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Rapid assessment of solar PV micro-system energy generation in Poland based on freely pvlib-python library

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Abstract
Poland has experienced a remarkable growth in renewable energy adoption, notably in photovoltaic (PV) solar systems. The majority of installations are prosumer PV micro-installations, exceeding predicted capacity targets outlined in the Energy Policy of Poland until 2040. Despite the significant growth in installed PV capacity, there is still a lack of comprehensive research focusing on fast assessment of energy generation capacity for solar PV micro-systems. This study aims to address this gap by providing a comprehensive analysis of energy production potential across different configurations and locations in Poland. Using geocoding techniques, solar irradiation data from PVGIS database and pvlib-python library, a methodology was developed to rapidly estimate energy generation from 1 kWp solar PV systems . Results reveal spatial disparities in energy yield from solar PV micro installations in Poland, influenced by factors such as geographical location and panel orientation and inclination. Recognizing that the presented energy indicators provide valuable initial parameters for determining solar PV system power output, this data can serve as a critical reference point for stakeholders, assisting them in estimating potential energy generation capacities in different regions of Poland.

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1. Introduction

In recent years, Poland has witnessed significant changes in its renewable energy landscape, particularly in the domain of photovoltaic (PV) solar systems. This transformation is underscored by the remarkable growth in installed capacity, which raised from 4.1 gigawatts (GW) in 2020 to a substantial capacity of 17 GW in December 2023 (ERO, 2024). This expansion is attributed to several factors that have facilitated the widespread adoption of solar photovoltaics systems throughout the country. Notably, supportive governmental actions, characterized by substantial funding and well-designed incentive programs initiated in 2019, have played an important role in driving the uptake of solar technology. Furthermore, the evolution of the Polish energy sector, marked by fluctuating energy prices and a gradual transition towards sustainable practices, has established PV solar systems as an attractive, cost-effective and environmentally conscious alternative. The declining costs associated with PV solar technology further reinforce its popularity, as evidenced by the 91% decrease in the cost of crystalline solar PV modules sold in Europe between December 2009 and December 2022, alongside an 89% reduction in the global average levelized cost of electricity (LCOE) from utility-scale PV plants from 2010 to 2022 (IREA, 2023; Noel. 2023; Biswas, 2023). The analysis of these trends, coupled with the declining cost of PV solar panels, offered invaluable insights into the substantial 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 December 2023, the total installed capacity of PV micro-installations (individual installation up to 50 kWp) reached an impressive 10.6 GW. Data from the Energy Regulatory Office (ARE) indicates that the total number of prosumer photovoltaic micro-installations reached 1,383,476. It's worth noting that in 2021 the Council of Ministers in Poland approved a document "Energy Policy of Poland until 2040 (PEP2040)" (MCE, 2021). Projections within this document anticipated a significant increase in the capacity of photovoltaic systems: up to 5-7 GW in 2030 and 10-16 GW in 2040. As seen, these forecasts have already been exceeded in 2023 with prosumer PV micro-installations playing a pivotal role in achieving and exceeding the predicted capacity targets. Despite regulatory adjustments, including changes in the energy billing system for PV micro-installations, it is expected that the numbers of these installations will continue to grow in Poland (Mularczyk et al, 2022). This persistent growth underscores the sustained enthusiasm and commitment towards decentralized renewable energy solutions, positioning prosumer PV micro-installations as key components of Poland's energy transition strategy.

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 underscore that 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 (Dharshing, 2017; Rukh Shakeel, 2023; Rigo et al., 2023; Akrofi et al., 2023; Sirgin et al., 2015). 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 (ElNozahy, et al., 2013). To address these challenges, increasing self-consumption of locally generated energy becomes crucial. Achieving this goal requires the proper selection of each single solar PV micro-installation in relation to the household energy consumption. Understanding household or facility energy needs and consumption patterns, including daily and seasonal energy consumption, peak usage time 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. Various methods presented in the literature offer insights into increasing self-consumption of energy for both off-grid and grid-connected systems (Luthander et al., 2015; Martín-Chivelet et al., 2017; Maranda, 2019; Chattopadhyay et al., 2017; Weniger et al., 2014; Modawy et al., 2023).

A critical aspect in optimizing the performance of PV systems lies in accounting for solar irradiation - 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 valuable insights into 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 (Kapica et al., 2021).

While Poland's geographical location may not suggest enormous potential for solar energy projects, it offers suitable conditions for the effective operation of photovoltaic (PV) systems, despite variable weather patterns and changing seasons. Optimal solar conditions in Poland, characterized by a balance that avoids excessive heat and sunshine which could damage solar systems due to overheating pose an interesting issue for research (Klepacka et al., 2019; Igliński et al., 2023).

The objective of this paper is to develop a rapid methodology for assessing the energy production potential of PV-micro-systems across Poland. Despite the significant growth in installed PV capacity, there is still a lack of comprehensive knowledge regarding the potential energy generation capacity of solar PV micro-systems that highlights spatial disparities in energy yield influenced by geographical location, panel orientation and inclination. The perspective on the spatial dynamics of solar PV micro-systems adds a unique dimension to the current discourse on PV micro-systems. However, it is important to acknowledge some limitations of our study. The methodology is currently applied only to territory of Poland. While we believe that approach can be adapted to other countries, this has not been empirically tested within the scope of the paper. The model relies on several simplified assumptions, such as ignoring real-world factors like shading, soiling which can affect energy production. Also the study does not extensively cover the temporal variability of energy production on a daily or monthly basis, we provide a general assessment of energy yields. To address these limitations future directions, such as: expansion to other regions, incorporation of real-world factors, temporal analysis or economic impact studies would enhance the robustness of the research.

2. Experimental

The research methodology presented in this study was specifically developed for Poland. However, it can be adopted and adapted for use in other countries or regions.

To cover the entire territory of Poland an extensive dataset of all municipalities was chosen. The comprehensive repository of data is driven by the National Official Register, which maintains the Territorial Division of the Country System (TERYT) (SP, 2024). As of January 1th, 2023, this system (known as SIMC) contains a total of 102311 records. However, despite containing names and related descriptors for each municipality, it lacks the geographical coordinates. To attain these data for each municipality geocoding using OpenStreetMap (OSM) was employed. OpenStreetMap was chosen because it provides a global and open-access mapping solution. It covers a wide range of geographic locations, making it a versatile tool for geocoding in various regions. OSM provides a geocoding service through its Nominatim API (Arsanjani et al, 2015). This service is freely accessible under certain usage policies.

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. 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 pros and cons. The advantages is solar irradiation data is 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 (Stowell et al, 2020; Ernst et al., 2016). Well-known sources are: PVGIS (SARAH & ERA5 datasets), NSRDB PSM3 and CAMS Radiation Service. PVGIS stands for Photovoltaic Geographical Information Systema and it was developed by EU Science Hub as an initiative by the European Commission's Joint Research Centre (JRC) (Huld, 2012). Solar radiation data are available from different datasets in PVGIS: SARAH, SARAH2, ERA5 and NSRDB PSM3. The latest version uses data from PVGIS-SARAH2 dataset. SARAH2 is the successor of SARAH1 and PVGIS encourages to use SARAH2. The authors used it in developed model.

Accessing data from PVGIS-SARAH2 can be achieved directly via a web application from re.jrc.ec.europa.eu, but it 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 (Holmgren et al., 2018). 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. The complete code of the model is downloadable from the GitHub (Github, 2024).

The overall research procedure is given in Figure 1. For each location – a single municipality geocoded with OpenStreetMap – hourly solar irradiation data was obtained from PVGIS-SARAH2 dataset. 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:

- horizontal PV system calculation - PV power output was calculated for a horizontal PV system,
- orientation and tilt variation calculations - these calculation were performed for a PV system with east, south and west-facing orientation and a tilt of 30 degrees.

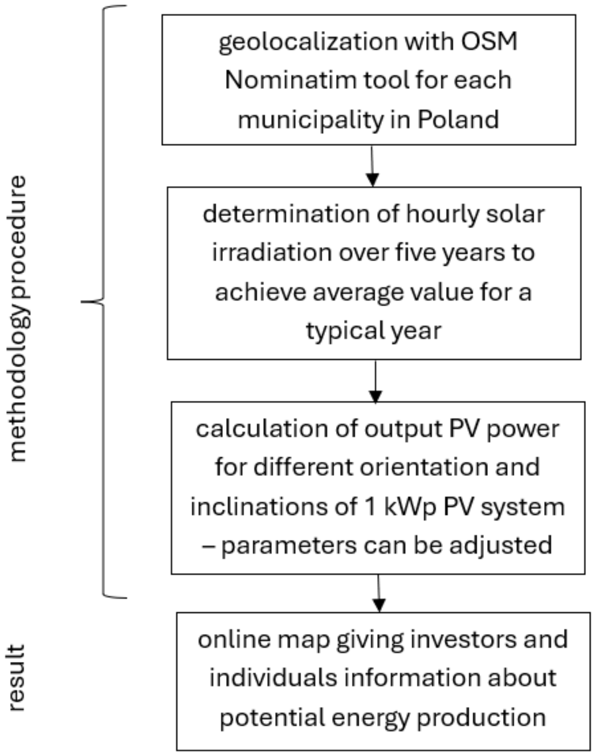

Fig. 1. The procedure for energy production assessment from a solar PV system

The final results offer the insight into the expected energy generation from solar PV micro system of 1 kWp power under varied configuration. The calculations are based on the averaged solar irradiation values providing estimates for the anticipated performance over the specified period. A crystalline silicon technology was chosen due to its efficiency, reliability in converting sunlight into electricity as well as its cost-effectiveness and popularity among residential, commercial and utility-scale solar installations (Ballif et al., 2022).

3. Results and discussion

3.1. Energy production assessment

Following the presented methodology indicative results for potential energy generation from a 1 kWp solar PV microsystem are achieved. The data covered almost all locations across Poland as specified in the Territorial Division of the Country System (TERYT).

A visual representation of the potential energy yield from a 1 kWp solar PV system is illustrated in Figure 2. The map uses a gradient of colours, with darker orange shades indicating higher energy yields. It is important to note that this map is illustrative and does not include a scale to quantify the yield values directly. For comprehensive map with detailed data and precise yield values authors encourage to visit https://ekordo.pl/pvgis_pv_maps. These complete maps provide a more granular view of the energy yield potential, supporting more accurate and informed assessments.

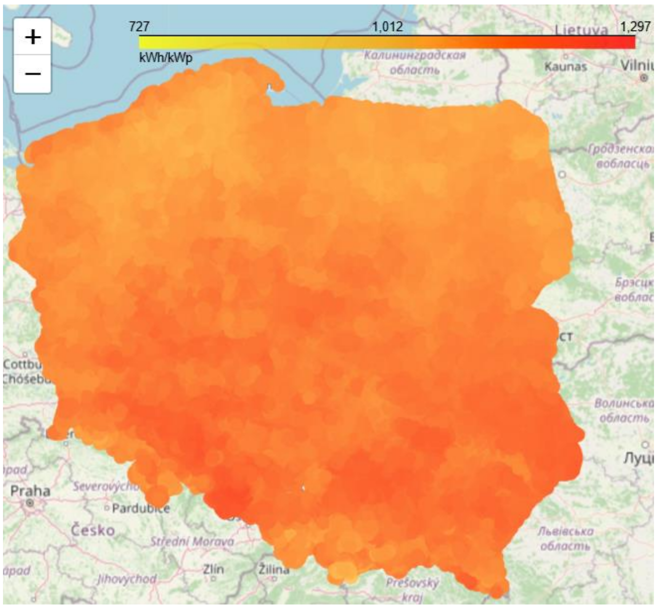

Fig. 2. The potential energy yield from a 1 kWp solar PV system

At a more detailed level these locations are visually represented as coloured markers on a map, each marker represents four different values of potential energy production. These values correspond to the specific physical orientation and fixed inclination of the solar PV system. An example is given in Figure 3.

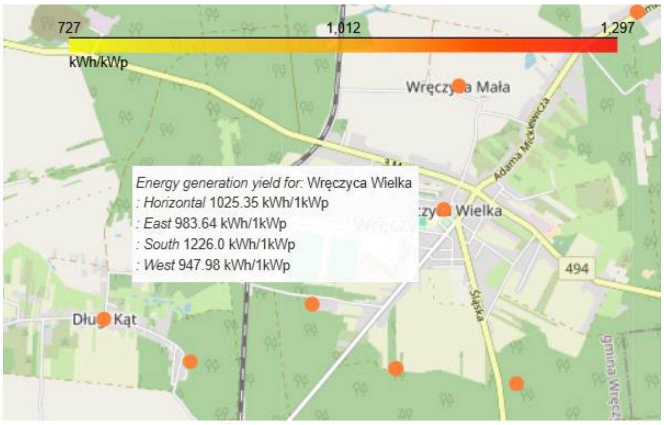

Fig. 3. The detail information about potential energy generation from PV microsystem

The yearly average energy yield (in kilowatt-hours) from a 1 kWp solar PV system, appropriately configured for east, south and west-facing orientations, along with a fixed tilt of 30 degrees is presented in Table 1.

Table 1. Statistical analysis of annual average energy yield from 1 kWp solar PV microsystem in Poland's voivodships

Voivodeship	Orientation	Mean Energy Yield (kWh)	Variance	95% Confidence Interval (kWh)
Lower Silesia	East	990.46	15.23	985.12-995.80
	South	1246.18	20.12	1239.85-1252.51
	West	961.45	12.34	956.87-966.03
Kuyavia-Pomerania	East	964.84	13.56	960.12-969.56
	South	1211.23	20.12	1205.10-1217.36
	West	942	12.34	937.45-946.55
Lublin	East	987.51	14.67	982.52-992.5
	South	1229.81	18.79	1223.73-1235.89
	West	961.20	13.12	956.31-966.09
Lubusz	East	972.34	15.01	982.52-992.5
	South	1216.23	19.34	1223.73-1235.89
	West	938.97	11.95	956.31-966.09
Łódź	East	986.96	14.98	981.72-992.20
	South	1232.77	20.00	1226.44-1239.10
	West	953.89	12.25	949.29-958.49
Lesser Poland	East	967.45	15.13	962.18-972.72
	South	1216.84	19.22	1210.67-1223.01
	West	937.80	12.11	933.19-942.41
Masovia	East	972.57	14.89	967.34-977.80
	South	1214.39	18.97	1208.21-1220.57
	West	947.13	11.68	942.59-951.67
Opole	East	997.65	15.45	992.30-1002.99
	South	1256.00	20.34	1249.56-1262.44
	West	970.69	12.78	966.00-975.38
Subcarpathia	East	982.23	14.56	977.25-987.21
	South	1237.19	19.01	1231.00-1243.38
	West	960.26	11.98	955.60-964.92
Podlaskie	East	942.30	15.23	937.06-947.54
	South	1169.96	18.65	1163.90-1176.02
	West	922.54	12.45	917.77-927.31
Pomerania	East	923.03	15.12	9127.76-928.30
	South	1158.82	10.03	1152.63-1165.01
	West	912.99	12.38	908.24-978.42
Silesia	East	973.42	14.67	968.42-978.42
	South	1214.63	18.89	1208.45-1220.81
	West	942.91	11.78	938.54-996
Holycross Province	East	990.77	14.89	985.54-996.0
	South	1244.00	19.78	1237.72-1250.28
	West	967.96	12.23	963.37-1250.28
Warmia Masuria	East	925.53	15.34	920.23-930.83
	South	1159.41	18.45	1153.35-1165.47
	West	911.70	12.56	906.92-916.48
Greater Poland	East	981.32	14.98	976.08-986.56
	South	1233.63	19.22	1227.46-1239.80
	West	951.84	11.89	947.20-956.48
West Pomerania	East	939.34	15.01	934.10-944.58
	South	1177.90	18.56	1171.84-1183.96
	West	922.36	12.34	917.78-926.94

The small variances observed in the energy yield estimates indicate a consistency in the data. The narrow confidence intervals suggest that the average energy yields are reliable and can be a starting point for further planning or decision-making. There are noticeable differences in the energy yields among different voivodeships. For instance, regions like Lower Silesia or Opole have higher average yields compared to Podlaskie and Pomerania. South-facing PV systems consistently show the highest energy yields across all regions, highlighting the importance of optimal panel orientation for maximizing solar energy catch. East and west orientations yield slightly lower energy production, but still are viable options.

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

A 9.79 kWp PV microsystem is situated on the roof of a residential building in Wreczyca, 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.

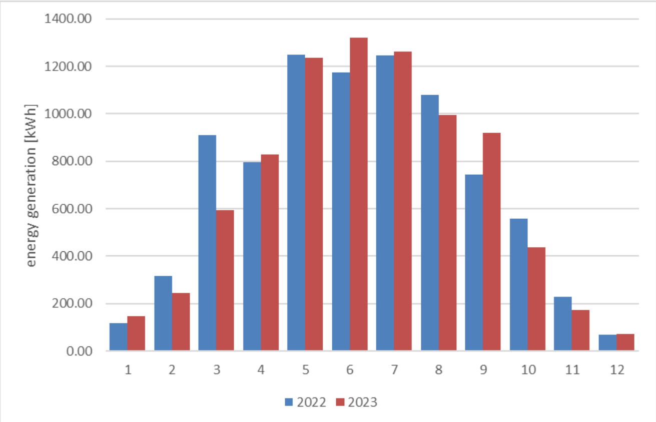

Fig. 4. Energy obtained from PV microsystem located in Wreczyca. Monthly data per 2022 and 2023 year

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

Energy	2022	2023
kWh	8488.97	8227.95

Taking the energy yield values obtained in the model the following data were determined for the eastern and western parts of the 9.79 kWp PV installation:
- 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 much higher than the actual values obtained from the PV micro-installation by nearly 1MWh.

3.3. Discussion

While previous research by Castillo et al. (2016) and Amato et al. (2016) has highlighted the potential for PV systems in various European countries, our study specifically targets Poland. The data presented in Table 1 and Figure 2 highlight spatial disparities in average energy yield generated from a 1 kWp solar PV system across various regions. Regions such as Lower Silesia, Opole and Holy Cross Province generally demonstrate higher energy yields, underscoring their solar energy potential. In contrast, areas like Podlaskie, Pomerania or Warmia-Masuria generally demonstrate lower yields. The orientation of PV systems plays a crucial role in energy generation as demonstrated in the data. Optimal energy yields are often associated with a 'south' orientation, which maximizes exposure to solar sunlight. The results align with established principles in solar energy engineering confirming the importance of the physical orientation of panels for efficient energy production. Opole province stands out with the highest yearly average energy yield, showing its potential as a favourable region for solar energy installations in Poland. The city of Dobieszów in Opole province's Kedzierzyn-Kozle county achieves the highest energy generation underlining the local variations within a province. Conversely, Kiry, a village in Lesser Poland's Tatra mountains, experiences the lowest energy yield, emphasizing the impact of geographical features on solar radiation.

The disparities presented in the results have practical implications for stakeholders, including policymakers, investors, and individuals considering solar energy adoption. Regions with higher energy yields, as identified in the study, may be more conducive to solar energy projects. This information aids in strategic planning, investment decisions, and the formulation of targeted policies to promote solar energy in specific regions. Research by Rigo et al. (2023) and Akrofi et al. (2023) has explored the social and economic benefits of renewable energy adoption.

The methodology applied in this study involves the use of geocoded data from OpenStreetMap to gather geographical coordinates and solar irradiation data from PVGIS-SARAH2 database. Integrating geocoding techniques enhance the methodology used by Huld et al. (2012) and Stowell et al. (2020) because allows for more granular data analysis providing a detailed assessment of spatial disparities in PV energy yields.

The transformations and calculations were performed using the freely available pvlib-python library. This approach allows for a comprehensive assessment of energy yields across different orientations and locations. The primary advantage of this method is its ability to provide rapid and scalable estimates of potential energy production.

But while the methodology offers significant insights, it's essential to acknowledge its certain limitations. The calculations are based on a set of assumptions and modelling techniques that do not account for real-world factors such as shading, soiling or specific local weather conditions. The study does not also extensively cover the temporal variability of energy production. The results should serve as a reference point for estimation of PV energy generation. As demonstrated in chapter 3.2, there can be substantial differences between the calculated and actual energy yields due to these factors. For example, on very sunny days, energy generated by the PV panels may be cut off by the inverters if their capacity is lower than the total output of the panels. Additionally, zero losses were assumed in the calculation. In practice, various losses occur, including performance losses outside standard test conditions (STC), external shading, dirt and soiling, thermal losses, mismatch and DC cabling losses and conversion losses from DC to AC (Bruce, 2023). According to the Global Solar Atlas 2.0 technical report by the World Bank Group losses can range from 7.1% to 90.5%, with an average of around 9% (WBG, 2019). Panel degradation also plays a significant role. The 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 (Bruce, 2023). Thus, accounting for a 9% loss for the PV installation in Wreczyca, 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 closely matches the actual energy obtained from an installation.

To address these limitations and further enhance the robustness of our research we consider the following future directions: incorporation of real-world factors, temporal analysis and expansion to other regions in our next research.

4. Summary and conclusion

The rapid growth of PV solar energy systems in Poland has been observed for several years, primarily driven by the governmental actions that encompass substantial funding and incentive programs. As a result, the dominance of PV micro-installations is significant, contributing to the significant growth of the total installed PV capacity in Poland.

In the paper, a methodology is presented to estimate the energy generation capacity of solar PV systems across different orientations and inclinations in Poland. The research results demonstrate regional disparities in PV energy yield. Regions such as Lower Silesia, Opole, and Holy Cross Province exhibit higher yields compared to areas such as Podlaskie, Pomerania, or Warmia-Masuria. The 'south' orientation of PV panels generally offers the highest energy yield. With this information investors and individuals can make more informed decisions about their PV installation. It may also encourage individuals and businesses to adopt sustainable practices, such as investing in solar energy, contributing to the overall transition towards cleaner and more environmentally friendly energy sources.

The case study of a 9.79 kWp photovoltaic installation in Wreczyca shows the actual energy production over a two-year period (2022-2023). The calculated energy yield values for the installation correspond to real-world data after considering practical factors such as inverter limitations, module efficiency losses and other technical aspects that contribute to the observed and calculated differences. The presented energy indicators provide valuable initial parameters for determining solar PV system power output, and this data can 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.

Compared to existing methods, presented methodology provides a rapid and cost-effective way to estimate energy production from PV systems on a large scale. Traditional methods often require extensive onsite measurements and detailed simulations, which can be time-consuming and expensive. This method can be easily applied across large geographical areas providing comprehensive insights that can guide regional and national planning.

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