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Rooftop Low Angle Tilted Photovoltaic Installation Under Polish Climatic Conditions

Agata Zdyb[1*], Grzegorz Szałas[1]

[1] Faculty of Environmental Engineering, Lublin University of Technology, Nadbystrzycka 40B, 20-618 Lublin, Poland

* Corresponding author's email: a.zdyb@pollub.pl

ABSTRACT

The performance of a 15 kWp roof mounted, low angle tilted photovoltaic installation over the year 2019 has been analyzed in terms of the role of solar irradiation, ambient and module temperature, clouds cover and wind speed. The studied photovoltaic system operates under warm summer humid continental climate with the considerable influence of temperate oceanic zone. The role of significant changes of weather conditions in warm and cold part of the year has been shown. The negative impact of external temperature increase on the modules efficiency has been observed. The experimentally determined temperature coefficient of efficiency of the modules is equal to -0.06%/°C. Relatively high sum of insolation registered in the location in 2019 together with a lack of shade assure annual energy yield of 1098 kWh/kWp, energy density 188 kWh/m^2, capacity factor 12.53% and performance ratio 82%.

Keywords: photovoltaic, climatic conditions, rooftop installation, polycrystalline modules.

INTRODUCTION

The use of solar radiation energy in photovoltaic (PV) technology plays a significant role in the process of transition to alternative energy sources and transformation of the global energy system. The Sun is the most powerful renewable energy source; therefore the use of photovoltaic modules spreads around the world, in places at various latitudes. The growing popularity of photovoltaics is influenced by the improvement of the price to efficiency ratio due to a number of modifications introduced recently to silicon modules of first generation. The laboratory efficiency of 26.7% was reached by monocrystalline Si solar cells and 22.3% by multi-crystalline Si [Green, 2021]. These achievements indicate the potential for further rise in the PV efficiency, also on an industrial scale. The performance ratio of the photovoltaic systems also increased in recent decades from 70% before 2000 to 80-90% reported nowadays [Photovoltaics Report, 2020].

Monitoring of the photovoltaic system performance provides the data on final energy yield, inverter efficiency, array and system losses, reliability of installation components and operation results for various technologies of PV modules [Belluardo et al., 2015; Zdyb and Gułkowski, 2020]. The study on the performance of the PV system carried under real external conditions demonstrates the role of different factors such as: solar irradiance, temperature, wind, humidity and dust [Lorenzo et al., 2014; Dirnberger et al., 2015; Louwen et al., 2017]. This kind of research is of great importance, since the tests of PV modules are performed by the manufacturers under standard test conditions (STC) which include fixed irradiance of 1000 W/m^2, temperature 25 °C and air mass 1.5. Additionally, some characteristic parameters of the newly produced modules are determined at the nominal operating cell temperature (NOCT); however, the indoor tests do not provide much insight into the final energy production under realistic ambient conditions. Therefore, the performance of photovoltaic systems is monitored at different latitudes and analyzed taking into account climatic variations. The research of this type is carried out both at high and low latitudes, at locations that significantly differ in terms of climate type [Gaglia et al., 2017; Romero-Fiances et al., 2019; Gułkowski et al., 2019]. Most of the investigations are devoted to different kinds of silicon modules since this technology is widespread in the photovoltaic market and applications. Silicon modules were always leading photovoltaic technology and in recent years they have been responsible for over 90% of global annual energy production.

The aim of this paper is the analysis of the outdoor performance of the rooftop photovoltaic installation composed of polycrystalline silicon modules. The PV installation is mounted on the roof of the building belonging to Lublin University of Technology, Poland, in which the modules are oriented to south and tilted at 14° angle, with no shading. The Köppen–Geiger climate classification system assigns this location to warm summer humid continental climate (Dfb); however, nowadays the considerable influence of temperate oceanic (Cfb) zone occurs due to climate changes. Since the arrangement of the modules is atypical (14° tilt angle) and no shading occurs, the installation can be analyzed as a representative example of the low angle tilted system operating under realistic environmental conditions. The photovoltaic performance was demonstrated, analyzed and discussed in the context of the influence of particular external factors such as: irradiation, temperature, cloudiness and wind.

MATERIALS AND METHODS

Photovoltaic system

The total nominal power of the photovoltaic installation is 15 kWp. It consists of 60 polycrystalline modules made in the glass-glass technology. This technology reduces the degrading influence of external factors, such as salt spray or ammonia. Additionally, the modules are resistant to potentially induced degradation (PID). In the studied installation, the Centrosolar S250P60 Professional model photovoltaic modules with a nominal power of 250 Wp were used. Their external dimensions are 1660 mm x 990 mm x 40 mm and the glass thickness on both sides of the module is 3.2 mm. Each module consists of 60 rectangular polycrystalline solar cells with the dimensions of 156 mm x 156 mm and has 3 bypass diodes. The nominal efficiency of the module is 15.2%. The advantages of the mounted modules, apart from resistance to damaging external factors, are increased resistance to snow pressure (up to 5400 Pa) and a positive power classification factor (-0 / +4.99 W). The selection of such panels was made on the basis of climatic studies at the place of their installation, e.g. average level of scattered radiation intensity, and the available area of the roof.

The modules are tilted at an angle of 14°, oriented to the south and mounted in 15 rows of 4 modules on a flat roof of the building located on the campus of the Lublin University of Technology, Poland (51°14’47”N, 22°34’6”E) at an altitude of 186 m above sea level (Fig. 1). The installation is divided into 3 strings connected to two maximum power point trackers (MPPT) of the inverter, which allows adapting to changing sunlight conditions.

A 15 kW SMA Sunny Tripower 15000TL three-phase inverter was used to convert the direct current produced by the photovoltaic panels into the alternating current in on-grid system. The inverter has a high efficiency factor of 98.1%; it is covered by a 5-year warranty and has the ability to connect by Bluetooth and LAN. Owing to a properly selected inverter, the installation can work efficiently under changing weather conditions and the diagnosis of possible failures can be carried out faster. The inverter used is a transformerless device with an integrated switch. In case of too high voltage obtained in the installation, it will turn it off in order to avoid damaging the installation elements. It can operate in the temperature range from -25 °C to 60 °C. The specific data of PV modules and the inverter are listed in Table 1.

Figure 1. PV installation on the roof of the building, Lublin University of Technology, Poland

Table 1. Characteristic parameters of the PV modules and inverter

PV module		Inverter	
Parameter	Value	Parameter	Value
Nominal power	250 Wp	Maximum DC power	15340 W
Number of solar cells	60	Starting input voltage	150 V
Current (Impp)	8.41 A	Number of MPPT inputs	2
Voltage (Umpp)	29.73 V	Rated Power	15000 W
Short-circuit current (Isc)	8.91 A	Maximum efficiency	98,10%
Open-circuit voltage (Uoc)	37.62 V	Maximum output current	16 A
Efficiency (STC)	15.20%	Own energy consumption	1 W
Temperature coefficient of power	-0,43%/ºC	Noise level	51 dB
Area	1.64 m^2	Degree of protection	IP 65

Monitored parameters

The research was based on the investigation of the installation performance under changing external conditions, such as irradiance, ambient temperature and the temperature of the modules, clouds cover, wind and snow load. In order to monitor these parameters, the photovoltaic installation is equipped with the Sunny SensorBox remote weather measurement system, the Sunny WebBox device and the SMA Meteo Station in order to monitor the performance and diagnose any errors. Some of the data were also collected by the local weather station 12 km away. The accuracy of the Sunny SensorBox Integrated Solar Radiation Sensor was ± 8% and the accuracy of Sunny SensorBox Module Temperature as well as Environment Temperature Sensor was ± 0.5%. The measurements were performed over the entire year 2019 at 5-minute intervals and then analyzed.

RESULTS AND DISCUSSION

Weather data

Insolation and ambient temperature are two main factors influencing the performance of PV modules. Figure 2 presents the distribution of insolation in the studied location, over the entire year 2019. The measured sum of insolation was equal to 1333 (kWh/m^2)/y, which is a value greater than 1313 (kWh/m^2)/y in 2018 or 1160 (kWh/m^2)/y registered in 2017. The significant difference between the weather conditions in cold and warm part of the year characteristic for the studied location is reflected by the ratio of insolation received in two parts of the year. With the insolation sum of 1019 kWh/m^2, the warm half of the year (April to September) offered favorable conditions for the photovoltaic conversion, comparing to colder months (October to March) when the insolation was 23.6% of the annual sum.

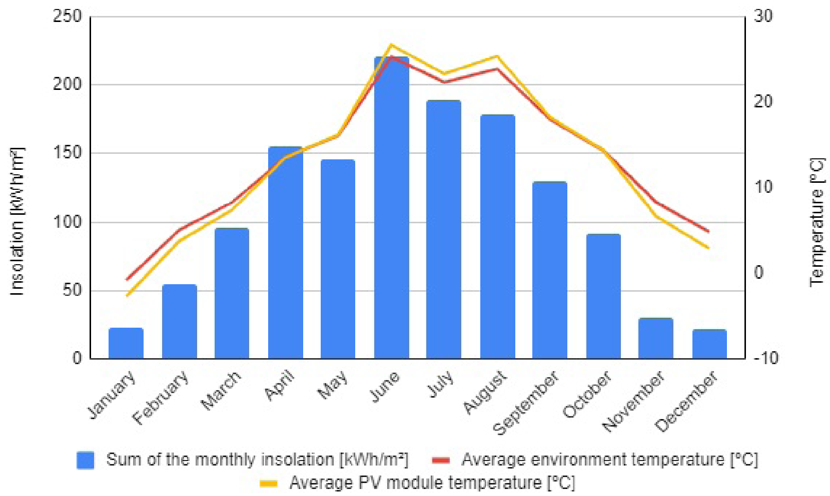

Figure 2. Average monthly insolation, ambient temperature and temperature of the modules in 2019

The trend of insolation changes is followed by the fluctuations of ambient temperature and module temperature, which is depicted in Figure 2. Average monthly external temperature varies from -0.83 °C in January to 25.28 °C in June. The average monthly temperature of modules reached over 26 °C, however the average daily temperature was up to 33 °C with instantaneous values reaching even 43 °C.

The heating of modules by solar radiation is also dependent on the cloudiness. In the studied location, almost 200 days are accompanied by 0-5% cloud cover, while the coverage of 50-75% was observed only on 47 days, among them May with surprisingly high number of cloudy days. During the entire year, the clouds cover exceeding 5% occurred on almost 50% of the days.

The effect of wind on the temperature of modules was also assessed. However, in the studied location relatively low wind speed is registered. The wind speed values in the range of 2-6 m/s occurs on almost 50% of the days. Therefore the difference between module temperature and ambient temperature does not change much under the influence of the wind speed change, which is depicted in Figure 3.

Seasonal performance assessment

The distribution of electric energy production depicted in Figure 4 reflects the changes of the insolation over the entire year 2019. During the warm part of the year (April – September) 12399.95 kWh of electric energy was produced

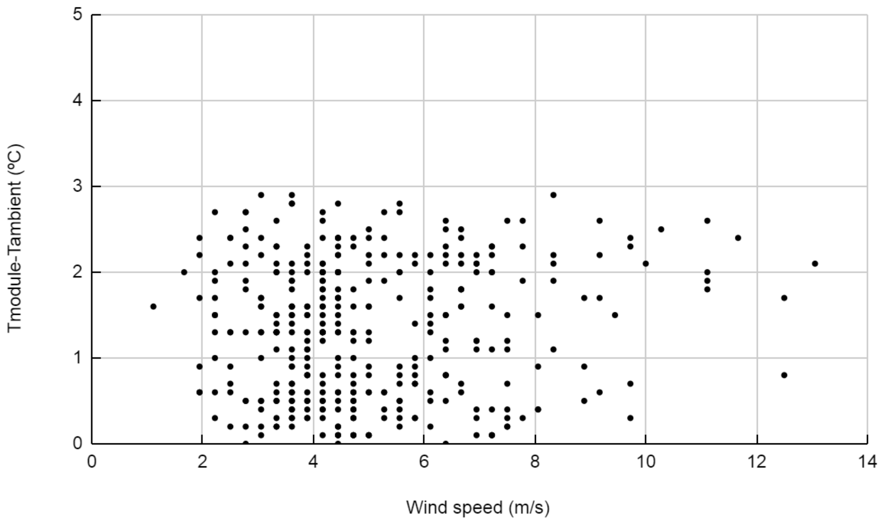

Figure 3. The dependence of the difference between module temperature and ambient temperature vs. wind speed

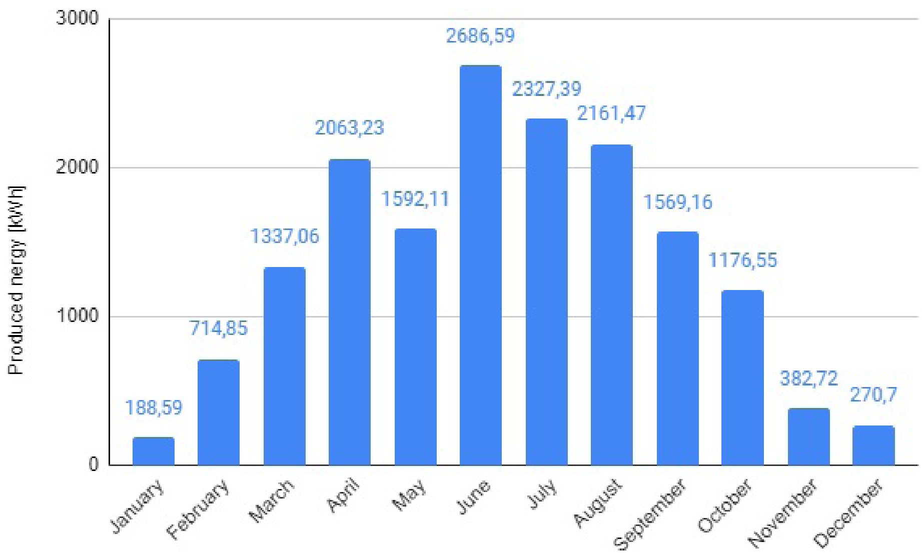

Figure 4. Values of the electric energy produced in 2019

by the system which is 75.29% of total annual production. The percentage share of the energy production in the subsequent months (Figure 5) confirms the domination of the warm half of the year. This observation is characteristic to the studies of this type performed at high latitude because of the uneven distribution of insolation in warm and cold part of the year.

In terms of monthly energy yield (Fig. 6), the values below 90 kWh/kWp per month were registered in cold part of the year and 106.14-179.11 kWh/kWp in warm part of the year. The obtained monthly energy yield was high comparing to values below 120 kWh/kWp in the most sunny months at similar latitude of 53°N, in Ireland [Ayompe et al., 2011].

Significant differences of energy production in the warm and cold half of the year were also analyzed by the comparison of PV performance in four chosen characteristic days with extreme values of electric energy produced. Figure 7 presents the produced energy and average solar irradiance for two days belonging to the warm part of 2019 (June 25th and August 14th) and the other two belonging to the cold part of the year (January 31st and March 8th). The maximum of daily energy production was observed on June 25th due to high solar radiation intensity. March 8th was a day on which the sky was partially overcast; however, it was the most productive day in cold part of the year. The reason for the lowest energy production registered on January 1st was low solar radiation intensity connected to the cloud cover exceeding 70% and snow load on the PV modules.

The instantaneous electrical power produced by the installation during the four analyzed days is shown in Figure 8. Besides the differences in the value of power produced in particular days,

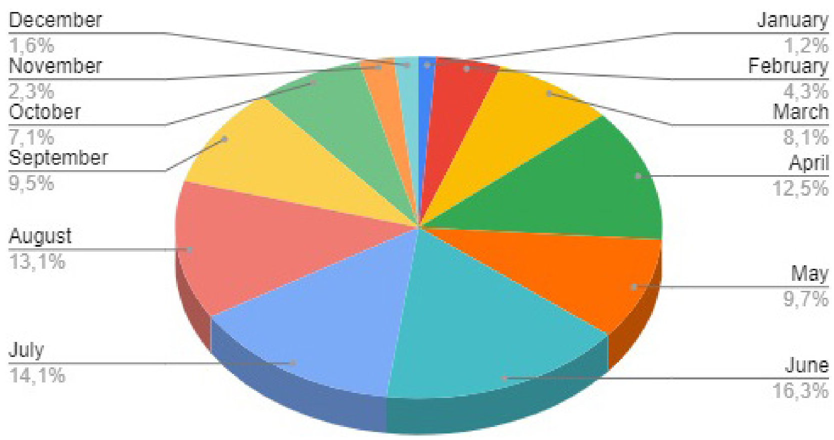

Figure 5. Monthly share of the electric energy produced by PV installation in 2019

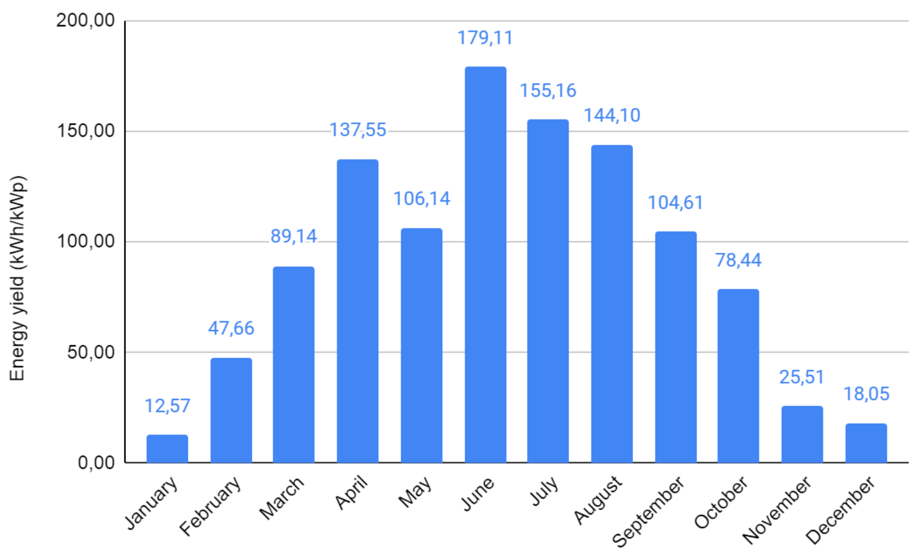

Figure 6. Monthly energy yield in 2019

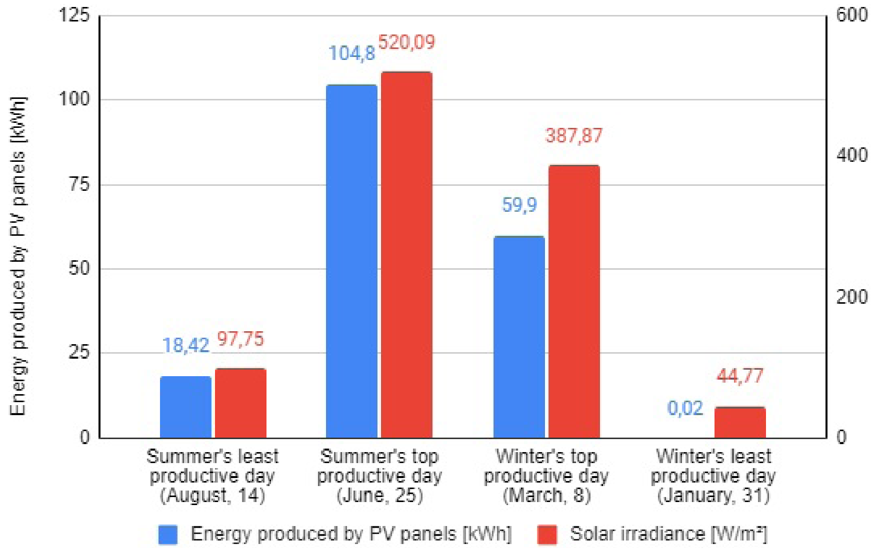

Figure 7. Production of electric energy and solar irradiance on four characteristic days

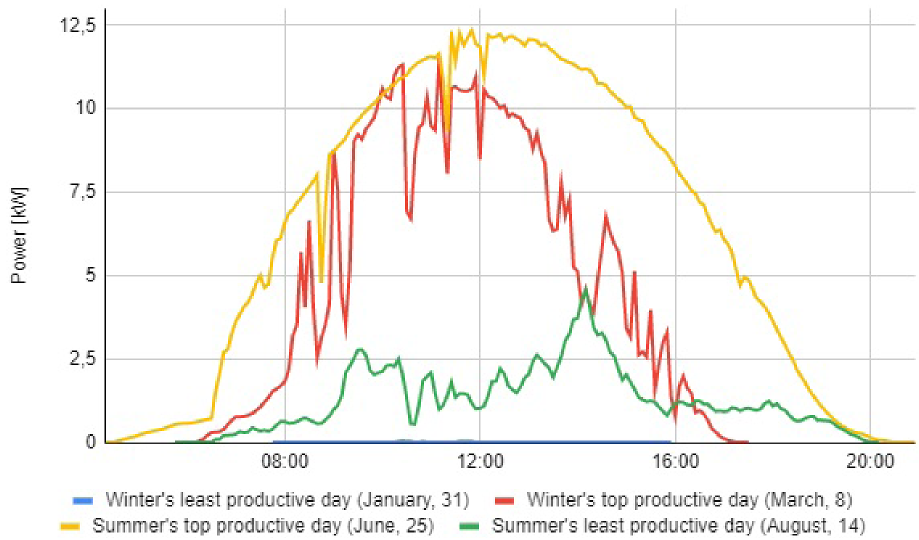

Figure 8. The instantaneous electrical power produced by the installation during the four analyzed days

the fluctuations triggered by the temperature changes and cloudiness (v.i.) are depicted.

Further analysis of the experimental data was devoted to the efficiency of the modules, which was determined as the ratio of the electrical power output P_{out} and incident solar irradiance on the surface of PV modules according to the following equation [Gaglia et al., 2017]:

$$\eta = \frac{P_{out}}{G \cdot A} \quad (1)$$

where: G – solar irradiance [W/m^2], A – area of PV module [m^2].

The data reveals that the efficiency is close to nominal value of 15.2% when the temperature of the modules is below 10 °C, which is achieved in cold half of the year, according to temperature dependency presented in Figure 9. The temperature increase over 30 °C, accompanied by the rise of insolation, results in the efficiency drop below 14%. In literature the decrease of the STC efficiency from 11.31% (for multicrystalline silicon module) to mean annual value of 8.7% was observed at low latitude [Gaglia et al., 2017] and from 19.3% (for monocrystalline silicon module) at STC to annual average daily module efficiency of 14.9% at high latitude [Ayompe et al., 2011].

The temperature coefficient of efficiency determined based on the experimental data is equal to -0.06%/°C which is very close to -0.065%/°C calculated based on the manufacturer data according to the following dependence:

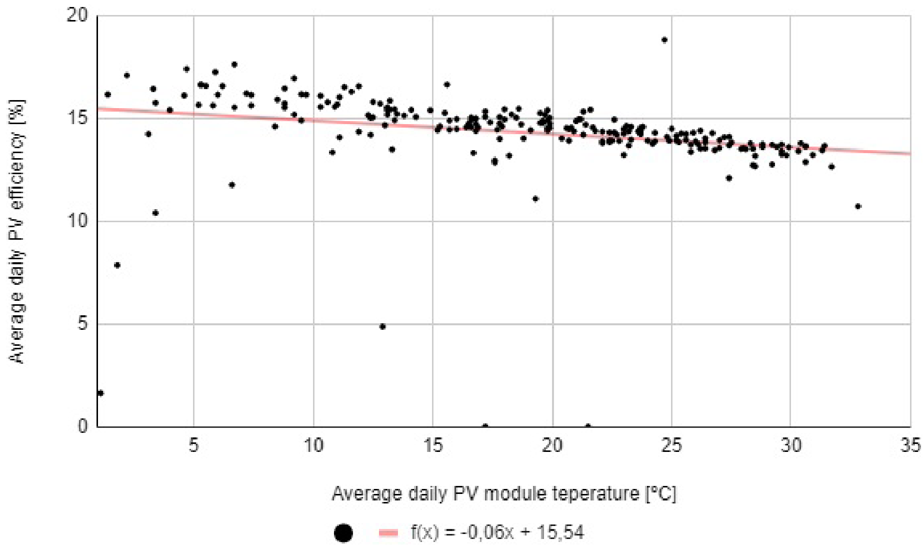

Figure 9. The dependence of the module efficiency on its temperature

$$\mu = \beta\eta \quad (2)$$

where: β – temperature coefficient of power and
η – the efficiency at STC.

In general, silicon photovoltaic technologies are known for sensitivity to the temperature growth; however, the maintenance of STC temperature coefficient observed in this work is beneficial. The comparison of the temperature coefficient of power for the studied modules (equal to -0.43%/°C) with the literature data indicates that this value is typical. Other pc-Si modules investigated in literature have the temperature coefficient of power determined by the manufacturer of -0.41%/°C or -0.507%/°C and the temperature coefficient of efficiency -0.06%/°C [Adaramola et al., 2015; Allouhi et al., 2019].

The temperature of the modules is a significant parameter influencing the final performance. This parameter depends on ambient temperature which changes due to the variations of solar irradiance (Fig. 2) and cloudiness. The example of dependence between clouds cover and temperature of the modules in February, 2019 is shown in Figure 10. In February, there were 22 days with less than 5% cloudiness. As can be seen in Figure 10, the modules were heated during the least cloudy days. This is due not only to their operation but also to heating triggered by ambient temperature. The periods characterized by low clouds cover 0-5% correspond to an increase of temperature of the modules to 5-10 °C in the analyzed cold month.

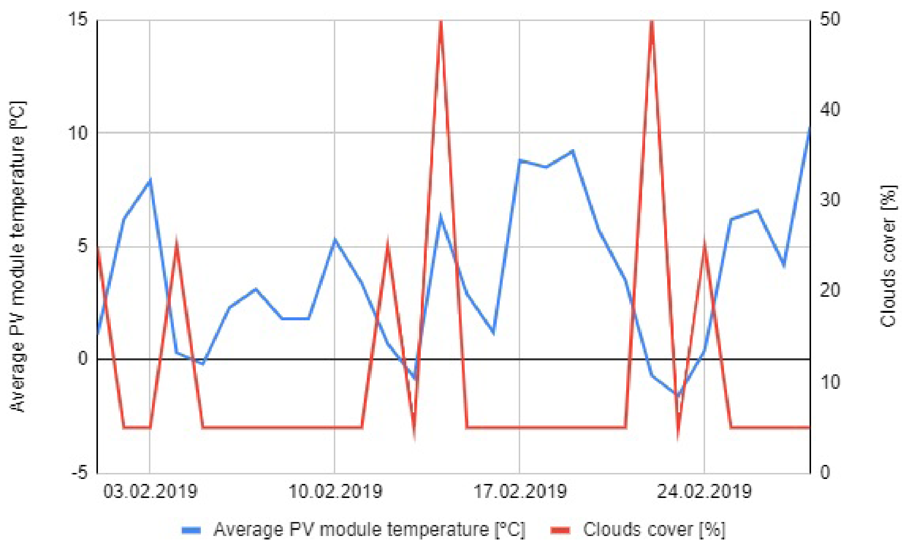

Figure 10. The fluctuations of clouds cover and average daily module temperature in February, 2019

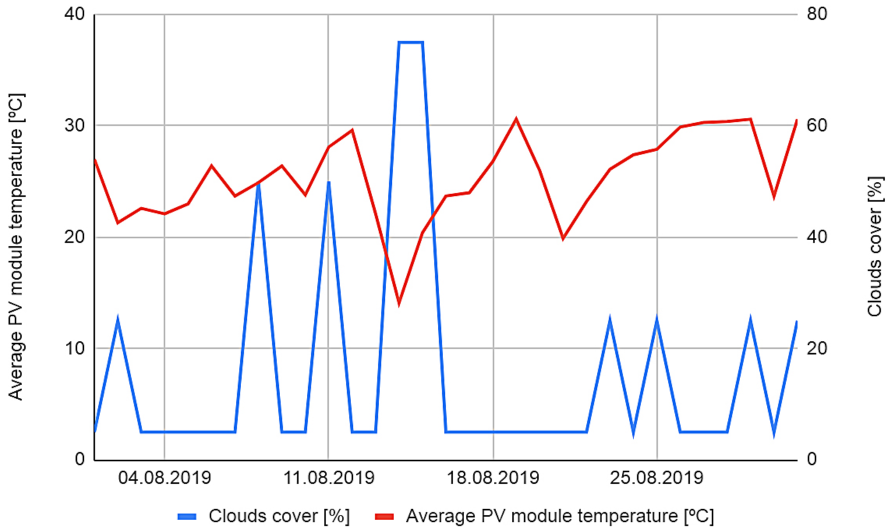

Figure 11. The fluctuations of clouds cover and average daily module temperature in August, 2019

The analogous dependence was attained in August, which represents the warm part of the year with most sunny days (Figure 11).

The performance ratio of the installation, which expresses the difference between the actual performance and theoretical performance at STC, can be calculated as a ratio of the final yield Y_F and the reference yield Y_R, according to the formula:

$$PR = \frac{Y_F}{Y_R} \tag{3}$$

The reference yield Y_R is the total in-plane solar insolation H (kWh/m^2) divided by the array reference irradiance (1000 W/m^2) and the final yield Y_F is the ratio of the monthly AC energy production E (kWh) and the peak power P_R (kWp) of the PV system at STC:

$$Y_F = \frac{E}{P_R} \tag{4}$$

The capacity factor of the installation was determined as the electrical energy output divided by the maximum possible energy output, based on the total nominal power, over the entire year. Energy density was calculated as a quotient of the annual electrical energy output and active surface area of all photovoltaic modules in the installation. The annual yield was determined as a ratio of the annual electrical energy output and the total nominal power of the installation. Table 2 presents the comparison of performance ratio and other parameters characteristic for the photovoltaic rooftop installations consisting of poly-Si modules, mounted in different places, at various latitudes with the installation studied in this work.

At low latitudes, the annual energy yield, energy density and capacity factor exhibit high values. At high latitude location, these parameters are usually lower. The example of good quality monocrystalline silicon modules (efficiency of

Table 2. The comparison of PV parameters from literature data with this work

Location	Experimentally determined efficiency of the array (%)	Performance ratio (%)	Capacity factor (%)	Energy density (kWh/m^2)	Annual yield (kWh/kWp)	Ref.
Morocco	14.91	85.37	21.81	282.93	-	[Nour-eddine et al., 2020]
Ghana	-	71.3	12.9	152.4	1143	[Quansah et al., 2017]
India	-	85.12	17.68	-	-	[Kumar, 2015]
Morocco	12.57	82.63	21.03	267.89	1761	[Allouhi et al., 2019]
Turkey	11.36	81	13	177.7	1189	[Elibol et al., 2017]
Norway	13	83.03	10.58	-	931.26	[Adaramola et al., 2015]
Slovenia	-	68.84	11.85		1038	[Seme et al., 2019]
Poland	14.5	83	12.89	173.6	1130	[Zdyb and Gułkowski, 2020]
Poland	14.2	82	12.53	188	1098	This work

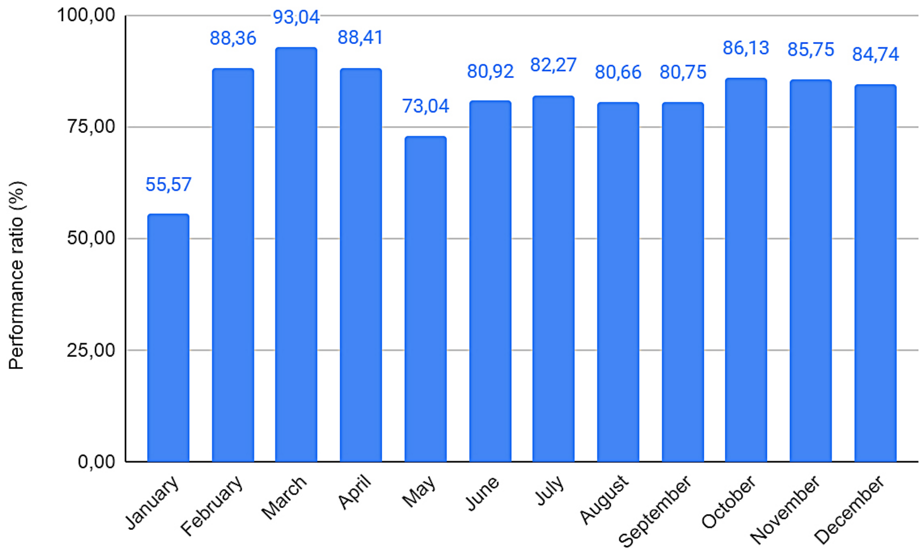

Figure 12. Performance ratio in 2019

19.3%) operating in Ireland shows that annual yield can be as low as 885.1 kWh/kWp at high latitude [Ayompe et al., 2011]. However, in this work, the average efficiency of the pc-Si modules, based on the experimental data is better than in Turkey or Morocco, probably due to beneficial influence of relatively low ambient temperatures.

The distribution of performance ratio of the studied installation in consecutive months of 2019 (Fig. 12) exhibits the highest values in cold half of the year, which confirms beneficial influence of low temperature. The exception is January, however in this month the efficiency was deriorated by snow load on the modules. Similar tendency, however not so clear, was observed in Ireland where PR up to 90% was obtained in winter months [Ayompe et al., 2011].

Ecological effect

Production of electrical energy in the traditional process of coal combustion is accompanied by the emission of CO_2, toxic chemicals and dust. The amount of sulfur oxide and dust strongly depends on the content of sulfur and quality of the carbon. The ecological effect of the operation of the studied PV installation can be assessed based on the annual production of electric energy by the installation and the emission factors per unit of electric energy produced in the traditional way [Dragan and Zdyb, 2017; Quansah et al., 2017]. The values of emissions avoided presented in Table 3 are estimated for the electricity production of 16470.42 kWh, since this is the ammount of electric energy produced by the studied photovoltaic installation in 2019.

Table 3. The amounts of emissions avoided due to the application of photovoltaic installation

Pollutant	The emitted amount (kg)
SO_x/SO_2	8.42
NO_x/NO_2	9.49
CO	3.74
CO_2	11842
Dust TSP	215
Benzopyrene	0.04

CONCLUSIONS

The 15 kWp rooftop installation was monitored over the entire year 2019 and the influence of real external conditions on the performance parameters was evaluated on monthly and seasonal basis. The weather conditions in the location of the installation are characterized by the significant seasonal differences which is reflected by distribution of energy production over the year. The changes of the instantaneous power over a day are also strongly influenced by external conditions. Over 76% of the year sum of insolation occurs in warm part of the year in which the photovoltaic modules reach the temperature of 10-25 °C. The decrease of efficiency of the modules was observed under the grow of modules temperature. Among the factors affecting the energy yield, the increase of cloud cover and the limited access to direct light was confirmed to favor lowering of the temperature of the modules. The experimentally determined temperature coefficient of efficiency is very close to the one provided by the manufacturer. In terms of temperature influence, the modules less sensitive to temperature grow e.g. thin film CdTe or CIGS, could be probably a better choice in the studied location.

The average daily efficiency of the modules exhibits satisfactory value, 1% lower than the efficiency under STC. The annual energy yield close to 1100 kWh/kWp indicates that the installation works correctly and thus contributes in reduction of harmful emissions. Due to atypical, low tilt angle of the modules and proper distance between the rows of modules there is no shading, which is beneficial for the performance of the installation. However, it is worth to notice that the snow should be removed if it is cumulated on the modules surface. Further investigations will be aimed at developing the application devoted to prediction of the need to clean the modules.

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