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Investigation of the Opportunities of Covering the Electricity Needs of Street Lighting System by Photovoltaic Power Plants, Owned by the Municipality

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Abstract. A methodology has been developed for analysis of the opportunities of providing the energy consumption of the street lighting system of a small settlement by photovoltaic power plants, owned by the municipality and for the realization of revenues through the sale of electricity to the Electricity Distribution Company. An example of a modern highly efficient street lighting system equipped with LED lighting is considered and projects of photovoltaic power plants, based on monocrystalline and polycrystalline silicon solar panels, characterised by excellent technical and economic parameters are proposed.

INTRODUCTION

Energy efficient street lighting is a priority at both national and European level, as it is one of the major energy consumers in municipalities [1]. This makes the aim of building renewable energy plants, and in particular rooftop photovoltaic plants, to produce an equivalent amount of energy appropriate.

Street lighting systems should meet the basic regulatory requirements for lighting and energy efficiency to provide good visual conditions and the lowest possible lighting costs, including projects, operation, electricity, operational and financial management. Optimal costs for good visual conditions are achieved during the design phase by the choice of luminaires with appropriate light distribution, allowing implementation of lighting systems with minimal capital investment, but also having high light output. This choice also provides lower electricity costs. Regardless of the results achieved in the terms of energy efficiency of the lighting system, its owner, usually a municipality or a town hall, will always have electricity costs, which especially if purchased on the open market in the ‘day ahead’ segment will be a significant part of the municipality budget. This raises the question of whether the municipality as a legal entity, owner of many real estates, could build on their roofs its own sources of electricity necessary for street lighting system and for other own needs. Such an option is building of rooftop photovoltaic power plants, as the electricity generated during the day is sold or used for own needs, and during the dark part of the day, outside the peak consumption, it is bought from the free market. Thus, by selling electricity during the day, municipalities would realize revenues or save costs, which would then be used to buy electricity at night for the street lighting.

The existing opportunities of upbuilding of solar installations are diverse, which allows making an appropriate choice according to the specific conditions and needs. It should be carried out taking into account the amount of the initial investment and the service life of the facilities.

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In the present study such an alternative of providing funds has been considered, as a methodology for estimating costs and revenues regarding the construction of lighting systems, production of the photovoltaic system and financial balance assessment has been developed.

VARIANT CALCULATION FOR THE STREET LIGHTING SYSTEM

In the suggested variant calculation, to determine the electricity cost of the street lighting, a small settlement in the region of Sofia is considered, and its lighting system is designed. Street lighting system meets the basic regulatory requirements for lighting and energy efficiency of BDS EN 13201:2015 [2].

The streets belong to M6 and P5 lighting classes. The brightness factor of the pavement surface of all streets and public spaces is R3. The main streets of the settlement have sidewalks on both sides of the road and their width is between 6.0 and 10.0 m. All the other streets consist of a roadway and grass strips without sidewalks. Light centre height of the luminaires is 6.0 to 8.0 m. Pole distance is up to 35 m and the arrangement is one-sided. Two-sided arrangement is appropriate only when large public spaces like squares are designed.

The development of light-emitting diodes creates preconditions for achieving much higher technical and economic indicators than those of conventional lighting. For this reason, they are considered the most highly efficient sources nowadays [3]. Their service life reaches up to 100 000 hours. Usually after this period the lamp loses about 20-30 % of its brightness [4]. The comfortable perception of LED radiation by the human eye directly depends on the colour temperature of the LED source [4].

The main criteria for the choice of the street luminaires have been namely the high efficacy and the long service life, declared by the manufacturer. Luminaires with light distribution curve, suitable in conditions of narrow street without sidewalks and where pole distances are long, have been selected. Their colour temperature is 4 000 K [5].

DIALux evo 10.0 [6] software is used for carrying out multivariate design while implementing the project.

Specific geometry of the light system (l – pole distance; b – street width; h – light center height) and P - active power of the chosen luminaires are performed in *Table 1*. Calculated values of L_m - brightness/E_m - illuminance and consumption, including linear power density of the street lighting are also shown.

TABLE 1. Parameters of the lighting system

№	P, [W]	l, [m]	b, [m]/ h, [m]	L_{av}, [cd/ m^2]/ E_{av}, [lx]	Dp, [W/lx.m^2]	De, [kWh/ m2. yr]	W, [kWh/ yr. pcs]	P_{lin}, [kW/ km]	W_{lin}, [kWh/ km. yr]
1	21	35x1	9,5/ 8,0	0,30 (L_{av})	0,013	0,3	83,5	0,630	2,506
2	19	35x1	8,5/ 7,5	0,31 (L_{av})	0,015	0,3	75,6	0,570	2,267
3	19	35x1	8,0/ 8,0	0,31 (L_{av})	0,016	0,3	75,6	0,570	2,267
4	19	35x1	6,0/ 8,0	0,34 (L_{av})	0,018	0,4	75,6	0,570	2,267
5	14	25x2	20,0/ 7,5	0,33 (L_{av})	0,010	0,2	111,4	1,840	3,341
6	10	35x1	6,0/ 6,5	3,12 (E_{av})	0,015	0,2	39,8	0,300	1,193

It is easily seen that only four types of luminaires have been chosen for the whole settlement (of 21W, 19W, 14W and 10W). The entire length of the streets is 20,1 km and 87% of it are narrow streets with light class P5, where 10W luminaires are mounted. The total annual consumption is calculated by the length of the streets and the linear power density P_{lin}.

Because of the inability to control the environmental factors, appropriate value of required net installed power of the photovoltaic system should be determined, including an additional reserve to compensate any adverse conditions. Namely these factors (energy production depends on the geographical location and orientation of the site; production is irregular during the day and year; inappropriate weather conditions lead to uncertainty in production) are related to the main weak spots of the photovoltaic systems.

Despite of all mentioned above, photovoltaic plants are still of interest due to their undeniable economic and technical benefits. Among the main advantages of using solar energy is that it is environmentally friendly, increases security by reducing dependence on the supply of conventional fuels and leads to decentralization of electricity production. Building a photovoltaic plant requires less initial investment and has a better return than a traditional power plant. The possibility of electricity production and conversion near the place of usage reduces losses from transmission and distribution of energy. There is also a possibility of integration into buildings roofs and facades [7].

PHOTOVOLTAIC SYSTEM

Examining the available buildings of the municipality showed that there were enough buildings, suitable for rooftop photovoltaic plants installation (town hall with a roof area of 264 m^2, kindergarten – of 57, 55 and 36 m^2, school– of 800 m^2 and a gym – of 390 m^2 and a community centre – of 450 m^2). The school building was chosen due to its appropriate location and orientation and because of its large flat roof without shaded parts neither in summer, nor in winter.

Two projects have been implemented, using monocrystalline and polycrystalline solar panels [8], [9] (90 pcs, 29.70 kWp for each of the options) and invertors [10] (2pcs. for each of the options), available at Bulgarian market. The total price of these components, including VAT is BGN 35 600 and BGN 26 150, respectively.

The simulation was held using PVSOL2022 (R3) software [11].

The results based on the climatic data for the region of Sofia are presented in Table 2. It is easily seen that at the same peak power for both kinds of panels, those of lower efficiency (polycrystalline) obtain larger dimensions and, accordingly, mass and need a larger area to be installed on. At the same time, due to the lower load over the inverters, the total efficiency of the system is further reduced, and therefore the estimated produced electricity. Here S is the net area of the panels, not the total roof area needed for the photovoltaic system to be installed. Critical for reaching optimal performance of solar modules, especially of the monocrystalline ones is providing operational conditions of zero shading (distance between each two rows should be at least three times the perpendicular from the highest point of the panel to the roof). [12] Meeting this condition leads to increasing the area needed for the photovoltaic system to be installed to 337,5 m^2 and to 376,3 m^2 for the photovoltaic system according to Variant I and Variant II respectively.

TABLE 2. Indicators of the photovoltaic systems

Variant	Type of panels	Pwp, [Wp]	η, [%]	S, [m^2]	S_1, [m^2]	m, [kg]	W, [kWh/ yr]	Добив, [kWh/ kWp]	PR, [%]
I	Monocrystalline silicon	330	19,56	151,9	337,5	1 755	35 878	1 207,34	89,6
II	Polycrystalline silicon	330	17,02	175,0	376,3	2 025	35 434	1 192,40	88,4

The annual load distribution, based on the Standard Load Profile for Street Lighting without interruption during the dark hours and the estimated active power, produced by the power plant perform significant nonconformity.

Due to this feature of the trend, it is envisaged that the two systems should be connected only by accounting.

Fig.1 performed annual active power distribution of lighting of 1 km of a street of P5 class, where luminaires of 10W are installed and annual net power distribution, needed according to Variant I. Calculations are made considering 8% losses in transmission.

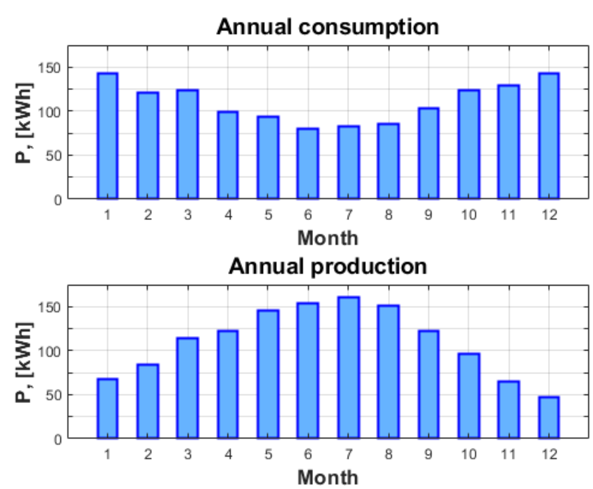

FIGURE 1. Annual load profile of consumption of 1 km (10W luminaires) of the street lighting system and of annual load profile of production of photovoltaic power plant at the same annual power base

METODOLOGY AND ASSESSMENT OF ECONOMIC EFFICIENCY

The proposed valuation methodology is based on the comparison of cost and revenue parts. The calculation algorithm is implemented using Matlab R2021a, but it could be easily adapted for MS Office Excel or another spreadsheet environment. It consists of a few logical steps:

- determining the annual power consumption of the street lighting system and calculating its price at current market prices for consumers;
- figuring out the approximate annual operational (administrative and technical) costs of the photovoltaic system;
- determining the annual power (in kWh) needed for gaining the amount of money to cover the costs of the street lighting at the current market prices of electricity;
- calculating the installed power (in kWp) of the photovoltaic system, capable of this production;
- designing the photovoltaic system and looking for a building with a suitable roof in the building stock of the municipality;
- calculating the initial investment needed for constructing the designed photovoltaic system (including administrative costs);
- calculating the estimated annual income from the sales of electricity at the current market prices for producers;
- determining the financial indicators, analyse the data and deciding if it is cost effective to build the designed photovoltaic system.

The input data of the developed algorithm is related to the technical parameters of the lighting system and the photovoltaic system, to the costs of construction and operation of the systems and the revenues by the sold electricity.

The output data of the algorithm are the amounts of annual revenues and costs and economic indicators – net present value, coefficient of net present value, internal rate of return and payback period [13].

The revenue part of the balance sheet is formed from electricity sold at a fixed preferential price for rooftop power plants up to 30 kWp. A balance sheet where the revenue part is calculated according to the base price of Day Ahead Market at the Independent Bulgarian Energy Exchange was used for a comparison of the payback period.

The expenditure part of the balance sheet consists of three groups of costs: direct initial investment, operation and taxes on the electricity produced. Direct initial investment includes administrative costs for issuing documents (project, survey application, resolution to connect the electricity net, constructive resolution), fees (fees for connecting electricity network, for security of the electrical system, for access, for balance, for the Sustainable Energy Development Agency) and for accounting and legal services for establishing a legal entity. The second part of the costs are related to the physical side of the photovoltaic system: construction, solar modules, inverters, DC and AC connecting cables, connectors and switchboards with control and protection electrical devices. In addition, a sun tracking system and a system for data collection and monitoring could be included as recommended elements. The costs of installing the system have to be included here also. A contingency stock of 3% of the initial investment is also provided. The maintenance of the system is related to expenditures for current administrative expenses (accounting and legal services of a legal entity, credit servicing, insurance, internet access) and for operating expenses. The tax part reports the sales tax of the sold electricity.

Calculated sums of expenditures according to each of the variants are shown in Table 3.

TABLE 3. Expenditure part of the balance sheet

Expenditure	Variant I, [BGN]	Variant II, [BGN]
Initial investment:		
• administrative	- 4 360,10	- 4 360,10
• for system elements and installation	- 59 422,00	- 49 451,00
Current costs:		
• administrative	- 1 400,00	- 1 400,00
• operational	- 1 700,00	- 1 500,00
Sales tax	- 1 184,00	- 1 169,30
Electricity for lighting	- 3 639,90	- 3 639,90

The initial investment, annual saved costs, cash flow and payback period, calculated at prices as of May.2022 are presented in Table 4, both for Variant I and Variant II.

TABLE 4. Initial investment, cash flow and payback period

Variant	I_0, [BGN]	C, [BGN/yr]	CF (Fixed price), [BGN/yr]	PB (Fixed price), [yr]	CF (Free market price), [BGN/yr]	PB (Free market price), [yr]
I	63 544	3 639,90	363,90	17,5	6 176,10	7,0
II	53 811	3 639,90	476,00	14,8	6 216,30	5,9

CONCLUSION

A highly efficient lighting system of a small settlement is designed, and two projects of rooftop photovoltaic plants are proposed to cover its electricity costs. The obtained results lead to the following conclusions:

- The municipality owns plenty of buildings, some of which fulfilling the requirements for construction of effective photovoltaic power plants on their roofs.
- Both photovoltaic systems of monocrystalline and polycrystalline solar panels are able to provide enough energy, to supply the street lighting of the settlement after paying their own operational costs.
- The price of electricity and the operational costs are close in value for both variants.
- Under current market conditions, the advantage in the efficiency of monocrystalline solar panels is not enough to compensate their higher price. The construction of a photovoltaic plant, using polycrystalline panels, is more cost-effective for the region of Sofia.
- The payback period, based on saved costs is quite longer if selling electricity at fixed price (although preferential) than selling it at the free market. It is 17,5 years for Variant I which is longer than 15 years life of guaranteed operational life of solar panels and it is 14,8 years of Variant II.

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