Rocznik Ochrona Środowiska

Volume 23 Year 2021 ISSN 1506-218X pp. 694-714

https://doi.org/10.54740/ros.2021.049 open access

Received: 07 September 2021 Accepted: 13 October 2021 Published: 06 December 2021

Statistical Analysis of Electrical and Non-Electrical Parameters of Photovoltaic Modules in Controlled Tracking Systems

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Abstract: The paper presents statistical analysis of measurement results of electrical parameters for photovoltaic modules installed in stationary and dual-axis configurations. The parameters which were taken into account included: coefficient of variation, skewness and standard deviation. Also a correlation was determined between independent variables such as insolation, sunshine duration, cloudiness, ambient temperature and atmospheric pressure, and the dependent variable in the form of the daily electricity from photovoltaic conversion. In order to determine the repeatability of electricity waveforms occurring between summer months as well as between summer and winter months, the non-parametric U Mann-Whitney test was used. In order to analyse the repeatability of daily peak hours in which the highest value of the hourly electricity production is observed, the non-parametric Kruskal-Wallis test was used. The tested systems were connected to the power grid and operated independently. Test stands consisting of polycrystalline photovoltaic modules, single-phase on-grid inverters, irradiance sensors and a temperature recorder, were located on the building rooftop of the Faculty of Control Robotics and Electrical Engineering of the Poznan University of Technology in Poland (Central Poland, 52°24.4152′N, 16°55.7958′E) at the height of 30 metres above the ground level. A significant increase in the production of electricity using the PV module spatial positioning system was demonstrated in relation to modules based on the year-round modified design.

Keywords: tracking PV system, photovoltaic conversion, energy gain, spatial optimization, statistical analysis

1. Introduction

Functionally, electricity is the most beneficial form of energy which can be used and converted into other forms of energy both in all kinds of business units and in the existential sphere (in private life). Worldwide, electricity demand is constantly increasing. Conventional energy sources have a definitely negative effect on the environment. For this reason, the constantly growing interest of researchers and users is focused on unconventional thermal and electrical energy sources. As far as thermal energy is concerned, solar collectors are in use. Their geometrical characteristics and the scope of diagnostics are presented, among other things, in publications (Kuczynski et al. 2021, Znaczko et al. 2021). On the other hand, in the area of electricity sources, wind turbines, PV plants and their hybrid systems play the leading role.

In the majority of their activities in the economic sphere and in everyday life, people act in such a way as to achieve optimal results of their undertakings. Such conduct can be observed, for instance, in the optimisation of logistic processes (Hanczar et al. 2017, Izdebski 2014, Izdebski & Jacyna 2018, Jacyna et al. 2018, Karkula & Stryhunivska 2017, Kostrzewski 2017, Kostrzewski 2017a, Woźniak et al. 2016), storage (Duda et al. 2019, Jacyna et al. 2016), travel (Chamier-Gliszczynski 2011c, Chamier-Gliszczynski 2017), waste recycling (Chamier-Gliszczynski & Krzyzynski 2005, Chamier-Gliszczyński 2010, Chamier-Gliszczyński 2011, Chamier-Gliszczyński 2011a, Chamier-Gliszczyński 2011b, Merkisz-Guranowska 2010, Merkisz-Guranowska 2012, Merkisz-Guranowska 2018, Wędrychowicz et al. 2019). Also, all elements of the power supply systems are subject to optimisation analyses. Various criteria are adopted for this optimisation. These can include the minimisation of the consumption of raw materials (investment costs) or electricity (operational costs), maximisation of profits or generation capacity (Woźniak et al. 2017), reduction in the process implementation time, (Bednarek et al. 2009, Kasprzyk et al. 2010, Kasprzyk et al. 2017, Nowak et al. 2015, Tomczewski et al. 2018, Jajczyk et al. 2008, Jajczyk 2016), and occupational safety issues (Gabryelewicz et al. 2018). In the light of the current climatic crisis (global warming), ecological issues are extremely important objectives and criteria for optimal human activities. All activities which bring positive effects in this respect deserve special attention.

This paper deals with the issues related to the conversion of solar energy into electricity. The subject of analysis concerns photovoltaic systems for electricity production: the stationary system (with the unchangeable, possibly most beneficial positioning) and the tracking system (with the dual-axis control system for the position of panels in relation to the incident sunlight).

In view of the stochastic nature of electricity generation by such types of systems, the issue which has drawn particular attention of the authors is statistical analysis of electrical and non-electrical parameters related to their operation and generating capacities. Owing to the properly prepared results of measurements and calculations regarding these systems (which take into account their random nature and use appropriately selected statistical techniques), it is possible to make relatively reliable estimations as to the energy gain, which can be obtained as a result of conversion of the stationary system into the tracking system. Such considerations are very important as the possibility of obtaining energy efficiency improvements in PV systems is always the expected outcome of any scientific-technical activities.

2. Current status of the problem

In an era of global climate warming, any action aimed at limiting the occurrence of this disastrous state for the Earth is extremely valuable. One of such environmentally friendly measures is to generate electricity by means of renewable sources. The work of many scientific-research centres is focused on applying unconventional, new ideas, as well as increasing the energy efficiency of the existing technical solutions for green energy sources, i.e. ultimately achieving the highest possible energy gains from these technologies. With these objectives in mind, a wind resource assessment (WRA) was performed around high-rise buildings in realistic urbanised areas, in order to investigate the feasibility of installing wind turbines in relation to the urban wind energy generation. The results of this wind resource assessment suggest an effective strategy of wind turbine installations in order to implement the potential of urban wind energy in a realistic, compact urban area of high-rise buildings (European Commision 2020). It has been demonstrated that economic analysis of electricity supply systems for buildings and industry should include a detailed feasibility study, as well as the prospect of life cycle of electricity generation facilities. Electricity demand of the facility under consideration was assessed by means of pre-design modelling and simulation, and suitable configurations of the system were identified taking into account the costs of its life cycle. The potential for using photovoltaic (PV) panels as wall claddings was investigated in order to achieve the most advantageous energy management (both for electrical and thermal reasons) in commercial facilities (Dobrzycki et al. 2020). The subject of verification was also whether the presence of PV modules had a noticeable effect on heat transfer by the external building wall, on which the system was located. Owing to these measures, an improvement in the thermal performance of the building wall (by increasing the thermal resistance of the wall) and reduction in the consumption of gas to heat the facility are both achieved (this is also related to a reduction in carbon dioxide emissions into the atmosphere), while generating electricity in the PV system for internal needs of the factory. The use of photovoltaic roof tiles that integrate PV cells with the roof cover was taken into account (Kurz et al. 2019). Energy balance of the systems investigated (the PV tile and the entire roof) was presented, and on this basis, changes in the temperature of the PV cells of the tile, operating under different environmental conditions, were determined. Thermal and electrical parameters of these systems were identified.

In many centres around the world, scientists have been working on optimising generation of electricity from wind, i.e. by means of wind turbines. In order to ensure the correct operation of the power system and reliability of electricity supplies from generation systems, whose output power varies in time and additionally has a stochastic character, solutions are proposed to improve reliability indicators of electricity supply from such sources as wind farms, through their cooperation with a kinetic energy storage. This ensures the achievement of partial stabilisation of their output power. Optimisation of the wind farm-energy storage system, operating in a specific geographical location, is carried out. Algorithms are developed to minimise the unit discounted cost of electricity generation in systems containing a wind farm and a kinetic-type storage (Tomczewski et al. 2019). Research is carried out into the aerodynamic properties of horizontal axis wind turbines in static and dynamic flow deflection conditions, which may significantly affect the aerodynamic properties of the turbines (Bugała et al. 2020). More and more perfect fault monitoring systems are developed to ensure the highest possible reliability of operation of these power generation systems and to avoid their unplanned shutdowns and electricity blackouts. Stochastic dynamic analyses of offshore wind turbine structures are carried out to evaluate the safety and reliability of their structures, the efficient design of their support structures is implemented, and the control of the energy produced by a floating offshore wind turbine disturbed by sea waves is considered in detail (Malhotra 2007). Furthermore, this study focuses on investigating the aerodynamics and motion characteristics of the floating vertical axis wind turbine (VAWT), whereby the wind turbine is of the H-type, and the floating foundation has a truss structure. Also, analyses of energy efficiency of vertical axis (two-rotor) wind turbines, used in household electrical micro-installations in areas with less advantageous wind conditions are carried out. (Bugała et al. 2020). The introduction of simple and cheap wind turbine designs (vertical-axis hybrid turbines) in spaces with less favourable climatic conditions would allow for the achievement of the technical and economic justification for their widespread use in most areas throughout the country.

Technologies of photovoltaic panel production are also subject to intensive modifications. The search is on for innovative solar cell designs as an alternative to standard silicone solar cells. One such alternative design is the heterojunction solar device with a carbon/silicone nanotube (CNT/Si), in which a new organic material is added as an intermediate layer between the CNT film and the silicone surface (Markosea et al. 2020). Special multi-junction solar cells are being developed, which results in the achievement of higher efficiencies of these energy conversion components. Newer and newer chemical additives are incorporated into photo-active layers of cells, which results in the improvement of the overall photovoltaic efficiency of such energy sources (Wei 2010). Techniques of mechanical final panel treatment are being upgraded (e.g. the introduction of the ultrasonic vibratory treatment of the perovskite substrate). A variety of maximum power point tracking control algorithms are being investigated for reliability (Nelatury 2013, Ramos-Hernanz et al. 2020). Algorithms for the detection of various anomalies in PV systems are being developed, including sub-optimal orientation, daytime shading, sunrise/sunset, short and prolonged daytime zero and low maximum power production. The impact of shading on the operation of PV installations is being considered and statistical methods for assessment of the performance of systems operating under such conditions are being developed (Trzmiel et al. 2020). The interaction between photovoltaic panels and their associated converters is being improved. Possibilities of the most beneficial interoperation of photovoltaic systems with energy storages (super capacitors, batteries) and power grid are analysed in order to achieve the best energy management (Ciccarelli et al. 2018, Fahmi et al. 2015, Jajczyk et al. 2019, Jajczyk et al. 2020). There are also discussions regarding the profitability of investments in solar photovoltaics in the light of the national laws on renewable energy sources being introduced.

Large-scale research is being conducted on the optimisation of operation of hybrid renewable electricity generation systems that consist of wind turbine units and photovoltaic panels. Maps of territorial locations are being created in different regions of the world, where both wind and sun have great potential for energy generation. Various correlations of photovoltaic systems and wind turbines are being implemented in order to achieve the highest energy gains from an appropriately selected structure of these electricity sources in the given location. Different types of mechanical designs are being developed, the task of which is to direct and improve the intensity of air flow into wind turbines in order to increase the rotational efficiency and energy production (particularly in areas characterised by low wind speed) and, at the same time, to use this air motion for cooling the photovoltaic installations to improve their energy efficiency and limit excessive penetration of thermal (solar) radiation into building premises, where these installations are being set up.

The improvement of the energy efficiency of photovoltaic sources can be further achieved by applying tracking systems that allow photovoltaic panels to be continuously repositioned in relation to the Sun in order to achieve the largest possible energy gain from the installed generation infrastructure (Awasthi et al. 2020, Roth et al. 2004, Rubio et al. 2007).

The presented literature review shows unambiguously that the interest in various areas of use of green energy sources is very vivid, gains more and more significance, and brings huge benefits pro-climate activities.

This paper presents the study of photovoltaic energy generation systems, i.e. the stationary and analogue ones, equipped with a tracking system that controls the most beneficial positioning of panels in relation to the sun. The results of measurements are of stochastic nature definitely. When repeated multiple times, they give different results because of the unique weather conditions currently existing at the given time. In the comparative analyses of these systems in terms of energy gain – resulting from the use of the tracking system that controls the changes in positions of panels that convert solar energy into electricity – in order to achieve representative results which provide the possibility of their practical use, the statistical processing of measurement results has been introduced.

3. Measurement results

The measurements were conducted on a test stand that consisted of 220 W polycrystalline photovoltaic modules, Enecsys 240 W single-phase on-grid inverters, LB-900 irradiance sensors and the PT-100 temperature recorder.

The inverters used in the maximum power point tracking system use the Perturbation and Observation method *P&O.* In the *P&0* method, the operating voltage of the PV generator is disturbed by a small increase in dU_{PV}, as a consequence there is a change in power dP_{PV}. If the increase in power occurs, changes in operating voltage in the same direction should be continued. Otherwise, the direction of voltage increase should be changed.

Diagram of operation of *P&O* method implemented in microinverter is presented in Figure 1.

The photovoltaic modules were installed in a location with geographical coordinates 52°24′24″N, 16°55′47″E and were set at an optimum tilt angle towards the Sun, determined as a result of using an active two-axis tracking system controlled by an astronomical clock, with an additional position correction system operated by means of photo-optical sensors. In addition to this, the PV module identical in terms of electrical parameters was installed in a stationary system at a constant tilt angle (in the annual cycle). The comparison of the recorded measurement results from these two systems makes it possible to determine the percentage energy gain resulting from a change in the spatial orientation of this solar energy converter into electricity. Figure 2 presents the production of electricity for a selected month from the entire study period (June 2017 -May 2018) for the tracking and stationary systems.

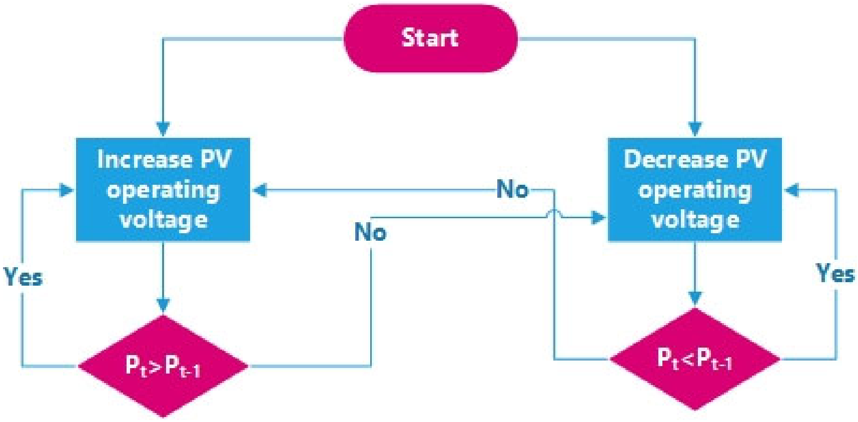

Fig. 1. Diagram of operation of *P&O* method (P_t – power at a given moment t, P_{t-1} – power at a previous moment $t-1$)

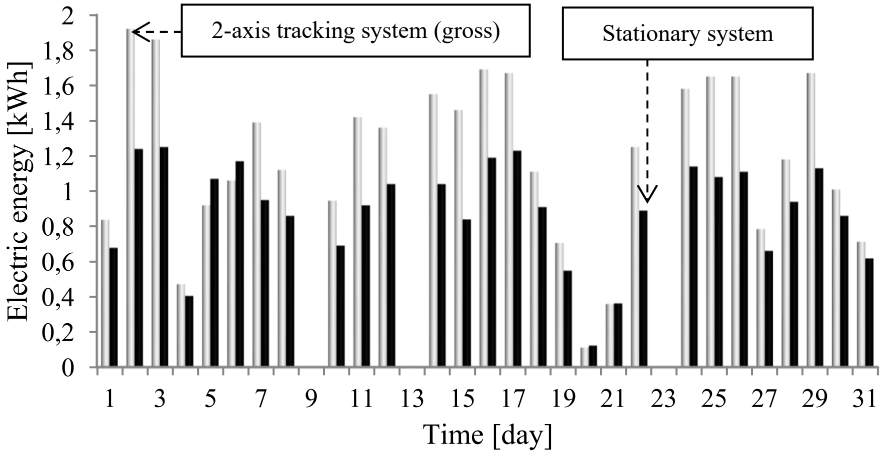

Fig. 2. Monthly production of electricity by the photovoltaic module in the stationary and tracking systems, August 2017

Figures 3 and 4 present results of measurements of irradiance and insolation for photovoltaic modules for a selected month of the year.

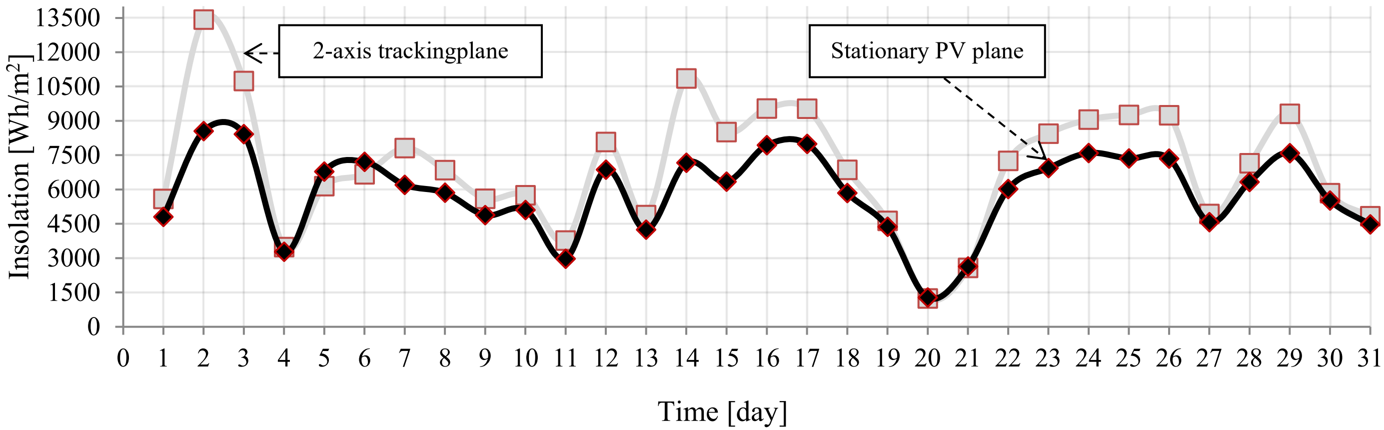

Fig. 3. Distribution of insolation on stationary and tracking planes, August 2017

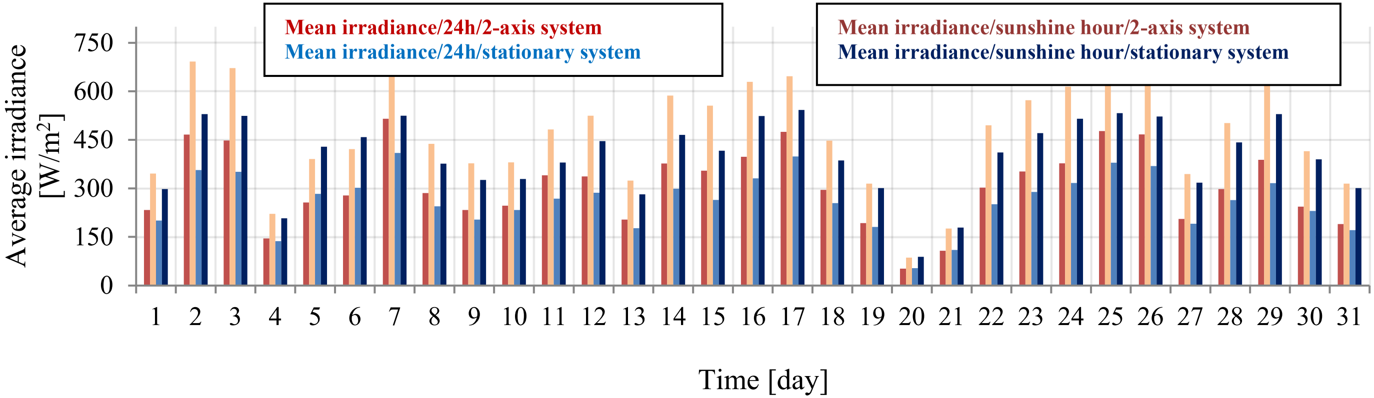

Fig. 4. Average irradiance on the stationary and tracking planes in an all-day cycle for sunshine hours

4. Statistical analysis of measurement results

The following results of measurements were subjected to statistical analysis: electricity (treated as a response variable), as well as irradiance, insolation, sunshine duration, cloudiness, air temperature, day length, atmospheric pressure (assumed as explanatory variables), recorded in the period between June 2017 and May 2018. Because of the association of the electricity variable, which is analysed in detail, with more than one explanatory variable, in order to present the mutual relationship between the variables, the multiple regressionmodel is used.It allows for analysis of the relationship between the response variable and the set of other predictors.The general form of the regression model is described by the following relationship:

$$\hat{x} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n x_n + \varepsilon \quad (1)$$

where:
x_n – the n-th independent variable in the model,
β – model parameters describing the effect of the given variable
on the dependent variable,
ε – random component.

A 123-element sample from the whole measurement period was used to estimate the β parameters. Production of electricity from photovoltaic conversion, considering the four explanatory variables occurring with the highest rank, is described by equation (2):

$$\hat{x} = 0.13 \cdot n + 28.64 \cdot u + 35.90 \cdot z - 9.69 \cdot t + 108.40 \quad (2)$$

where:
n – insolation,
u – sunshine duration,
z – cloudiness,
t – maximum air temperature.

Pearson's correlation coefficient $r_{x,y}$ between the variables used in the regression model has been calculated on the basis of relationship (3) and the results have been presented in Table 1.

$$r_{x,y} = \frac{\frac{1}{n}\cdot\sum_{i=1}^{n}(x_i-\overline{x})\cdot(y_i-\overline{y})}{\sqrt{\frac{1}{n}\cdot\sum_{i=1}^{n}\left(x_i-\overline{x}\right)^2}\cdot\sqrt{\frac{1}{n}\cdot\sum_{i=1}^{n}\left(y_i-\overline{y}\right)^2}} = \frac{\mathrm{cov}(x,y)}{S_x\cdot S_y} \tag{3}$$

where:
S_x, S_y – standard deviation of variable x and y,
N – size of the population.

Table 1. Correlations between variables used in the regression model determined with the Statistica software

Variable	Correlation analysis				
	Insolation	Skycloud	Temperature	Number of sunny hours	Electricenergy
Insolation	1.000000	0.650988	0.510682	0.924923	0.966914
Skycloud	0.650988	1.000000	0.424817	0.652897	0.678909
Temperature	0.510682	0.424817	1.000000	0.566304	0.442228
Number of sunny hours	0.924923	0.652897	0.566304	1.000000	0.924317
Electricenergy	0.966914	0.678909	0.442228	0.924317	1.000000

Statistical analysis allows for the indication of potentially excessive variables in the regression model. This is evidenced by the low tolerance value ($1 - r^2$) for the analysed variables (Table 2). Variables with a tolerance below 0.1 participate in the creation of the model, which may turn out to be statistically useless. This provides grounds for exclusion of variables that contribute to the increase of the standard estimation error of the regression model. The low value of the tolerance determined for such variables as insolation and sunshine duration and the high value of the coefficient of determination r^2 may be due to the strong correlation between them. Due to the fact that the results of the determined correlation between the explanatory variables and between the explained variable, in selected cases, assume close values, the accuracy of the results was increased.

Table 2. Tolerance values determined for independent variables in the regression model

Variable	Redundancy of independent variables			
	Tolerance	R^2 value	Partial correlation	Semi-partial correlation
Insolation	0.140189	0.859811	0.784536	0.276389
Skycloud	0.553175	0.446825	0.267678	0.060690
Temperature	0.671802	0.328198	-0.387213	-0.091745
Number of sunny hours	0.129874	0.870126	0.383443	0.090696

For additional verification of the correlation between the independent variables (such as insolation, sunshine duration and cloudiness) and the dependent variable, correlation diagrams were created as shown in Figure 5.

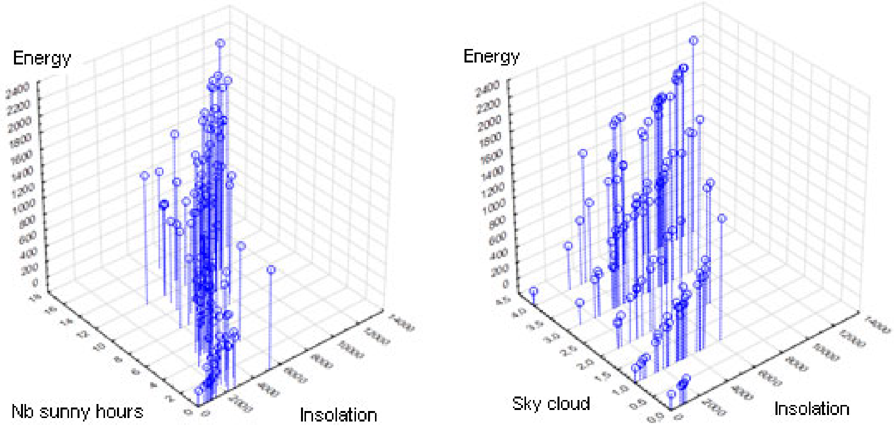

Fig. 5. Three-dimensional scatter plot for the dependent variable “electricity” [Wh] and the independent variables “insolation” [Wh/m^2], “sunshine duration” [h] and dimensionless“sky cloudiness”

In order to additionally check the correctness of the created model, a normality residual plot of the developed model was made (Fig. 6). It revealed the presence of few influential observations distorting the regression model.

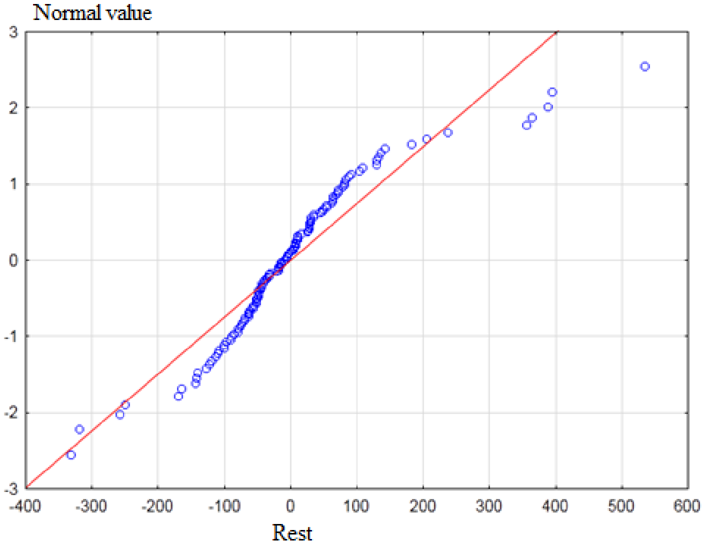

Fig. 6. Normality of residuals in the regression model for all analysed samples

Based on analysis of the temporal distribution of values of recorded electricity coming from photovoltaic conversion in the case of modules characterised by stationary installation as well as installation in the variable position system, it possible to indicate days with an almost symmetrical waveform of this electrical value in relation to midday hours, and days characterised by strong irregularities. The skewness coefficient was used as a measure of asymmetry while in order to assess the homogeneity of the daily waveform of electricity produced, the value of the coefficient of variation was calculated. The values of parameters were determined on the basis of sunshine hours and for the entire measuring day. The skewness coefficient was determined by the following relationship:

$$A_S = \frac{\overline{x} - M_o}{S} \tag{4}$$

where:
$\overline{x}$ – mean value,
M_o – median,
S – standard deviation.

Skewness is a measure of asymmetry of distribution in relation to the normal distribution, treated as the symmetrical one. For the symmetrical distribution, the value of this parameter is equal to zero. The higher is the value of the skewness coefficient, the higher is the asymmetry in relation to the mean value. The asymmetry coefficient equal to zero indicates the symmetry of distribution of the variable – a positive value means the right-sided asymmetry, while a negative value means the left-sided asymmetry. A positive value of skewness was obtained for the analysed data, which means a distribution with a slight asymmetry extending towards positive values. For a group of days of the summer month, it is close to zero, indicating an almost symmetrical distribution. For the winter months, with a strongly random distribution of the solar radiation power density, an increase in the asymmetry coefficient is observed both for the photovoltaic module in the tracking configuration and the stationary configuration. The highest values of this parameter, exceeding 2, are observed for winter months (Table 3).

Coefficient of variation v is the quotient of variation of a given parameter around the mean population value (standard deviation of a population) to the determined mean value. The range of variability of this dispersion measure for the PV module installed as a stationary system, determined for sunshine hours, indicates low and moderate variabilities on the basis of the adopted scale:

$v < 50\%$ – low variability,
$50\% < v < 100\%$ – moderate variability,
$v > 100\%$ – high variability.

The coefficient of variation determined for all hours of the day takes significant values, indicating high variability of the electricity parameter, especially for photovoltaic modules installed in a stationary configuration.

On the other hand, it is assumed that if the coefficient of variation does not exceed 10%, then the characteristics show statistically insignificant variation. High values of standard variation in relation to the mean value may lead to a reduction in the quality of the forecasting model.

Table 3. Results of statistical analysis for selected days of the month of July, December, April and January

Parameter	12/07/17		03/07/2017		26/07/2017	
	Track. system	Fixed system	Track. system	Fixed system	Track. system	Fixed system
Daily average [Wh]	84.63	49.92	74.29	45.75	70.67	44.58
Average sunshine hours [Wh]	135.40	85.57	111.44	78.43	113.07	76.43
Stand. dev./day [Wh]	76.91	62.19	69.06	57.93	69.08	54.54
Stand. dev./sunshine hours [Wh]	50.89	59.82	54.90	56.48	53.30	51.64
Skewness/day [-]	0.00	0.84	0.09	0.93	0.19	0.79

Table 3. cont.

Parameter	12/07/17		03/07/2017		26/07/2017	
	Track. system	Fixed system	Track. system	Fixed system	Track. system	Fixed system
Coefficient of variation/day [-]	0.91	1.25	0.93	1.27	0.98	1.22
Coefficient of variation/sunshine hours [-]	0.38	0.70	0.49	0.72	0.47	0.68
	18/12/2017		11/12/2017		29/12/2017	
Daily average [Wh]	0.79	1.25	9.29	6.83	6.83	4.79
Average sunshine hours [Wh]	4.75	6.00	37.17	27.33	23.43	16.43
Stand. dev./day [Wh]	1.98	2.70	22.71	15.21	14.07	9.70
Stand. dev./sunshine hours [Wh]	2.17	2.53	32.05	19.10	17.04	11.45
Skewness/day [-]	2.72	2.28	2.93	2.70	2.33	2.23
Coefficient of variation/day [-]	2.50	2.16	2.44	2.23	2.06	2.02
Coefficient of variation/sunshine hours [-]	0.46	0.42	0.86	0.70	0.73	0.70
	11/04/2018		25/04/2018		02/04/2018	
Daily average [Wh]	37.29	23.29	55.42	40.21	55.54	41.58
Average sunshine hours [Wh]	63.93	46.58	95.00	74.23	111.08	83.17
Stand. dev./day [Wh]	49.01	30.95	69.14	55.76	69.60	59.00
Stand. dev./sunshine hours [Wh]	49.13	28.81	66.59	56.69	59.31	59.19
Skewness/day [-]	1.34	0.99	0.74	1.04	0.85	1.17
Coefficient of variation/day [-]	1.31	1.33	1.25	1.39	1.25	1.42
Coefficient of variation/sunshine hours [-]	0.77	0.62	0.70	0.76	0.53	0.71
	18/01/2018		08/01/2018		15/01/2018	
Daily average [Wh]	1.29	1.71	1.42	1.75	11.71	8.46
Average sunshine hours [Wh]	6.20	8.20	8.50	7.00	46.83	29.00
Stand. dev./day [Wh]	3.21	3.52	3.58	3.92	22.58	17.06
Stand. dev./sunshine hours [Wh]	4.35	2.48	4.09	4.97	19.84	20.05
Skewness/day [-]	3.06	1.94	2.88	2.59	1.71	2.12
Coefficient of variation/day [-]	2.48	2.06	2.53	2.24	1.93	2.02
Coefficient of variation/sunshine hours [-]	0.70	0.30	0.48	0.71	0.42	0.69

In order to determine the repeatability of waveforms of electricity obtained from photovoltaic conversion, occurring between summer months as well as between summer and winter months, the non-parametric U Mann-Whitney test, which consists of the comparison of two independent groups (months of the year), was used. In this case, the normal distribution of quantitative variables and equivalence of groups are not required. The fulfilment of the last condition in the analysed cases is difficult due to a different number of days of the respective months of the year. In addition to this, the non-parametric method used is suitable for small populations where the variables are measured on the quantitative, ordinal or dichotomous scale. The starting point was the formulation of null (H0) and alternative (H1) research hypotheses:

- H0: distribution of mean observation ranks in analysed groups (months of the year) does not differ significantly,
- H1: there are significant differences in distributions of variables in both groups (months of the year).

Observations with an equal value in the created ordered series have been assigned ranks – also the tied ranks. If the probability parameter p takes a value that is lower than the assumed significance level $\alpha = 0.05$ there are justified grounds to reject the null hypothesis H0 and accept the alternative hypothesis H1. Detailed results of the U Mann-Whitney test for the months of June, July, August, December and January are presented in Table 4.

The determined value of the test probability p indicates that when comparing summer and winter months with each other (June-January, July-December), the assumed significance level α assumes higher values. For this reason, there are grounds to reject the null hypothesis and accept the alternative hypothesis, according to which there are significant differences in monthly distributions of production of electricity from photovoltaic conversion for both-periods using systems for the positioning of photovoltaic modules. In the case of summer months (June-July, June-August), there are no grounds to reject the null hypothesis. The lack of statistically significant differences was also demonstrated for the two winter months – December 2017 and January 2018.

In order to analyse the repeatability of daily peak hours, in which the highest value of the hourly production of electricity from the whole day is observed, appropriate 60-minute daily periods were indicated for each day of the analysed month of May, June, July and August 2017/2018. The comparison of four independent groups was made using the non-parametric Kruskal-Wallis test, which is an extension of the U Manna-Whitney test. None of these two tests require the fulfilment of many conditions characteristic of parametric tests. Statistical significance of the Kruskal-Wallis test points to differences between the tested groups. The starting point was the formulation of zero (H0) and alternative (H1) research hypotheses:

- H0: distribution of mean ranks in analysed groups (months of the year) does not differ significantly,
- H1: there are significant differences between groups in the repeatability of peak hours.

Table 4. Results of the U Mann-Whitney test, including the correction of continuity for the months of June, July, August, December, January 2017 and 2018

Variable	Results of the U Mann-Whitney test, July 2017 & December 2017								
	Sum of rank A	Sum of rank B	U	Z	p	Z correction	p	Number of valid samples in group A	Number of valid samples in group B
Electric Energy	1239	714	218	3.6886	0.0002	3.7029	0.0002	31	31
Results of the U Mann-Whitney test, June 2017 & January 2018									
Electric Energy	1367	524	28	6.2970	0.00	6.2989	0.00	30	31
Results of the U Mann-Whitney test, June 2017 & July 2017									
Electric Energy	950	941	454	-0.1515	0.8796	-0.1515	0.8796	31	30
Results of the U Mann-Whitney test, June 2017 & August 2017									
Electric Energy	1008	882.5	386.5	1.1252	0.2605	1.1253	0.2605	30	31
Results of the U Mann-Whitney test, December 2017 & January 2018									
Electric Energy	860.5	1092.5	364.5	-1.6261	0.1039	-1.6542	0.0981	31	31

The value of $p = 0.3279$ determined by means of the *Statistica* software is higher than the assumed significance level $\alpha = 0.05$. Thus, there are no grounds to reject the null hypothesis which assumes the lack of significant differences in the occurrence of peak hours for the analysed months of the year. The differences are, therefore, statistically insignificant.

The additional U Mann-Whitney test, however, confirmed the occurrence of significant differences between peak hours (mean observation ranks) for summer and winter months with the assumed significance level of $\alpha = 0.05$. Test results for the selected pair of months are presented in Table 5.

Table 5. Results of the U Mann-Whitney test which confirm the significance of differences between the peak hours of the months of June 2017 and January 2018

Variable	Results of the U Mann-Whitney test, June 2017 & January 2018								
	Sum of rank A	Sum of rank B	U	Z	p	Z correction	p	Number of valid samples in group A	Number of valid samples in group B
Peak hour	354	207	54	-2.1626	0.0306	-2.1874	0.0287	24	13

Table 6 presents the percentage energy gain resulting from the use of the dual-axis positioning of the photovoltaic module in relation to the stationary system.

Table 6. Percentage gain resulting from the content of electrical energy produced by the dual-axis tracking system in the period between 07.2017 and 05.2018

Month	07.17	08.17	09.17	10.17	11.17	12.17	01.18	02.18	03.18	04.18	05.18
Energy gain [%]	51.5	45.51	35.12	35.61	27.25	32.31	22.62	34.44	39.21	33.32	52.42

5. Summary

The determined statistical parameters, including the asymmetry coefficient and coefficient of variation, may indicate that the daily distribution of electricity production for a representative 123-day measuring period, differs from the normal distribution. Additionally, the extension of the analysis to include days of winter months results in the increase in the standard error of electricity estimation using the determined regression model, and the further distortion of the shape of the actual distribution in relation to the normal distribution. This may be due to a strong correlation of electricity values with the insolation level (Table 1), which varies for the winter period and the pre-winter months. For this reason, it is necessary to consider the appropriateness of dividing the available measuring data into characteristic periods and using separate forecasting models for them.

Both the quantitative and qualitative comparative analysis of the monthly production of electricity from photovoltaic conversion shows less variability of its waveforms for the summer months. The main parameter in the presented analysis is the coefficient of variation, understood as the ratio of the standard deviation to the arithmetic mean. Its value varies from 0.36 to 0.51 for the months of June to August. This is almost 5 times lower than the results obtained for December and more than 3 times lower in the case of January the following year. The value of the coefficient of variation exceeding 0.6 indicates that a significant percentage of the mean value is its standard variation. The distribution of the values of the measure and is heterogeneous, therefore, the arithmetic mean should not be the main statistical measure. However, using only the value of the standard variation in comparative analysis may turn out to be insufficient because of significant differences in the average monthly value of electricity production for extreme months of the measuring year.

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