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Multi-criterion optimisation of photovoltaic systems for municipal facilities

Tomasz Szul, Jarosław Knaga, Krzysztof Nęcka

Krakow University of Agriculture, Faculty of Powering and Automation of Agricultural Processes
ul. Balicka 116B, 30-149 Kraków, Poland, e-mail: tomasz.szul@ur.krakow.pl

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Summary. This study provides a technical and economic analysis of a photovoltaic plant providing power supplies to a municipal waste water treatment plant. Power generation in a photovoltaic farm was considered in its two aspects, that is connected to the grid with an option of feeding power to the grid in case of overproduction and as an autonomous system which will generate power exclusively for the needs of the waste water treatment plant without the possibility of supplying power to the grid. On basis of the analysis it was concluded that the operation of the photovoltaic farm within the power grid is a better solution. In spite of small unit profit of the project, it brings about a positive environmental effect in form of reduction of CO_2 emission. In order to implement photovoltaic installations in its facilities, the municipality should apply for various subsidies due to the fact that only a subsidy covering above 50% of investment costs will guarantee a minimum profitability of such a project.
Key words: photovoltaic farm, technical and economic analysis of photovoltaic installations, waste water treatment plant, subsidies for renewable energy sources.

INTRODUCTION

Total capacity of commercial power plants in Poland amounted to 37,4 GW as per the end of 2012. 82% of them were power plants fired mainly with non-renewable resources, such as hard coal and brown coal. According to the Energy Regulatory Office [URE 2013], power capacity of renewable energy installations amounts to 4,4 GW, out of which 2,5 GW is made up by wind turbines, 0,96 GW by hydroelectric power stations and 0,82 GW by biomass-fired plants. Solar power stations are a novelty in this listing, as currently there are only nine photovoltaic farms operating in Poland, with a summed capacity of 0,0013 GW. In near future another four sites are planned to be commissioned which will increase the nationwide solar power output up to 0,0063 GW. The development of such installations is determined both by means of appropriate regulations [directive 2009], as well as environmental and economic aspects. Renewable energy sources do not emit any harmful pollution to the atmosphere, including the most burdensome CO_2. The necessity to reduce the emission of greenhouse gases provides a very strong impulse for the development of environment-friendly energy sources. This necessity is imposed on Poland under international obligations stipulated in the Kyoto protocol and the United Nations Framework Convention on climate change [4, 9]. As an additional stimulus for the development of renewable energy sources, the Ministry of Economy enacted a decree of 18th October 2012 which forces the power distribution companies to acquire power from renewable energy sources. According to the decree valid as of 1st January 2013, the percentage share of renewable energy sources in the Polish power system should increase regularly by one per cent from 12 in 2013 to 20% in 2021 [Decree 2012]. Apart from promoting major sites using renewable energy sources, works are currently being conducted on the creation of an efficient supporting system of renewable energy sources, as a development opportunity not only for local communities, but also local governments, as assumed among other in the act on power efficiency according to which the public sector should play a leading role in the promotion of energy savings and usage of renewable energy sources [Journal of Laws 2011]. Out of many available renewable energy sources, small photovoltaic installations attract ever larger interest of administrators of municipal buildings, as they may be used to cover their own power demand and to sell the excess of electric power [19]. The economic calculation is the essential criterion influencing the selection of a power system to be installed [16, 20]. In practice, an energy balance analysis cannot act as a decisive factor for the selection of a given type of installation. A potential user should assess both the technical and economic aspects of each of the considered systems and choose the most advantageous one from the perspective of its entire lifespan [1, 8, 13, 15].

The goal of this study is to deliver a technical and economic analysis of a photovoltaic plant providing power supplies to a municipal waste water treatment plant located in the South of Poland. The scope of research covers an operating analysis of a photovoltaic farm in its two aspects, that is connected to the grid with an option of feeding power to the grid in case of overproduction and as an autonomous system which will generate power exclusively for the needs of the waste water treatment plant without the possibility of submitting power to the grid.

SCOPE OF RESEARCH

The facility covered in this research is a municipal waste water treatment plant which is planned to be equipped with a photovoltaic farm in order to cover the electric power demand of the receivers located within the plant. The receivers include lamps, electric sockets for portable receivers and three-phase receivers. Asynchronous motors powering the waste water treatment process machinery will act as the main power receivers. The power demand of currently installed and operating receivers within the waste water treatment process amounts to 105,9 kW. The total power demand of electric power receivers amounts to 116,9 kW. As the assumed coincidence factor amounts to 0,41, peak power demand of the facility is 48,1 kW. After the commissioning of the second reactor, the planned power of installed receivers will grow to 182,7 kW, while their peak power will reach 75 kW. Real yearly consumption of electric power by all receivers operating in the waste water treatment plant at 150 [MWh].

TECHNICAL ANALYSIS

The following criteria were used for the calculation of active surface of photovoltaic modules:

1. Maximum photovoltaic farm power should not exceed the peak power subscribed with the power supplier, increased by the mean value of power demanded by electric devices installed at the waste water treatment plant.
2. Power generated by the PV farm should cover at least 90% of demand in the summer half of the year (April-September).
3. Points 1 and 2 should be fulfilled assuming that two reactors of the plant are operating; therefore, a growth of power consumption and power demand by electric devices of the waste water treatment plant by 62,26% was assumed.
4. The smallest photovoltaic farm to be considered in the analyses should meet the criterion 1 and 2 at current power and energy demand, that is operation of a single waste water treatment plant reactor.

On basis of the adopted criteria 1-4, and considering the limit values of solar radiation flux density, that is from 200 W/m2 up to 350 W/m2, three variants of photovoltaic module surface were adopted according to insolation value of 200 W/m^2 **W1**, 250 W/m^2 **W2**, 350 W/m^2 **W3**. The parameters and average costs of such installations are provided in table 1.

Table 1. Listing of photovoltaic plant parameters for three variants

Variant	W1	W2	W3
Mean power demand [W]	30000	30000	30000
Threshold flux density [W·m^2]	200	250	350
Efficiency rate	13,9	13,9	13,9
Required receiving module surface [m^2]	1100	860	620
Peak farm power [Wp]	153061	120000	85714
Maximum farm power [W]	137755	108000	77143
Cost of photovoltaic modules, PLN	1726531	1353600	966857
Installation cost (20% cost of cells), PLN	345306	270720	193371
Project costs, PLN	25000	25000	25000
Inverter, PLN	160000	160000	100000
Power connections and commissioning, PLN	69061	54144	38674
System maintenance and insurance	17265	13536	9669
Total installation cost kPLN	**2343**	**1877**	**1334**

After determining the power generation potential for such a selection modules, a further analysis of coverage of power demand of the waste water treatment plant could be performed. The conducted research considered a photovoltaic farm connected to the grid with an option of feeding power to the grid in case of overproduction and an autonomous system which will generate power exclusively for the needs of the waste water treatment plant without the possibility of submitting power to the grid. For the purpose of the analysis, a mean power output in a 25-year lifespan was adopted. Due to the planned commissioning of the second power plant reactor, the analysis of power demand was performed with the consideration of the forecast energy consumption after the extension. Within the calculations of the coverage rate, the decrease of efficiency rates of photovoltaic cells was considered along the lifespan. The estimated mean coverage of power demand of the waste water treatment plant within 25 years of lifespan amounts variant-specifically to 36-65% in case of a farm connected to grid, while in case of an autonomous solution, the coverage the plant's power demand will be confined within 16-27% depending on the adopted variant.

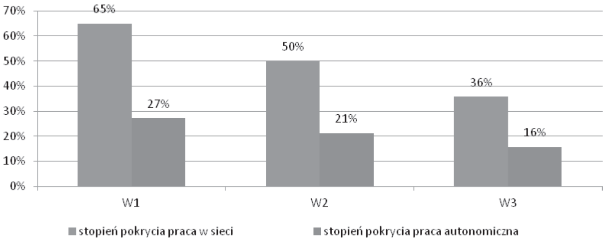

Fig. 1. Coverage of power demand of the waste water treatment plant in a lifespan perspective of 25 years.

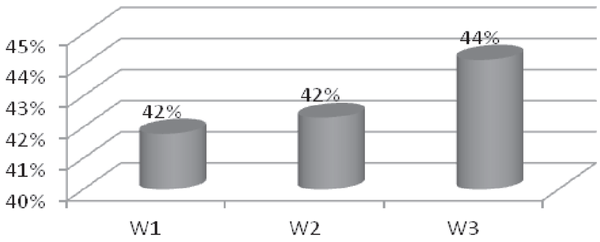

Fig. 2. Photovoltaic farm underload in autonomous operation

If the farm operates autonomously, 42-44% of power is lost due to the insufficient operating coherence of waste water treatment processes with the photovoltaic farm. As a solution for this problem, electric batteries could be used, however due to the high power storage costs amounting from 0,6 to 1,2 PLN per kWh [7] such option has not been considered in further research.

ECONOMIC ANALYSIS

The project economic efficiency analysis was performed on basis of the following economic factors [2, 5, 6]:
– simple payback period (SPBP),
– pay-back period (PBP),
– net present value (NPV),
– net present value ratio (NPVR),
– internal rate of return (IRR),
– dynamic generation cost (DGC).

The selection of a specific photovoltaic system of the waste water treatment plant should be based on objective criteria. Excess of effects over expenditures is regarded commonly as such a criterion. The technical and economic analysis was performed on basis of simple and complex evaluation methods of asset investments, based on discount rate and considering the currency value fluctuation in time, risk and inflation.

Simple pay-back time. Defined as the time necessary to retrieve the capital expenditures incurred for the delivery of the specific project:

$$SPBT = \frac{NI}{WRK} \text{ [years]}.$$

Calculated from the commissioning of investment until the gross sum of benefits gained from the investment compensates the expenditures.

Pay-back period (PBP), that is the period in which discounted cash flows cover the incurred capital expenditures. Discounted pay-back period considers the changing value of the investment amount in time:

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

Net present value (NPV). Sum of all future income of the investment lifespan calculated per the current year and reduced by the incurred capital expenditures:

$$NPV = \sum_{n=1}^{n=t} \frac{WRK_n}{\left(1+i\right)^n} - NI \text{ [PLN]}.$$

Net present value ratio (NPVR) captures the relation of project net value and the value of capital expenditures necessary to acquire NPV:

$$NPVR = \frac{NPV}{WRK} \text{ [PLN]}.$$

NPVR is an auxiliary index allowing to select the investment option by comparing projects that are similar in terms of structure, capital expenditures, lifespan etc. In most cases, the following condition has to be met:

$$NPVR \to \max.$$

Internal rate of return (IRR). Calculated on basis of cash flow; it is such a discount rate value at which the net present value equals zero (5):

$$\sum_{n=1}^{n=t} \frac{WRK_n}{\left(1+IRR\right)^n} - NI = 0 \text{ [\%]}.$$

Dynamic generation costs equals the price which enables the acquisition of discounted income equalling discounted costs. In other words, DGC shows the technical cost of acquisition of a unit of environmental effect [Rączka 2002]. This cost is indicated in PLN per unit of environmental effect. The lower the DGC value is, the higher the efficiency of the project:

$$DGC = p_{EE} = \frac{\sum_{t=0}^{t=n} \dfrac{KI_t + KE_t}{(1+i)^t}}{\sum_{t=0}^{t=n} \dfrac{EE_t}{(1+i)^t}}. \text{ [PLN/kgCO}_2\text{]},$$

where:
re – energy price growth rate,
n – 1..25 consecutive cost year (n=25 estimated number of installation lifespan years).
NI – capital expenditures [kPLN],
WRK – value of yearly benefits [kPLN],
KI_t – investment costs incurred in a given year – t,
KI_t – operating costs incurred in a given year – t,
i – discount rate (down to second decimal),
t – year, value from 0 to n, where 0 is the year of first costs and n the last year of system operation,
EE_t – environmental effect rate in physical units acquired in each year. Environmental effect to which p_{EE} price per physical unit is assigned (assuming that price is constant during the entire period covered by the analysis),
p_{EE} – price for physical unit of environmental effect.

The following components were used for the purpose of financial projection:
1. Sales revenues on ownership rights to power generation with a renewable energy source, so-called green certificates. Value of ownership rights in 2011 amounted on

average to 285 PLN/MWh and it is estimated to grow by 2-3% per year (2% in the analysis).
2. Costs avoided thanks to not purchased power. In the analysis, an electricity price growth of 4,5% was adopted (according to historical data from 2000-2010).
3. Operation and maintenance costs – in the calculations, a growth by 4% was assumed.

Table 2 provides a projection of yearly profit (value of yearly benefits) in kPLN gained thanks to the operation of the PV farm (mean value for a 25 year lifespan) according to the specific variants.

The following data were used to calculate the economic rates.

– capital expenditures in the installed photovoltaic farm (as in table no. 1) W1 – 2343 kPLN, W2 – 1877 kPLN, W3 – 1334 kPLN
– **Table 2.** Value of yearly benefits

Variant	W1 in grid	W2 in grid	W3 in grid	W1	W2	W3
kPLN	224,86	169,89	121,47	80,32	59,37	45,03

– discount rate 5,91%,
– project lifespan 25 years,
– in the calculation, three project funding levels were used: 100% of own funds, 50% subsidy and 75% subsidy from environmental funds.

In the calculations it was assumed that the provisions on the acquisition of green certificates will remain in power after 2012. The results of the performed economic analysis are specified in table 3.

While analysing the evaluation factors one can conclude that the operation of the photovoltaic farm within the power grid is a better solution, as confirmed by all rates. Out of grid-connected variants W1 is the best one, regardless of the subsidy value from funds supporting renewable energy sources. In case of smaller own funds, W3 is an alternative solution, as confirmed by IRR and PBP, which are the most advantageous in comparison to variant W2. The exemplary course of NPV rate as a function of installation lifespan is presented on the diagram (fig. 3 and 4). According to these diagrams (fig. 3 and 4), the operation of the photovoltaic farm as an autonomous facility will generate losses in each variant, as indicated by the negative NPV values and PBP return period exceeding project lifespan. A subsidy covering above 50% of investment costs will guarantee a minimum profitability of such a project.

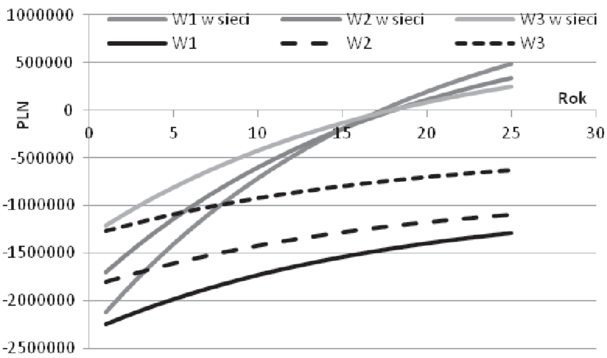

Fig. 3. Course of NPV rate in the operating period, assuming own project funding

Table 3. Values of profitability rates of the photovoltaic farm delivery

Variants of grid-connected installation				
Rate	Subsidy value	W1	W2	W3
NPV	Own funds	485,4 kPLN	342,3 kPLN	253,3 kPLN
	Subsidy 50%	1 756,5 kPLN	1 274 kPLN	915,2 kPLN
	Subsidy 75%	2 338 kPLN	1 756,9 kPLN	1 246,2 kPLN
IRR	Own funds	8,01%	7,77%	7,84%
	Subsidy 50%	19,23%	18,07%	18,20%
	Subsidy 75%	38,93%	36,71%	36,95%
SPBP	Own funds	10,7 years	10,9 years	10,8 years
	Subsidy 50%	5,1 years	5,4 years	5,4 years
	Subsidy 75%	2,6 years	2,7 years	2,7 years
PBP	Own funds	17,3 years	18,0 years	17,8 years
	Subsidy 50%	6,3 years	6,8 years	6,7 years
	Subsidy 75%	2,9 years	3,1 years	3,0 years
Autonomous variants				
NPV	Own funds	- 1 290,3 kPLN	- 1 097,9 kPLN	- 627,2 kPLN
	Subsidy 50%	- 127,3 kPLN	- 166,2 kPLN	34,6 kPLN
	Subsidy 75%	454,1 kPLN	299,6 kPLN	365,6 kPLN
IRR	Own funds	-	-	0,15%
	Subsidy 50%	4,73%	3,96%	6,45%
	Subsidy 75%	13,19%	11,99%	15,92%
SPBP	Own funds	29,0 years	31,4 years	24,5 years
	Subsidy 50%	14,5 years	15,7 years	12,3 years
	Subsidy 75%	7,2 years	7,8 years	6,1 years
PBP	Own funds	no capital return	no capital return	no capital return
	Subsidy 50%	exceeds 25	exceeds 25	22,4 years
	Subsidy 75%	9,7 years	10,9 years	7,8 years

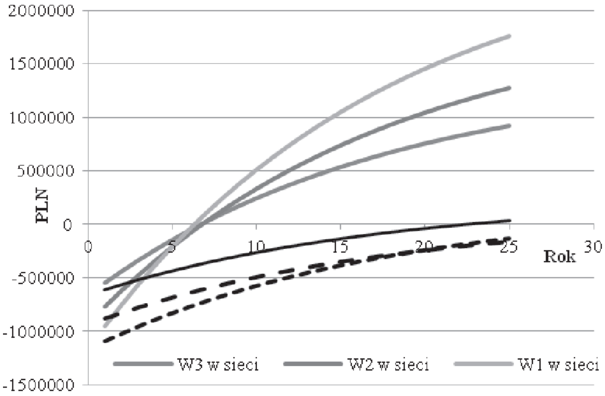

Fig. 4. Course of NPV rate in the operating period, assuming 50% subsidy from funds supporting renewable energy sources

Having analysed the project by means of NPVR and DGC rates one can state that power generated in photovoltaic farms connected to the grid, in spite of small unit investment profits (from 0,18 in variant W2 up to 0,21 PLN to variant W1), brings about a positive environmental effect in form of reduction of CO_2 emission (fig. 5). The environmental effect generation cost clearly distinguishes variant W1 (DGC=-0,4PLN/kgCO_2) from other variants (fig. 5).

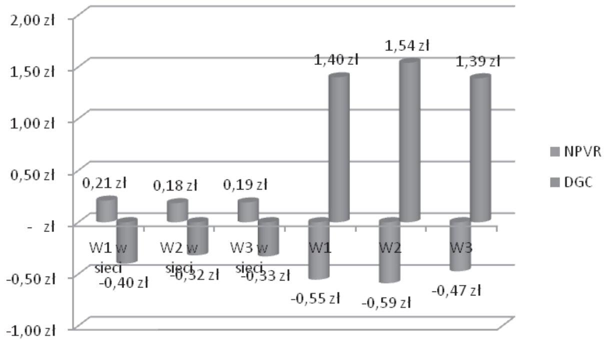

Fig. 5. NPVR rate and technical generation cost in case of own funding

Also in this case, if a municipality due to limited funds does not choose W1, it may choose W3 as an alternative. It is worth noting that complete own funding for autonomous operation is not efficient.

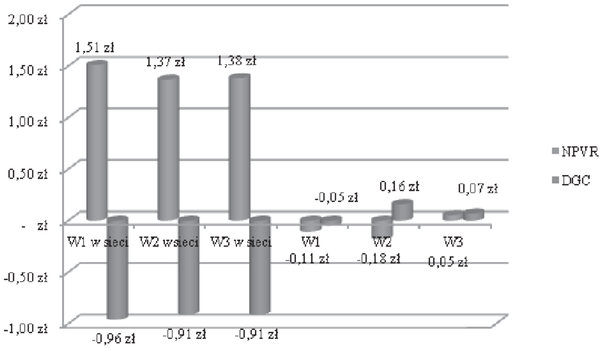

Fig. 6. NPVR rate and technical generation cost in case of 50% subsidy from funds supporting renewable energy sources

While analysing the diagram (fig. 6) one can notice that in spite of disadvantageous economic NPVR rates of the autonomous system regardless of the variant, in case of a 50% subsidy of renewable energy sources, the W1 variant is profitable from the environmental point of view (DGC < 0).

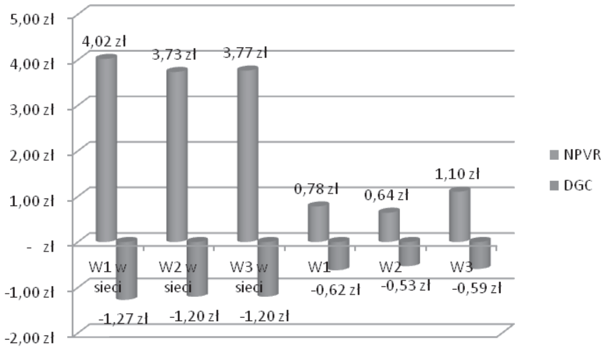

Fig. 7. NPVR rate and technical generation cost in case of 75% subsidy from funds supporting renewable energy sources

In case of subsidising 75% of project value, all variants are profitable for the municipality, while the best one is W1 in case of grid connection and W3 in case of autonomous operation (fig. 7). This variant generates the greatest benefits (NPVR=1.1PLN) compared to others, while it is only slightly worse (0.03PLN) in its environmental aspect than others.

CONCLUSIONS

1. While analysing the evaluation factors one can conclude that the operation of the photovoltaic farm within the power grid is a better solution, as confirmed by all rates. Out of grid-connected variants W1 is the best one, regardless of the subsidy value from funds supporting renewable energy sources. In case of smaller own funds, W3 is an alternative solution, as confirmed by IRR and PBP, which are the most advantageous in comparison to variant W2.
2. Having analysed the project by means of NPVR and DGC rates one can state that power generated in photovoltaic farms connected to the grid, in spite of small unit investment profits brings about a positive environmental effect in form of reduction of CO_2 emission. The environmental effect generation cost clearly distinguishes variant W1 (DGC=-0,4PLN/kgCO_2) from other variants. If a municipality due to limited funds does not choose W1, variant W3 is the best alternative. It is worth noting that complete own funding for autonomous operation is not efficient.
3. In case of subsidising 75% of project value, all variants are profitable for the municipality, while the best one is W1 in case of grid connection and W3 in case of autonomous operation. This variant generates the greatest benefits (NPVR) compared to others, while it is only slightly worse in terms of environmental aspect than others.

REFERENCES

1. **Bartnik R. 2008**. Rachunek efektywności techniczno-ekonomicznej w energetyce zawodowej. Oficyna Wydawnicza Politechniki Opolskiej. Opole.
2. **Bławat F. 2010**. Analiza Ekonomiczna. Wydawnictwo Politechniki Gdańskiej. Gdańsk.
3. Dziennik Ustaw z 2005 roku. Protokół z Kioto do Ramowej konwencji Narodów Zjednoczonych w sprawie zmian klimatu. Dz.U.05.203. 1684.
4. Dyrektywa Parlamentu Europejskiego i Rady 2009/28/WE z dnia 23 kwietnia 2009 roku w sprawie promowania stosowania energii ze źródeł odnawialnych zmieniająca i w następstwie uchylająca dyrektywy 2001/77/WE oraz 2003/30/WE.
5. **Jerzemowska M. (red.) 2006**. Analiza ekonomiczna w przedsiębiorstwie. PWE. Warszawa.
6. **Johnson H. 2000**. Ocena projektów inwestycyjnych. Maksymalizacja wartości przedsiębiorstwa. LIBER. Warszawa.
7. **Knaga J., Szul T. 2012**. Optimising the selection of batteries for photovoltaic applications. TEKA. Commission of Motorization and Energetics in Agriculture – 2012, Vol. 12, No. 1, 73–77.
8. **Laudyn D. 1999**. Rachunek ekonomiczny w elektroenergetyce. Oficyna Wydawnicza Politechniki Warszawskiej. Warszawa.
9. **Ministerstwo Gospodarki 2009**. Polityka energetyczna Polski do 2030 roku. Załącznik do uchwały 202/2009 Rady Ministrów z dnia 10 listopada 2009.
10. **Modzelewski A. 2010**. Wyzwania związane z inwestycjami w nowe moce wytwórcze Elektroenergetyka: współczesność i rozwój. Nr 2-3(4-5). Polskie Sieci Elektroenergetyczne Operator S.A. s. 38-45.
11. Ramowa Konwencja Narodów Zjednoczonych w sprawie Zmian Klimatu (UNFCCC), Rio de Janeiro, 1992.
12. **Rączka J. 2002**. Analiza efektywności kosztowej w oparciu o wskaźnik dynamicznego kosztu jednostkowego. TRANSFORM ADVICE PROGRAMME Investment in Environmental Infrastructure in Poland. NFOŚiGW. Warszawa.
13. **Rogowski W. 2004**. Rachunek efektywności przedsięwzięć inwestycyjnych. Oficyna Wydawnicza. Kraków.
14. Rozporządzenie Ministra Gospodarki z dnia 18 października 2012 r. „w sprawie szczegółowego zakresu obowiązków uzyskania i przedstawienia do umorzenia świadectw pochodzenia, uiszczenia opłaty zastępczej, zakupu energii elektrycznej i ciepła wytworzonych w odnawialnych źródłach energii oraz obowiązku potwierdzania danych dotyczących ilości energii elektrycznej wytworzonej w odnawialnym źródle energii", Dz.U. 2012 nr 0 poz. 1229
15. **Skorek J. 2002**. Ocena efektywności energetycznej i ekonomicznej gazowych układów ko generacyjnych małej mocy. Wydawnictwo Politechniki Śląskiej. Gliwice.
16. **Szul T. 2012**. Energetyczne wykorzystanie biogazu do produkcji energii elektrycznej i ciepła w skojarzeniu w średniej wielkości oczyszczalni ścieków. Część 2. Analiza ekonomiczna . Technika Rolnicza, Ogrodnicza, Leśna nr 2.
17. **Urząd Regulacji Energetyki. 2013**. Sprawozdanie Prezesa Urzędu Regulacji Energetyki w 2012 r. Warszawa.
18. Ustawa z dnia 15 kwietnia 2011 r. o efektywności energetycznej. Dz.U. z 2011 nr 94 poz. 551.
19. **Wiśniewski G (red.), Więcka A., Dziamski P., Kamińska M., Rosołek K., Santorska A. 2012**. Małoskalowe odnawialne źródła energii i mikroinstalacje. Instytut Energii Odnawialnej. Publikacja Fundacji im. Heinricha Böll. Warszawa.
20. **Wojciechowski H. 2010**, Efektywność techniczna i ekonomiczna rozproszonych i rozsianych układów wytwarzania energii, „Instal" nr 6.

OPTYMALIZACJA WIELOKRYTERIALNA SYSTEMÓW FOTOWOLTAICZNYCH DLA OBIEKTÓW KOMUNALNYCH

Streszczenie. W pracy przedstawiono analizę techniczno-ekonomiczną elektrowni fotowoltaicznej pracującej na potrzeby gminnej oczyszczalni ścieków. Produkcję energii w elektrowni fotowoltaicznej rozpatrzono w dwóch aspektach tj. włączonej do sieci z możliwością oddawania energii do sieci w czasie jej nadprodukcji, oraz w układzie autonomicznym, w którym energia będzie tylko na potrzeby oczyszczalni ścieków bez możliwości oddawania do sieci. Na podstawie analizy stwierdzono, że lepszym rozwiązaniem jest praca elektrowni fotowoltaicznej w sieci energetycznej. Pomimo, niewielkich jednostkowych zysków z inwestycji, przynosi ona korzystny efekt ekologiczny w podstacji kosztów ograniczenia emisji CO2. Gmina chcąc implementować instalację fotowoltaiczną w swoich obiektach powinna ubiegać się o różnego typu subwencje na ten cel, ze względu na to, że jedynie dotacja wyższa niż 50% kosztów inwestycji pozwoli na uzyskanie minimalnej rentowności przedsięwzięcia.

Słowa kluczowe: elektrownia fotowoltaiczna, analiza techniczno-ekonomiczna instalacji fotowoltaicznych, oczyszczalnia ścieków, dotacje na odnawialne źródła energii.