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ENERGY AND ECONOMIC EFFICIENCY ASSESSMENT OF STREET LIGHTING IN A RURAL COMMUNE

Summary

An energy and economic efficiency audit of lighting systems in three options, i.e. high pressure sodium discharge lamps, lamps with LED type luminaires powered from the grid and a lighting system with an autonomous power supply i.e. a hybrid lamp (with a LED type luminaire) powered by electricity generated by photovoltaic panels and a wind turbine was performed for a sample rural commune for which a development of street lighting is scheduled. The audit included selecting the number of luminaires and their power, calculating the energy saving, as well as an economic feasibility analysis of the undertaken actions in accordance with the guidelines set forth in the Resolution by the Minister of the Economy on Energy Efficiency. Two options for financing the investment were considered: the commune's own funds or the commune uses grants from the Rural Area Development Programme. The economic analysis showed that a commune looking to build street lighting using solely its own funds should opt for high pressure sodium discharge lamps. Lighting with LED type luminaires, despite using half as much energy as sodium discharge lamps, once the cost of replacing luminaires is taken into account will generate the highest service costs, and as such its operating cost will be higher. The street lighting system with LED type luminaires is economically justified only if a commune receives grants from external sources for the purchase of energy saving light systems. Building lighting systems with an autonomous power supply is economically unjustified as the cost associated with replacing batteries is three times higher than the cost of purchasing energy for high pressure sodium discharge lamps.
***Key words**: energy efficiency audit, street lighting, high pressure sodium discharge luminaires, LED type luminaires, autonomous lighting*

OCENA EFEKTYWNOŚCI ENERGETYCZNEJ I EKONOMICZNEJ OŚWIETLENIA DROGOWEGO W GMINIE WIEJSKIEJ

Streszczenie

Dla przykładowej gminy wiejskiej, w której planowana jest rozbudowa oświetlenia drogowego wykonano audyt efektywności energetycznej i ekonomicznej systemów oświetlenia dla trzech wariantów, tj. lampy sodowe wysokoprężne, lampy z oprawami typu LED zasilanymi z sieci energetycznej oraz system oświetleniowy z autonomicznym zasilaniem, tj. lampa hybrydowa (z oprawą typu LED) zasilana energią generowaną w panelach fotowoltaicznych oraz turbinie wiatrowej. Audyt obejmował dobór liczby i mocy opraw, obliczenie ilości zaoszczędzonej energii, jak również analizę opłacalności ekonomicznej podjętych działań zgodnie z wytycznymi zawartymi w rozporządzeniu ministra gospodarki o efektywności energetycznej. Rozważano dwie opcje finansowania inwestycji takie jak: środki własne gminy lub gmina korzysta z dofinansowania inwestycji z Programu Rozwoju Obszarów Wiejskich. Na podstawie wykonanej analizy ekonomicznej ustalono, że: gmina, która będzie chciała wybudować oświetlenie drogowe bazując wyłącznie na środkach własnych powinna wybrać lampy wysokoprężne sodowe. Oświetlenie z oprawami typu LED, mimo że w porównaniu z lampami sodowymi zużywa o połowę mniej energii, to po uwzględnieniu kosztów wymiany opraw generuje najwyższe koszty obsługi, a zatem jego koszt użytkowania będzie wyższy. System oświetlenia drogowego z oprawami typu LED jest uzasadniony ekonomicznie jedynie w przypadku, gdy gmina otrzyma dofinansowanie ze źródeł zewnętrznych na zakup energooszczędnych systemów oświetleniowych. Budowa oświetlenia z autonomicznym zasilaniem jest ekonomicznie nieuzasadniona, ponieważ koszt związany z wymianą akumulatorów jest trzykrotnie wyższy od zakupu energii przy oświetleniu sodowym wysokoprężnym.
***Słowa kluczowe**: audyt efektywności energetycznej, oświetlenie drogowe, oprawy sodowe wysokoprężne, oprawy typu LED, oświetlenie autonomiczne*

1. Introduction

In accordance with the Energy Efficiency Ordinance [14], which implements Directive of the European Parliament and the Council on Energy Efficiency [1], public sector entities are bound to introduce "energy efficiency improvement measures". Article 8.1 of the said Ordinance defines the types of undertakings used to improve energy efficiency that public sector units should apply and finance, and in particular: purchase energy efficient products or services the performance of which dissociated with energy consumption, purchase or rent energy efficient buildings or parts of, which at least satisfy the minimum requirements within the scope of energy saving and thermal insulation or implement other energy efficient improvement measures within the scope of the buildings' energy performance. Products or services purchased by public authority bodies have to satisfy the criterion for classification to the highest energy efficiency class possible to achieve - for products which consume energy, if compliance with economic feasibility and technical suitability criteria is maintained and if it is inimically justified. The aforementioned Ordinance upholds the effectiveness of the Resolution by the Minister of the Economy on the detailed scope and manner for performing an energy efficiency audit, standard energy efficiency forms and methods for calculating energy efficiency. [7].

According to the Resolution the performed energy efficiency audit shall include:

1) an indication of acceptable, technical and economically justified types and variations for the performing the undertaking aiming to improve energy efficiency, taking into account the use of various technologies,

2) a detailed description of the types and variations for the performing the undertaking aiming to improve energy efficiency,

3) an indication of the attainable energy saving, together with an economic feasibility evaluation of each of the undertakings which might be performed with aiming to improve energy efficiency, and in particular:

a) the adopted assumptions and sources of data used for energy savings calculations,

b) the manner for performing data analyses, calculation methods and applied mathematical models as well as a detailed description of formulae, indexes and coefficients used in these calculations,

c) an economic feasibility assessment for the different types and options for the performance of undertakings aiming to improve energy efficiency, which includes: the types of capital expenditures, the adopted current and forecast prices of fuel or energy as well as the expected payback period.

The Commune constitutes the basic public sector unit, which, pursuant to the Ordinance on Commune Local Government performs its tasks within its own scope and at its own responsibility [12]. Pursuant to the Ordinance [12], commune's own tasks include satisfaction of local community needs, including inter alia supply of electricity (Article 7 par. 1.3). Details of the task were set forth in the Energy Law [13], which contains a provision which stipulates that the commune's own tasks within the scope of electricity, heat and gas fuels supply include planning of lighting in public space and roads which are within the commune and financing lighting on streets, squares and public roads which are within the commune. By financing lighting the Energy Law means financing the costs of electricity consumed by light units as well as the costs of maintaining them, (Article 3.22 of the Ordinance). Whereas planning and financing public road lighting by the commune encompasses all public roads with the exception of motorways and express roads in the meaning of the Toll Motorways Act.

Street lighting, an account of communication safety is one of the more significant issues in terms of lighting technology. A correctly designed and executed lighting infrastructure guarantees safety and convenience for vehicle and pedestrian traffic, reduces the number of accidents and contributes to an appropriate light environment comfort. The selection of light luminaires and light sources should comprise a key stage in designing steel lighting. This should combine energy efficiency and low maintenance costs. It is required for street lighting specification light sources to exhibit significant light yield. Whereas the optical system which is employed together with the light source should ensure optimal light distribution and effective use of the light source [15]. Street lighting should be designed in accordance with the guidelines of an appropriate lighting standards. The standard currently in force, PN-EN 13 201:2007, is divided into four parts, which contain the guidelines for selecting the lighting class for different types of roads [3], lighting requirements [4], lighting parameters calculation methods [5] and the metering methodology [6].
Rural and urban-rural communes should apply the Rural Area Development Programme (RADP), rural development and renovation task [2] for support within the scope of modernisation and development of commune lighting. The aid will be granted in the form of qualified costs refunds up to a maximum of 75 per cent of the costs of the undertaking. The development programme prefers relatively small investment projects. The maximum amount of aid for the execution of projects in a single village is PLN 500 thousand. An investment may be performed in a village of up to 5 thousand residents. The minimum aid for a single project is PLN 25 thousand. If communes want to perform own tasks associated with the development of street lighting network, apart from the requirements set forth in the lighting standards, have to apply the provision of the Energy Efficiency Ordinance pertaining to the performance of undertakings aiming to improve energy efficiency.

That is why the purpose of the work was to draw up an energy efficiency audit for the development of street lighting in a sample commune in accordance with the guidelines set forth in the resolution on the scope and manner for performing energy efficiency audits. The article presents the lighting options using HPS high pressure sodium discharge lamps, lamps with LED luminaires and hybrid lamps with LED luminaires which work in an autonomous system.

2. Scope of the audit

The lighting development project was performed for a rural commune located in Sanok county in Podkarpackie province. The commune authorities are planning a development of street lighting on a section of approx. 5.1 km, along commune roads located within a rural built-up area. The right-of-way comprises the following elements: an approx. 7.8-8.5 m wide carriageway, an approx. 1.6-1.8 m wide pavement and a 1.5 m road verge (where the light posts will be located). The roads being considered are local L class roads [8] with small traffic intensity facilitating direct access to properties. According to the PN-EN 13 201:2007 standard, the roads in question can be classified as M4 and the lighting system calculations were performed for such parameters in order to determine the number of luminaires and system power rating. The calculations determined the following number of commercially available luminaires which satisfy the adopted assumptions (Tab. 1). The luminaires will be mounted on 6m tall posts. Similar results in terms of the choice of luminaires and light sources for rural roads (per 1 km of road) can be found in work [9].

Table 1. Results for the lighting system under analysis
Tab. 1. Wyniki dla analizowanego systemu oświetlenia

Specification	Lighting system	
	High pressure sodium discharge	LED
Light stream [lm]	17300	6300
No. of luminaires [pcs]	194	232
Luminaire power [W]	150	60
System power [kW]	29.1	13.92

Source: own work / Źródło: opracowanie własne

3. Analysis of proposed street lighting options

Three street lighting options were subject to analysis - two using energy from the grid:
- Option A – high pressure sodium discharge lamps,
- Option B - Lamps with LED luminaires,

and an independent system:
- Option C - with an autonomous power supply i.e. a hybrid lamp (with a LED type luminaire) powered by electricity generated by photovoltaic panels and a wind turbine.

The system in option C comprises the following elements:
1. A photovoltaic cell; power rating 140 Wp – two modules with total power of 280 Wp, monocrystal structure modules, lifetime between 25 and 30 years. The power of two 1 sq. m panels in operating conditions is approximately 230 W with 950 W/m^2 radiation intensity.
2. A wind turbine with nominal power of 600 W.
3. 150 Ah lithium-ion battery. The system comprises two such batteries.
4. System operation controller.
5. Lamp with a 60 W led luminaire.
6. A steel pole protected with a zinc layer (6 m tall post, with a bracket for a lamp, a solar panel and a wind turbine, overall height of wind turbine approx. 8.6 m).

Energy consumption was estimated for the above elements assuming an annual operating time for street lighting 4024 hours. Whereas for lighting system under option C - with autonomous power supply, a 0 kWh power consumption was assumed, as the energy powering the LED luminaires comes entirely from, renewable sources. Calculation results are shown in the Tab. 2.

Table 2. Electricity consumption for lighting under given options

Tab. 2. Zużycie energii elektrycznej dla oświetlenia w danej opcji

Specification	Lighting system		
	Option A	Option B	Option C
Annual electricity consumption [kWh]	117098	56014	0

Source: own work / Źródło: opracowanie własne

It is estimated that high pressure sodium discharge lamps street lighting (option A) will consume twice as much electricity from the grid as that using LED luminaires (option B).

In order to compare the given options, option A was taken as the point of reference - high pressure sodium discharge lamp street luminaires (consuming the most electricity) and it will be compared to option B (LED fittings) and C (set with autonomous power supply).

4. Street lighting system economic assessment indicators

The selection of a given system should be based on objective criteria. It is generally considered that results which exceed the expenditures are one such criterion - this includes both the initial costs as well as all the cost incurred during the assumed period of system use [10]. An economic analysis was performed on the basis of complex real investment assessment methods, based on a (discounted) percentage rate, which takes into account the value of money over time.

These methods are:

- NPV (net present value).

It's sum of the present value of all future incomes throughout the lifetime of the investment less capital expenditures (1):

$$NPV = \sum_{n=1}^{n=t} \frac{WRK_n}{(1+i)^n} - NI \quad \text{[PLN thousand]} \tag{1}$$

- PBP (pay-back period).

Period of time over which discounted cash flows will cover the capital expenditure. Discounted expenditures payback period takes into account the variable value of the invested amount over time:

$$PBP = \frac{\ln\left[\dfrac{1}{1-\left(\dfrac{NI}{WRK}\right)\cdot i}\right]}{\ln(1+i)} \quad \text{[years]} \tag{2}$$

- IRR (Internal Rate of Return).

The discount rate at which the net present value NPV is equal to zero. For an investment to be profitable, the following criterion has to be satisfied: $IRR > i$.

$$\sum_{n=1}^{n=t} \frac{WRK_n}{(1+IRR)^n} - NI = 0 \tag{3}$$

– CCE (Cost of Conserved Energy).

If the cost of conserved energy is less or equal to the price paid for the energy, there are grounds to consider the investment profitable.

$$CCE = \frac{NI \cdot \dfrac{i}{1-(1+i)^{-n}} + Ke,o}{\Delta E} \quad \text{[PLN/kWh]} \tag{4}$$

where:

NI – initial costs (cost system purchase and start-up) [PLN thousand],

Ke,o – annual system operation costs [PLN thousand],

t – next system use year,

i – discount rate ([11] was taken to be 3%),

n – 1..25 subsequent cost years (n=25 the assumed system life cycle years),

WRK – value of annual benefits [thousand, PLN],

ΔE – annual energy saving [kWh].

In order to perform an economic analysis for the contrition and operation of street lighting in the commune subject to analysis, market prices were assumed, calculating their mean value on the basis of prices available in 2016. Capital expenditure costs for building a street lighting system were analysed (geodesic services, earth works, cabling, foundation and pole assembly, street light boxes with electrical connections), which oscillate between PLN 6.9 - 8.5 thousand (PLN 7.7 thousand average) per lamp post (6 m high). That price excludes assembly of luminaires, for which the prices are as follows:
- high pressure sodium discharge lamp luminaire with a 150W light bulb - PLN 400,
- 60W LED luminaire - PLN 1200,
- luminaire assembly (regardless of which type) - cost of labour - PLN 250.

Due to the fact that the commune satisfies the conditions stipulated in the Rural Area Development Programme (RADP) rural development and renovation task guidelines, in calculating the capital expenditures the possibility that the commune will take advantage of grants of up to 75% of qualified costs associated with the purchase and assembly of LED luminaires - in this case the cost of a fitting taking into account the grant is PLN 565 per piece. Additionally, the capital expenditure was estimated for the autonomous lighting system (option C), where the most efficient photovoltaic module and battery were taken, and the remaining elements were from the middle-class range: LED lamp, controller, wind turbine, pole. A list of unit costs for the autonomous lighting system is shown in Tab. 3.

The cost of a street lighting set working in an autonomous system was estimated at approx. PLN 14 thousand. The market purchase price of hybrid street lighting sets available on the market with parameters similar to those adopted in the calculation is within the approximate PLN 12 to 16 thousand range. Also in this case the possibility of the commune taking advantage of investment grants at a maximum level of PLN 500 thousand was taken into account.

For the needs of the analysis electricity costs incurred in purchasing from “the grid” were determined. Street lighting should be charged under tariff D11. The commune incurs fixed and variable energy costs. These can be split into monthly costs incurred for the connection, i.e. 30.33 PLN/month (meter) and electricity costs i.e. 0.5226 PLN/kWh (including distribution and electricity). 5 lights connections were assumed for subsequent calculations (street light boxes). Operating costs should include high pressure sodium discharge bulb replacement, whose lifetime is estimated at 20000 h, which subject to 4024 h/year operation gives an average time of 5 years. The cost of replacing a bulb (incl. labour) is estimated at PLN 200. The expenditure associated with replacing LED luminaries, whose lifetime is estimated at 50000 h (or approx. 12 years under scheduled usage) should also be taken into account. Two LED luminaires price options were taken into account for the calculations:

- in the first (B_1, C_1) the luminaire replacement cost (incl. labour) remains at the current level, i.e. PLN 1450 / piece.
- under the second option (B_2, C_2) a 20% reduction in the prices of LED luminaries was assumed - this gives a cost of replacing a luminaire together with labour of PLN 1210/piece.

For hybrid lighting, additional outlays were assumed, which have to be incurred associated with replacing batteries, whose lifetime is estimated at 7 years. A 30% reduction in the price of batteries was assumed for the calculations resulting from technological progress, which gives PLN 2980 per set (including PLN 40 labour).

An economic analysis will be performed for two scenarios:

- the commune pays for the investment entirely using its own funds,
- the commune is awarded a grant from the Rural Area Development Programme used towards the purchase of LED luminaires and capital expenditures associated with implementing the system with the autonomous power supply.

The economic assumptions for the calculations taking into account capital expenditures, cost of energy and operation are shown in Tab. 4.

Table 3. The cost of purchase and installation of hybrid lamps with LED luminaries
Tab. 3. Koszt zakupu i instalacji lamp hybrydowych z oprawami LED

Name	Pieces	Unit price [PLN, thousands]	Total price [PLN, thousands]	Lifetime	Lifetime in years
Photovoltaic cells	2	0.7	1.4	-	30
150 Ah Li-ion battery	2	2.1	4.2	approx. 2400 charging cycles with discharge down to 30-50%	7
Controller	1	1.2	1.2	-	30
LED luminaire	1	1.2	1.2	approx. 50000 h	12.5
Wind turbine	1	2.5	2.5	-	30
Pole	1	2.0	2.0	-	30
Assembly (foundation with pole assembly)	1	1.7	1.7	-	
		Total	14.2		

Source: own work / Źródło: opracowanie własne

Table 4. Basic assumption for economic analyses
Tab. 4. Podstawowe założenia analiz ekonomicznych

Specification	Value				
	Option A	Option B		Option C	
NI – capital expenditures, [thousand, PLN]	1703	commune’s own funds 2039		commune’s own funds 3294	
		RADP grant 1834		RADP grant 2794	
n – total lifetime in years	25				
		B_1	B_2	C_1	C_2
o – average annual cost of operation (replacement of faulty light sources and batteries) [thousand, PLN]	7.76	28	23.4	28	23.4
				98.76 batteries	
(gross) energy unit price acc. to operator's tariff	0.5226 PLN/kWh 363.96 PLN/annum (meter)			0	
i– discount rate	3%				
ke – annual energy purchase costs (energy + fixed costs) [thousand, PLN]	63	31		0	
Ke,o – annual costs incurred in connection with the street lighting ion the commune *(o+ke)*	70.76	59	54.4	126.76	122.16
WRK – value of annual benefits *Ke,o A - Ke,o* B_1*; (*B_2*); Ke,o A - Ke,o* C_1*; (*C_2*)* , [thousand, PLN]	–	11.76	16.36	-56	-51.4

Source: own work / Źródło: opracowanie własne

The economic analysis showed that a commune looking to build street lighting using solely its own funds should opt for high pressure sodium discharge lamps - all the economic indicators listed in Tab. 5 confirm this. Lighting with LED type luminaires, despite using half as much energy as sodium discharge lamps, once the cost of replacing luminaires is taken into account - regardless of the adopted option for the forecast change in luminaire price, still generate the highest operating costs. The discounted investment payback period is between 32 and 65 years. Also the CCE indicators show that the cost incurred to conserve energy exceeds that of the cost of purchasing energy and is between 0.57 and 0.64 zloty per kilowatt hour. The worst indicator values were returned by the autonomous power supply lighting option. Despite the fact that it does not consume energy from the grid, due to the high battery and luminaires replacement costs (as well as the capital expenditures), installation of lamps of this type is not profitable, and as such the commune would incur significant losses, which over the 25 year period in questions could amount to approx. PLN 2.5 million (NPV coefficient). The CCE cost of conserved energy is more than three times higher than purchasing energy from the grid.

Table 5. Results of economic analysis - the commune pays for the investment entirely using its own funds
Tab. 5. Wyniki analizy ekonomicznej – gmina finansuje inwestycję w całości ze środków własnych

Specification	Option		Option	
	$A \rightarrow B_1$	$A \rightarrow B_2$	$A \rightarrow C_1$	$A \rightarrow C_2$
NPV [thousand, PLN]	-131	-51	-2566	-2486
PBP [years]	65	32	-	-
IRR [%]	0.01	1.57	-	-
CCE [PLN/kWh]	0.64	0.57	1.77	1.74

Source: own work / Źródło: opracowanie własne

If the commune would take advantage of the grants within the scope of the Rural Area Development Programme (RADP), which assumes a refund of qualified costs up to a maximum of 75 per cent of the costs of the investment associated with building lighting which relies on energy saving technologies (application of energy saving light sources), then the capital expenditure associated with the purchase and installation of LED luminaires will be comparable with the costs associated with high pressure sodium discharge lighting. In this case the values of economic indicators confirm that construction of a lighting system with LED luminaires is justified (Tab. 6). The investment payback period, depending on the applied price option for replacement of LED luminaires, will be between 9 and 14 years. During the assumed lifetime, the commune's benefits on that account may amount to between approx. PLN 75 and 150 thousand. The CCE cost of conserved energy is less than the energy purchase price. Also the value of the IRR indicator (7-11%) confirms the profitability of this type of investment.

For hybrid lighting, despite the fact that the values of economic indicators are better than in the option without the grant, still the installation of this type of lighting is completely unprofitable for the commune (it may incur a loss of up to approx. PLN 2 million, and the cost of conserved energy is three times higher than its purchase price). Lamps of this type should only be installed in places where, for whatever reason, electricity from the grid is not available.

Table 6. Results of economic analysis – investment co-financed by RADP
Tab. 6. Wyniki analizy ekonomicznej – inwestycja współfinansowana przez Program Rozwoju Obszarów Wiejskich

Specification	Option		Option	
	$A \rightarrow B_1$	$A \rightarrow B_2$	$A \rightarrow C_1$	$A \rightarrow C_2$
NPV [thousand, PLN]	74	154	-2066	-1986
PBP [years]	14	9.2	-	-
IRR [%]	7.5	11.7	-	-
CCE [PLN/kWh]	0.46	0.38	1.55	1.5

Source: own work / Źródło: opracowanie własne

5. Conclusions

Based on the performed energy efficiency audit for the three options for developing street lighting on commune roads, the following conclusions may be drawn:

A commune looking to build street lighting using solely its own funds should opt for high pressure sodium discharge lamps - all the economic indicators confirm this. Lighting with LED type luminaires, despite using half as much energy as sodium discharge lamps, once the cost of replacing luminaires is taken into account will generate the highest service costs, and as such its operating cost will be higher - overall, with an assumed 25 year system lifetime, the commune stands to lose approx. PLN 130 thousand. The cost incurred to conserve energy (expressed as the CCE indicator) exceeds that of the cost of purchasing energy and is between 0.57 and 0.64 zloty per kilowatt hour.

The street lighting system with LED type luminaires is economically justified only if a commune receives grants from external (RADP) sources (for the purchase of energy saving light systems. In this case the investment payback period may be between 9 and 14 years as compared to high pressure sodium discharge lighting. The CCE cost of conserved energy is between 0.38 and 0.46 PLN/kWh and is less than the energy purchase price. By obtaining a grant for installation of energy efficient lighting, over a 25-year use period a saving of PLN 150 thousand is possible.

Building lighting with an autonomous power supply i.e. a hybrid lamp (with a LED type luminaire) powered by electricity generated by photovoltaic panels and a wind turbine is economically unjustified even regardless of how the investment would be financed. The cost of using just the batteries used in this system will be three times higher than the cost of purchasing energy fore the high-pressure sodium discharge lighting. An investment of this type would expose the commune to losses of between PLN 2 million and 2.5 million over a 25-year use period.

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