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A specific yield comparison of 2 photovoltaic installations – Polish case study

Abstract: The energy sector, particularly that related to renewable energy, is growing rapidly. The analysis of factors influencing the production of electricity from solar radiation is important in terms of the ever-increasing number of photovoltaic (PV) installations. In Poland, the vast majority of installed PV capacity belongs to prosumers, so a comparative analysis was conducted for two domestic installations, one in southern Poland and the other located in central Poland. Operating conditions were compared, specifically with regard to irradiance, outdoor temperature and the calculated temperature of photovoltaic cells. The specific yield was then compared in daily, monthly and annual statements. The effects of the previously mentioned parameters on the energy yields of the two installations were considered. The installation in southern Poland in 2022 produced 5,136.6 kWh, which corresponds to a specific yield of 1,019.17 kWh/kWp, while the energy production of the installation in central Poland was 4,248.9 kWh, which corresponds to a specific yield of 965.67 kWh/kWp.

Keywords: energy, prosumer, photovoltaic, PV, specific yield

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Introduction

In recent years, the number of domestic photovoltaic installations has been increasing both in Poland and in the rest of Europe (Kausika et al. 2018; Sribna et al. 2021). Photovoltaics, in terms of installed capacity, is the most popular renewable energy technology in Poland and constitutes a significant area of investment in the energy sector. In 2022, the installed capacity exceeded 12.4 GWp, which is an increase of 4.7 GWp from the previous year. The largest group among PV owners are individual prosumers, whose total installed capacity in 2022 was 9.3 GWp (Raport 2023). For users of photovoltaic installations, one of the most important parameters in technological, economic and environmental terms is energy production (Gułkowski 2022; Dzikuć et al. 2022; Piwowar et al. 2023). The most key factors influencing the productivity of photovoltaic panels are solar radiation (Kausika et al. 2018; Raport 2023; Sirisamphanwong and Ketjoy 2011) module tilt angle and azimuthal angle (Babatunde et al. 2018) as well as module temperature (Sirisamphanwong and Ketjoy 2011; Hasan et al. 2022).

Solar radiation is one of the most important factors affecting the productivity of a photovoltaic system. The intensity of radiation is affected by many factors, such as cloud cover and the relative position of a point on the Earth to the Sun, which varies throughout the day and year (Hasan et al. 2022). Latitude has a significant impact on energy production. Installations at higher latitudes have a much lower annual production total than those operating closer to the equator. An example on the European scale is Norway, for which the annual insolation value varies between about 600 and 913 kWh/m^2/year, depending on latitude (Adaramola and Vågnes 2015), and Sardinia, where this value can exceed 1,700 kWh/m^2/year (Ghiani et al. 2013). Poland's location between latitudes of 49°00′ and 54°50′ north affects the change in the sum of irradiance over the year, resulting in significant changes in the installation's specific yield (Gułkowski 2022). The average insolation in Poland is taken as 1,000 kWh/m^2/year, but the values of annual differences between northern and southern Poland can reach up to 200 kWh/m^2/year (Olczak et al. 2021a). In general, it is roughly assumed that under Polish conditions, 1 kWp yields 1000 kWh per year. For the aforementioned countries, Poland and Norway, the difference in solar irradiance depending on latitude is 200–300 kWh/m^2/year. In Poland, the difference with respect to the maximum achieved is 20%, but in the case of Norway, the difference reaches up to 50%.

The topic of analyzing the impact of various factors on the operation and performance of PV systems has been the target of work on the Polish scale and beyond. A study of the impact of PV technology and orientation with respect to different sides of the world has been presented in work by S. Gułkowski. Panels made with double-sided technology had a higher energy production rate than other installations with the same location (1,102.9 kWh/kWp/year for double-sided technology and 1,041.8 kWh/kWp/year for single-sided). Under high irradiation conditions, they showed levels of efficiency that were higher by 10% than installations with single-sided technology (Gułkowski 2022).

The geographic orientation of the photovoltaic modules affects production during certain times of the year as well as day. During winter months, higher output was recorded due to the southeast orientation (222.3 kWh/kWp/year and for other orientations, the values ranged between 184.6 kWh/kWp/year and 204.6 kWh/kWp/year). However, the highest total annual efficiency was achieved by south-facing panels (966.8 kWh/kWp) compared to other orientations (east -west 868.8 kWh/kWp/year, south-east 895.7 kWh/kWp/year, south-west 910.7 kWh/kWp/year) (Gułkowski 2022).

The angle of the modules relative to the horizontal position for a specific latitude is one of the most important factors affecting energy production and it can be influenced during the construction of the installation (Dobrzycki et al. 2021). Climatic conditions, the topography of the terrain and the method of installation are important to take into account when choosing the optimal angle, but the main factor is the amount of solar radiation falling on the surface of the PV module, which under ideal conditions should fall vertically in order to obtain the greatest amount of electricity produced. In the northern hemisphere, panels mounted on roofs with a lower angle have a higher productivity during the summer, while during the winter months, higher production is favored by higher tilt angles (Babatunde et al. 2018). Depending on the latitude, the angles of the modules for which the sum of irradiation assumes a maximum value change. For Northern Cyprus, the optimal angle is 32° (Babatunde et al. 2018), while for Poland the average optimal tilt angle for single-sided panels is 37° (Dobrzycki et al. 2021). The tilt angle also depends on the manufacturing technology. The aforementioned single-sided technology has its angle maximizing the sum of yields in the range of 20–45°, which is why it is the most common option chosen by owners of single-family houses. The optimal range of angles for double-sided technology is 60–75°; therefore, it is recommended to install them on flat roofs or on the ground (Dobrzycki et al. 2021).

Outdoor temperature has a significant impact on the temperature of photovoltaic cells and consequently on the efficiency of electric power generation (Zdyb and Gułkowski 2020). There have been many studies describing the negative impact of high temperature on energy production – one such study was conducted in Peru. Under high insolation conditions, an annual production of 1770–1992 kWh/kWp and a performance ratio (*PR*) of 84% was achieved. Conducting such measurements under similar insolation conditions but with higher temperatures resulted in an annual production of 1,540 kWh/kWp and a *PR* of 82%. *PR* also fluctuated over the months, with 20% more in winter than in summer (Romero-Fiances et al. 2019). This study shows the significance of the impact of relatively high ambient temperatures on the operation of panels.

Conducting comparative work on various PV installations is an important part of environmental and economic considerations when planning new PV installations (Zdyb and Gułkowski 2020), which are growing rapidly in Poland. The total installed capacity is projected to reach 27 GWp by 2025 (Raport 2023). Analysis of external factors on which production is directly dependent, such as temperature or insolation, is one of the most important elements (Hasan et al. 2022). Regions with locally low annual insolation, frequent cloud cover or high outdoor temperatures may be eliminated from further investment (Bódis et al. 2019). The study of these parameters also makes it possible to determine the degradation of PV, its operation in retrospect, and differences in the performance of installations operating under similar conditions (Micheli et al. 2014).

1. Object and place of research

The performance analysis was conducted for two photovoltaic installations located in Poland. One of them, with a capacity of 5.04 kWp, is located in the Lesser Poland region and the other, with a capacity of 4.4 kWp, is located in the Mazovia province. In both cases, the panels are made with monocrystalline technology. The difference in latitude between the two installations is 1.83°. A detailed study of weather and performance data was made for 2022, and total irradiance and average annual temperature differences were compiled for the period 2011–2022.

One of the studied photovoltaic installations is located in the village of Łęki (50.02° N 20.69° E) in Poland. The panels are mounted on the roof of a residential building, the slope of which is 30°, the orientation of the panels is southeast and the azimuthal angle is 45°. The installation consists of 14 Longhi HPH360 modules with a total installed capacity of 5.04 kWp (Olczak et al. 2021a; LONGI Solar n.d.).

The second installation under study is located in Solec (52.03° N 21.11° E), which is also in Poland. The panels are oriented 50° to the east, and inclined at 30° to the horizontal plane, also placed on the roof of a residential building. The installation consists of 10 Jinko modules connected to a microinverter. The total installed power is 4.4 kWp (Olczak 2022).

Table 1. Parameters and configuration of PV installation

Tabela 1. Parametry i konfiguracja instalacji PV

Parameter	Unit	Łęki	Solec
Name of PV panels	—	Longhi HPH 360	Jinko TR 60M
Total length	m	1.776	1.868
Total width	m	1.052	1.134
Nominal power	kWp	0.36	0.44
Total power of installation, PPV	kWp	5.04	4.4
Current temperature coefficient	%/°C	0.057	0.048
Voltage temperature coefficient	%/°C	–0.286	–0.280
Power temperature coefficient	%/°C	–0.370	–0.350
Technology	—	Mono-PERC	Mono-TR
Number of panels	—	14	10
Tilt angle	°	30	30
Orientation/azimuth angle	°	SW, 45	SE, 50
Panel efficiency	%	19.2	20.77

Sources: Olczak et al. 2021a; LONGI Solar n.d.; Olczak 2022.

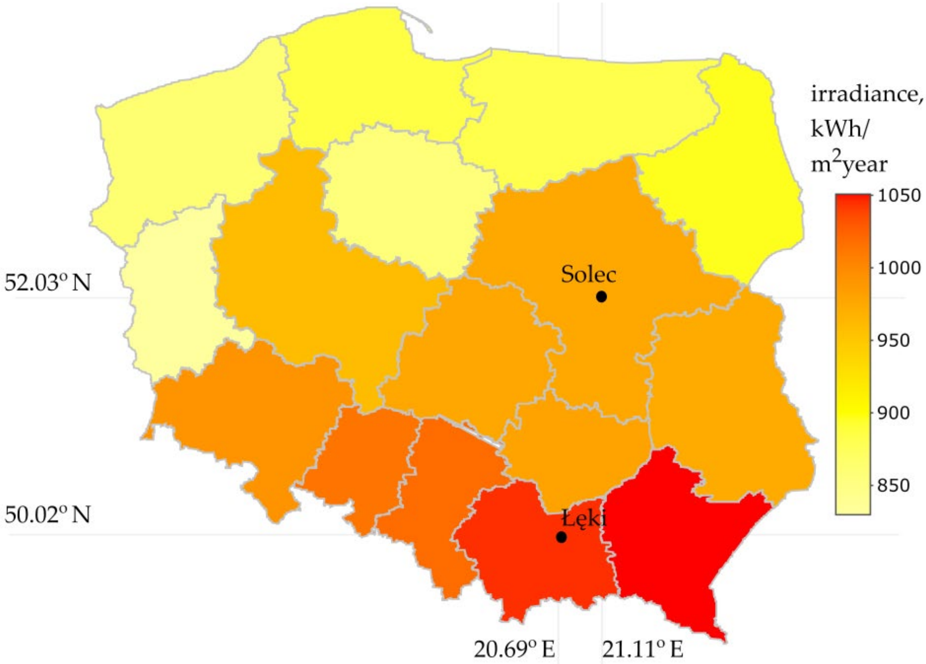

Fig. 1. Location of the analyzed installations on a map of Poland together with yearly horizontal irradiation calculated per province's capital city
Source own study based on Olczak et al. 2021a; Portal Gov.pl

Rys. 1. Lokalizacja analizowanych instalacji na mapie Polski wraz z rocznym nasłonecznieniem poziomym obliczonym dla stolicy województwa

2. Weather data

The weather data used for the analysis of the installation came from the ERA5 online database 19. The data was obtained for each hour of the study period for the considered locations – Łęki (50.2° N 20.69° E) and Solec (52.03° N 21.11° E). The parameters used in the analysis were:

- Surface solar radiation downwards, *ssrd*, for the years 2011–2022, assumed as irradiance (I) in the following analysis (Copernicus Climate Change Service (C3S) 2017),
- Outdoor temperature, *t2m*.

3. Methodology

The energy produced per day by the PV system was calculated according to the formula:

$$E_{AC,hd} = \sum_{hd=1}^{24} P_{AC,hd} \cdot h \tag{1}$$

where:

$E_{AC,hd}$ – energy produced per day [kWh],
$P_{AC,hd}$ – average power during the hour (data from the installations inverters) [kW],
hd – hour in a day.

Calculation of specific productivity on a daily (2), monthly (3) and annual (4) basis:

$$SYd = \frac{E_{AC,hd}}{P_{PV}} \tag{2}$$

$$SYm = \sum_{d=1}^{eom} SYd \tag{3}$$

$$SYy = \sum_{m=1}^{12} SYm \tag{4}$$

where:

SYd – daily specific yield [kWh/kWp/day],
SYm – monthly specific yield [kWh/kWp/month],
SYy – annual specific yield [kWh/kWp/year],
$E_{AC,d}$ – energy produced per day [kWh],
d – day of a month,
eom – end of a month (from 28 to 31),
m – month of a year.

The temperature of the photovoltaic cell was determined according to the formula (Olczak et al. 2021b):

$$TC(\tau) = t2m(\tau) + G(\tau) \cdot \frac{TC.NOCT - Ta.NOCT}{G.NOCT} \cdot \left(1 - \frac{\eta p}{ta}\right) \tag{5}$$

where:

TC – PV cell temperature [°C],
$t2m$ – time-dependent outdoor temperature, data from ERA5 [°C],

G – solar irradiance incident on the surface depending on tilt angle, azimuth and time [W/m^2], G was assumed as total surface solar radiation downwards (*ssrd*) in order to simplify calculations, data from ERA5 service,
$TC.NOCT$ – nominal operating temperature of the cell, 40 [°C],
$Ta.NOCT$ – ambient temperature for which NOCT is determined, 20 [°C],
$G.NOCT$ – solar radiation for which NOCT is determined, 800 [W/m^2],
ηp – efficiency of panels [%],
ta – transmittance and absorption coefficient, 0.9 [–],
τ – hour of the year.

In addition, the differences between irradiance and specific yield, equations (6) and (7) were calculated as percentage differences with respect to the values calculated for the Łęki, and the absolute difference in outdoor temperature and photovoltaic cell temperature, equations (8) and (9):

$$Idif = \frac{I(Solec) - I(Leki)}{I(Leki)} \cdot 100\% \tag{6}$$

$$SYdif = \frac{SY(Solec) - SY(Leki)}{SY(Leki)} \cdot 100\% \tag{7}$$

$$Tdif = T(Leki) - T(Solec) \tag{8}$$

$$TCdif = TC(Leki) - T(Leki) \tag{9}$$

where:
$Idif$ – difference in irradiance [%],
$SYdif$ – difference in specific yield [%],
$Tdif$ – difference in outdoor temperature [°C],
$TCdif$ – difference between photovoltaic cell temperature and outdoor temperature T [°C].

To calculate the outdoor temperature affecting the temperature of the cells, a weighted temperature was determined to eliminate the influence of recorded temperature datain particular, when hourly energy production was 0 kWh/kWp (for example, at night). The weighted average (energy productivity of the installation) of the outdoor air temperature was calculated according to the formula:

$$Tavg = \frac{\sum_{hd=1}^{24} E_{AC,hd} \cdot T}{\sum_{hd=1}^{24} E_{AC,hd}} \tag{10}$$

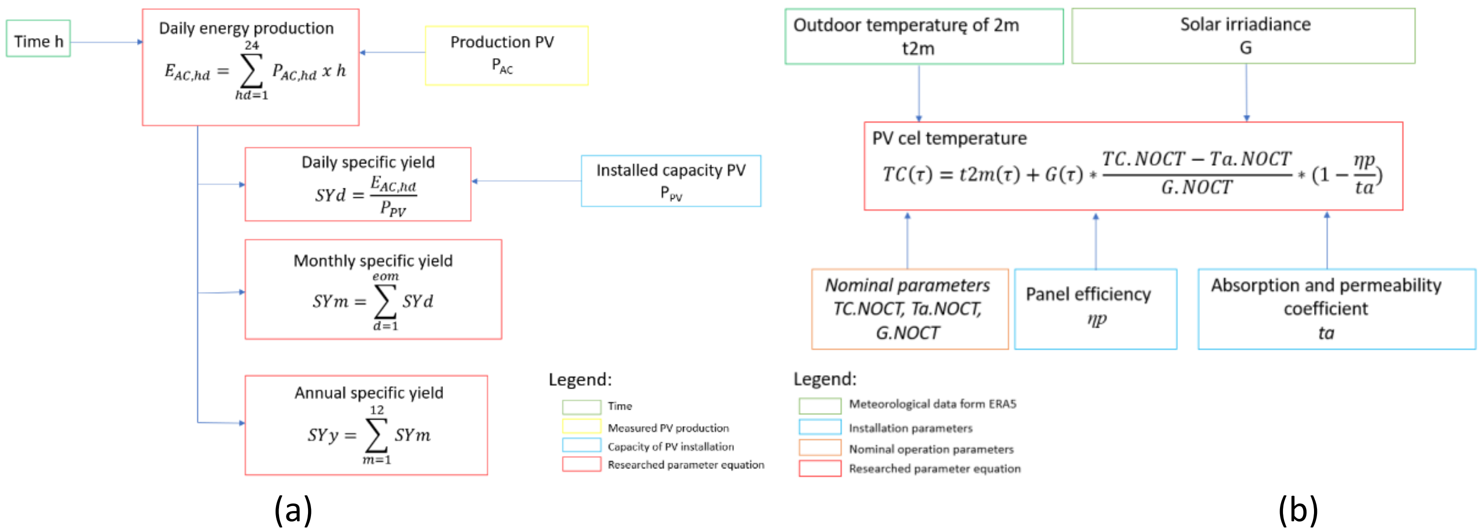

Fig. 2. Representation of how to calculate the specific yield (a) and temperature of a photovoltaic cell (b) and legends Source own study

Rys. 2. Przedstawienie sposobu wyliczenia wydajności specyficznej (a) oraz temperatury ogniwa fotowoltaicznego (b) oraz legenda where:

$Tavg$ – weighted (by PV energy productivity) average outdoor temperature [°C],

$E_{AC,hd}$ – energy produced per hour [kWh],

T – average outdoor temperature, data from ERA5 [°C].

Below are figures visualizing the process of determining the specific yield and temperature of the photovoltaic cell.

4. Results

The following chart (Fig. 3) shows the summed annual downward surface solar irradiance recorded for the compared localities. The data refers to the period 2011–2022. In Łęki, the summed value of annual irradiance was higher than in Solec, with the exception of 2018. In 2022, the irradiance for Łęki was the highest of the analyzed years and amounted to 1181.1 kWh/m^2. For Solec, the irradiance value in 2022 was 1141.1 kWh/m^2, and this is one of the higher values over the considered years. In the chart below, the values above the bars shows the percentage differen-

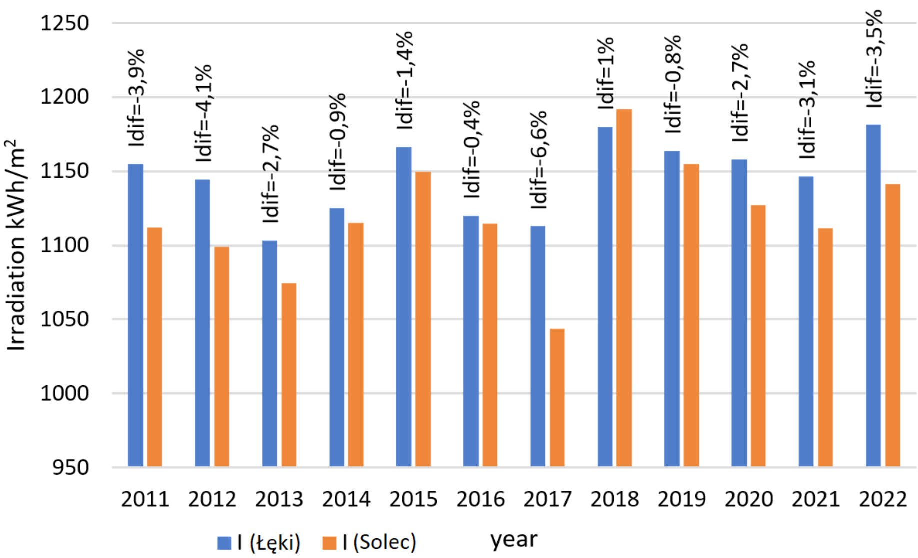

Fig. 3. Summary of annual total irradiance (I) in both localities from 2011 to 2022 and percentage differences in irradiation (Idif) for Łęki

Rys. 3. Zestawienie sumarycznych rocznych wartości napromieniowania (I) w obu miejscowościach w latach 2011–2022 oraz procentowe różnice w napromieniowaniu (Idif) w odniesieniu do Łęk ces in irradiance between Łęki and Solec, calculated according to formula (7). The year 2022 was particularly favorable for Łęki in terms of total irradiation, the difference between the two localities is one of the higher ones over the years under consideration, 3.5% which is exactly 40 kWh/m^2.

Figures 4 (a) and (b) show the distribution of downward surface solar irradiance by month from 2011 to 2022. In the winter months, the irradiance value in Łęki was higher than in Solec, while in Solec, higher values were recorded in the summer months. In the case of Solec, the differences in monthly irradiance values over the surveyed years are lower than in the case of Łęki. Over the years, irradiance values have remained similar in both localities during the winter months. However, for the summer months, it can be assumed that the differences between years are due to atmospheric conditions.

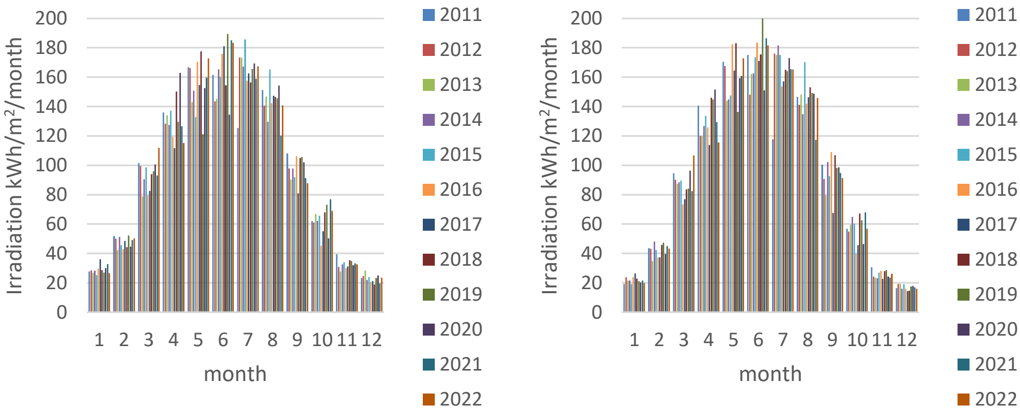

Fig. 4. Distribution over the period 2011–2022 for (a) Łęki and (b) Solec

Rys. 4. Rozkład w okresie 2011–2022 dla (a) Łęki i (b) Solec

Figure 5 shows the summed value of monthly surface downward radiation for both localities in 2022. From April to July, the summed values were similar, while the largest value of difference was observed in the winter months. In December, the radiation in Łęki was 46.4% higher than in Solec, and in January, it was 33.2% higher. In April, August and September, the sum of surface radiation was slightly higher for Solec by 0.3, 3.4 and 3.7%, respectively. The annual sum of downward surface radiation is higher for Łęki (1181.1 kWh/m^2) than for Solec (1141.1 kWh/m^2). The average monthly radiation for the 2011–2022 period for Solec was lower than the radiation in 2022, in the months of April through to June. For the other months, the two values were equal except for August and September, when the average monthly radiation for 2011–2022 was higher. In the case of Łęki, the average radiation values from 2011 to 2022 were higher in January, April and August to December than the total radiation in 2022, with both values being equal for July. In the remaining months, the irradiance value in 2022 was higher.

The average annual difference in air temperature between Łęki (10.1°C) and Solec (9.6°C) is 0.5°C. The average monthly temperature values for the two localities are compared in Figure 6.

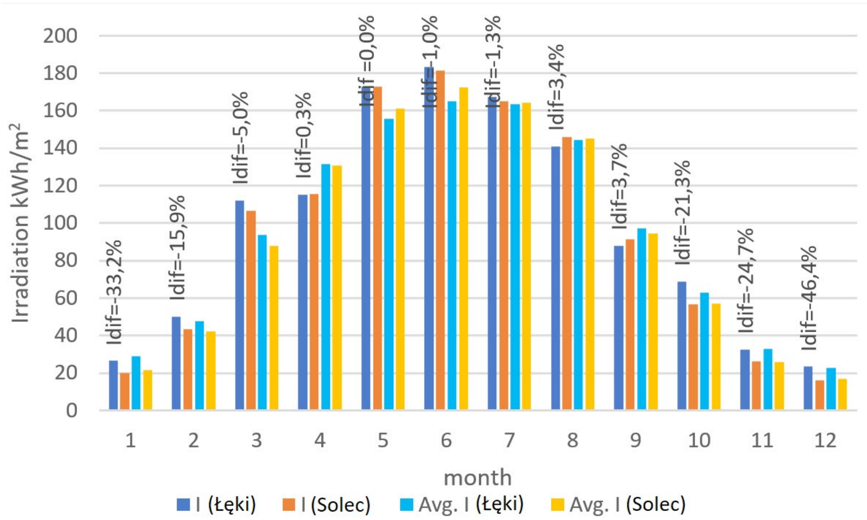

Fig. 5. Summary monthly irradiance measured on a horizontal plane from ERA5 (I) for Łęki and Solec in 2022 and average monthly irradiance (Avg) from 2011–2022 and percentage differences in irradiance (Idif) with respect to Łęki

Rys. 5. Sumaryczne miesięczne napromieniowanie zmierzone na płaszczyźnie poziomej z ERA5 (I) dla Łęk i Solca w 2022 roku oraz średnie miesięczne promieniowanie (Avg) na przestrzeni 2011–2022 oraz procentowe różnice w napromieniowaniu (Idif) w odniesieniu do Łęk

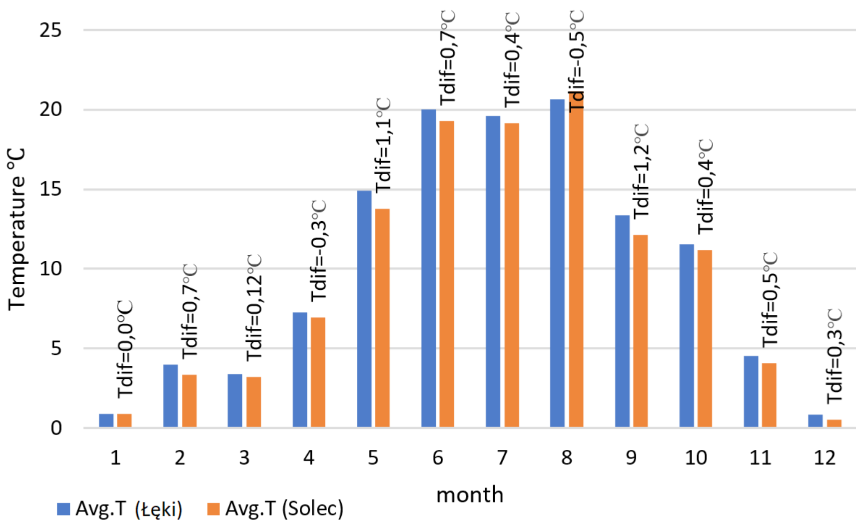

Fig. 6. Average monthly outdoor temperatures (Avg) for Łęki and Solec in 2022 and temperature differences (Tdif) between Łęki and Solec

Rys. 6. Średnie miesięczne temperatury zewnętrzne (Avg) dla Łęk i Solca w 2022 roku oraz różnice w temperaturze (Tdif) między Łękami a Solcem

In Łęki, a higher average air temperature than in Solec was observed in every month except August. The difference values were calculated as the difference between the temperature in Łęki and the temperature in Solec. In the summer months, the differences are nominally larger than in the winter months. The largest differences occurred for September (1.2°C) and May (1.1°C). The lowest value of temperature difference occurred in March (0.2°C), while in January the average values were equal.

Figure 7 shows the specific yield of PV installations calculated for the surveyed villages, Łęki and Solec, and the average radiation values in each month. In total, the specific yield in Łęki was 1019.16 kWh/kWp and in Solec it was 965.66 kWh/kWp, so the difference is 53.51 kWh/kWp. The values above the bars express the percentage difference in specific yield between localities calculated according to formula (7). In the summer months, the specific yield was significantly higher than in the winter months. In April, June, July and August, the energy production of the installation located in Solec was higher than that of Łęki, but the maximum difference was 2.2%. In the winter months, the difference between the two localities is much greater than in the summer months, reaching up to 69% in December, yet the difference in absolute values is only 3.61 kWh/kWp (Łęki 8.85 kWh/kWp and Solec 5.24 kWh/kWp). Differences can be caused by a number of reasons, such as atmospheric conditions, measurement error of the equipment, contamination of the panels as well as the location of the two installations and, consequently, the altitude of the Sun. Łęki is located in southern Poland, which means that in the winter months,

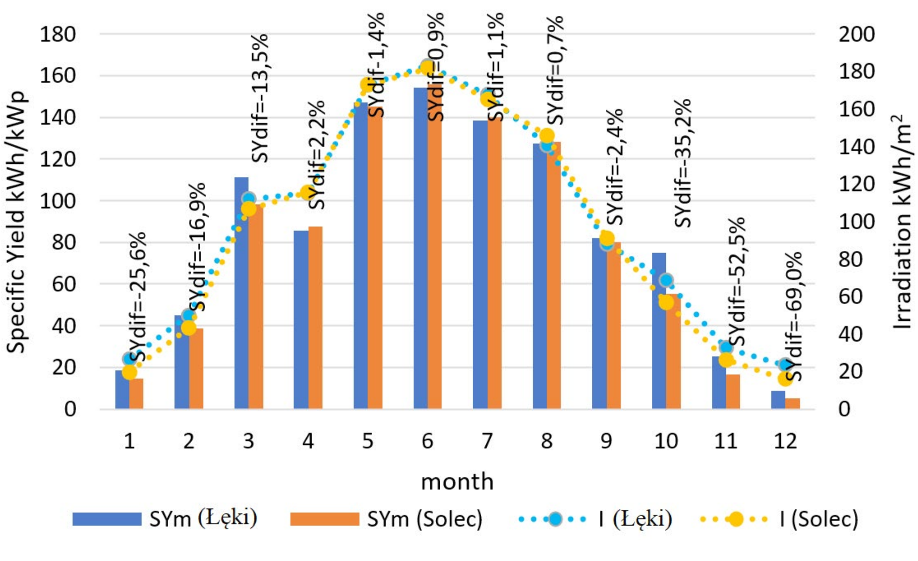

Fig. 7. Summary monthly specific yield (SYm) for the villages of Łęki and Solec, the total monthly radiation (I) of both villages in 2022, and the percentage difference in specific yield (SYdif) related to Łęki

Rys. 7. Sumaryczna miesięczna wydajność właściwa (SYm) dla miejscowości Łęki i Solec, sumaryczne miesięczne promieniowanie (I) obu miejscowości w 2022 roku oraz procentowa różnica w wydajności właściwej (SYdif) odniesiona do Łęk the days last longer and the angle of the Sun's rays tends to be greater than in Solec, located in central Poland.

The specific yield is directly dependent on downward surface solar radiation, as can be seen in Figure 7. The higher irradiance value in March than in April is probably due to atmospheric conditions, in particular cloud cover, which must have been significant in April. The lowest efficiency of PV installations of Łęki as well as Solec was achieved in December, with 8.85 kWh/kWp and 5.24 kWh/kWp, respectively. In June, both villages reached the maximum specific capacity – Łęki 154.3 kWh/kWp and Solec 155.73 kWh/kWp.

Figure 8 (a) and (b) shows the specific yields for Łęki and Solec each day in 2022. Comparing the two graphs, it can be seen that in the summer months, the specific yields are higher in Solec, and in the winter months, they are higher in Łęki, but the course of the two graphs are similar. There are peaks on similar days (for Łęki, 6.62, 6.47, 6.38 kWh/kWp; for Solec, 6.39, 6.73, 6.92 kWh/kWp) as well as smaller values (for Łęki, 0, 0.0013, 0.08 kWh/kWp; for Solec, 0, 0.0046, 0.01 kWh/kWp) of energy production. In both localities, the value of 7 kWh/kWp was not exceeded.

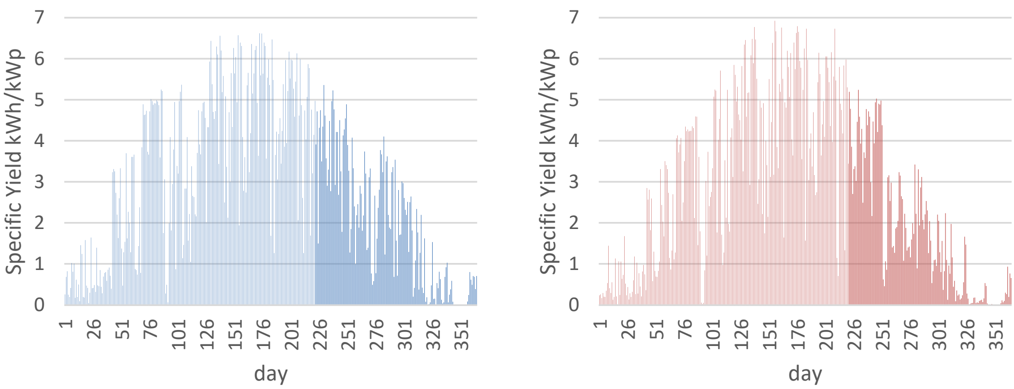

Fig. 8. Daily specific capacities in 2022 for (a) Łęki and (b) Solec

Rys. 8. Dzienne wydajności specyficzne w 2022 roku dla (a) Łęk i (b) Solca

The months with the highest and lowest specific yields were analyzed in more detail and are presented in Figures 9 (a) and (b). The average specific yield for the two localities in June differs by 0.1 kWh/kWp, for Łęki it was 5.1 kWh/kWp and for Solec it was 5.2 kWh/kWp. The values above the bars shows the maximum and minimum values of the specific yield, which for Łęki were 6.6 kWh/kWp on June 22 and 1.9 kWh/kWp on June 4, and for Solec the values were 6.9 kWh/kWp on June 5 and 1.6 kWh/kWp on June 13. The differences between the maximum and minimum values had the same value, amounting to 0.3 kWh/kWp.

Summary daily yields are at similar levels over the month, significant deviations from the average are most likely due to the occurrence of unfavorable weather conditions with regard to

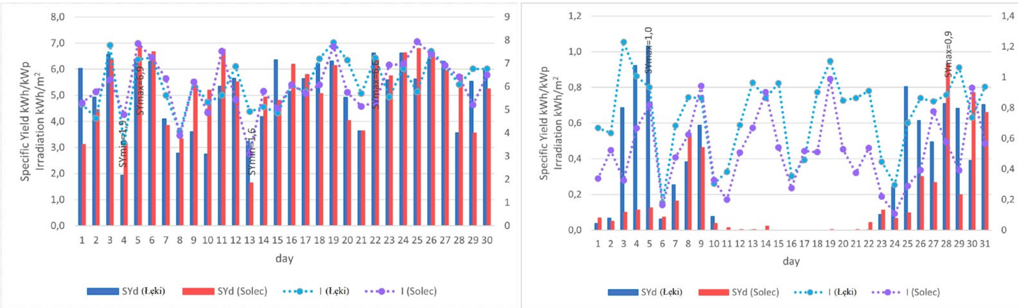

Fig. 9. Summary daily specific yield (SYd) of Łęki and Solec, average daily radiation (I) of both localities in (a) June and (b) December

Rys. 9. Sumaryczna dzienna wydajność specyficzna (SYd) Łęk i Solca, średnie dzienne promieniowanie (I) obu miejscowości w (a) czerwcu i (b) grudniu

PV energy production. In most cases, there is a co-occurrence of similar values in terms of specific yield vs. surface solar radiation, but exceptions can be observed. Such examples occurred on June 1 or June 9, when the radiation values were equal and the specific yield of the installation differed significantly (on June 1, the difference was 2.9 kWh/kWp – 93.6%, on June 10 the difference was 2.5 kWh/kWp – 47.2%), or when the radiation in one locality is higher and a higher specific yield is achieved for the other locality (on June 2 in Łęki the radiation was 4.6 kWh/m^2 and the output was 4.9 kWh/kWp while in Solec, the radiation was 5.8 kWh/m^2 and the output was 4.5 kWh/kWp).

The second month subjected to more detailed analysis is December, the month with the lowest total specific yield value. The average value of specific yield for Łęki was 0.3 kWh/kWp and for Solec it was 0.2 kWh/kWp. The maximum values differ between them by 0.1 kWh/kWp (Łęki, 1 kWh/kWp on December 5; Solec, 0.9 kWh/kWp on December 28). The differences between the values of specific yield between the two localities are significant. On a preponderance of days, production in Łęki is significantly higher than in Solec, especially at the beginning of the month, the exceptions being December 8, 28 and 30. Between December 11 and 21, production in both localities is zero or close to zero, the chart shows small bars on these days. Such results are most likely due to the snow cover on the plant elements, which prevented the inflow of solar radiation, which, as can be seen in the graph, did not stand out on these days compared to the rest of the month.

The average solar radiation values in December are about three to four times lower compared to June, which results in significantly lower output in both localities. Throughout practically the whole month, the irradiance values in Łęki were higher than in Solec. This is due to the location of both localities, Solec is located in higher latitude than Łęki, making both the length of the day and the angle of incidence of the sun's rays smaller. There is a correlation between solar radiation and specific yield, and there are exceptions like in the case of June, when the radiation in both localities is the same, or close to it, and the values of specific yield differ significantly from each other, although in the case of December, these differences may be due to snow accumulation.

Figure 10 presents a summary of the monthly average values of the weighted average outdoor temperature (T) as well as the average cell temperature (TC) in Łęki. The outdoor temperature as well as the cell temperature are dependent and so the graphs run close to each other. In January and December, all of the parameters shown had similar values, the cell temperature in Łęki was greater than the weighted outdoor temperature of 1.8°C in January and 1.7°C in December. As the sun's height above the horizon increased, the difference between the weighted outdoor temperature and the cell temperature increased. The largest difference occurred in June, for Łęki it was 7.1°C. The differences between the cell temperature and the weighted outdoor temperature are greater in the summer months than in the winter months, this is due to increased solar irradiance. From June onwards, the irradiance gradually decreases from about 359.6 to 84.0 kWh/m^2, the difference between temperatures also decreases from 7.1°C in June to 1.7°C in December. In March, higher irradiance (287.8 kWh/m^2) can be seen than in February (165.1 kWh/m^2) and April (262.5 kWh/m^2), as well as a change in the temperature difference, which is 2.5°C between March and February and 0.5°C between March and April. The outdoor temperature was 1°C higher in August, this difference between the temperature difference in August was 0.6°C lower, which is due to a reduction in irradiance.

The months with the highest and lowest energy production values were also the months with the highest and lowest average temperatures. Figure 11 (a) and (b) show graphs of daily average photovoltaic cell temperatures (TC) and average outdoor temperatures (T) for June and December.

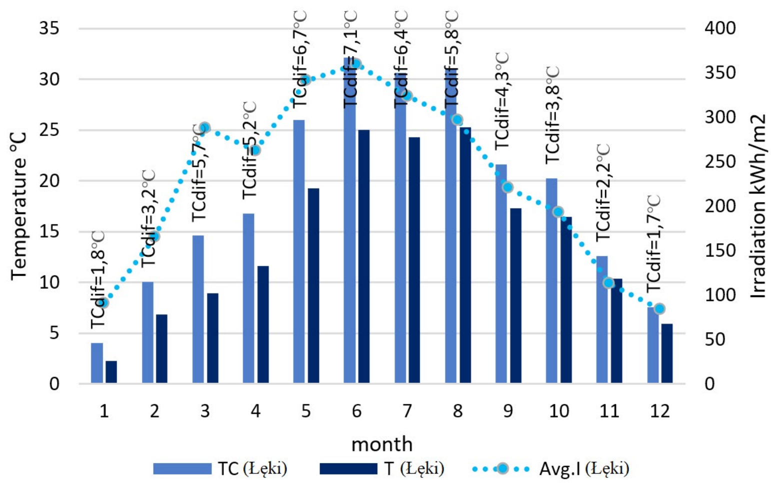

Fig. 10. Weighted average monthly outdoor temperatures (T) and average monthly cell temperatures (TC) in 2022 in Łęki and the difference between TC and T (TCdif)

Rys. 10. Średnie miesięczne temperatury ważone zewnętrzne (T) oraz średnie miesięczne temperatury ogniw (TC) w 2022 roku w Łękach oraz różnica między TC a T (TCdif)

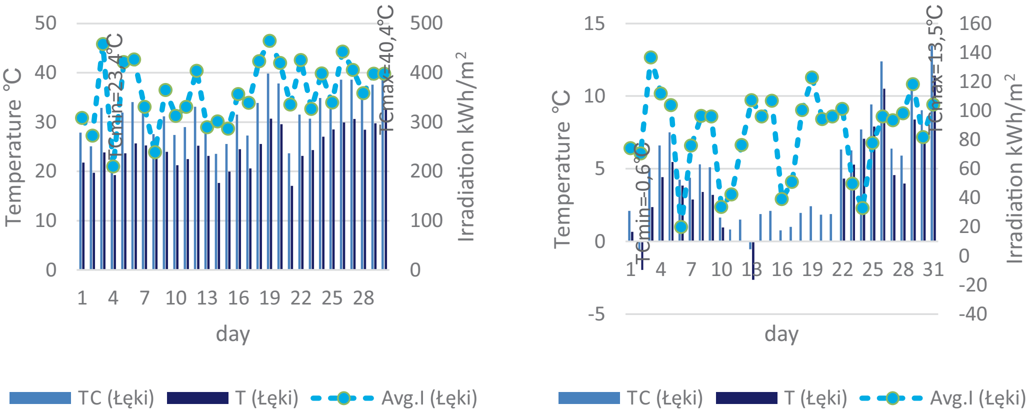

Fig. 11. Daily weighted average outdoor temperatures (T) and daily average cell temperatures (TC) in Łęki in (a) June and (b) December, along with labeled maximum (TCmax) and minimum (TCmin) cell temperatures

Rys. 11. Średnie dobowe temperatury ważone zewnętrzne (T) oraz średnie dobowe temperatury ogniw (TC) w Łękach w (a) czerwcu i (b) grudniu, wraz z oznaczonymi maksymalnymi (TCmax) i minimalnymi (TCmin) temperaturami ogniw

In June, the maximum calculated cell temperature was 40.4°C, which was on June 30, and the lowest was 23.4°C, which was on June 4. This month also shows the effect of irradiance on cell temperature, but June 3, with the month's highest irradiance of 458.1 kWh/m^2, recorded an average cell temperature of 32.9°C. The lowest calculated temperature (23.4°C) occurred for the month's lowest irradiance of 210.0 kWh/m^2.

In December, the maximum average cell temperature occurred on December 31 and was 13.5°C. The lowest average cell temperature occurred on December 2 and was –0.6°C. Only for two days, December 2 and 13, was there a negative cell temperature. On days 11, 12, 14 and 21, the weighted outdoor temperature is not visible on the graph, as it takes a value of 0°C on these days due to zero energy production and the way it is calculated. As in the case of June, the maximum cell temperature does not occur at the highest irradiance (December 3, 136.7 kWh/m^2, TC equal to 5.0°C).

Summary and conclusion

The annual energy produced by the installation in Łęki was 5,136.6 kWh in 2022, which corresponds to a specific yield of 1,019.17 kWh/kWp, while in Solec the production was 4,248.9 kWh with a specific yield of 965.67 kWh/kWp. The difference in specific yield was

53.5 kWh/kWp. The total annual irradiance in Łęki was 1,181.14 kWh/m^2 in 2022 and in Solec, it was 1,141.14 kWh/m^2. The average values of outdoor temperature in the two localities differed by only 0.4°C, with a value of 10.1°C in Łęki and 9.7°C in Solec. For both localities, the month with the highest production and insolation was June. In Łęki, the total specific yield for the month was 154.3 kWh/kWp with a total irradiance of 183.4 kWh/m^2, and in Solec it was 155.73 kWh/kWp with a total irradiance of 181.6 kWh/m^2. The month with the lowest production was December for both Łęki and Solec and the specific yields were 8.85 and 5.24 kWh/kWp, respectively, with total irradiation of 23.4 and 16.0 kWh/m^2, respectively. An analysis of the daily amount of energy produced reveals significant differences from day to day. The conclusion drawn from the observations is that it is not possible to predict the daily production accurately, as well as the fact that the amount of energy produced by PV cannot be controlled.

The differences in energy production and specific yield are mainly due to the azimuthal angle of the installation and atmospheric conditions. The angle of inclination of the panels compared to the horizontal does not affect the differences between the two installations, as it was 30° in both cases. The geographic orientation of the installation in Łęki was tilted 45° to the west relative to the south orientation and the installation in Solec was tilted 50° to the east. The installation's orientation to the south, with an azimuthal angle of 0°, is optimal; deviation from this angle results in a negative impact on energy production. The differences in irradiance as well as specific yield in the winter months are mainly due to the height of the sun above the horizon, which is higher in this period in the southern part of Poland, i.e. in Łęki. In addition, there may be a snow cover on the photovoltaic panels in winter, which prevents solar radiation from reaching their surface.

The efficiency of photovoltaic panels directly affects the conversion of solar radiation into electricity. In Łęki, the panels efficiency was 19.2% and in Solec it was 20.77%. The effect of solar radiation and ambient temperature on the temperature of the photovoltaic cell was analyzed using the example of the installation in Łęki. An increase in the temperature of the cell resulted in a decrease in the efficiency of the generated energy by 0.370%/°C for the studied installation. An increase in solar radiation not only resulted in an increase in energy production but also affected the temperature of the cell.

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Porównanie jednostkowych uzysków energetycznych z dwóch instalacji PV – studium przypadku w Polsce

Streszczenie

W związku z dynamicznie rozwijającym się sektorem energetycznym, w szczególności związanym z energią pozyskiwaną ze źródeł odnawialnych, oraz z ciągle rosnącą liczbą instalacji fotowoltaicznych, ważne jest wzięcie pod uwagę czynników wpływających na produkcję energii z promieniowania słonecznego. Większość instalacji PV należy do prosumentów, dlatego praca porównawcza została przeprowadzona dla dwóch przydomowych instalacji, jednej w Polsce południowej i drugiej znajdującej się w Polsce środkowej. Porównano nasłonecznie, temperaturę zewnętrzną, jak i temperaturę ogniw fotowoltaicznych oraz wydajności właściwe w zestawieniach dziennych, miesięcznych i rocznych. Rozważono wpływ wcześniej wymienionych parametrów na uzyski z obu instalacji. Instalacja w Polsce południowej w 2022 roku wyprodukowała 5136,6 kWh, co odpowiada wydajności właściwej na poziomie 1019,17 kWh/kWp, natomiast produkcja instalacji w Polsce środkowej wyniosła 4248,9 kWh, co w przeliczeniu na wydajność właściwą wyniosło 965,67 kWh/kWp. Sprawność paneli fotowoltaicznych bezpośrednio wpływa na przetwarzanie promieniowania słonecznego na energię elektryczną. W Łękach sprawność ta wynosiła (w 2022 roku) 19,2%, a w Solcu 20,77% (instalacja z mikroinwerterami). Na przykładzie instalacji w Łękach przeanalizowano wpływ promieniowania słonecznego i temperatury otoczenia na temperaturę ogniwa fotowoltaicznego. Wzrost temperatury ogniwa skutkował spadkiem sprawności wytwarzanej energii o 0,370%/°C w przypadku badanej instalacji.

Słowa kluczowe: energia, prosument, fotowoltaika, PV, uzyski