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Comparative analysis of production costs of electricity generated from various renewable energy sources

***Abstract**. The article presents a comparison of costs of electricity production in a wind power plant and using photovoltaic systems. The comparative analysis also included the total costs of energy production and estimation of the return on investment time.*

Streszczenie.** W artykule przedstawiono porównanie kosztów produkcji energii elektrycznej w elektrowni wiatrowej i z wykorzystaniem systemów fotowoltaicznych. Przeprowadzono analizę porównawczą odnawialnych źródeł energii elektrycznej uwzględniającą całościowe koszty produkcji energii oraz oszacowanie czas zwrotu inwestycji.* ***Porównanie kosztów produkcji energii elektrycznej w elektrowni wiatrowej i z wykorzystaniem systemów fotowoltaicznych

Keywords: technical and economic analysis of the investment, wind power plant, photovoltaic power plant.
Słowa kluczowe: analiza techniczno-ekonomiczna inwestycji, elektownia wiatrowa, elektrownia fotowoltaiczna.

Introduction

In the last decades, there has been rapid development and use of renewable energy sources (RES) throughout the world. This began to result not only from ever more restrictive decrees requiring the reduction of environmental pollution, but mainly due to economic reasons. Renewable energy sources have almost unlimited renewable energy resources compared to fossil fuels, and that type of resources is constantly shrinking. Political events in the 1970s and the associated fuel and energy crisis caused an increase in a number of research on the use of renewable energy in the industrialized countries to obtain an alternative in the use of oil and gas. The society around the world is also aware that by using fossil fuels further to the same extent and even more, they contribute greatly to pollution of the Earth's environment, causing high emission of carbon dioxide into the atmosphere, which significantly contributes to the greenhouse effect.

Overall demand for electricity in Poland and around the world increases every calendar year, thanks to the constantly growing economic development. As a result of this process, new investments are needed to maintain the country's energy demand at an appropriate level. An additional factor affecting the need for new investments in the Polish energy sector is the aging process of existing power units. Investment in renewable energy sources allows to significantly reduce expenses and time devoted to the construction of new power plants, whose main fuel is fossil fuels.

Solar and wind energy have the largest share in the energy market, due to the fact that this type of energy is available in almost every corner of the globe. However, the distribution of this energy is uneven, there are places where the value of solar or wind energy is higher, and in others it is much smaller. Therefore, areas that are extremely profitable for the use of solar energy and in other places for wind energy can be distinguished all over the world.

Making a comparative analysis of the cost of production of electricity is an essential element of investment in green energy. This is due to the fact that every individual investing their funds in this type of venture, hopes that with time obtains revenues, which will result in the total return on investment. The investor before taking any action, carefully consider all the analysis aiming at determining the approximate unit cost of production, which is incurred as a result of the production of electricity.

Each electricity production costs have three main factors on which they depend:

- capital expenditures, financial resources that have been invested in the construction of the installation,
- fixed costs, resulting from the need to maintain a continuous operation of the power plant, which includes, among others: employee salaries, renovation and maintenance fees,
- variable costs, containing mainly finances related to the cost of fuel purchase, in the case of renewable energy sources, and more specifically solar and wind energy; these costs are negligible because they only include concession fees.

The LCOE (Levelized Cost Of Energy) method is the most frequently used method to calculate the costs of electricity production.

$$LCOE = \frac{\sum_{t=0}^{N} \frac{[I_t + M_t]}{(1+r)^t}}{\sum_{t=0}^{N} \frac{E_t}{(1+r)^t}} \quad (1)$$

where: I_t – capital expenditures in the i-th year, M_t – operating expenses, E_t – electricity production in the i-th year, r – discount rate.

The LCOE method takes into account all necessary factors contributing to the cost of electricity production. It is widely used for comparative analyzes of various methods of electricity production.

The main condition for the profitability of each investment in renewable energy is the simple payback period of SPBT expenditures, which is defined as follows:

$$SPBT = \frac{K_i}{WRK} \quad (2)$$

where: *SPBT* – time of return of investment outlays, K_i – investment outlays, *WRK* – the value of the average annual benefits of the investment.

One of the conditions necessary to implement the case of the profitability of the entire investment is the total payback period of incurred financial outlays, so that it is shorter than the assumed time of operation of the invested installation.

Analyzed object

The subject of the comparative analysis of unit costs of electricity production along with the payback period will be an example of a 5 kW wind and solar power plant. The installations are located on the outskirts of the city of Wroclaw.

A 5 kW wind power plant with a 10 m high mast was installed near a single-family building on the outskirts of Wrocław. For the comparative analysis, a complete set of wind power plant was selected, the most important part being an electric generator with a wind turbine with the parameters shown in table 1. A power plant connected to the power grid without the use of a battery bank.

Table 1. Technical parameters of the electric generator and wind turbine

Technical parameters of the wind turbine	
Diameter of the rotor	7 m
Nominal power	5 kW
Wind speed at nominal power	8.8 m/s
The starting wind speed	3.0 m/s
Wind speed off	2.0 m/s ↓ i 18 m/s ↑
Speed range	60 ÷ 200 rpm
Number of blades	3
Technical parameters of the generator	
Type	PMG
Nominal power	5.5 kW
Nominal RPM	187.5 RPM
Efficiency	0,97
Drive system	without gear

On the basis of data available from the manufacturer, the turbine power distribution for individual wind speeds was determined.

On the basis of data on environmental conditions, the frequency of individual wind classes from the Weibull distribution was obtained (3).

(3) $$\boldsymbol{p(V)} = \frac{\boldsymbol{k}}{\boldsymbol{A}} \times (\frac{\boldsymbol{V}}{\boldsymbol{A}})^{\boldsymbol{k-1}} \times \boldsymbol{e}^{[-(\frac{V}{A})^{k}]}$$

where: *p(V)* – frequency of wind speed appearance value V, *k* – shape parameter, *A* – scale parameter, *V* – wind speed.

The Weibull distribution (Tab. 2) presents the percentage distribution of individual wind classes based on long-term measurements at a height of 12 meters, which may occur during the year in a given area.

Table 2. Weibull distribution for specific wind speed speeds

Wind speed [m/s]	Frequency ofappearance [%]
1	13,99
2	19,28
3	19,33
4	16,20
5	11,89
6	7,81
7	4,66
8	2,54
9	1,28
10	0,59
11	0,26
12	0,10

Losses resulting from wind power plant equipment were assumed, such as 1% loss on pipes, inverter losses of 7% and generator losses of 3%. The total losses were 11%.

On the basis of the data from Table 2 and losses resulting from the used devices, as well as on the basis of formula (4), the electric energy output from the 5 kW wind power plant was calculated assuming that the system will operate 365 days a year (8,760 hours).

(4) $$P_{real} = (k \times P) \times t \times \eta$$

where: *k* – the percentage of the Weibull distribution corresponding to a given wind speed, *P* – wind turbine power for a given wind speed, *t* – number of hours in a year, *η* – system efficiency.

Substituting for formula (4) we get the following value

(5) $$P_{real_{3\frac{m}{s}}} = (k \times P) \times t \times \eta =$$

$$= \left(\frac{19.33}{100} \times 0.20\right) \times 8760 \times 0.89 = 301.4\ [kWh]$$

On this basis the production of electricity for different wind speeds. During the year (8,760 hours), the wind power plant located in Wrocław will produce 6203.1 kWh.

Photovoltaic installation with a capacity of 5 kW with an area of 34 m2 was mounted on the roof of a single-family building on the outskirts of Wrocław. Installation placed directly in the southern direction at an angle 45°.

A complete photovoltaic system composed of 250 W polycrystalline solar panels was selected for the comparative analysis (Tab. 3). The installation will work as a grid-connected, i.e. integrated with the electrical network, without the use of batteries.

Table 3. Technical parameters of the positioned photovoltaic installation

Mechanical parameters	
Photovoltaic cells	60 arts; polycrystalline 156x156 mm
Frame	Anodized aluminum
Protective glass	Tempered glass 3.2 mm
Weight	19 kg
Dimensions	1640x992x40mm
Electrical parameters	
Max power. [P_{max}]	250 W
The current at the maximum power point [I_{mpp}]	8,20 A
Voltage at max. Power point. [V_{mpp}]	30,5 V
Short circuit current [I_{sc}]	8,79 A
Maximum voltage (idle) [V_{oc}]	37,3 V
Efficiency of modules	15,4 %
Working temperature	-40 do +85 °C
The maximum system voltage	1000V DC
Efficiency after 12 years	90 % of base power
Efficiency after 25 years	80 % of base power

On the basis of data on environmental conditions, data on insolation of the given area were obtained. Using the solar data from the meteorological station and the calculated day length of individual months of the year, the average monthly intensity of solar radiation on the surface for south orientation and slope for three planes : 30 °, 40 °, 60 °. formula (6).

(6) $$I_{śrS\_30} = \frac{I_{S\_30}}{t} = \frac{32931\ [\frac{Wh}{m^2}]}{255\ [h]} = 129.1\ [\frac{W}{m^2}]$$

where: $I_{śrS\_30}$ - sum of total solar radiation on the surface with south orientation and inclination to 30 °, *t* - number of daytime hours in the month.

Losses resulting from photovoltaic plant equipment were assumed, such as 1% losses on wires, 5% loss of the inverter, 7% solar losses on solar modules, 2% shading losses and 1% stain loss . Total losses amounted to 16%.

Based on the number of daytime hours and losses resulting from the devices used, based on formula (7), the yield on electricity from photovoltaic panels with a total capacity of 5 kW was calculated assuming that the installation will operate 365 days a year.

(7) $$P_{real} = t \times \frac{I_{avg}}{STC} \times E_p \times \eta$$

where: *t* – number of daily hours in the month, I_{avg} – the average intensity of solar radiation for a given month [W/m2], *STC* – intensity of solar radiation in laboratory conditions – 1000 [W/m2], E_p – power of photovoltaic panels – 5 [kW], *η* – overall installation efficiency – 84 [%].

Substituting for formula (8) we get the following value

$$(8) \qquad P_{real_{january-S45}} = 255\ [h] \times \frac{139.7\left[\frac{W}{m^2}\right]}{1000\left[\frac{W}{m^2}\right]} \times 5[kW] \times 0.84 = = 149.6\ [kWh]$$

During the year, the energy yield from the 5 kW photovoltaic plant would amount to 4,200,2 kWh with the assumption of losses at the level of 16%.

Based on data from the photovoltaic cell manufacturer (Tab. 3), it was assumed that the nominal power of photovoltaic panels after 12 years will be 90%, and in the 25th year of operation 80% of the nominal power. On this basis, the electricity yield was calculated within 25 years of using the photovoltaic system, which is 94714.4 kWh; with the assumption that the insolation conditions will not change, and the power drop of photovoltaic panels will decrease linearly.

Economic analysis

In the calculation of the investment payback period, a system of guaranteed price tariffs supporting the use of renewable energy sources was used.

The Act on renewable energy sources [1] includes options related to the settlement of electricity. One of them is a system of guaranteed tariffs, also known as FIT tariffs (Feed-In Tariff). Such tariffs guarantee for a period of 15 years a fixed rate for the purchase of electricity produced as part of renewable energy technologies. In the case of installations with power from 3 to 10 kW, the rate is 0.45 PLN / kWh.

The Act on renewable energy sources [1] also introduces the possibility of using the net-metering system. The net-metering system, ie net electricity balancing, is used in installations with a capacity of up to 40 kW. The main element of such a system is a two-way electricity meter set up by the grid operator. The meter measures the difference between produced and consumed electricity. As a result of surplus production, energy is sold.

The first object to be analyzed is the wind power plant.

When determining the unit costs of electricity production, the cost of a wind power plant should be taken into account along with the assembly of PLN 48,000.00, the lifetime of a wind power plant for 25 years, annual operating costs and others - PLN 350, capital expenditures in the i-th year - PLN 48000.00 PLN, operating expenses - PLN 350, electricity production in the i-th year [kWh] and discount rate - 10%.

Based on formula 1, calculations of averaged unit costs of electricity production were carried out throughout the entire lifetime of the wind power plant is 0.88 [PLN/kWh].

The unit cost of electricity production from a 5 kW wind power plant, over a 25-year period of operation, amounted to 0.88 PLN / kWh.

It was assumed that the annual consumption of electricity by a household is 2,600 kWh. It was also assumed that 65% of all electricity produced will be sold under guaranteed tariffs at a price of PLN 0.45 / kWh. The share of energy consumed for own needs will amount to 35%. The remaining missing part of electricity will be purchased from the distribution system operator at the price of PLN 0.45 / kWh.

The cost of purchasing electricity from a distribution network for a household consuming 2600 kWh / year would amount to PLN 1690 / year in the G11 tariff.

The entire wind power plant is 100% financed by the investor without the participation of loans.

Energy produced, 35% of electricity is consumed for own needs is PLN 2171.1.

The amount of electricity purchased from the DSO, in the assumption: consumption - 2600 [kWh], own production 2171.1 [kWh] is 428.9 [kWh].

The cost of purchasing electricity from the DSO (the amount of energy purchased - 428.9 [kWh], cost - 0.45 [PLN / kWh]) is PLN 193.01.

The amount of electricity produced by wind power plant and sold to the power grid - 65% of production is 4032.0 [kWh].

Revenue from the sale of electricity - 4032.0 [kWh], selling price 0.45 [PLN / kWh] is PLN 1814.40.

Total annual income from a wind power plant is PLN 1621.39.

Profit resulting from income (1621.01 [PLN]) and from the amount saved for buying all electricity in a year (PLN 1690.00 [PLN]) is PLN 3311.39.

As a result of the FIT tariffs being discontinued after 15 years, the electricity generated will be settled as part of the net-metering system.

Electricity surplus (calculated for the annual period) is 3603.1 [kWh].

Profit resulting from the sale of produced surplus electricity under the net-metering system is PLN 900.79.

The fee resulting from the transmission of electricity purchased from the DSO is PLN 115.80.

Annual profit after the period of validity of the guaranteed tariffs is PLN 2161.89.

As a result of the calculations of sales of produced electricity under the guaranteed tariffs after 15 years, a cumulative profit of PLN 58822.92 was obtained.

The average annual profit over the 15 years of validity of the guaranteed tariffs is PLN 3881.93.

The payback period is (based on formula (2) is 12.4 [year].

From the calculation of a simple return on financial outlays, it appears that the total investment in a wind power plant will be recovered after around 12 years.

Assuming that the installation will operate uninterruptedly and without failure over the assumed exploitation period (25 years), after a period of 12.4 years, electricity will be sold, which will accumulate pure profit.

Total profit after deducting investment costs for a wind power plant is PLN 31847.78.

The total profit after 25 years of operation of the wind power plant - in the assumption of using the guaranteed tariffs up to the 15th year of use and the net-metering system in the years 16-25 - would amount to PLN 31847.78.

The second object to be analyzed is the photovoltaic power plant.

It was assumed that the annual consumption of electricity by a household is 2,600 kWh. It was also assumed that 65% of all electricity produced will be sold under guaranteed tariffs at a price of PLN 0.45 / kWh. The share of energy consumed for own needs will amount to 35%. The remaining missing part of electricity will be purchased from the distribution system operator at the price of PLN 0.45 / kWh.

The cost of purchasing electricity from a distribution network for a household consuming 2600 kWh / year would amount to PLN 1690 / year in the G11 tariff.

The entire photovoltaic installation will be 100% financed by the investor without the participation of loans.

Energy produced, 35% of electricity consumed for own needs is 1470.1 [kWh].

The amount of electricity purchased from the DSO, in the assumption of consumption - 2600 [kWh], own production 1470.1 [kWh] is 1129.9 [kWh].

The cost of purchasing electricity from the DSO (the amount of energy purchased - 1129.9 [kWh], cost - 0.45 [PLN / kWh]) is PLN 508.46.

The amount of electricity produced by the solar system and sold to the power grid - 65% of production is 2730.1 [kWh].

Revenue from the sale of electricity - 2730.1 [kWh], sales price 0.45 [PLN / kWh] is PLN 1228.55.

Total annual income from a solar system is PLN 720.08.

Profit from income and from the amount saved for buying all electricity in a year is PLN 2730.12.

As a result of the FIT tariffs being discontinued after 15 years, the produced electricity will be settled as part of the net-metering system.

Electricity surplus (calculated for the annual period - the amount of energy produced in 16 - including 3683.2 [kWh]) is 1083.2 [kWh].

Gain resulting from the sale of produced surplus electricity under the net-metering system is PLN 270.81.

The fee resulting from the transmission of electricity is PLN 353.93.

Annual profit after the period of validity of the guaranteed tariffs is PLN 1606.88.

As a result of calculations of sales of produced electricity under guaranteed tariffs, after 15 years a cumulative profit of PLN 38568,31 was obtained.

The average annual profit over the 15 years of validity of the guaranteed tariffs is PLN 2571.22.

The payback period is (based on formula 2) is 12.4 [year].

From the calculation of a simple return on financial outlays, it appears that the total investment in the solar system will pay back after around 12 years.

Assuming that the installation will work without interruption and failure-free for the assumed exploitation period (25 years), after a period of 12.4 years, electricity will be sold, which will accumulate clean profit.

Total profit after deducting the costs of investments in a solar plant is PLN 22236.20.

The total profit after 25 years of photovoltaic system operation - assuming the use of guaranteed tariffs up to the 15th year of use and the net-metering system in the years 16-25 - would amount to 22236,20 PLN.

Conclusions

The production of electricity from a wind power plant as well as using photovoltaic panels depends to a large extent on the location of a given installation. Comparing two analyzed RES installations with the same power (5 kW), located in the same places, it can be deduced from the produced electricity during the calendar year that the investment in a wind power plant is more profitable. In the case of a wind power plant, the energy yield was 6203.1 [kWh], while in the solar system under analysis 4200.2 [kWh]. The second aspect in favor of wind energy in this case is the maintenance of constant production parameters over the entire lifetime, where photovoltaic panels after about 25 years have only 80% of the initial power.

The analysis of unit costs of electricity production using the LCOE method for a wind power plant and photovoltaic system made it possible to determine the expenses for producing one kilowatt hour. In the case of a wind power plant, this cost was 0.88 [PLN / kWh], while in a solar system the price is slightly higher, as it amounts to 0.90 [PLN / kWh].

Analyzing the period of return of a given investment over time, the method of a simple payback period of SPBT expenditures was used.

In the case of the analyzed wind power plant with a capacity of 5 [kW] with a total cost of 48000.00 [PLN], using the tariffs guaranteed for 15 years of operation, the payback period was 12.4 years, i.e. when the guaranteed tariffs are still in force. The calculated profits after the exploitation period of 25 years amount to PLN 31847.78.

In a solar plant with the same power as in the case of a wind power plant, but with a smaller total cost of 31900.00 [PLN]. In the case of guaranteed tariffs, the payback period was 12.4 years, while in the case of profits they amounted to PLN 22236.20.

Summing up, the financial analyzes carried out for two different types of power plants using renewable energy sources allow to conclude that an investment in wind power for a given installation site would be the best solution, both in economic and production terms of electricity.

It should also be remembered that the profitability of a photovoltaic plant depends on many variable factors, such as: the amount of investment, the price of electricity that will be sold to the grid, installation performance, legal regulations and exchange rates. It should be noted that an important aspect is to find a source of financing for such projects, because during the investment the photovoltaic plant does not generate any income. If there is a lack of sufficient funds for the implementation of the project, you should look for external financing, for example a subsidy. When analyzing profitability, one should also remember about the costs related to the modernization and decommissioning of the power plant after the end of its operation period.

The support period for designed photovoltaic systems is 15 years and it is quite reasonable, which allows investors to fully calculate the profitability and net profit of the project. However, instability of the support system increases the investment risk, which results in increased interest in EU subsidies, which in turn, from the banks financing the investment, increase the debt repayment ratio. It is worth adding that banks often do not want to support such projects, which adversely affects and slows down the development of the entire photovoltaic industry.

As of today, with the current costs of construction of photovoltaic power plants, their efficiency and legal regulations, such investments are unprofitable from the economical point of view.

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