (3)$$

where: V_{0d} – open circuit voltage [V], g_d – electrolyte coefficient [V], ρ_d – internal resistance parameter [ΩAh], M_d – battery type factor [-], C_d – capacity factor [-], H – normalized depth of discharge ($1 - Q/Q_n$, where: Q – current battery capacity and Q_n is the rated capacity).

Similarly, the voltage value V for the charging state is determined, taking into account the above-mentioned factors for the charging state. The charging and discharging process of the battery is managed by the charge controller. The simulation model defines voltage values that protect the battery against excessive discharge and gassing, which can occur when the voltage at its terminals is too high. A voltage of 24.2 V was defined as the value below which the battery load is disconnected; at a voltage of 25.6 V, the load is reconnected. For gassing protection, a voltage of 28.8 V was defined above which the battery is disconnected from the power source.

The third part of the model, marked with a dashed green line, shows simulation blocks corresponding to 30 and 70 W road lighting fixtures, which constitute the system load. Analysis was performed for two variants of luminaire operation according to the schedule shown in Figure 4.

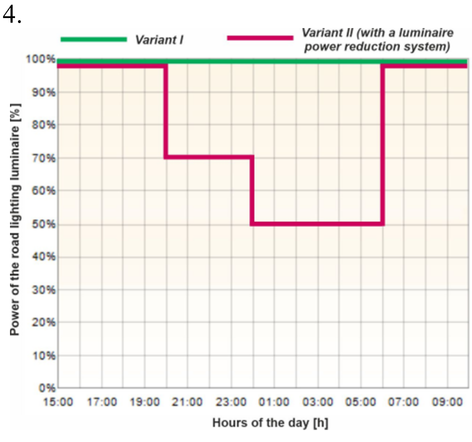


Fig. 4. Road lighting luminaires operation schedule for two variants

In variant I, the luminaire operates at its full rated power from dusk to dawn. In the case of variant II, a power and luminous flux reduction system was used. In this option, the luminaire operates at its full rated power from dusk until 8:00 PM and from 6:00 AM until dawn. During low-traffic hours, from 8:00 PM to midnight, the luminaire operates at 70% of its rated power, and from midnight to 6:00 AM, it operates at 50% of its rated power.

4 Simulation test results

The annual power generated by the photovoltaic panel, the battery capacity and the annual load profile for a 70 W luminaire (variant I) are shown in Figure 5.

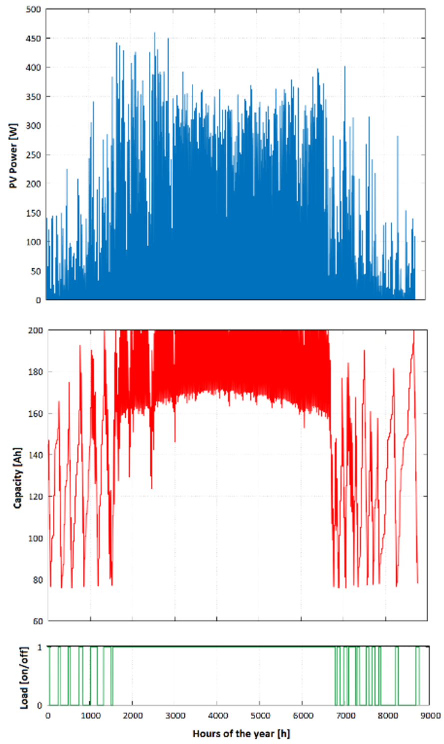


Fig. 5. Power generated by the photovoltaic panel, battery capacity and operating status of the lighting luminaire as a function of hours of the year (70W lighting luminaire, variant I).

Based on the graphs, it can be seen that the luminaire operates as designed during the spring and summer months, where it is not additionally disconnected to protect the battery from excessive discharge. During this period, the battery capacity averages between 100 and 80% of its rated capacity. In the autumn and winter months, the energy generated from the photovoltaic panel is too low to ensure proper system operation. During this period, characterized by the longest operating time of the street lighting luminaires, the greatest energy shortage occurs, resulting in the luminaires being disconnected during operation to protect the battery from excessive discharge. The battery is discharged to approximately 80 Ah (40% of the rated value), after which the luminaire is disconnected, which is relatively often idle during this period (value 0 on the load graph – green).

A detailed graph for the most critical month – December – is presented in Figure 6, additionally taking into account the voltage at the battery terminals. The graph shows that in December, the power generated by the photovoltaic panel only reaches an average of 150 W at peak power. While the luminaire is operating, it draws energy from the battery, simultaneously reducing the voltage at its terminals. At 24.2 V, the charge controller disconnects the luminaire from the battery to protect it from excessive discharge. The luminaire is reconnected when the battery voltage reaches the load reconnection value set by the charge controller (25.6 V). The power generated by the photovoltaic panel in December is so low that the time to reach this voltage is long, and the period when the luminaire is inactive can last up to several days (load state 0 – green). In this month, the number of days when the luminaire is inactive exceeds the number of days when it is operating properly.

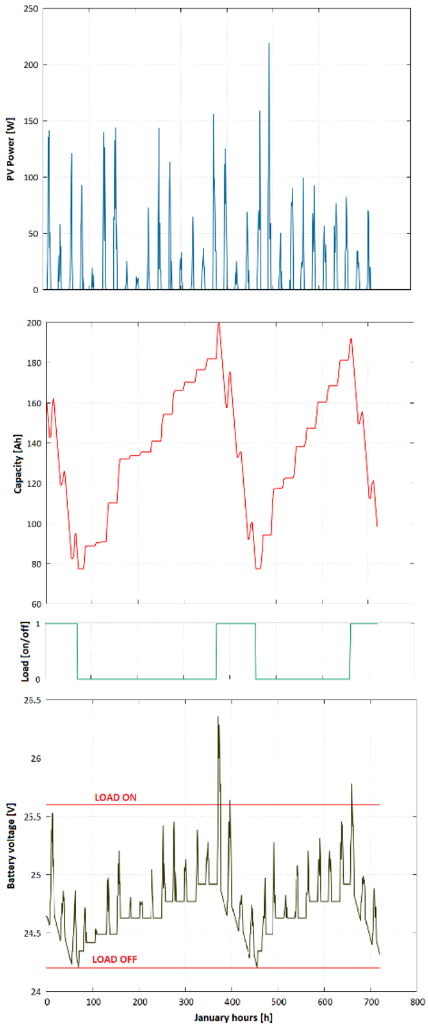
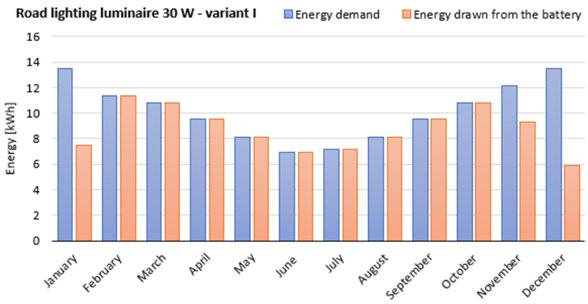


Fig. 6. Power generated by the photovoltaic panel, battery capacity, operating status of the lighting luminaire and battery voltage as a function of December hours (70W lighting luminaire, variant I).

Figures 7 and 8 show the monthly energy demand and the energy drawn from the battery for 30 W and 70 W lighting luminaires for both operating variants.

In the case of a 30W road luminaire operating at full rated power throughout the entire period (variant I), the luminaire operates correctly from February to October. Energy shortages and shutdowns occur from November to January, with the greatest energy shortage occurring in December, when less than 6 kWh of energy was drawn from the battery, while the demand was nearly 14 kWh. For variant II, in which the luminaire operated with a power and luminous flux reduction system, there were also periods when the luminaire did not work properly, but this deficiency was smaller compared to variant I. In November, there were no luminaire shutdowns, and the greatest energy deficiency occurred in December and amounted to approximately 44%.

a)



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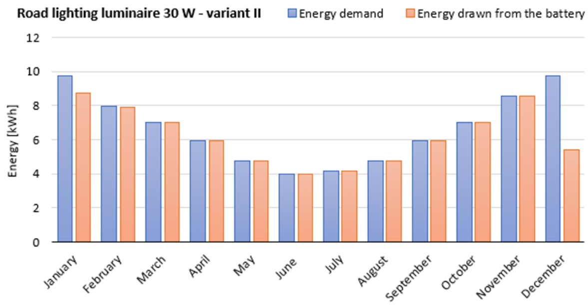
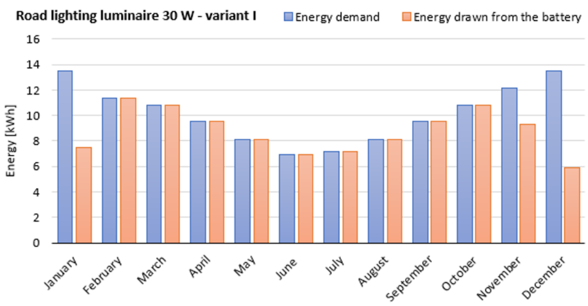


Fig. 7. Energy demand and energy drawn from the battery for a 30W luminaire: a) variant I, b) variant II.

a)



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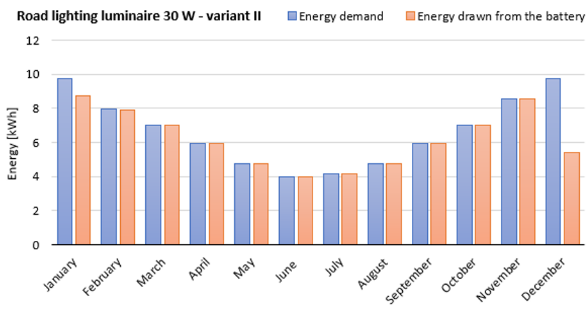

Fig. 8. Energy demand and energy drawn from the battery for a 70W luminaire: a) variant I, b) variant II.

In the case of a 70W luminaire, the period of time during which the luminaire is not operating properly is significantly longer compared to a 30W luminaire. For this luminaire, the period of shutdown is from October to February and is similar for both luminaire operating modes. The greatest energy shortage occurs in the winter months, where the shortage in December is over 80% for variant I (4.2 kWh consumed with a demand of 31.5 kWh) and over 70% for variant II (5.2 kWh consumed with a demand of 22.7 kWh).

Table 2 summarizes the main information regarding the annual operation of the autonomous lighting system for the luminaire power of 30 and 70 W and two operating variants.

Table 2. List of required and achieved parameter values

Parameter	LED luminaire 30 W		LED luminaire 70 W	
	Var. I	*Var. II*	*Var.I*	*Var. II*
Annual energy demand [kWh]	121,6	79,5	283,6	185,4
Annual energy drawn from the battery [kWh]	105,1	74,1	198,7	138,9
Share of consumed energy in annual demand [%]	86,4	93,3	70,1	74,9
Number of days per year when the luminaire does not work properly	36	16	85	61

5 Conclusions

This article presents the results of simulation studies analyzing the operation of an autonomous solar-powered road lighting system. Based on the results, it can be concluded that in Polish conditions, ensuring proper system operation throughout the year is challenging. The greatest challenge is the winter period, particularly January and December, when the luminaire operates for the longest period and the lowest energy output from photovoltaic panels. This period experiences the greatest energy shortage, and the period during which the luminaire is inactive can last up to several consecutive days.

Estimating the available energy from photovoltaic panels for a given location is a key element in designing a solar-powered lighting system. Another important factor is the selection of appropriate energy storage technology and a controller to ensure proper operation and protect against excessive battery discharge. A significant factor influencing the operation of a street lighting system is the power of the luminaires used, which, as it increases, increases the number of days of incorrect operation, especially in winter. The power of a luminaire depends on the lighting class used and the requirement to meet lighting parameters. However, research results show that the use of a luminous flux reduction system can reduce the number of days per year when a luminaire does not operate properly.

Street lighting luminaires powered by PV panels are economically viable in specific locations, such as those with challenging ground conditions or those lacking infrastructure. It's worth noting the significant implementation costs of this type of system compared to a street lighting system powered from a traditional grid. It's estimated that the cost of a new renewable energy installation is 200-300% higher than a traditional installation, primarily due to the high cost of the battery and PV panels. This makes off-grid installations currently unprofitable in locations where connection to the existing power grid is possible.

The dynamic development of LED lighting technology, photovoltaic panel technology and energy storage technology makes lighting systems based on renewable energy sources an interesting alternative to traditional systems powered by low-voltage lines in selected situations. Energy shortages in solar-powered systems can be minimized by using an additional energy source, such as wind energy. Other locations and climatic conditions, characterized by greater sunlight and less winter exposure, may also affect the proper operation of autonomous road lighting systems throughout the year. These factors will be considered in planned further research related to the analysis of the operation of autonomous lighting systems.

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