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Energy Production from PV Systems Located in Poland Based on Solar Irradiation Data Obtained from PVGIS

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Abstract: Solar photovoltaic systems (PVs) are becoming more popular in Poland, as the country aims to increase its share of renewable energy sources and reduce its dependence on coal. According to the official data the total installed PV capacity in Poland reached 15.6 GW in September 2023 while at the end of 2020 it was 4.1 GW. This situation was caused by many factors, but mainly by government subsidy programs for households and rising electricity prices. A number of photovoltaic installations with a capacity of up to 50 kWp were carried out, although the installation should always be adapted to the needs of a given household. Estimating the yield of solar energy systems is crucial for that. It can be done by several methods, but always as initial step in modelling of solar energy systems weather data, especially solar irradiation is required. To get this data we can arrange the measurement from ground stations or use reanalysis models and satellite-derived datasets. There are several different datasets, both public and commercial, of solar irradiance data ready to use. This data provides insights into the average solar irradiance levels throughout the year, aiding in estimating the energy generation capacity. The paper contributes the knowledge of energy generation capacity that can be quickly counted for a solar PV micro-system with different orientation and inclination as a multiplier of the energy value obtained from a solar PV system of 1 kW-peak for a significant number of locations in Poland based on open-source solar irradiation data

Keywords: energy generation; solar irradiance; Poland; PV system power output; PVGIS dataset

1. Introduction

In Poland, significant changes have occurred in the landscape of renewable energy sources, especially in photovoltaic (PV) solar systems, in recent years. The installed capacity of PV solar energy systems has seen remarkable growth, rising from 4.1 gigawatts (GW) at the end of 2020 to a substantial capacity of 15.6 GW in September 2023 [1]. This outstanding growth is primarily due to various factors that accelerated the widespread adoption of solar photovoltaics across the nation. The convergence of supportive governmental actions, including substantial funding and well-designed incentive programs started in 2019, has significantly contributed to driving the uptake of solar technology. Additionally, the evolution of the Polish energy sector, marked by fluctuating energy prices and a gradual shift towards sustainable practices, has made PV solar systems an attractive, cost-effective and environmentally conscious alternative. Between December 2009 and December 2022 the cost of crystalline solar PV modules sold in Europe declined by 91%, and the global average levelized cost of electricity (LCOE) from utility-scale PV plants between 2010 and 2020 decreased by 89% [2]. In 2022, the year-on-year reduction was 3%. Analyzing these trends along with the declining cost of PV solar panels [3] provides invaluable insights into the gigantic rise of PV solar energy systems in Poland.

The majority of installed solar photovoltaic systems in Poland are prosumer micro-installations. As of the end of September 2023, the total installed capacity of PV micro-installations (individual installation up to 50 kWp) was 10.2 GW, accounting for nearly 70% of the total photovoltaic capacity

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in Poland. According to the Energy Regulatory Office (ARE) [1], the total number of prosumer photovoltaic micro-installations as of the end of September 2023 reached 1,349,736, increasing by 201.1 thousand within 12 months. It's worth noting that in 2021, the Council of Ministers in Poland approved a document "Energy Policy of Poland until 2040 (PEP2040)" [4]. The PEP2040 assumed a significant increase in the capacity of photovoltaic systems: up to 5-7 GW in 2030 and 10-16 GW in 2040 [4]. As seen, these predictions in the PEP2040 have already been exceeded in 2023 and prosumer PV micro-installations contributing to the current capacity. Despite changes in the energy billing system for PV micro-installations it is expected that their numbers will continue to grow in Poland [5].

Household interest in adopting photovoltaic (PV) installations differs from the motives of institutional investors or governmental bodies aiming for high financial returns and renewable energy integration. Studies show that specific household attributes significantly influence the decision to install solar PV systems. These factors include income levels, educational backgrounds, homeownership status, duration of intended house usage, and, subsequently, the consideration of investment profitability [6,7]. Such factors, along with installation location possibilities and household electricity consumption determine usually the size of solar PV micro-installations. However, integrating large numbers of PV micro-installations with electrical distribution network may cause some technical issues such as frequency regulation, excessive grid traffic and energy quality problems [8]. To address this, increasing the self-consumption of locally generated energy can mitigate excessive grid traffic. To reach this goal the capacity of each single solar PV micro-installation should be properly selected in relation to the household energy consumption. Understanding household or facility energy needs and consumption patterns is crucial. Factors like daily and seasonal energy consumption, peak usage times, and load profiles determine the size and configuration of the required solar PV system. Analyzing historical energy bills or conducting on-site energy audits helps estimate consumption patterns. There are various methods presented in the literature to increase the self-consumption of energy, for both off-grid and grid-connected systems [9–13]. However, incorporating weather data, specifically solar irradiation, is essential as a starting point for estimating energy output potential of a solar PV micro-installation.

Solar irradiation represents the amount of solar energy received per unit area. Geographical locations with higher solar irradiance typically yield greater energy production from PV systems. Therefore, analyzing solar irradiation data specific to the installation site is fundamental operation. Tools such as solar irradiance maps, satellite data or local meteorological database provide insights into the average solar irradiance levels throughout the day, month, or year, aiding in estimating the energy generation capacity. Consequently, electricity production from a 1 kW-peak (kWp) grid-connected solar PV power plant covering the certain period of time is often presented. A Global Solar Atlas (GSA) can serve as a good example. GSA, released in January 2017, is an enhanced web-based platform that offers access to data needed for preliminary assessment of solar energy projects [14].

Although Poland's geographical location doesn't inherently suggest enormous potential for solar energy projects, it offers suitable conditions for the effective operation of photovoltaic (PV) systems, despite its variable weather patterns and changing seasons. Poland's solar conditions are considered optimal, as too much heat and sunshine can actually damage solar systems due to overheating [15,16].

The current paper aims to contribute the knowledge of energy generation capacity that can be quickly counted for a solar PV system with different orientation and inclination as a multiplier of the energy value obtained from a 1 kWp solar PV system across numerous locations in Poland.

2. Materials and Methods

To cover the whole extend of Poland territory an extensive set of all municipalities was chosen. In Poland, the comprehensive repository of data for all municipalities is driven by the National Official Register, which maintains the Territorial Division of the Country System (TERYT) [17]. As of January 1th, 2023, this system, abbreviated as SIMC, contains a total of 102311 records. However, despite containing names and related descriptors for each municipality in SIMC database, it lacks the geographical coordinates expressed in latitude and longitude necessary for precise location identification within Poland. To attain these geographic coordinates for each municipality from SIMC database, geocoding using OpenStreetMap (OSM) was employed. OpenStreetMap is one of the largest and most detailed sources of mapping data. It provides a geocoding service through its Nominatim API [18], which is freely accessible under certain usage policies. Nominatim API was utilized for geocoding, successfully decoding over 88% of 102311 municipality records, which were used for further calculations.

For each PV (photovoltaic) system the initial step in modeling is to obtain weather data, especially solar irradiation. There are three primary sources for solar irradiance data for the site of interest: measurement using pyranometers from ground stations, reanalysis models and satellite-derived datasets. By using quality-controlled ground-based instruments measurements from ground stations allow to assess irradiance of the highest level of data accuracy. The ground measurement networks include the Baseline Surface Radiation Network (BSRN), Measurement and Instrumentation data Center (NREL MIDC), Solar Radiation Monitoring Laboratory (SRML), Surface Radiation Budget Network (SURFRAD) and the US Climate Reference Network (CRN). An online overview of global solar radiation monitoring stations is available [19]. However, accessing measured data for specific locations is limited due to maintenance requirements and high equipment costs. For this reason, data from geostationary meteorological satellites are often used to assess the solar irradiation data. Such approach has some pros and cons. The advantages is that solar irradiation data are available in the whole of the area covered by the satellite images and long time series of data are available without gaps. Another advantage is a low cost. The disadvantage of this method is that the solar radiation at ground level must be calculated using complicated mathematical algorithms and satellite-derived datasets are typically limited to ±60° latitude due to the view angle of satellites. Despite this inconvenience satellite-based solar radiation data is now widely used in pV system calculations, both from public and commercial sources [20,21]. Well-known sources are: PVGIS (SARAH & ERA5 datasets), NSRDB PSM3 and CAMS Radiation Service. PVGIS stands for Photovoltaic Geographical Information Systema [22]. It was developed by EU Science Hub as an initiative by the European Commission's Joint Research Centre (JRC) and works as a web application that allows the user to get data on solar radiation at any place in most parts of the world and it is completely free to use. Solar radiation data are available from different datasets in PVGIS: SARAH, SARAH2, ERA5 and NSRDB PSM3. The newest version of PVGIS v. 5.2 uses data from PVGIS-SARAH2 dataset. SARAH2 is the successor of SARAH1 and PVGIS encourages users to use SARAH2. The time period covered by PVGIS-SARAH2 is between 2005 and 2020 year.

Accessing data from PVGIS-SARAH2 can be achieved directly via a web application from re.jrc.ec.europa.eu, which suits single-location use. Alternatively, web APIs from PVGIS allow direct calls using various programming languages such as Python, NodeJS, Perl, Java, and others. For current research, a Python script utilizing the pvlib-python library was employed [23]. Pvlib-python library provides a set of functions and classes grouping in subpackages for simulating the performance of photovoltaic energy systems. Within *iotools* subpackage there is a collection of functions that offers access to 12 different solar irradiance datasets. Functions prefixed with 'pvgis' allow retrieval of data from the PVGIS system. In the script, the function *pvlib.iotools.get_pvgis_hourly* was used to obtain hourly solar irradiation and modeled PV power output from PVGIS. A snippet of the code is illustrated in Figure 1, and the complete code is downloadable from the GitHub webpage [24].

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```
import pvlib
# get hourly solar irradiation and modeled PV power output
# at lat, lon within start-end period for 1 kWp PV system
def obtain_pv_power_from_PVGIS_hourly1(
    lat, lon, start, end, surf_tilt, surf_azimuth):
    poa, _, _ = pvlib.iotools.get_pvgis_hourly(
        latitude = lat,
        longitude = lon,
        start = start,
        end = end,
        raddatabase = 'PVGIS-SARAH2',
        components = True,
        surface_tilt = surf_tilt,
        surface_azimuth = surf_azimuth,
        pvcalculation = True,
        peakpower = 1,
        pvtechchoice = 'crystSi',
        mountingplace = 'free',
        loss = 0,
        trackingtype = 0,
        url='https://re.jrc.ec.europa.eu/api/v5_2/',
    )
    poa['P'] = poa['P'].div(1000)
    return poa
```

Figure 1. A snippet of the code for hourly solar irradiation and modelled PV power output using PVGIS system.

The procedure was as following. For each location – a single municipality geocoded with OpenStreetMap – hourly solar irradiation data was obtained from PVGIS-SARAH2. This data spanned five years, from 2015 to 2020. The hourly data within this timeframe was aggregated by summing up the values. The cumulative data was then averaged to determine a representative value for solar irradiation over the five-year period. Four distinct calculations were performed for each location, varying the PV system configuration as follows:

- calculation of PV power output was conducted for a horizontal PV system, where the panels were flat, disregarding tilt and orientation,
- calculations were performed for a PV system appropriately for an east, south and west-facing orientation and a tilt of 30 degrees to explore the performance implications of the orientation and tilt angle widely applied in Poland.

The final results of calculation provide insight into the expected power output from a PV system of a power of 1 kWp under varied configuration (azimuth, tilt) at different locations in Poland based on the averaged solar irradiation values that were employed to estimate the anticipated performance of PV system setup over the specified five-year period. A crystalline silicon technology was chosen for the solar PV system due to its efficiency, reliability, cost-effectiveness and popularity among residential, commercial and utility-scale solar installations [25].

3. Results and discussion

3.1. Energy yield assessment

Using the methodology outlined in Section 2, indicative results for potential energy production from a 1 kWp photovoltaic installation were derived. These calculations encompassed nearly all locations across Poland as specified in the Territorial Division of the Country System (TERYT). At a more detailed level, these locations are depicted as colored markers on a map, each representing four different energy generation values. These values correspond to the physical orientation and fixed inclination of the solar PV system. A view of such a visual representation is shown in Figure 2.

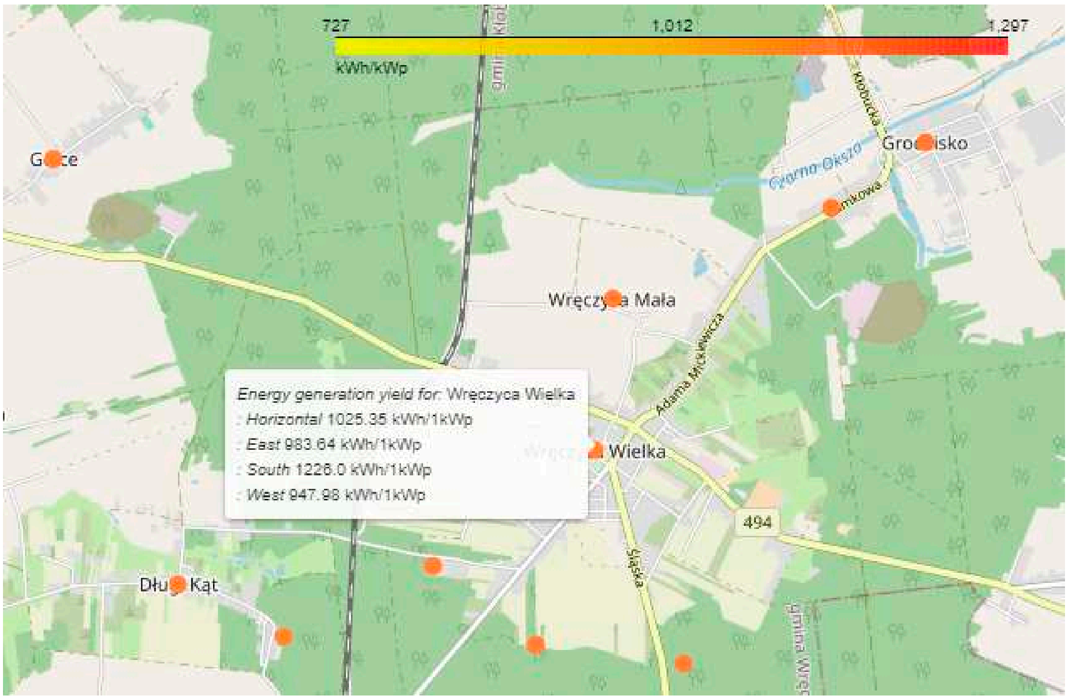
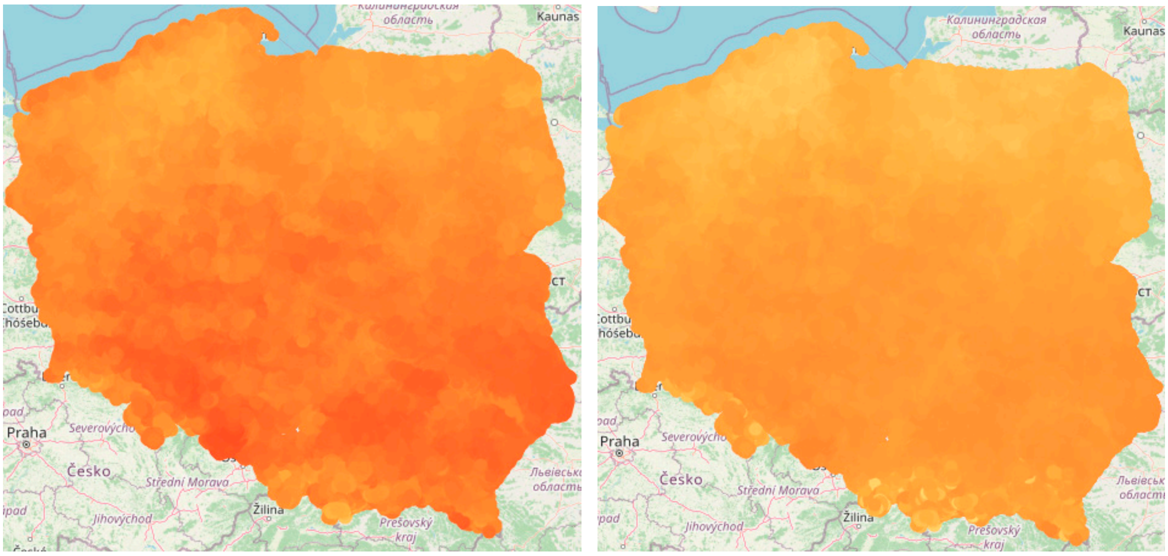


Figure 2. The detail information about potential energy generation from a 1 kWp solar PV system.

Full extent map is accessible online at *https://ekordo.pl/pvgis_pv_maps*. The view of energy generation yield from a solar PV system located in Poland, for different orientation is given in Figure 3.



(**a**) (**b**)

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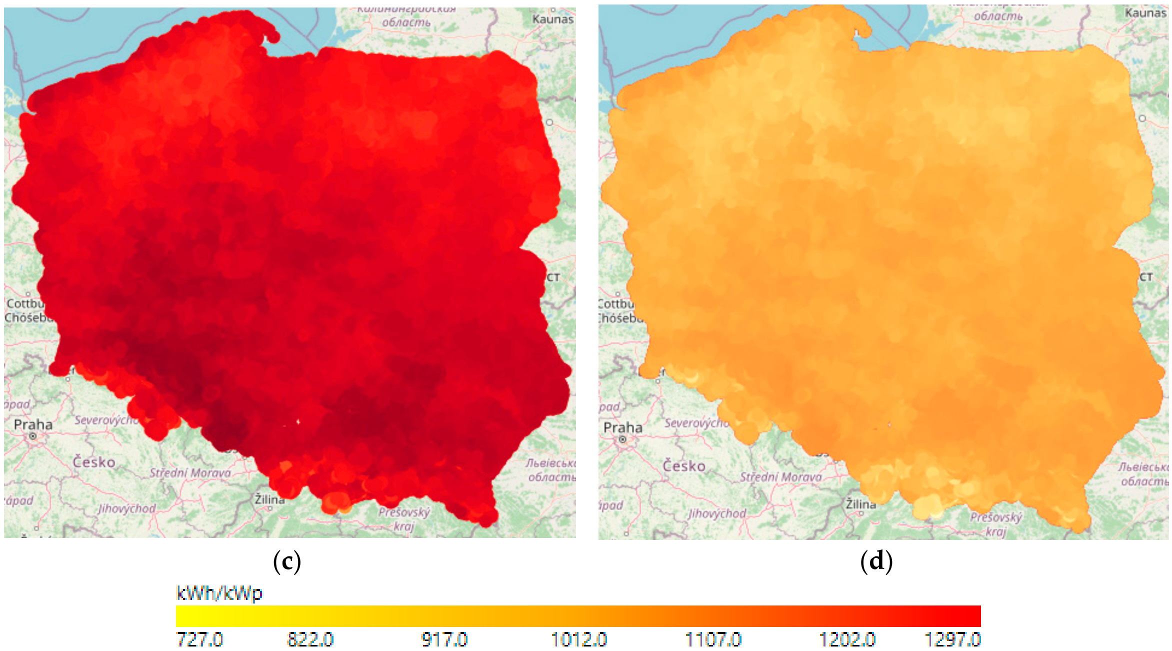

Figure 3. The potential energy yield from a 1 kWp solar PV system located in Poland's municipalities. PV system orientation: (**a**) horizontal; (**b**) east; (**c**) south; (**d**) west .

The yearly average energy yield from solar PV system appropriately for an east, south and west-facing orientation and a tilt of 30 degrees in individual voivodeship is given in Table 1.

Table 1. The yearly average energy yield (kWh) from solar PV system of 1 kWp power at different orientation and inclination on the area of individual voivodships in Poland.

Voivodship	**Orientation of PV system**		
	E(ast)	**S**(outh)	**W**(est)
Lower Silesia	990.46	1246.18	961.45
Kuyavia-Pomerania	964.84	1211.23	942.00
Lublin	987.51	1229.81	961.20
Lubusz	972.34	1216.23	938.97
Łódź	986.96	1232.77	953.89
Lesser Poland	967.45	1216.84	937.80
Masovia	972.57	1214.39	947.13
Opole	997.65	1256.00	970.69
Subcarpathia	982.23	1237.19	960.26
Podlaskie	942.30	1169.96	922.54
Pomerania	923.03	1158.82	912.99
Silesia	973.42	1214.63	942.91
Holy Cross Province	990.77	1244.00	967.96
Warmia-Masuria	925.53	1159.41	911.70
Greater Poland	981.32	1233.63	951.84
West Pomerania	939.34	1177.90	922.36

The data presented in Table 1 highlights disparities in average energy yield generated from a 1 kWp solar PV system across various regions in Poland. For instance, regions such as Lower Silesia, Opole and Holy Cross Province generally demonstrate higher energy yields compared to areas like Podlaskie, Pomerania, or Warmia-Masuria. Optimal energy generation from PV systems tends to be highest with a 'south' orientation, as this position maximizes exposure to solar sunlight, making solar panels most effective.

The highest value of yearly average energy yield for voivodship of Poland was obtained for Opole province. However, the highest value of energy generation was achieved for Dobieszów, a city

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located in Opole province's Kedzierzyn-Kozle county. Conversely, the lowest energy yield was generated for Kiry, a village near Zakopane in Lesser Poland voivodship, in Tatra mountains.

3.2. Comparison with the energy generated in a real PV system

A 9.79 kWp photovoltaic installation is situated on the roof of a residential building in Wreczyca-Wielka, a village located in the south part of Poland close to Czestochowa, a city primarily famous for the home of the Jasna Góra Monastery and Black Madonna.

Due to the orientation of the building on a north-south axis, the installation is divided into an eastern and western part. Actually the eastern side comprises a power of 5.5 kWp, while the western side consists of photovoltaic mono-crystalline-silicon panels of 4.29 kWp. Initially, the PV micro-installation was connected to the electrical grid in 2016 under prosumer rules, but in the 2020 the installation underwent expansion to the power values given above. The energy generation from PV panels is managed by two Fronius inverters operating in a master-slave configuration. The power of the inverter operating in master mode is 3.7 kW, while the other is 3 kW.

The monthly distribution of energy obtained from 9.79 kWp photovoltaic installation over a two-year period (2022-2023) is shown in Figure 4. Table 2 shows the total energy produced by this installation. The annual amount of energy produced does not exceed 8,500 kWh.

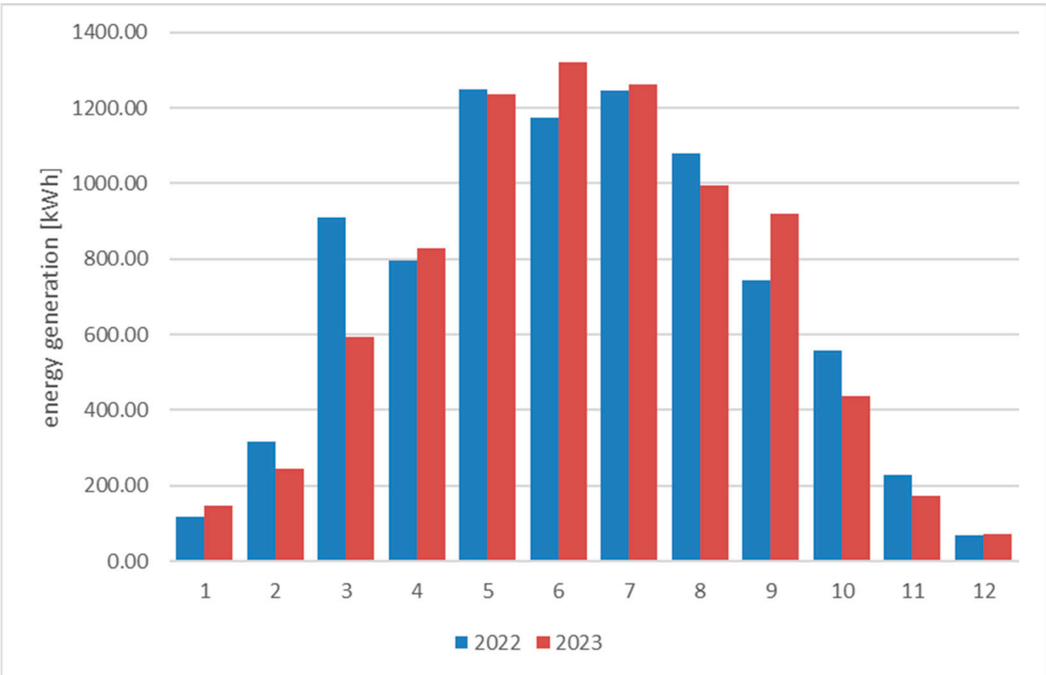

Figure 4. Energy generated by the solar PV system in Wreczyca-Wielka. Monthly data per 2022 and 2023 year.

Table 2. Annual energy yield from 9.79 kWp solar PV system.

Energy	2022	2023
kWh	8488.97	8227.95

Taking the determined energy yield values calculated from the solar irradiance data according to the procedure in Section 2 for a solar PV system located in Wreczyca-Wielka the following values were determined for the eastern and western parts of the 9.79 kWp PV installation to give an estimation of the energy generation:

- eastern : 5,5 kWp x 983.64 kWh/kWp = 5410.02 kWh

- western: 4.29 kWp x 947.98 kWh/kWp = 4066.83 kWh

The total value is 9476.85 kWh and is higher than the actual values obtained from the PV micro-installation by nearly 1MWh. Such a large difference can be attributed to a number of factors in this case. On very sunny days, some od the energy generated by the PV panels can be cut off by the inverter with a power output that is less than that of the panels located both on both the east and west sides of the building. In addition, zero losses were assumed in the calculation of the energy yield indicator. In practice, the following should be taken into account: losses due to performance of PV modules outside of STC conditions, losses due to external shading if exists, losses due to dirt and soiling, losses due to thermal losses, mismatch and DC cabling losses and losses on conversion of DC to AC [26]. According to the technical report Global Solar Atlas 2.0 by World Bank Group each installation has its own working conditions and possible losses ranges within 7.1 – 90.5%, mostly 9% [27]. Panel degradation also plays a role. It has been observed that performance degradation rate of PV modules is higher at the beginning of the exposure, and then stabilizes at a lower level. Initial degradation may be close to value of 0.8% for the first year and 0.5% or less for the next years [28]. Thus, taking into account the losses at 9% for the PV installation in Wreczyca-Wielka, the energy yields are as follows:

- eastern : 5,5 kWp x 869.38 kWh/kWp = 4781.59 kWh

- western: 4.29 kWp x 839.50 kWh/kWp = 3601.45kWh

and the total energy generation is 8383.05 kWh, which is closer to the energy obtained from an installation.

4. Conclusions

The rapid growth of PV solar energy systems in Poland has been observed for a several years, primarily driven by the governmental actions encompassing substantial funding and well-crafted incentive programs addressed to the public. As a result the dominance of micro-installations in the Poland's PV landscape is significant, accounting for a significant portion of the total installed PV capacity. Despite changes in the energy billing system for PV micro-installations it is assumed that PV micro-installations will continue to develop in Poland.

In the paper, a comprehensive methodology is presented to estimate the energy generation capacity of solar PV systems across different orientations and inclinations in various locations in Poland. This methodology utilizes geocoding techniques to cover the entire territory of Poland and extracts solar irradiation data from PVGIS-SARAH2 dataset, providing hourly data over a five-years period. By aggregating and averaging this data, the study calculates energy yield indicators for 1 kWp PV systems across multiple locations in Poland. As result the research demonstrates regional disparities in PV energy yield across Poland. Regions such as Lower Silesia, Opole, and Holy Cross Province exhibit higher yields compared to areas such as Podlaskie, Pomerania, or Warmia-Masuria and the 'south' orientation of PV panels generally offers the highest energy yield.

The case study of a 9.79 kWp photovoltaic installation in Wreczyca-Wielka shows the actual energy production over a two-year period (2022-2023). The calculated energy yield values for the installation corresponds to real-world data after taking into account practical factors such as inverter limitations, module efficiency losses, shading and other technical aspects that contribute to the observed and calculated differences. However, the presented energy indicators for different PV system orientations in various locations across Poland provide valuable initial parameters for determining solar PV system power. These indicators serve as a critical reference point for stakeholders, assisting them in estimating potential energy generation capacities in different regions of Poland. Nevertheless, for a real-world performance evaluation of PV solar systems, more accurate assessments should be considered.

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Supplementary Materials: The following supporting information can be downloaded at: https://ekordo.pl/pvgis_pv_maps, Figure 3: title; The potential energy yield from a solar PV system of 1 kWp in the area of Poland

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