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Variability of electricity production from photovoltaic installations against the background of solar radiation in the Kraków-Częstochowa Upland

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ABSTRACT

The aim of the study was to determine the variability of electricity production from PV installations and its relationship with solar parameters. The analysis was performed on the basis of data from PV installations in Bębło, Kraków County. The level of sunshine, solar radiation, and UV index were obtained from measurements at two local weather stations (Bębło and Bolechowice). The data were compiled and approximated for the years 2021–2024. Linear trend equations were determined, along with the R2 determination coefficients. The average value of daily energy production for 4 years was 7.17 kWh. The day of the year with the highest average energy production over the 4 years was 10th May. Zero electricity production was also recorded during the periods of complete snow cover on the panels. There was a linear correlation between the amount of solar radiation and the UV index, with a coefficient of determination of 0.99. There was also a high level of correlation between the amount of energy production and these parameters. The total duration of the monthly sunshine was averaged at 55.1 hours. The month with the lowest insolation was December 2022 and the highest was May 2024. The highest daily values of solar radiation and UV index, as a 4-year average, were recorded in May and June. The UV index exceed the monthly average of 2.0 – which already indicated an average level of UV radiation risk to human health – only in these months. The results of the study allow this information to be estimated from photovoltaic data, which is already widely available, and PV installations in most cases accurately record their parameters.

Keywords: insolation, solar radiation, UV index, photovoltaic installation, energy production.

INTRODUCTION

Renewable energy sources (RES) are becoming increasingly popular. They are inexhaustible and reduce greenhouse gas emissions and other pollutants, contributing to the fight against climate change. They allow for greater energy independence from fossil fuel imports. The most important types of renewable energy sources include photovoltaic panels, solar collectors, wind and hydroelectric power plants, geothermal energy, biomass, biogas, and biofuels. The investments in RES can generate new jobs and stimulate the development of local economies [Wiśniewski et al., 2016; Curtis et al., 2021]. Poland is developing renewable energy sources to achieve the targets set by the European Union for the share of RES in gross final energy consumption [Etherden, 2014; Troster and Schmidt, 2019; Consectec/IAEW 2011; Heuser, 2012; Podewils, 2012]. Currently, photovoltaic installations are the most popular in Poland. They are installed in large companies, as well as in schools and public buildings. They have become more popular among individual consumers in their homes and properties. According to a report by the Energy Regulatory Office (URE), there are already 1.5 million different RES micro-installations operating in Poland, the vast majority (99.7%) are PV installations [Szymański, 2017; Report…2025].

The popularity of this solution has been driven by the high electricity costs and subsidies that support this type of energy generation. The variability in the production of electricity from photovoltaic installations depends on many factors. The amount of solar radiation reaching the panels is crucial. This is mainly influenced by the season, the associated angle of incidence of the sun's rays, cloud cover, temperature, and the presence of obstacles (e.g. trees, buildings). The impact of dirt on the panels, such as dust, leaves, and other contaminants, is also significant. In winter, snow cover often completely prevents the panels from producing energy [Wiśniewski et al., 2016; Karbowniczek, 2021; Tora et al., 2022; Sarniak, 2022; Kaczmarczyk, 2023].

The purpose of the study was to determine the variability in the production of electricity from PV installations on a daily and monthly basis in relation to the level of sunshine and associated solar radiation and the UV index. It also aimed to determine the relationship between energy production and solar parameters in order to approximate solar parameters based on the data from photovoltaic installations.

MATERIALS AND METHODS

The analysis of electricity production was based on the data from a photovoltaic installation located in Będło, Wielka Wieś municipality, Kraków district. The data on sunshine levels, solar radiation, and UV index were obtained from the measurements recorded at two local meteorological stations located in Będło and Bolechowice (Figure 1). The research area in question is located in the southern part of the Kraków-Częstochowa Upland and lies in the eastern part of the Silesian-Kraków Upland. It stretches from Kraków in a north-west direction to Częstochowa over a length of approximately 80 km. The surface of the uplands slopes gently towards the north-east, while towards the west it descends to the Silesian Uplands.

The terrain rises to an altitude of approximately 300 meters above sea level (m a.s.l.) in the eastern part and up to approximately 500 meters in the southern part. Most of the Upland lies within the climate zone of the Central Polish Uplands. Only the southern parts belong to the foothill region. The Kraków-Częstochowa massif is characterized by varied sunlight exposure, depending on the slope and terrain exposure. The valleys are less sunny, while the southern slopes are warmer and drier [Kondracki, 2009].

Methods

The paper compiles data on electricity production for the years 2021–2024 obtained from a photovoltaic installation installed on the roof of a house in Będło (longitude 21°59′17.66″, latitude 50°4′ 24.78″). The installation has been in operation since 30th November 2020 and is orientated at an azimuth of 180° with an inclination angle of 26°. The power of the installation is 2.6 kWp (kilowatt peak). An inverter with a production capacity of 400 W has been installed.

At the same time, the solar data from the summer period was recorded at meteorological stations in Będło and Bolechowice (Figure 1). These were external Meteo WiFi WeatherCloud weather stations, Vevor model TermHoff TH-WS5P. The data from the two weather stations were averaged, taking into account parameters such as

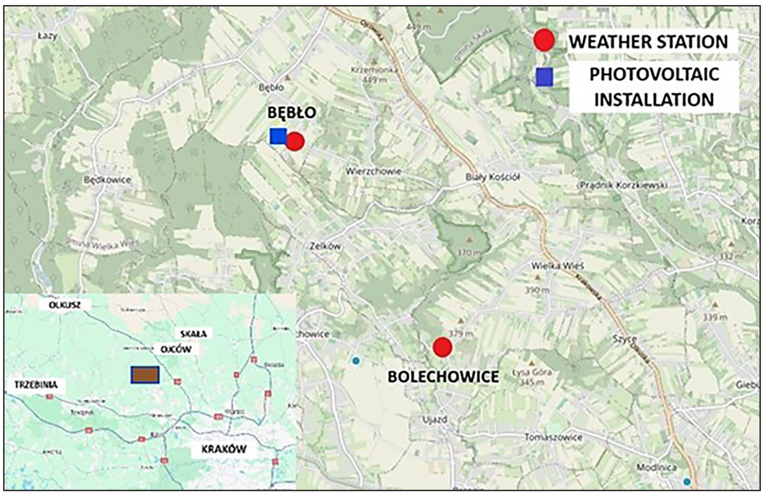

Figure 1. Location of the measuring stations (own study based on maps.google.com)

sunshine duration (in hours), and solar radiation (in W×m^{-2}) and the UV index, which is the international standard for measuring ultraviolet (UV) radiation emitted by the Sun on a given day and in a specific location [Liou, 2002; Degirmendžić, 2004]. The UV Index scale ranges from 0 to 16. Exposure to the Sun, 6 to 7 indicate high and very high risk, 8 to 10 indicate very high risk, and above 11 extreme risk [https://obserwator.imgw.pl/2020/07/26/uv-niebezpieczny-dar-od-slonca/; Weber, 1990; Autier et al., 1999; Dennis et al., 2003; Saraiya et al., 2004; Huncharek and Kupelnick, 2011]. On the basis of the data series, the relationships between the energy production expressed in kWh and the solar parameters were determined. Linear trend equations y = ax+b were determined along with the R2 determination coefficients. Similar relationships were determined between sun duration and solar radiation and index. On the basis of the average solar radiation sums for individual months [Matuszko, 2009], the percentage variability of the parameters was determined as the quotient of the sample value and the arithmetic mean of the sample. The results were approximated for the entire year, taking into account the variability of solar radiation, the height of the Sun above the horizon, and the length of days in the year.

RESULTS

Figure 2 shows the average daily electricity production for the years 2021–2024. Figure 3 presents the total monthly production for the same period. In the last four years, the highest level of electricity production was recorded on 26th May 2021 and amounted to 18.63 kWh. The average daily energy production for the four years was 7.17 kWh. The day with the highest average energy production in the four years was 10th May. Zero energy production was also recorded. These were periods of several or more days in January and December and a single occurrence of several days in the first ten days of February 2023. Zero production was due to the panels being completely covered with snow. The amount of electricity generated by photovoltaic panels depends on many factors. Figure 4 shows an example of the daily distribution of electricity generation for two different weather conditions.

The first involved one of the sunny days in July, the second a cloudy day. Significant temporary differences in energy production during cloud cover were due, among other things, to the fact that solar radiation also penetrates the cloud layer but with varying intensity. In the case of a day with full sunshine, the distribution of production resembles a normal Gaussian distribution. It is not fully symmetrical when the solar panels are not directly south-facing (Figure 5).

Table 1 presents the average monthly sums of the duration of sunshine and solar radiation for the city of Krakow and its surroundings for the years 1884–2007, while Table 2 presents the monthly sun height and day length [Matuszko and Jędrychowski 2006; Matuszko, 2009]. For the parameters above, their percentage variability

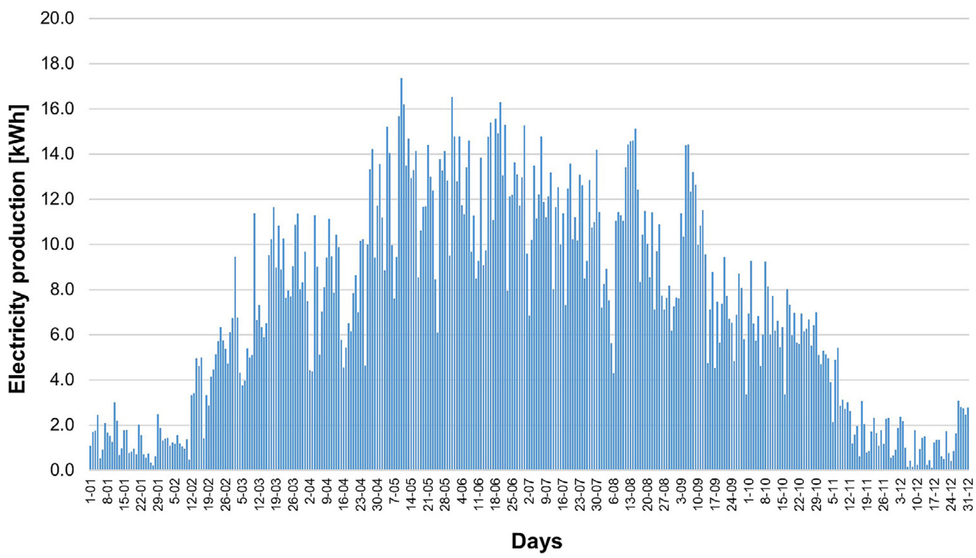

Figure 2. Average daily electricity production for 2021–2024

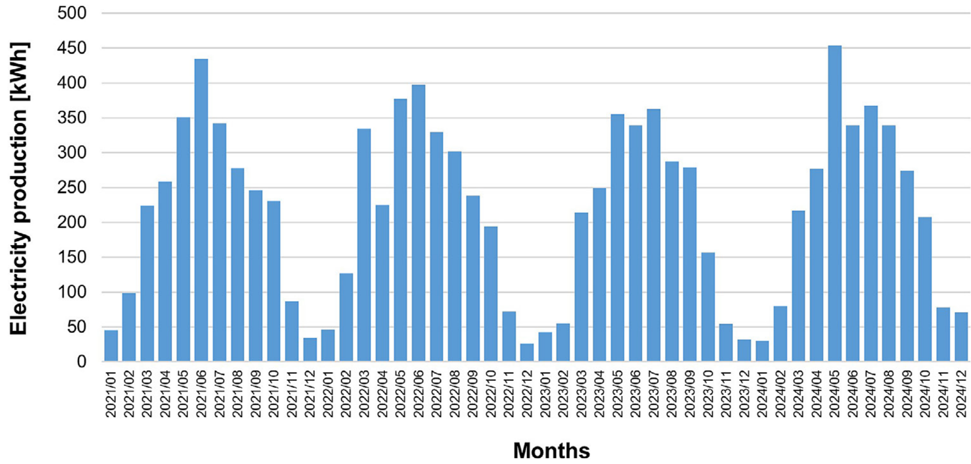

Figure 3. Monthly electricity production for 2021–2024

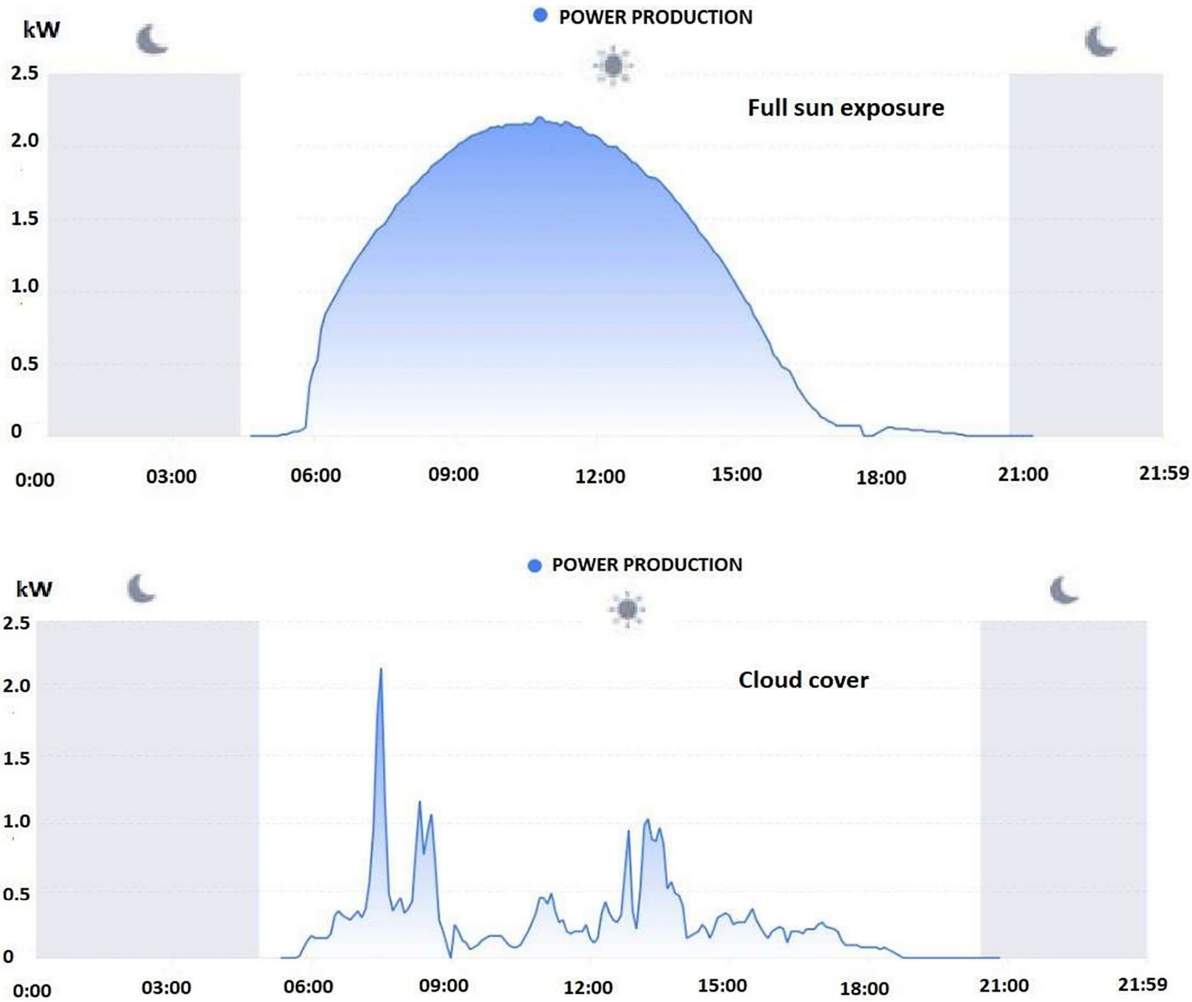

Figure 4. Daily electricity production under various weather conditions (personal development)

of determination, which was not less than 0.81. This means that the correlation coefficient for these relationships ranged from 0.90 to as high as 0.98 in the case of the relationship between solar radiation and energy production.

The highest daily values of solar radiation (Figure 9) and UV index (Figure 10), as a 4-year average, were recorded in May and June (maximum values on 10th May and 20th June). The highest monthly solar radiation (6835.4 $W \cdot m^{-2}$)

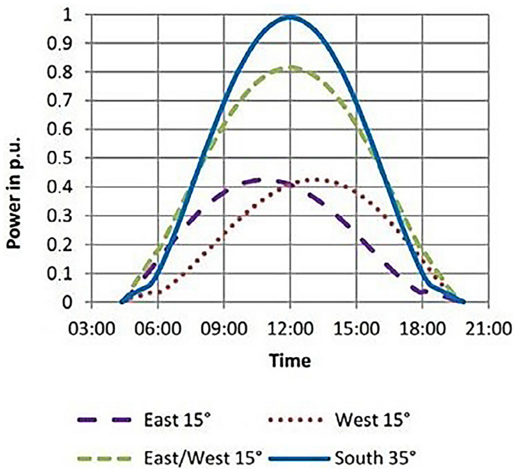

Figure 5. Distribution of energy production according to the orientation of the panels relative to the south [Troster and Schmidt, 2019]

was determined in relation to the annual average as well as in relation to July (Table 1) and June (Table 2), the months with the highest values of the entire year. Figure 6 shows the relationship between solar radiation and the UV index. It is strongly linearly dependent, as evidenced by the very high coefficient of determination $R^2 = 0.989$.

Figure 7 shows the relationship between electricity production and solar radiation levels for the summer period, while Figure 8 shows a similar relationship in relation to sunshine duration and the UV index.

In all these cases, the relational dependencies were linear and characterized by a high coefficient occurred in May 2024, and the second highest value (6792.1 W·m^{-2}) was recorded in May 2024. Only in these months of the entire 4-year period did the UV index exceed the monthly average of 2.0 on the aforementioned days, 10 May and 20th June. In turn, the highest daily values were recorded on 24th June 2022 (UV index 2.66) and 26th May 2021 (UV index 2.64). On these days, the UV index already indicated an average level of ultraviolet radiation risk to human health. On the basis of the relationships above, using the percentage coefficients of variation from Tables 1 and 2 (after averaging them), the sum of monthly sunshine (Table 3), the distribution of average daily solar radiation values, and the UV index for the years 2021–2024 were determined. In turn, Figures 11 and 12 present the monthly distribution of both parameters for the same research period. Their values were obtained on the basis of the measurements of the energy production from photovoltaic panels. Such an approximation of solar data series was possible owing to the high correlation coefficients presented in Figures 7 and 8.

The total duration of the monthly sunshine was averaged at 55.1 hours. In total, the Sun shone for 2643 hours over the four years of the analysis. The month with the lowest insolation was December 2022, with only 3.8 hours, compared to the average for that month of 5 hours. The longest insolation occurred in May 2024 (132.7 hours), with an average for that month of 113 hours.

Table 1. Average monthly sunshine duration, total radiation, and their percentage variation (own elaboration based on [Matuszko, 2009])

Month	Average monthly sunshine duration [in hours]	Average variation of the parameter [%]	Variation of the parameter compared to July [%]	Total radiation [MJ·m^{-2}]	Average variation of the parameter [%]	Variation of the parameter compared to July [%]
January	48.4	0.37	0.22	91.8	0.30	0.16
February	65.3	0.51	0.30	142.7	0.46	0.25
March	107.7	0.83	0.49	269.4	0.87	0.48
April	149.2	1.16	0.68	394.6	1.27	0.70
May	203.7	1.58	0.92	530.9	1.71	0.94
June	207.2	1.60	0.94	556.0	1.79	0.98
Jule	220.4	1.71	1.00	565.0	1.82	1.00
August	202.4	1.57	0.92	483.1	1.55	0.86
September	151.7	1.17	0.69	329.3	1.06	0.58
October	105.5	0.82	0.48	198.2	0.64	0.35
November	51.6	0.40	0.23	99.2	0.32	0.18
December	37.0	0.29	0.17	72.2	0.23	0.13

Table 2. Average monthly sun height at noon, length of day and their percentage variation (elaboration by themselves based on [Matuszko, 2009])

Month	Sun height at noon [°]	Average variation of the parameter [%]	Variation of the parameter compared to June [%]	Length of the day [hours and minutes]	Average variation of the parameter [%]	Variation of the parameter compared to June [%]
January	18.8	0.47	0.30	8.32	0.69	0.51
February	27.1	0.67	0.43	10.05	0.83	0.62
March	38.0	0.94	0.60	11.52	0.96	0.71
April	49.9	1.24	0.79	13.48	1.12	0.83
May	58.9	1.46	0.93	15.26	1.27	0.94
June	63.3	1.57	1.00	16.22	1.35	1.00
Jule	61.4	1.52	0.97	15.56	1.29	0.96
August	53.8	1.34	0.85	14.28	1.19	0.88
September	42.7	1.06	0.68	12.37	1.03	0.76
October	31.2	0.78	0.49	10.46	0.87	0.64
November	21.3	0.53	0.34	9.02	0.75	0.56
December	16.7	0.41	0.26	8.05	0.67	0.50

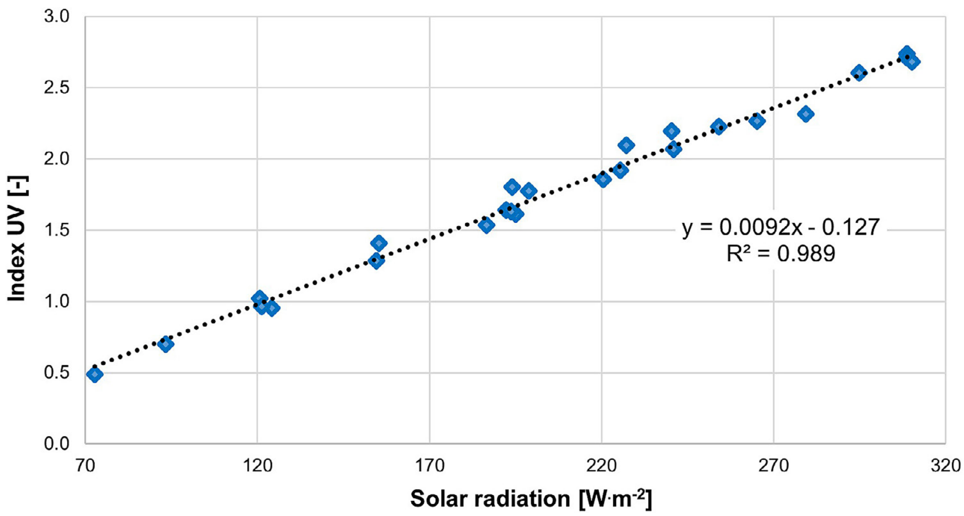

Figure 6. Relation between UV index and solar radiation (personal elaboration based on the data from 2 weather stations)

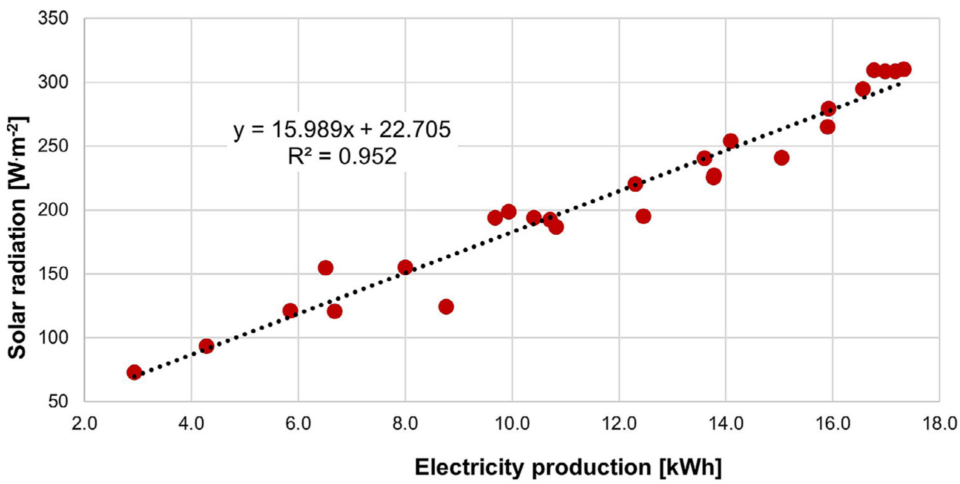

Figure 7. Relation between solar radiation and electricity production (personal elaboration based on the data from 2 weather stations)

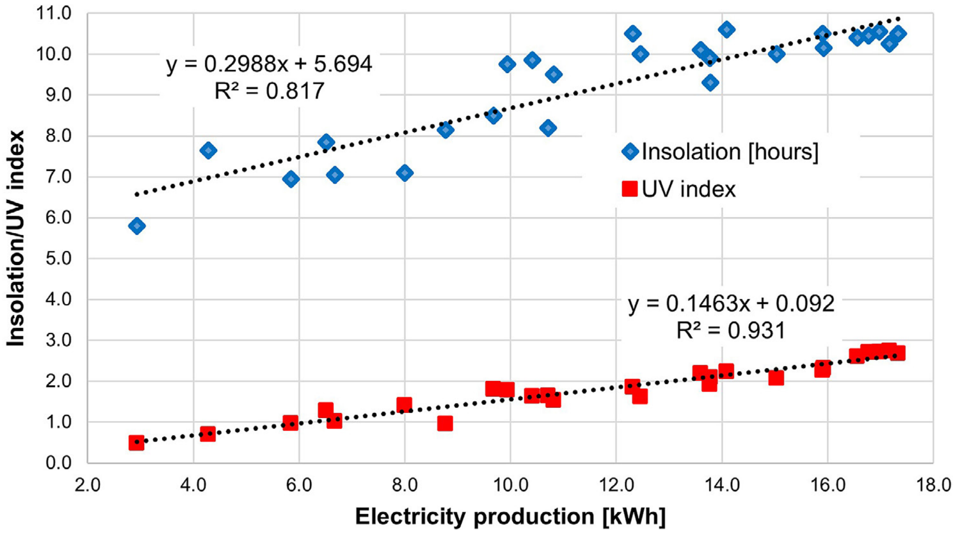

Figure 8. Relation between UV index and insolation and electricity production (personal elaboration based on the data from 2 weather stations)

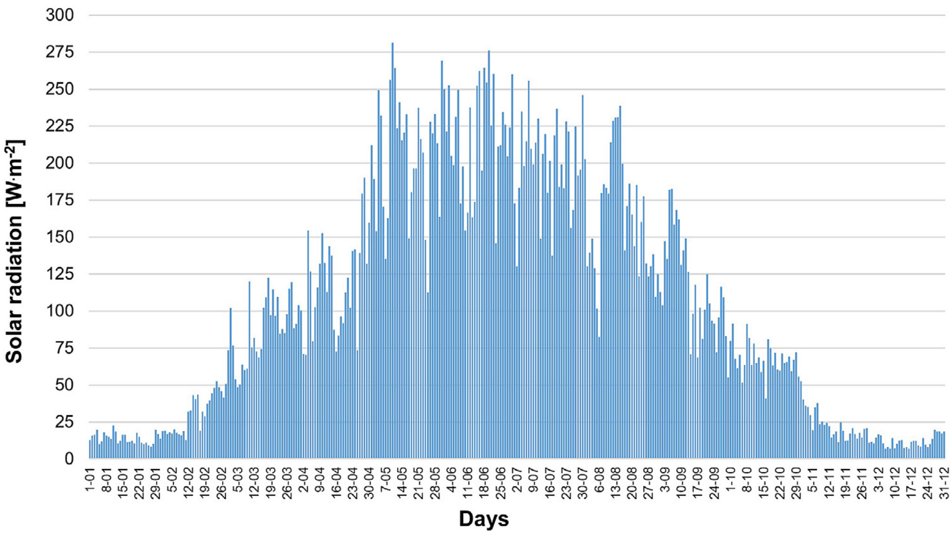

Figure 9. Approximate daily solar radiation (average for 2021–2024)

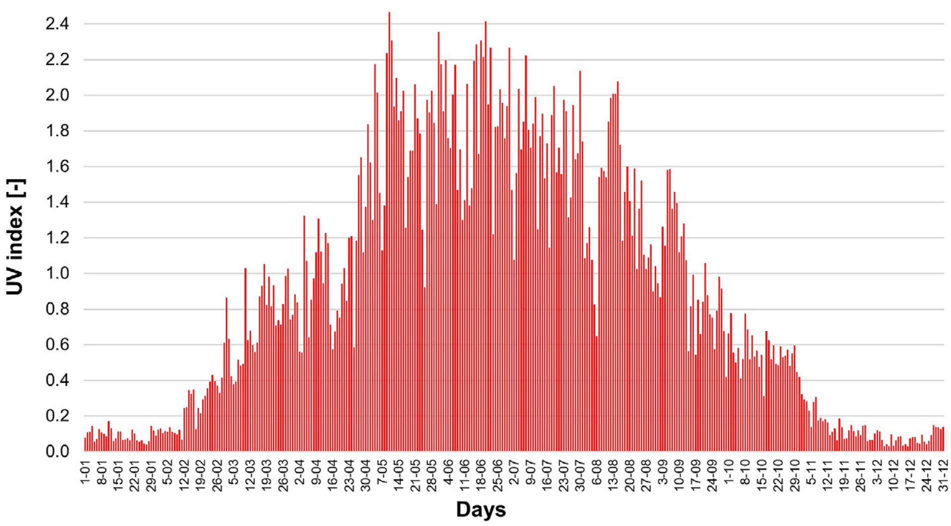

Figure 10. Approximate daily UV index (average for 2021–2024)

Table 3. Monthly total insolation in 2021–2024

Month	Insolation [Hours]	Month	Insolation [Hours]	Month	Insolation [Hours]	Month	Insolation [Hours]
2021/01	6.2	2022/01	6.2	2023/01	5.9	2024/01	4.7
2021/02	14.9	2022/02	18.4	2023/02	9.3	2024/02	12.5
2021/03	42.5	2022/03	61.8	2023/03	40.8	2024/03	41.3
2021/04	63.0	2022/04	55.5	2023/04	61.0	2024/04	67.2
2021/05	103.8	2022/05	111.1	2023/05	104.9	2024/05	132.7
2021/06	132.1	2022/06	121.2	2023/06	104.3	2024/06	104.3
2021/07	106.3	2022/07	102.7	2023/07	112.5	2024/07	113.8
2021/08	80.1	2022/08	86.5	2023/08	82.7	2024/08	96.7
2021/09	57.0	2022/09	55.4	2023/09	64.2	2024/09	63.1
2021/10	40.0	2022/10	34.1	2023/10	28.2	2024/10	36.2
2021/11	10.9	2022/11	9.5	2023/11	7.6	2024/11	10.0
2021/12	4.4	2022/12	3.8	2023/12	4.2	2024/12	7.5

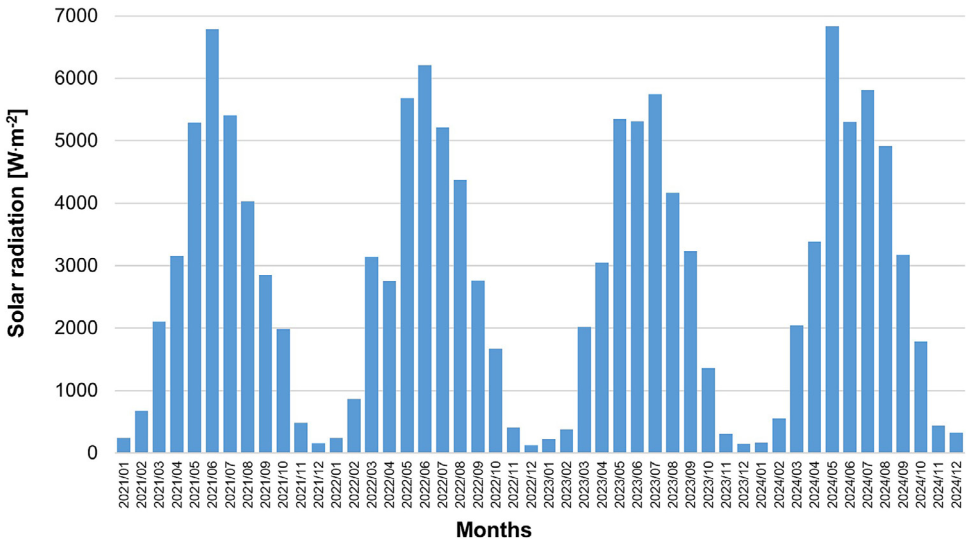

Figure 11. Approximate monthly solar radiation (average for 2021–2024)

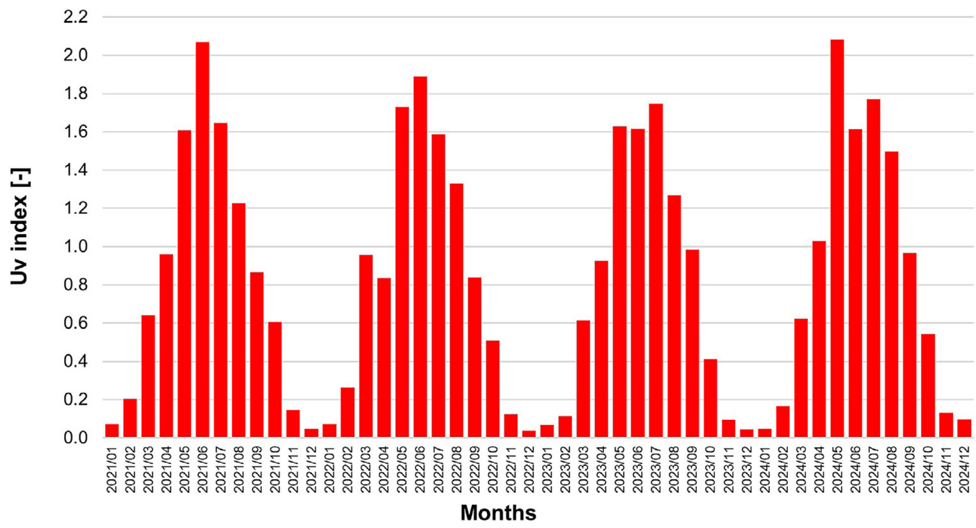

Figure 12. Approximate monthly UV index (average for 2021–2024)

CONCLUSIONS

The analysis of solar parameters such as sunshine duration, solar radiation and UV index is essential for the design and subsequent effective operation of a photovoltaic installation. The multitude of factors that determine the efficiency of PV installations requires a detailed analysis to improve their performance. For example, in addition to the knowledge of the aforementioned meteorological parameters, it is important to correctly design the inclination and azimuth of the panels, taking into account the terrain. Therefore, each region has its own specific characteristics in terms of its 'suitability' for the installation of photovoltaic panels. The study conducted such an analysis for an area that is orographically representative of the southern part of the Kraków-Częstochowa Upland.

The analysis showed a high level of correlation (0.99) between the amount of electricity produced by photovoltaic installations and the level of solar radiation. The months with the highest energy production were May and June. After approximating the results for the entire analyzed period, it was found that the highest level of sunshine occurred in 2021 and 2024. The minimum values of the parameters studied occurred in January and December, with less variation for these months in individual years than for the spring and summer period, especially May, June, and July. In 2021 and 2022, the highest values of all analyzed parameters were recorded in June. In 2023, it was July, and in 2024, it was May. The analysis allowed for the approximation of solar parameters for a longer period of time based solely on the data on energy production from PV installations. This is important from a cognitive point of view, as there is a lack of detailed measurements of solar parameters in the studied area. The monitoring network for sunshine is very limited, and there are often gaps in data continuity. The results of the work allow this information to be estimated from photovoltaic data, which is already widely available, and PV installations in most cases accurately record their parameter data.

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REFERENCES

1. Autier, P., Doré, J. F., Négrier, S., Liénard, D., Panizzon, R., Lejeune, F. J., Guggisberg, D., Eggermont, A. M. (1999). Sunscreen use and duration of sun exposure: A double-blind, randomized trial. *Journal of the National Cancer Institute, 91*(15), 1304–1309. https://doi.org/10.1093/jnci/91.15.1304
2. Consectec/IAEW. (2011, October). Bewertung der Flexibilitäten von Stromerzeugungs- und KWK-Anlagen. Berlin.
3. Curtis, T. L., Buchanan, H., Heath, G., Smith, L. L., Shaw, S. (2021). Solar photovoltaic module recycling: A survey of U.S. policies and initiatives (NREL/TP-6A20-74124). National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy21osti/74124.pdf
4. Degirmendžić, J. (2004). Changes in sunshine duration in Poland and their circulatory determinants (in Polish). In K. Kożuchowski (Ed.), *Skala, uwarunkowania i perspektywy współczesnych zmian klimatycznych w Polsce* 9–23. Wydawnictwo Biblioteka.
5. Dennis, L. K., Beane Freeman, L. E., VanBeek, M. J. (2003). Sunscreen use and the risk for melanoma: A quantitative review. *Annals of Internal Medicine, 139*(12), 966–978. https://doi.org/10.7326/0003-4819-139-12-200312160-00006
6. Energy Regulatory Office. (2025, March 17). URE report: 1.5 million renewable energy micro-installations now operating in Poland (in Polish). Report prepared pursuant to Article 6a(2)(1) of the Act of 20 February 2015 on renewable energy sources (Journal of Laws of 2024, item 1361, as amended). https://www.ure.gov.pl/pl/urzad/informacje-ogolne/aktualnosci/12551,Raport-URE-w-Polsce-dziala--juz-15-mln-mikroinstalacji-OZE.html
7. Etherden, N. (2014). *Increasing the hosting capacity of distributed energy resources using storage and communication* (Doctoral dissertation, Luleå University of Technology). https://urn.kb.se/resolve?urn=urn:nbn:se:hig:diva-45718
8. Heuser, R. (2012). Ost-West ist Trumpf. *Photon*, (6). https://energynautics.com/wp-content/uploads/2019/02/App22_ENA_Evaluating_the_Impact_of_PV_Module_Orientation.pdf
9. Huncharek, M., Kupelnick, B. (2011). Use of topical sunscreens and the risk of malignant melanoma: A meta-analysis of 9,067 patients from 11 case-control studies. *American Journal of Public Health, 92*(7), 1173–1177. https://doi.org/10.2105/ajph.92.7.1173
10. Instytut Meteorologii i Gospodarki Wodnej – Państwowy Instytut Badawczy. (2020, July 26). *UV – a dangerous gift from the sun* (in Polish). https://obserwator.imgw.pl/2020/07/26/uv-niebezpieczny-dar-od-slonca/
11. Kaczmarczyk, D. (2023). *Energy storage* (in Polish).

https://fotowoltaikaonline.pl/magazyn-energii

12. Karbowniczek, M. (2021). *Silicon photovoltaic cell technologies on the market* (in Polish). https://budownictwob2b.pl/instalacje/baza-wiedzy/fotowoltaika/51980-technologie-krzemowe-ogniw-fotowoltaicznych-na-rynku
13. Kondracki, J. (2009). *Regional geography of Poland* (in Polish). Warszawa: Wydawnictwo Naukowe PWN.
14. Liou, K. N. (2002). *An introduction to atmospheric radiation* (2nd ed.). Academic Press.
15. Matuszko, D. (2009). *The impact of cloud cover on sunshine duration and total solar radiation based on a series of measurements taken in Krakow* (in Polish) (1st ed.). Kraków: Wydawnictwo Uniwersytetu Jagiellońskiego.
16. Matuszko, D., Jędrychowski, I. (2006). Sunshine duration measurement in Cracow (in Polish). *Annales Universitatis Mariae Curie-Skłodowska, Sectio B, Geographia, Geologia, Mineralogia et Petrographia, 61*, 284–289.
17. Podewils, C. (2012). Warum nur 30 Gigawatt? *Photon*, (12).
18. Saraiya, M., Glanz, K., Briss, P. A., Nichols, P., White, C., Das, D., Smith, S. J., Tannor, B., Hutchinson, A. B., Wilson, K. M., Gandhi, N., Lee, N. C., Rimer, B., Coates, R. C., Kerner, J. F., Hiatt, R. A., Buffler, P., Rochester, P. (2004). Interventions to prevent skin cancer by reducing exposure to ultraviolet radiation: A systematic review. *American Journal of Preventive Medicine, 27*(5), 422–466. https://doi.org/10.1016/j.amepre.2004.08.009
19. Sarniak, M. (2022). *Installer's manual for photovoltaic systems* (in Polish). Grupa Medium.
20. Szymański, B. (2017). *Instalacje fotowoltaiczne* (6th ed.). GLOB Energia.
21. Tora, M., Karbowniczek, M., Tora, B. (2022). Photovoltaics in Poland: Current status and prospects (in Polish). *Zeszyty Naukowe Instytutu Gospodarki Surowcami Mineralnymi i Energią PAN, 110*, 111–118.
22. Troster, E., Schmidt, J. D. (2019). Evaluating the impact of PV module orientation on grid operation. In *2nd International Workshop on Integration of Solar Power into Power Systems*.
23. Weber, G. R. (1990). Spatial and temporal variation of sunshine in the Federal Republic of Germany. *Theoretical and Applied Climatology, 41*(1), 1–9. https://doi.org/10.1007/BF00866197
24. Wiśniewski, G. (Red.), Więcka, A., Bolesta, J., Czajka, P. (2016). *Polish renewable energy equipment manufacturing industry. Update of the company database and assessment of the industry's development potential until 2020 and 2030* (in Polish). Instytut Energii Odnawialnej.