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Influence of Selected Weather Conditions on the Photovoltaic System Efficiency in Central Poland – Case Study

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ABSTRACT

The article details the data obtained from monitoring the photovoltaic (PV) system in 2021–2023, equipped with a module for measuring basic weather parameters. The PV system under consideration, with a peak output of 3.2 kW_p, is connected to the electricity grid and is mounted on the flat roof of the building. The annual relative yields of the generated energy were about 10% less than estimated, and their monthly distributions were asymmetric. In the "summer" months (i.e., from April to September), the PV system generated, on average, about 75% of the whole year's energy. The histograms of the PV system's active power output showed that, on average, about 40% of the time, the PV inverter operated in underloaded mode. For selected weather conditions measured on site, a regression analysis was conducted with the active output power of the PV system. The main objective of the work was to develop a comprehensive method for analysing PV plant monitoring data and the impact of weather conditions on its performance. The proposed method was realized as a case study for central Poland but can be implemented anywhere.

Keywords: photovoltaics, PV installation monitoring, PV system, active power, weather conditions.

INTRODUCTION

Photovoltaics is a relatively new field in the technical sciences, which deals with the totality of devices for converting solar energy into the most popular and commonly used form of energy – electricity [1]. The performance of photovoltaic systems is unstable over time and is closely dependent on local variable weather conditions [2, 3]. Investigating the impact of local weather conditions at the site of the photovoltaic system makes it possible to forecast the amount of energy generated based on weather forecasts, which also influences the optimization of cooperation with local energy storage [4]. Photovoltaic systems are relatively rarely suitable for directly powering appliances and most often work as grid-connected or stand-alone systems equipped with local energy storage. Under Central Europe's weather conditions, photovoltaic development is conditioned by individual countries' different support systems for this type of investment [5]. The work titled: "A Statistical Analysis of Long-Term Grid-Connected PV System Operation in Niš (Serbia) under Temperate Continental Climatic Conditions" [6] analyses the grid-connected PV system performances over ten years under temperate continental conditions in Niš. Based on the experimental results, 10-year average annual efficiency values of the PV system were determined. The average annual value of PV performances for a 10-year measurement indicates that the behaviour of the given PV system over ten years does not change significantly. This analysis significantly impacts energy prediction, PV energy modelling, the economics and profitability of the grid-connected PV system utilization, and the PV systems' operation planning and maintenance.

Poland has seen a rapid increase in installed PV systems since 2015, following the introduction of the Law on Renewable Energy Sources (RES) [7]. At the end of October 2023, the total peak installed capacity of PV systems in Poland was 16.2 GW$_p$, accounting for 57.8% and the first position among all RES. The average size of new PV installations in Poland also increased, reaching 18.4 kW$_p$ in October 2023 (and at the end of March 2023, there were 22 kW$_p$), with prosumers injecting 26.4% more electricity into the power grid year-on-year (and at the end of March 2023 down 8% year-on-year) [8]. As of 01/04/2022, Poland has changed its billing system for PV micro-installations (with peak power up to 50 kW$_p$) from a volume billing system, known as Net-Metering, to a value billing system, known as Net-Billing, in which hourly energy prices will apply as of 01/07/2024. The forthcoming new billing system for surplus energy generated by PV systems will urge prosumers to install local energy storage, relieving the burden on power grids during peak generation hours by PV [8]. There are also observations of the operation of functioning PV systems under different environmental conditions through dedicated monitoring subsystems, which provide feedback for their design and operation process. Many research works have analysed the effects of temperature [9–13] and other environmental factor [14–16] on the operation of PV systems. There have also been studies on the effects of partial shading [17–19] and module contamination [20, 21] on the operation of PV systems.

This work aims to determine the impact and repeatability of weather conditions on PV system performance based on analyses of large datasets derived from monitoring. The results of these analyses will be used to forecast the performance [22] and plan the schedule of operational recommendations for PV systems in the considered location. It should be emphasized that the research constitutes a case study for Central Poland and is reliable only in this area.

MATERIALS AND METHODS

Construction of the measuring station

Figure 1 shows a schematic diagram of the PV system (micro-installation), with a peak power of 3.2 kW$_p$, which is connected to the electricity grid three-phase and mounted on the flat roof of the Warsaw University of Technology Plock Branch building at al. Jachowicza 2/4. The PV modules are inclined at an angle of 10° to the horizontal and have an azimuth of 182° (2° deviation to the East from the South direction). All PV system parameters and weather data measurements are recorded on the PV inverter manufacturer's server in the form of values averaged every 5 minutes [23].

The PV generator, built with PV modules – model BS-320-6MB5-EL [24] with sensors on the roof of the building, and the installation site of the FRONIUS SYMO 3.0-3-S inverter [25] with the Sensor Box [26] inside the building. Monitoring data to the inverter manufacturer's server was exported via a dedicated Datamanager 2.0 card (inverter equipment option for full monitoring of all data). The manufacturer of the PV inverter and Sensor Box module only specifies an accuracy of 3% of the measured value for solar intensity and 5% of the measured value for the other current inputs. For the measurement sensors used, the values of the corresponding calibration coefficients are also given. The ability to generate reports of detailed PV system monitoring data in MS Excel format required purchasing a premium account on the inverter manufacturer's server. This was necessary because of further analysis of the results and the possibility of exporting the data to the MATLAB package. Mounting the PV generator on the roof of the building was done using the AERO S system

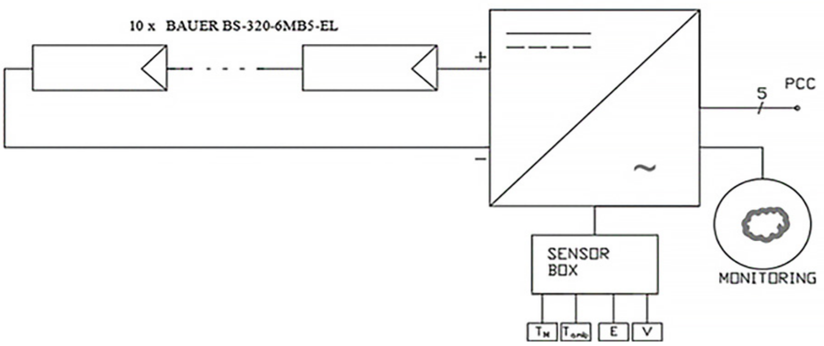

Fig. 1. Simplified schematic of PV system with weather data logging module Sensor Box with sensors: T_M – PV module temperature, T_{amb} – ambient temperature, E - solar irradiance, V – wind speed

ballast system [27]. The Nominal Power Ratio [14] of the PV generator relative to the nominal power of the inverter for the PV system under consideration is low and amounts to only 107%.

Research methods

In the first stage of the study, the annual relative yields of generated energy in the PV system were analysed and compared with the data estimated for the location under consideration by the Polish Photovoltaic Society (PPS) [28] and the Photovoltaic Geographical Information System (PVGIS) [29].

The next stage of the analyses carried out was to produce histograms based on the distribution series of the active output power of the PV system in the nominal power range of the PV inverter from 0 to 3 kW, divided into 10 class intervals. Year-round histograms were made, as well as by summer (from April to September) and winter (from October to March) half-years. Similar analyses were performed for weather parameters and presented in the form of histograms, which included only the operating time of the PV system and were assumed to occur after the solar irradiance exceeded 10 W/m^2. The study analysed large data sets from plant monitoring. For each of the years considered, files of about 25 MB were downloaded, containing 105108 data records each.

The final stage of the study was to determine the correlation of active power output with weather parameters, performed in the "Curve Fitter" module of the MATLAB engineering calculation package [30]. The paper details the correlation analysis for only two weather parameters: solar irradiance and module temperature. The other parameters, ambient temperature, and wind speed showed no significant relationship, and correlation analyses were not presented.

RESEARCH RESULTS

Figure 2 shows the annual relative yields of the electricity generation in the PV system by month and compares them with the estimated calculations in PVGIS. The average yearly value of relative yields in 2021–2023 was about 896 kWh/kW$_p$. The estimated values for this location are, according to PVGIS, about 930, and according to PPS, is 1037 kWh/kW$_p$. These results indicate lower energy yields from the PV system under consideration than values obtained through simulations performed using two different methods. They also confirm the large disproportion of generated energy at the considered location in the summer and winter semesters. A significant anomaly in the analysed results in Figure 2 is the data from February 2021, where minimal values of generated energy were observed. This was due to the persistence of snow cover for more than two weeks on the photovoltaic modules. Due to difficult access to the building roof, the PV generator was not cleared of snow. The roof hatch is permanently closed for safety reasons, and any

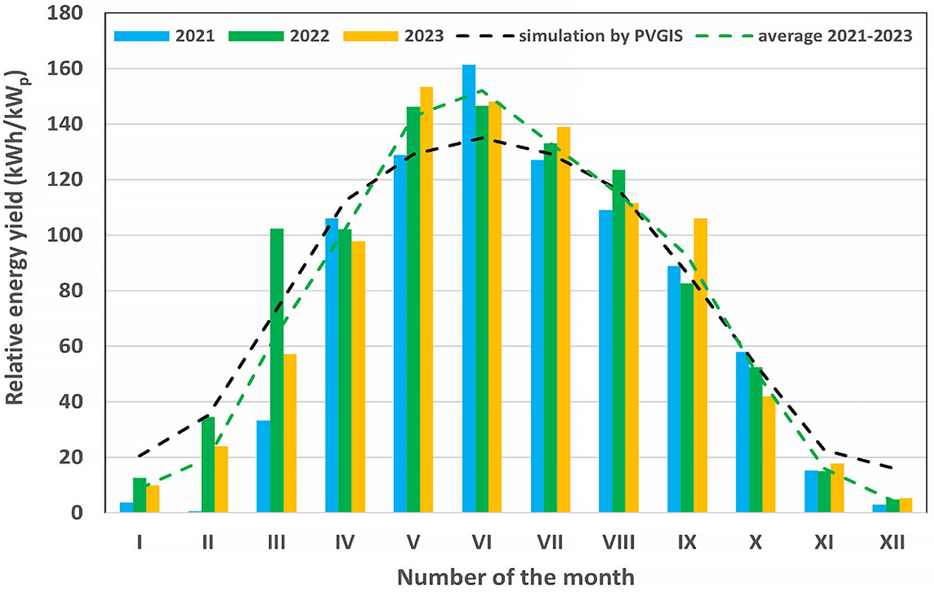

Fig. 2. Relative yields of energy generated from PV system in 2021–2023

access to the roof requires permission from the administrator, contingent on the PV system operator being equipped with safety equipment.

Figure 3 shows the 2021–2023 averaged PV system active power output frequency histograms year-round and for summer and winter in the PV inverter nominal power range from 0 to 3 kW, divided into 10 class intervals. In the first class interval, labelled as (0;300> in Figures 3 and 4, zero values were intentionally omitted because they represent nighttime intervals or low values of solar radiation (less than 10 W/m^2 as shown by the data analysis), which are irrelevant from the point of view of photovoltaics since no active output power is generated in the PV system at that time. Statistical distribution series were made for the averaged values of the PV inverter's active output power from the three years under consideration, 2021–2023, and shown in Figure 4 separately for the Summer and Winter months and averages for the entire year. The small size of the highest interval of the distribution series is a result of the small value of oversizing of the PV system (as mentioned earlier at 107%).

The conclusion of the analysis of the histograms (Figures 3 and 4) made on the basis of the distribution series of the active output power of the PV system in the nominal power range of the PV inverter from 0 to 3 kW was that, on average during this period, about 40% of the time the PV inverter operated in underloaded mode, falling within the first range of the distribution series, ending with an output power value of 300 W. In this power range, the inverter operates with low efficiency according to the characteristics quoted by the manufacturer, and this tendency intensifies in the winter months when the frequency of operation in the lowest power range exceeds 60%.

Similar statistical analyses (by year and averaged values) were performed for weather parameters and were also presented in the form of histograms, which included only data for the time of effective operation of the PV system and were assumed to occur after the value of 10 W/m^2 of solar irradiance was exceeded. From the point of view of analysing the operation of the PV system, the results of measurements of weather conditions are irrelevant when no output power is generated, that is, at night and before exceeding the value of 10 W/m^2, from which the generation of output power in the case under consideration begins. The following histograms are shown sequentially in Figure 5 for solar irradiance, Figure 6 for ambient temperature, and Figure 7 for PV module temperature. Comparing the statistical resolution series of ambient and PV module temperatures (in Figure 6 and 7, respectively), the initial values of -16 °C and -18 °C, respectively, are noteworthy. A morning module cooling effect, particularly pronounced in PV modules with aluminium frames, acts as a heatsink for silicon PV cells. The power temperature coefficient for a single PV module model BS-320-6MB5-EL is -0.039%/°C [24]. Figures 6 and 7 show the temperature distributions of PV modules and the environment under operating conditions, i.e. at irradiance above 10 W/m^2. The temperature rise of PV modules is affected by the type of ballast structure used on the flat roof of the building. The PV modules used in the case of a ground structure with a higher angle

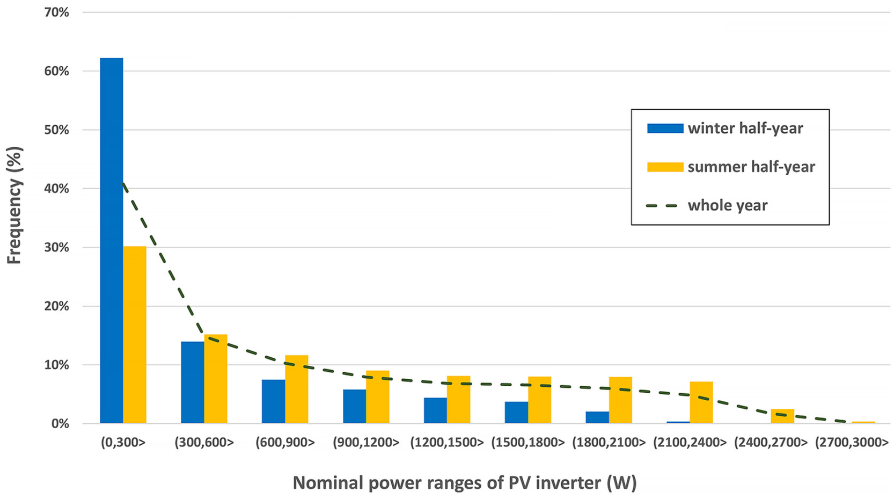

Fig. 3. Relative averaged from 2021–2023 PV system active power output rate whole year and by summer and winter months

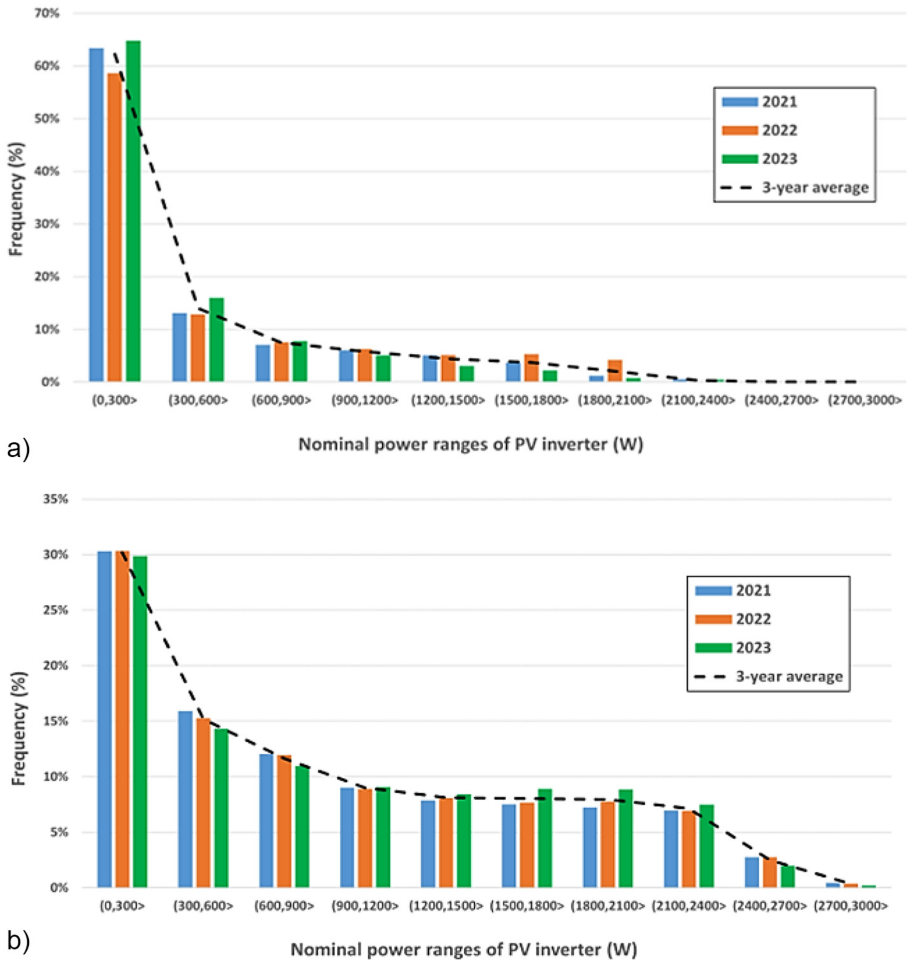

Fig. 4. Relative frequency of PV system active power output rate averaged over 2021–2023 by winter (a) and summer (b) half-years

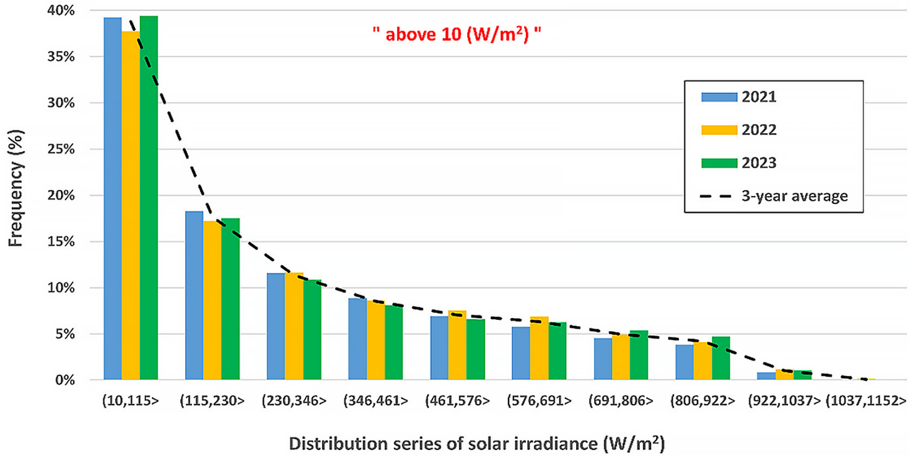

Fig. 5. Relative solar irradiance distributions in 2021–2023

would exhibit higher specific power at the same ambient temperatures.

Figures 8 and 9 show the dependence of solar irradiance and module temperature on the active output power of the PV system in 2021–2023. Linear regression analysis was performed for these two cases only, and the results are shown in the graphs below. The calculations were performed in the MATLAB engineering calculation package. Figures 8 and 9 show the repeatability of the results, and the clear correlation of the output power results with irradiance and the slightly larger scatter in the case of

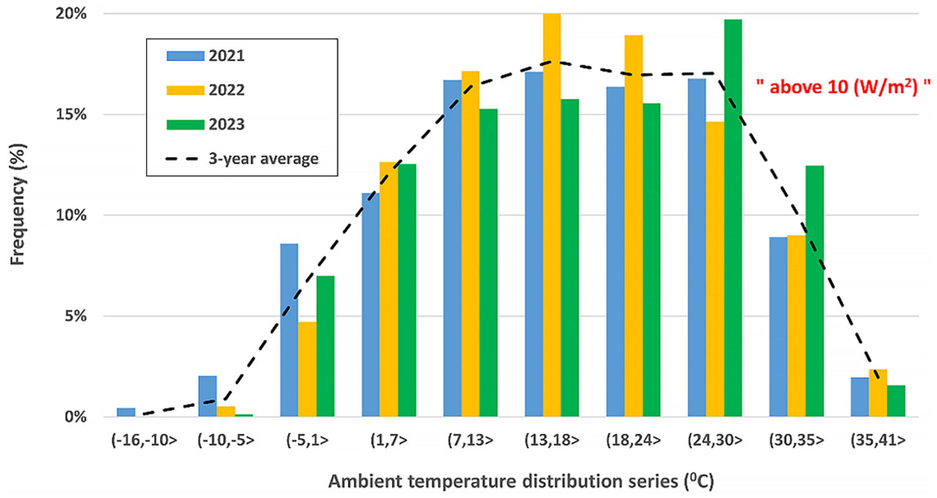

Fig. 6. Relative ambient temperature distributions in 2021–2023

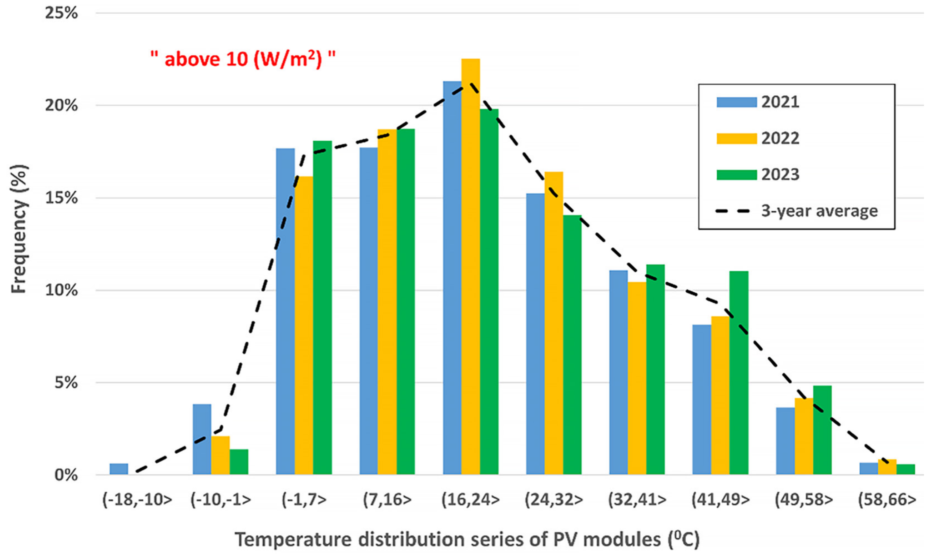

Fig. 7. Relative temperature distributions of PV modules in 2021–2023

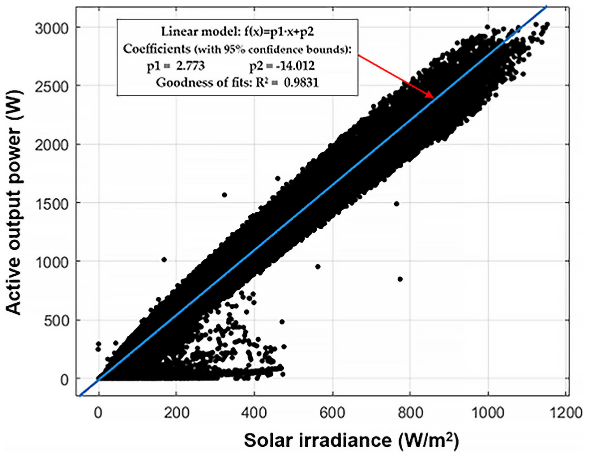

Fig. 8. Curve fitter of solar irradiance's dependence on the PV system's active output power in the years 2021–2023

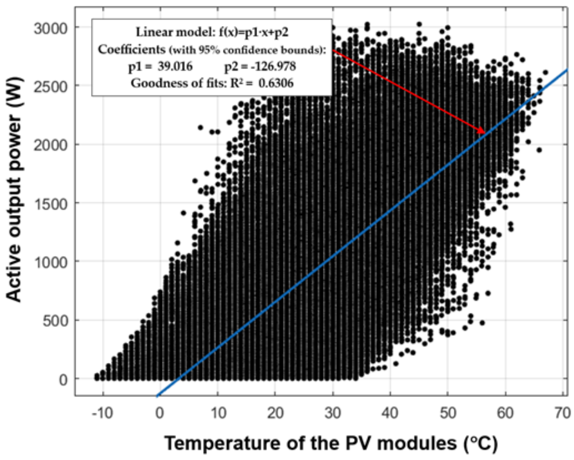

Fig. 9. Curve fitter of the temperature dependence of the PV modules on the active output power of the PV system in the years 2021–2023

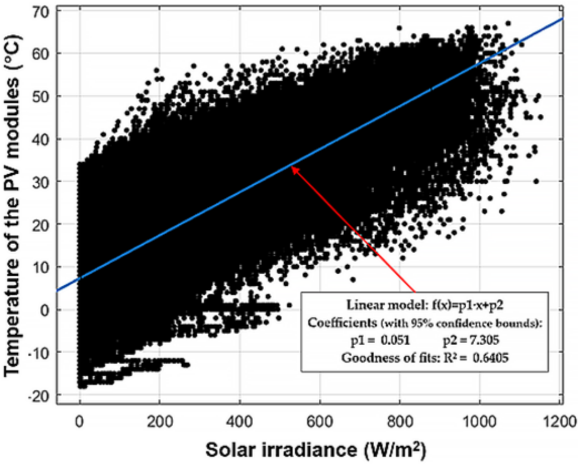

Fig. 10. Curve fitter of the temperature dependence of the PV modules on the solar irradiance in the years 2021–2023

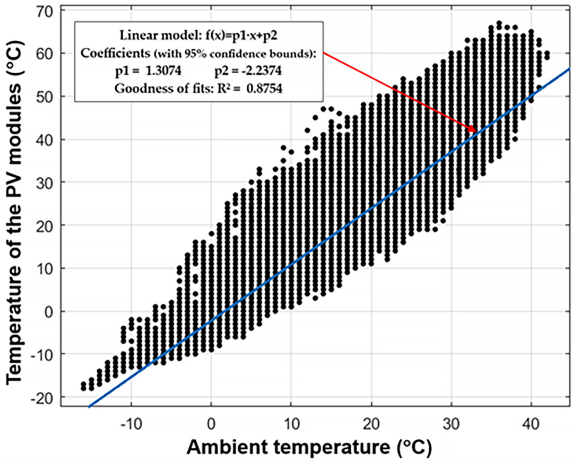

Fig. 11. Curve fitter of the temperature dependence of the PV modules on the ambient temperature in the years 2021–2023

PV module temperature. Figures 10 and 11 show the correlation relationships of the effects of radiation and ambient temperature on the temperature of PV modules in 2021–2023. These relationships explain the previously presented effect of measured weather parameters on PV system output.

Figure 12 shows the dependence of solar irradiance on wind speed at the PV system site. It isn't easy to talk about the correlation of these results here. Still, they are presented to show an interesting and reproducible relationship: the highest recorded wind speeds occurred at the lowest solar radiation values. Such results can provide a genesis for designing a PV system associated with a wind power plant to supplement the PV system's low generation at low solar radiation values. Based on this analysis, the yields of such a combined RES system can be simulation-estimated.

Measurements of wind speed at the PV system site did not show correlations with active power output, but an interesting conclusion emerges in this case, which is that the highest values of wind speed occurred in the same range of solar irradiance in which the PV inverter operated as underloaded (up to about 300 W/m^2). All wind speed values above 8 m/s observed over the three years occurred at solar irradiance below 300 W/m^2.This indicates that there is a great potential to compensate for the shortage of energy from the PV system – with energy from the wind. Figures 13

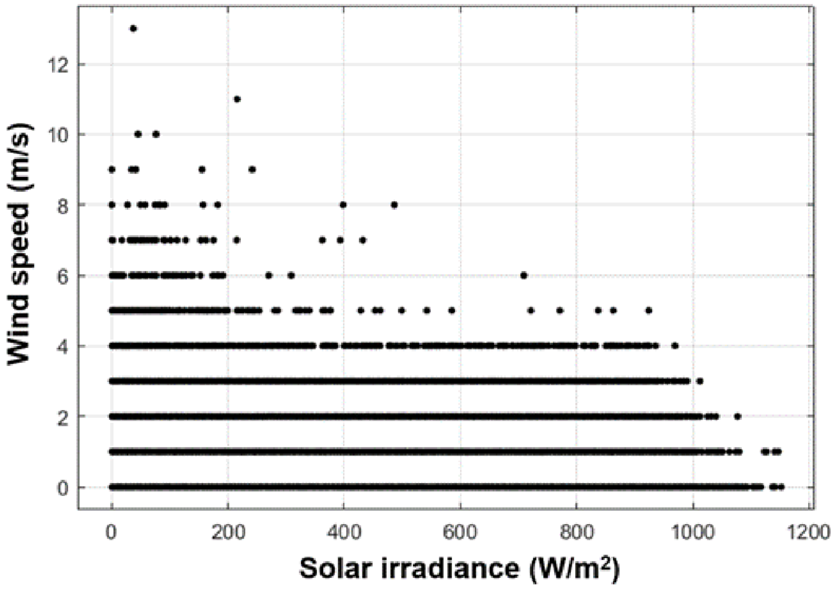

Fig. 12. Dependence of solar irradiance on wind speed at the PV system location

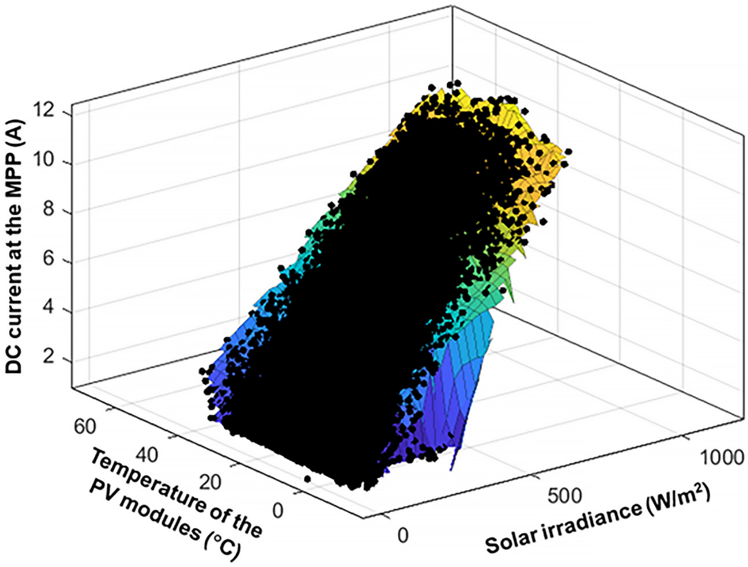

Fig. 13. Influence of solar irradiance and temperature of PV modules on DC current of PV generator at maximum power point (MPP)

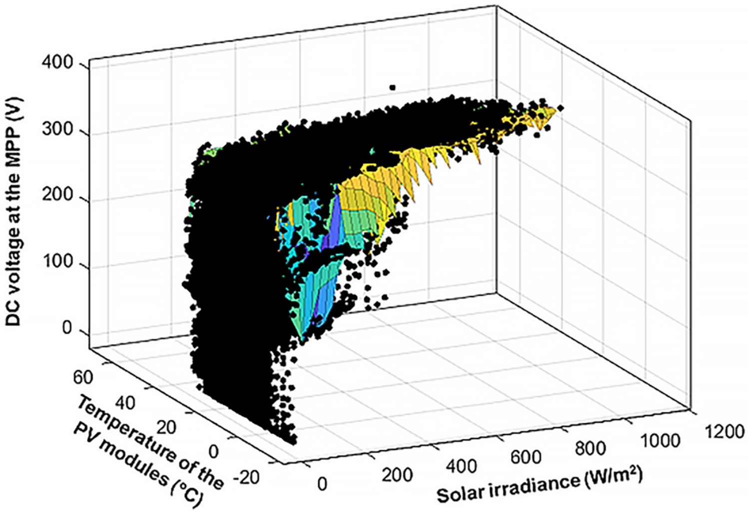

Fig. 14. Influence of irradiance and temperature of PV modules on DC voltage of PV generator at maximum power point (MPP)

and 14 show how solar irradiance and PV module temperature affect the DC current and voltage of a PV generator at the maximum power point (MPP) of the current-voltage characteristics. PV inverters for these PV generator parameters produce active output power. Particularly noteworthy is the graph for voltage (Figure 14), which stabilizes at a stable level after a rapid increase in value.

DISCUSSION AND CONCLUSIONS

The comparison of the annual relative yields of the generated energy in the PV system with the data estimated for the site under consideration by the Polish Photovoltaic Society and the PVGIS (Photovoltaic Geographical Information System) system showed that the relative yields of the generated energy were about 10% less than the estimates. Their distribution throughout the year was asymmetrical, and in the "summer" semester, the PV system generated, on average, about 75% of the year-round energy. This significant variation in generation throughout the year makes it virtually impossible to optimally design off-grid autonomous PV systems.

The conducted research is a case study for a specific location of the PV system installation.

Still, on the basis of this research, it can be concluded that the considered PV system underestimates the size of the peak power of the PV generator in relation to the nominal power of the PV inverter, which, in this case, is only 107%. The value of this indicator can be raised to at least 120%.

The conclusion of the analyses performed for weather parameters and presented in the form of histograms is that, based on them, it is possible to accurately determine the parameters of the PV system under different weather conditions, which is important in the design process. The regression analysis of active power output with weather parameters showed a very high dependence of active power output values with solar irradiance values, less so in the case of PV module temperature and ambient temperature, which is best illustrated by the 3D graphs made between these quantities. Statistical coefficients are given assuming a linear approximation model in the Curve Fitter module of the MATLAB engineering calculation package. Measurements of wind speed at the PV system site did not show correlations with active power output, but an interesting conclusion emerges in this case, can be drawn about the need to explore further the energy potential of a PV system combined with a wind turbine, the generation of which will make up for the shortfall in energy from photovoltaics - especially during nighttime hours and at low solar irradiance.

Changes to the value billing system (Net-Billing), planned for implementation as of 01/07/2024 in Poland, involving hourly billing for surplus energy injected into the power grid, will mean that not the maximum energy yield will determine the profitability of PV installations. PV installations with local energy storage or associated wind power will be more profitable. In the new system, it is not the amount of energy generated that will determine economic viability but the timing of introducing surplus energy into the power grid. The results of the analysis carried out in this work can be used to develop detailed algorithms for cooperating the PV system with electricity storage. The charging and discharging processes of energy storage with a specific capacity must be correlated with weather forecasts and, based on the study's results, planned optimally. The primary criterion for optimization in the new billing system in Poland will no longer be the maximum energy yield but the maximum degree of self-consumption and the selection of the optimal storage capacity for the PV system power. Forecasting the active output power generated in the system the following day must be correlated with the market price of energy, and this will be the data of the learning function in deep machine learning systems.

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