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THE ANALYSIS OF THE SOLAR POWER PLANT PERFORMANCE IN TEMPERATE CLIMATE

Due to gradual depletion of fossil fuels resources and emission of harmful chemicals accompanying the combustion process, the interest in alternative energy sources still increases. Among many kinds of alternative sources, solar radiation is very special because of its wide availability and large technical potential. Photovoltaic systems providing the electric energy are used in many countries. The most important part of photovoltaic system is a module, which parameters (e.g. efficiency, rated power, temperature coefficients of power and efficiency, short circuit current, open circuit voltage) are determined in laboratory tests under Standard Test Conditions (STC: 25°C, 1,000 W/m^2, air mass 1.5). However, in real outdoor conditions the modules exhibit lower efficiency since local climate influences their performance and different external factors generate energy losses in the whole system. The aim of this work is the performance analysis of a solar power plant connected to the grid, which total rated power is 2.985 MW and it works in temperate climate in eastern Poland. Insolation in the location was estimated according to Solargis data and the role of the modules tilt angle, of which the value is non-typical for the considered location was studied. The tilt angle smaller than optimal angle allows increasing the amount of the solar radiation collected in the summer period. The electric energy production based on the inverters data in 2016 and 2017 as well as yearly yield are presented. The results are compared to data coming from other solar power plants, also located at high latitude.

Keywords: photovoltaics, grid connected solar plant, photovoltaic performance, inclination angle, tilt angle

1. Introduction

The Polish National Renewable Action Plan required by the EU Renewable Energy Directive (2009/28/EC) predicts that electricity from all renewable energy

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sources (RES) should reach 19.13% of the final energy supply and their total share should achieve 15.5% in the gross final energy consumption by 2020. Since 2009, in Poland, some progress has been made in using of RES, especially wind, biomass and solar energy. Among many kinds of RES the Sun is the largest source, which can be considered as an infinite one from our perspective. The power of the solar radiation incoming to the Earth equals 120,000 TW annually and the solar radiation can be harnessed in all areas of the world [1]. Current energy demand equals to 15 TW and is supposed to grow up to 35 TW in 2050. Solar energy is a valuable alternative to fossil fuels combustion as it allows reduction of the release of harmful chemicals like oxides of carbon, sulfur and nitrogen as well as dust [2].

In 2017 in Poland cumulative installed photovoltaic (PV) capacity exceeded 200 MW (overall of 420 GW is installed in Europe) and nowadays it accounts for 2.3% of all renewable energy and 0.5% of the total capacity installed in the Polish energy system [3]. At present, according to the legal regulations introduced in 2016, net metering (up to 40 kW) and an auction mechanism for large-scale projects (over 40 kW) are two ways supporting photovoltaics, which replaced the green certificate mechanism in July 2016 (according to Renewable Energy Law introduced in Poland in 2015).

The most important parameter that has to be taken into account at the planning stage of photovoltaic system is solar irradiation. In Poland yearly irradiation is in the range of 950–1,250 kWh/m^2 at south azimuth and horizontal plane. Average value of irradiation is equal to 1,289 kWh/m^2 at 30^o of inclination angle [4]. The important parameter that provides information about the access to solar energy in a given location is also sunshine duration expressed in hours, which is a general indicator of cloudiness and depends on the length of the day and kind of season. In Poland most of PV installations are situated in the SE part of the country due to good insolation and favorable values of the sunshine duration (1680 h) compared to other locations. In this region in 2017 over 80 MW were connected to the grid. The solar power plant where we perform our investigations is also located in this part of the country.

The role of the location of PV systems is widely analyzed. In the given place various climate elements influence the performance of PV installations [5–7]. The most important factors are: solar irradiation, ambient temperature, wind speed, however it is worth to notice that spectral changes, humidity and dust also have a significant impact on the PV performance. The particular location, especially the latitude value, determines also the inclination angle of the modules due to changes of Sun declination.

This paper is devoted to analysis of the performance of the solar plant situated in eastern Poland, under temperate climate conditions. The results of energy production are correlated with annual irradiation changes and the role of inclination angle of the modules, which differs from the optimum value, is also discussed.

2. Experimental facility

The entire capacity of the studied plant, situated in eastern Poland (longitude 22°54'E, latitude 51°10'N), is equal to 2.985 MW. There are two separate parts of the plant (0.995 MW and 1.99 MW), and both of them consist of typical pc-Si modules (Fig. 1), which are the most popular kind of modules in both residential PV systems and plants. Detailed specification of the modules is presented in Table 1. The values of crucial parameters such as efficiency, fill factor as well as temperature coefficient are determined in laboratory tests and provided by the manufacturer. The modules are oriented horizontally and inclined at an angle of 25°. The role of this non-typical inclination angle is discussed further. In addition to modules, other components such as 51 three-phase inverters Powador 30.0 TL3, transformer stations and steal construction elements were used.

Table 1. Technical data of modules (according to manufacturer datasheet)

Module type	Selfa SV60P.3
Dimensions	1.670 m × 0.983 m
Weight	19.4 kg
Maximum power	250 Wp
Fill factor	76.7%
Efficiency	15.3%
Temperature coefficient of power	- 0.42%/°C

Fig. 1. Photovoltaic power plant in eastern Poland

3. Results

The optimum inclination angle of PV array depends mainly on the latitude. The approximate values of optimum inclination angle can be determined according to the following formulas [8]:

$$\beta_{opt} = \varphi - \delta \tag{1}$$

in which δ – Sun declination, φ – latitude,

$$\beta_{opt} = \varphi \pm 10^{o} \tag{2}$$

where the positive and negative sings are used for winter and summer respectively [9],

$$\beta_{opt} = \varphi \pm 15^{o} \tag{3}$$

or it can be just equal to latitude [10].

Since the above simple calculation methods lead to different results, to improve the PV performance the year fixed accurate optimum tilt angle should be evaluated carefully in a particular region, not only on the basis of available solar radiation. At the latitude of about 51^{o}, where the studied solar power plant is located optimal inclination angle changes from 15^{o} in June to 64^{o} in December. Because of the annual movement of the Sun there are significant differences of irradiance: from 218 W/m^2 at south azimuth in December to 570 W/m^2 at south azimuth and optimum inclination angle in July. At the described plant the modules are tilted 25^{o} to the ground. The irradiation on the module plane at this untypical angle differs from the values obtained for the plane inclined at the optimal angle equal to 35^{o} for the considered latitude. The estimates of long-term monthly irradiation averages in both cases are presented in Table 2.

According to Table 2, the average daily irradiation at the optimum angle is equal to 1.8 kWh/m^2/day in winter and 5.065 kWh/m^2/day in summer. At the angle of 25^{o} the daily irradiation value in winter is smaller and equals to 1.75 kWh/m^2/day, in summer this value is higher, equal to 5.1 kWh/m^2/day. The tilt angle of 25^{o} ensures thus better usage of available solar radiation in summer than the typical angle of 35^{o}. Taking into account a correction factor of 1.12 [6], average yearly irradiation at the plane tilted by 25^{o} is equal to 1,266 kWh/m^2. The amount of electric energy produced by the solar plant in year 2016 and 2017 is presented in Figs. 2, 3. In the warm half of the year (April to September) the generated electric energy is much higher than in cold part of the year (October to March) and achieves 78% of the total value.

Table 2. The irradiation on the plane tilted at 35° and 25° (south azimuth, latitude 51°), according to PVGIS data [11]

Month	Irradiation on optimally inclined plane [Wh/m²/day]	Irradiation on plane at angle 25° [Wh/m²/day]
January	1,020	938
February	1,680	1,590
March	3,680	3,530
April	4,890	4,830
May	5,450	5,540
June	5,530	5,690
July	5,410	5,530
August	5,160	5,150
September	3,950	3,830
October	2,700	2,530
November	1,240	1,150
December	844	771
YEAR average	3,470	3,430

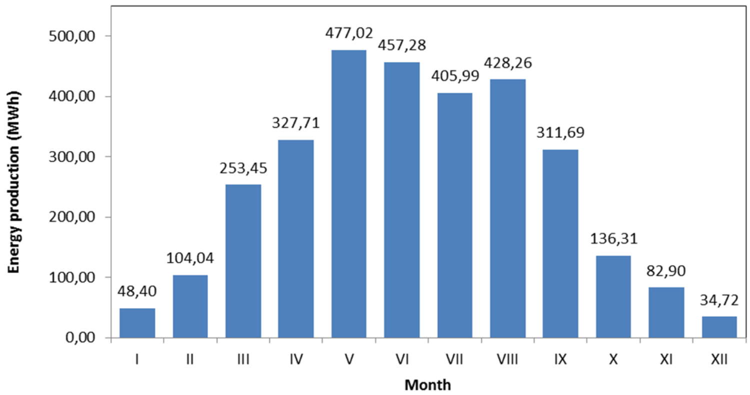

Fig. 2. Energy production in 2016

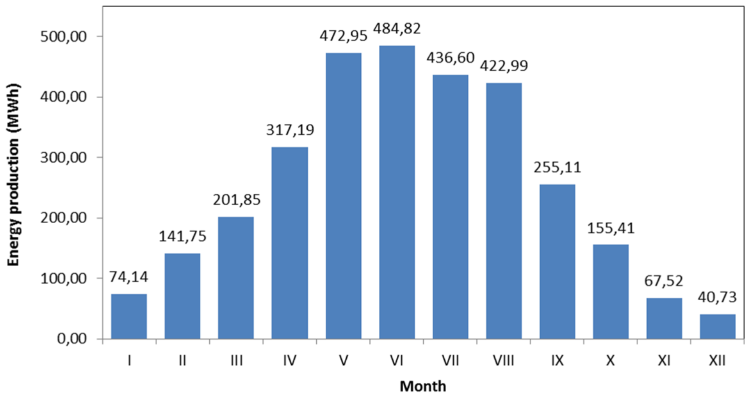

Fig. 3. Energy production in 2017

Basing on the energy production data, performance ratio, which is an important parameter characterizing the PV system, can be calculated according to the following equations:

$$PR = \frac{Y_f}{Y_r} \tag{4}$$

$$Y_f = \frac{E_o}{P_{DC}} \tag{5}$$

$$Y_r = \frac{Irr_p}{Irr_r} \tag{6}$$

in which: Y_f – final yield;
Y_r – reference yield;
E_o – final energy output [kWh];
P_{DC} – nominal DC power [kW];
Irr_p – total in-plane irradiation [kWh/m^2];
Irr_r – PV reference irradiance [kW/m^2].

PV reference irradiance is equal to 1,000 W/m^2. The performance ratio determined for the analyzed solar plant according to irradiation and energy output data of the PV system is equal to 81% which is a good value. The final yield of the photovoltaic power plant was compared with analogues values determined for other PV systems in Europe, including installations in countries located at higher latitudes such as Sweden, United Kingdom and Germany. The data in Table 3 show that the obtained final yield value is of the same order as in other places.

Table 3. The comparison of the data coming from different PV plants in Europe, according to data [12]

Plant location	Geographic coordinates	Nominal DC power [MWp]	Final energy output [MWh/year]	Yield, Y_f [kWh/Wp]
Kallinge Sweden	56°24'N 15°29'E	0.2	198	0.99
Liverpool United Kingdom	53°24'N 2°59'W	0.2	221	1.05
Trawniki Poland	51°10'N 22°54'E	3.0	3,068	1.03
Sława Poland	51°52'N 16°04'E	0.2	219	1.10
Bordziłówka Poland	51°51N 23°10'E	1.4	1,530	1.09
Espenhain Germany	51°12'N 12°31'E	5.0	5,000	1.00
Cruas France	44°39'N 4°45'E	1.2	1,800	1.45
Pagliare de Tronto Italy	42°86'N 13°77'E	0.2	235	1.18

4. Conclusions

At high latitude where the photovoltaic power plant is situated the solar irradiation received in the warm half of the year is significantly higher than in the cold part of the year. In the considered location, the inclination of photovoltaic modules at a smaller angle (25^o) than the yearly optimum angle (35^o) enables the collection of more solar radiation in summer which is reflected in high electric energy production during this period. Because of the significant differences between insolation in summer and winter at higher latitudes it would be worth considering applying the inclination angle smaller than the optimum value and subsequently giving priority to the collection of radiation in summer over the collection in winter. In addition to the variation of insolation it is also important that in the cold part of the year snowfall often occurs and residual snow causes shading and losses in energy production during this period. Therefore the horizontal orientation of modules, as in the case of the analyzed plant, is also a good solution that reduces negative consequences of residual snow.

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