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# SPATIAL SOLAR ENERGY POTENTIAL OF PHOTOVOLTAIC PANELS SURROUNDED BY PROTECTED MOUNTAIN RANGES

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Abstract

High growth of human population and dynamic socio-economic development have contributed to mounting demand for electric energy. Currently, electric energy is mainly generated from mined and combusted fossil fuels and by the nuclear power plants. The current geopolitical crisis forces mankind to reflect upon the search for alternative energy sources. In this paper analyses of the potential solar radiation volume for 12 months and annual total have been made and visualized on the maps. Additionally, the energy volume gained by the photovoltaic systems in a 12-month period and the annual total as well as underutilised solar radiation energy were calculated. It was found that the tested sites had a solar potential in the range from 113 kWh·m$^{-2}$ to 1314 kWh·m$^{-2}$. For process reasons, only 18 to 203 kWh·m$^{-2}$ could be converted into electric energy, which accounts approximately for 1/5 of the total radiation. The results can be useful to show the best

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investment site for commercial plants and households in the mountainous area. Surplus energy output should be stored or sold to the power grid. Moreover, the energy source from photovoltaic panels in these areas is only one of the options for green energy generation.

Keywords: carbonless policy, GIS-based assessment, photovoltaic (PV) panels, total solar radiation, green energy

## 1. INTRODUCTION

Global fossil energy sources are estimated to last for approximately 50 years longer. Therefore, renewable energy sources (RES), including energy derived from the sun [1], are very popular. The acquisition and conversion of solar radiation into electric energy, which occurs in photovoltaic cells, is attractive not only for economic but also for environmental reasons. In the European Union Member States, renewable energy sources are used more and more [2]. One of them is solar energy generation. Poland's PV sector is expected to continue to grow and has the potential to reach 9-10 GW in 2022 and up to 27 GW in 2030. The upward trend in total PV capacity will be sustained by improvements, particularly prosumer capacity projects [3].

In addition, scarce fossil fuel resources and public opposition to the construction of nuclear power plants have a clear impact on growing interest in renewable energy sources [4]. We can consider solar energy as one of the basic and key alternative sources. Solar energy is "clean", cost-effective and safe. Its main advantage is that it does not produce air emissions of pollutants during electric energy generation [5]. Moreover, the solar energy reaching the Earth far exceeds our demand. However, due to the fact that research work on solar energy conversion has started relatively recently, all aspects of solar energy generation and storage are not known [6]. Photovoltaics deals not only with issues related to solar energy, but also with the conversion of solar energy into electric energy. The investment into photovoltaic (PV) system is an easy and cost-effective manner to reduce the electric energy bill of any household [7].

An upward trend can be seen, also in people who are determined to take a step to-wards green energy when building a house and invest in photovoltaic systems. By connecting to the electric energy distribution network, we can not only save money, but also raise money [8].Energy generated by Renewable Energy Sources (RES) plays an increasingly important role in the global energy supply market. It represents an alternative to fossil fuels due to its comparability [9].The gradual conversion economy powered by non-renewable energy sources into the economy using low-carbon green systems that guarantee security of energy supply on a national scale can already be seen in Poland. Once the above requirements have been met, opening the RES market will not only be an ideal alternative but will also create a sustainable energy development programme [10]. Due to the climatic conditions in Poland, renewable energy is obtained from natural, recurring natural processes. Various RES types come directly from solar radiation or heat generated by the Earth's interior [11]. The geographical location of Poland with the mountain ranges in the southern part and the sea in the northern part of the country favours constant changes in the air mass inflow [12]. The suitability of regions in Poland for solar power plants was determined by such indicators as: annual and monthly radiation total volumes, number of hours with sunshine, surface albedo, atmospheric transparency, inflow of direct radiation calculated using length and time of occurrence criteria [13]. According to the data, the best solar conditions occur in the south-eastern region of Poland, and the highest radiation and insolation totals can be observed from April to September, reaching average annual conditions of approximately 1100 $kWh{\cdot}m^{-2}$ [14]. The Podlasie-Lublin region is equally favourable, due to the inflow of dry air masses from the east. The lowest solar radiation occurs in the Warsaw, Upper Silesia and north-eastern Poland. The inferior radiation conditions in these areas are influenced by air pollution produced by industry. The less comfortable conditions in the foothills region are influenced by orographic cloud cover occurring most frequently in June. Much higher total radiation can be expected when the PV systems are located on mountain peaks, especially those above 1000 m [15]. In Poland, the highest intensity of direct and indirect radiation (mean surface solar radiation) ranges from 80 to 140 W/m2 [16]. New solar technologies and systems, developed in recent years, allow to capture effectively and to convert solar energy, which can be managed in a more efficient manner. One example is photovoltaic conversion, which allows to generate electric energy [17]. Photovoltaics is a 'green' technology that aims at conversion of solar radiation into electric energy. It is one of the best developing methods currently using solar radiation [18]. Using this technology guarantees the return of some or even all of the money spent on electric energy consumption [19]. The photovoltaic systems consist of photovoltaic panels that convert solar energy into usable energy [20]. The generated electric energy is first used by the household's electrical system and the excess is sold back to the public grid or in the off-grid system when it is stored in a battery [21]. In case of insufficient energy output, power is taken from the grid. On the other hand, in the case of energy supply from solar systems, there is an option to sell it to the power grid on commercial basis [22].

Despite the highly developed technology based on deep learning and the global economy, we are still unable to take full advantage of solar energy generation [23]. The renewable energy sources still have great potential. In the near future, RES will be the main supplier of electric energy, especially, in the prospect of depleting conventional energy sources [24]. The comparison of the priorities and applicability of renewable energy sources using the Simultaneous Evaluation of Criteria and Alternatives (SECA) method, shows that the largest untapped resource is solar energy [25].

The aim of this study was to perform an analysis of the solar energy generation potential of photovoltaic panels placed in a low insolation valley surrounded by mountain ranges. The methodology was divided into phases and specific objectives were set to assess the energy potential:

1. to assess the solar energy generation potential of photovoltaic systems;
2. to execute the temporal variability of the solar radiation generation potential for the facility under study;
3. the influence of the variation of the spatial distribution of the potential amount of solar radiation on the efficiency of its acquisition;
4. study of the proximity of mountain protected areas to the location of photovoltaic systems.

## 2. MATERIALS AND METHODS

### 2.1 Research areas

The investigated sites were located in southern Poland, in the Małopolskie Province, in the Western Carpathians, and the land profile is mostly mountainous or has the character of a valley surrounded by the mountain ranges (Figure 1). The tested area has a cold temperate climate with an average temperature of 6.6 °C and an average annual precipitation of 851 mm. The warmest month of the year is July with a temperature of 16.5 °C and the coldest month is January with an average temperature of -4.8 °C. The highest gradients are found in the national parks covering Gorce, Pieniny and Babia Góra mountain ranges. The smallest slopes are characteristic for the tested valley (Figure 2). The viability of solar energy generation was tested based on 7 photovoltaic systems located in the area of the valley surrounded by the mountain ranges and by the legally protected ranges, as follows:

1. A PV System No. 1 is the northernmost site in the county. It was installed on the roof of a single-family detached house. It featured a capacity of 3.2 kWp and its energy output was approximately 3.200 kWh per year.
2. A PV System No. 2 was located on the roof of a single-family detached house, and consisted of 20 polycrystalline panels, facing southwest. It had a capacity of 10 kWp, and its energy output was approximately 5000 kWh per year.
3. A PV System No. 3 was installed on the roof of a single-family detached house. There were 33 monocrystalline panels installed, of which 21 on the south-eastern part of the roof and 12 on the south-western part. The system total power was 8.6 kWp. The system energy output was 7293 kWh per year.

4. A PV System No. 4 had a capacity of 8 kWp. It could generate approximately 7200 kWh of energy per year. It is located in the eastern part of the tested area.
5. A PV System No. 5 is located on the site of the Niedzica Hydropower Plant Complex. The panels were located on the roof of a rain shelter facing south. The panels were made of polycrystalline cells with a peak power of 15 kWp. The total number of panels was 60.
6. A PV System No. 6 is located on the roof of a single-family detached house and a garage, 19 panels each. One panel has a capacity, 260 watts, and the total output was 9.1 kWp.
7. A PV System No. 7 with a capacity of 5.1 kW showed an average energy output of 6022 kWh per year.

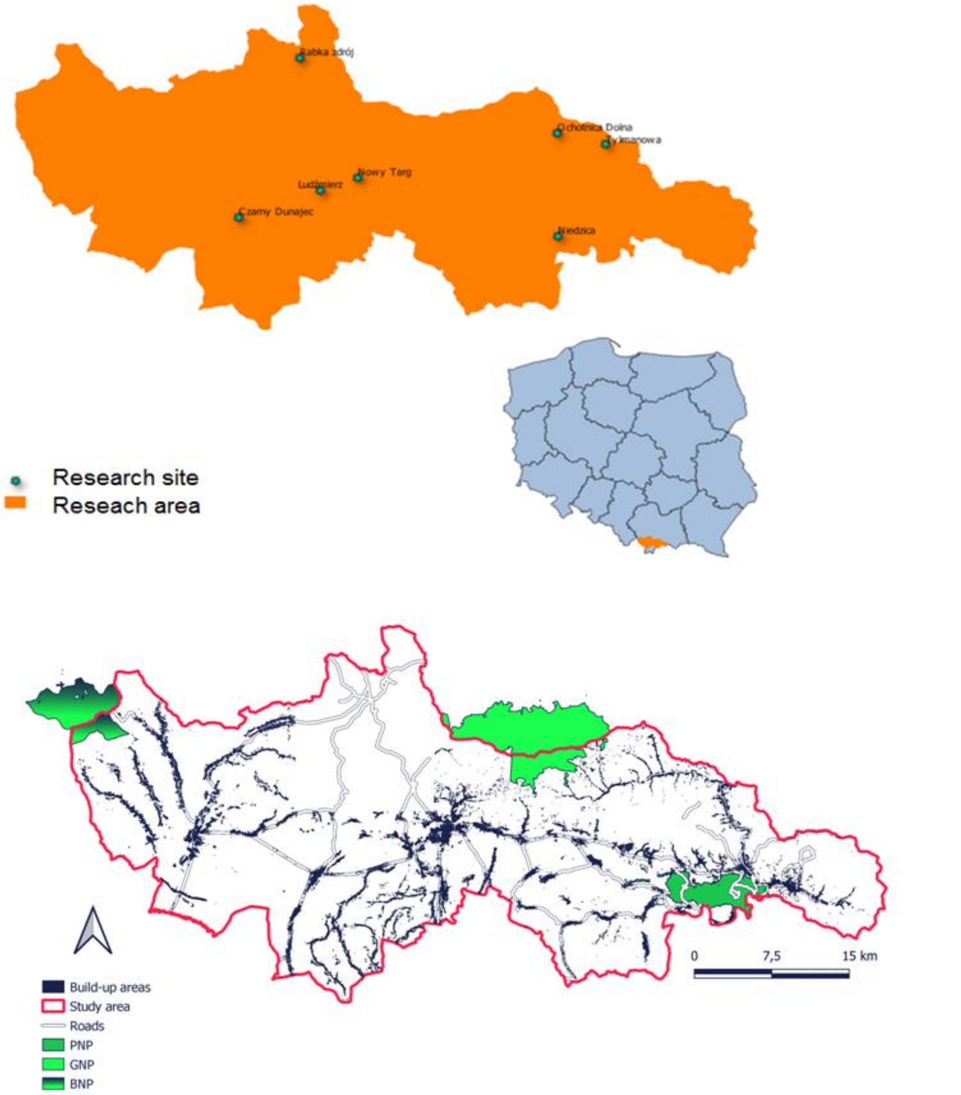


Fig. 1. Location of tested sites in Poland and National Parks in study area.
PNP – Pieniny National Park; GNP- Gorce National Park; BNP- Babiogórski National Park

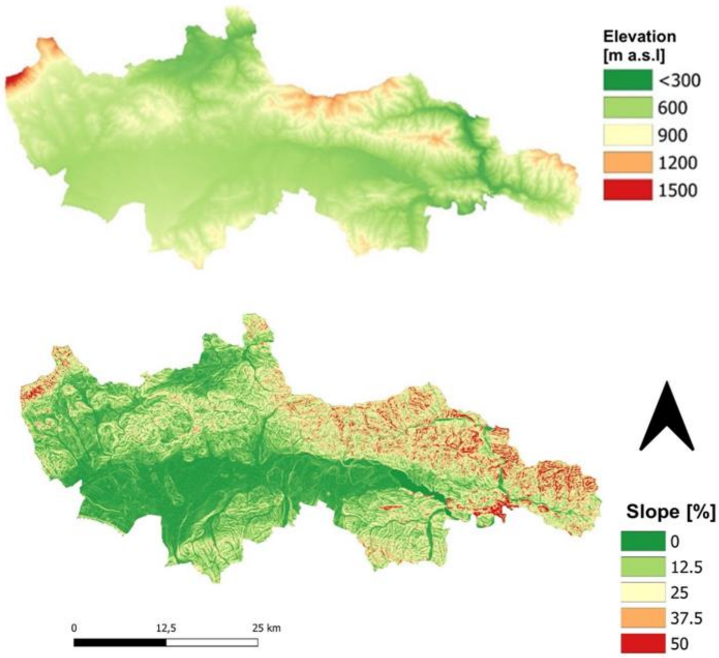


Fig. 2. A hypsometric and slope maps of the surveyed area

## 2.2. Output data

The information about PV System sites along with the system characteristics and total energy output per month data were downloaded from the websites. The information included: energy output in the period from 1 February 2019 to 31 January 2020,the installed capacity of the system, the installed inverter, and the system site.

## 2.3. Numerical model of terrain (NMT)

To model the solar radiation in the tested area, the Numerical Model of Terrain (NMT) was used, which was downloaded from the Copernicus, the European database portal. NMT is a raster image where one pixel corresponds to a generalized terrain elevation. The special resolution of downloaded terrain model was 25x25m per pixel.

## 2.4. Spatial analysis and modelling of solar radiation

The QuickMapServices plug-in was used in QGIS 3.12 software to determine the location of each of the 7 (seven) photovoltaic systems. The Numerical Model of Terrain (NMT) was then cropped to the tested area boundary using the "Raster - Cut" option. The resulting map was introduced with a new coordinate system EPSG:2180, which was the system selected for Poland. The values of the potential solar input to each installation were then modelled. The Numerical Model of Terrain was fed into ArcMap 10.3 software along with the PV system sites. Then using the ArcToolbox module and the Spatial Analyst Tools function, the Point Solar Radiation tool were used to obtain the volume of solar radiation that reaches a selected site on the ground in this case the 7 selected systems in the tested area. The output radiation values were converted into $kWh \cdot m^{-2}$. Then, the Area Solar Radiation tools were applied to obtain a map of the potential spatial distribution of radiation (Appendix, section B, Figure B2) . When developing solar radiation maps, it is necessary to pay attention to such components as sky sector map, horizon obscuration map analysis, and sun position map. The details are presented by means of the algorithm (Figure 3). The horizon obscuration map was created for all vertical points as a result of which the horizon obscuration line is determined. With sectors that show the sun's location at an interval of 0.5 h for the daytime and 1 month for the year, a map of the sun's location is created. The view shadow map can be superimposed on the sun position map, with this procedure it is possible to obtain a visualization of the sun's movement along the horizon for all points (Appendix, section B, Figure B1). As a result, direct radiation information is obtained. The map of sky sectors is created through deconcentration of the sky hemisphere above the horizon into 16 sectors and 8 circles. This procedure results in diffuse radiation data [26]. To determine the solar radiation, the following parameters were used:

- resolution,
- period of measurement performed,
- latitude,
- dispersion coefficient,
- hourly interval,
- geographic directions,
- transparency coefficient.

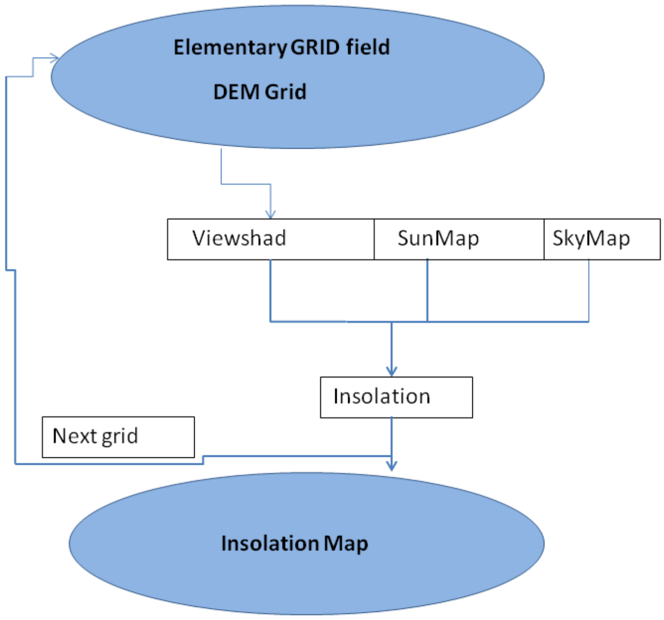


Fig. 3. Computational algorithm for solar radiation [26]

The energy volume per 1 m$^2$ of PV system has been calculated (2.1). To get the final result, information such as: number of photovoltaic panels in the selected PV system, system power [kWp], energy volume generated by the system per month, area of a single module [m$^2$] was required. The energy volume generated by 1 m$^2$ equals to:

$$\frac{energyvolumegeneratedbythesystempermonth}{systemarea}\left[kWh \cdot m^{-2}\right] \tag{2.1}$$

For test points with default values, the correction factors were calculated for each of the months analysed and each PV system. For each month, the annual average coefficients were calculated for each of the seven PV systems. The calculated averages were used to modify the obtained area modelling results with the Raster Calculator tool. In this way, 12 maps were obtained, showing the monthly solar energy yields that are achievable by the tested PV systems.

The last map made using the ArcMap software was a map of the differential between the potential solar radiation and the solar energy that can be absorbed by the tested PV systems. For test points with default values, the correction factors were calculated for each of the months analysed and each PV system. For each month, the annual average coefficients were calculated for each of the seven PV systems. The calculated averages were used to modify the obtained area modelling results with the Raster Calculator tool. In this way, 12 maps were obtained, showing the monthly solar energy yields that are achievable by the tested PV systems. In addition, we evaluated the reduction in the cost of electricity payments, assuming for single-family houses (objects 1-3 and 6-7). It was calculated that 1 kWp is about 800 kWh of energy produced. Expected average annual consumption for one person is 1100 kWh. It was adopted that an average of 4 residents live in a single-family detached house.

Using ArcMap software, the difference between the potential solar radiation and the solar energy that could be absorbed by the PV systems under study was determined quantitatively in the form of a final map.

## 3. RESULTS

### 3.1. Actual energy volume generated by the tested systems

The output data shows that the highest power was that of the PV System No. 5, which was 15 kWp. The lowest power had the PV System No. 1, amounting to 3.2 kWp. (Table 1). In the tested period, the highest energy in all the PV systems was obtained in the month of June. The energy output ranged from 436 kWh for the PV System No. 1 to 2241 kWh for the PV System No. 5. A similar energy volume was generated in July. The lowest energy outputs were obtained in December and January. During the interpretation of output data, it was observed that the power of the PV system was not proportional to the energy yield. For example, the PV System No. 2 with a power of 10 kWp generated less energy than the PV System No. 7, whose power was twice lower. The PV Systems Nos. 3 and 6, despite their lower power, generated more energy than the PV System No. 2. The PV System No. 5 generated more power (three times) than the PV System No. 2. In December all the tested PV systems recorded the highest decrease in energy output (Figure 5). The PV System No. 1, with a power of 3.2 kWp, recorded slightly lower energy yields in December than the PV Systems that outperformed them by up to 3 (three) and 5 (five) times in terms of power values of PV Systems Nos. 2 and 6. The PV System No. 7, characterized by a power of 5.1 kWp, also achieved higher energy yields in December than the more powerful PV Systems Nos. 2 and 4 (Table 1).

Table 1. Range and total energy yield for the tested area

| Research object | Power | Area | Monthly range output electrical energy | Sum |
|---|---|---|---|---|
| | kWp | m² | kWh | |
| 1* | 3.2 | 21 | 132–436 | 3576 |
| 2* | 10 | 65 | 158–692 | 5860 |
| 3* | 8.6 | 54 | 205–1073 | 7821 |
| 4 | 8.0 | 52 | 140–996 | 5536 |
| 5 | 15 | 97 | 320–2241 | 15300 |
| 6* | 9.1 | 57 | 133–1156 | 8139 |
| 7* | 5.1 | 33 | 187–865 | 6022 |

* Photovoltaic systems on the roofs of single-family houses

## 3.2. Potential solar radiation totals

The least solar radiation volumes reached the PV System No. 4, where the total of potential solar radiation was in the range from 7.8 kWh·m$^{-2}$ in December to 168.8 kWh·m$^{-2}$ in June. The highest total volume of solar radiation reached the PV System No. 7, where the total of potential radiation was 1046.7 kWh·m$^{-2}$ (Table 2). The highest totals of potential solar radiation were recorded in June (177.3 kWh·m$^{-2}$ for the PV System No. 7), the least volume of solar radiation reached the ground surface in December, and was true for the PV System No. 4. Unexpectedly, higher insolation values were recorded in February than in November, which is considered a late autumn period (Figure 4; Table 2).

Table 2. Potential solar radiation totals on the tested sites modelled by month

| | Month | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Research object | II | III | IV | V | VI | VII | VIII | IX | X | XI | XII | I | Sum |
| | kWh·m$^{-2}$ | | | | | | | | | | | | |
| 1 | 28.7 | 71.5 | 117.0 | 162.2 | 173.4 | 170.6 | 135.4 | 85.3 | 39.8 | 15.2 | 8.3 | 12.2 | 1019.6 |
| 2 | 29.3 | 72.8 | 118.7 | 164.4 | 175.7 | 172.8 | 137.3 | 86.7 | 40.6 | 15.6 | 8.6 | 12.6 | 1035.2 |
| 3 | 29.4 | 72.9 | 118.9 | 164.6 | 175.9 | 173.1 | 137.5 | 86.9 | 40.7 | 15.7 | 8.6 | 12.6 | 1036.9 |
| 4 | 27.4 | 68.9 | 113.6 | 157.6 | 168.8 | 165.8 | 131.5 | 82.6 | 38.1 | 14.4 | 7.8 | 11.6 | 988.0 |
| 5 | 28.2 | 70.2 | 115.1 | 160.0 | 171.4 | 168.3 | 133.4 | 83.8 | 39.2 | 15.0 | 8.2 | 12.0 | 1004.8 |
| 6 | 28.5 | 71.2 | 116.5 | 161.7 | 172.8 | 170.0 | 134.9 | 85.0 | 39.6 | 15.1 | 8.2 | 12.1 | 1015.6 |
| 7 | 29.8 | 73.7 | 120.0 | 166.0 | 177.3 | 174.5 | 138.7 | 87.8 | 41.3 | 16.0 | 8.8 | 12.9 | 1046.7 |

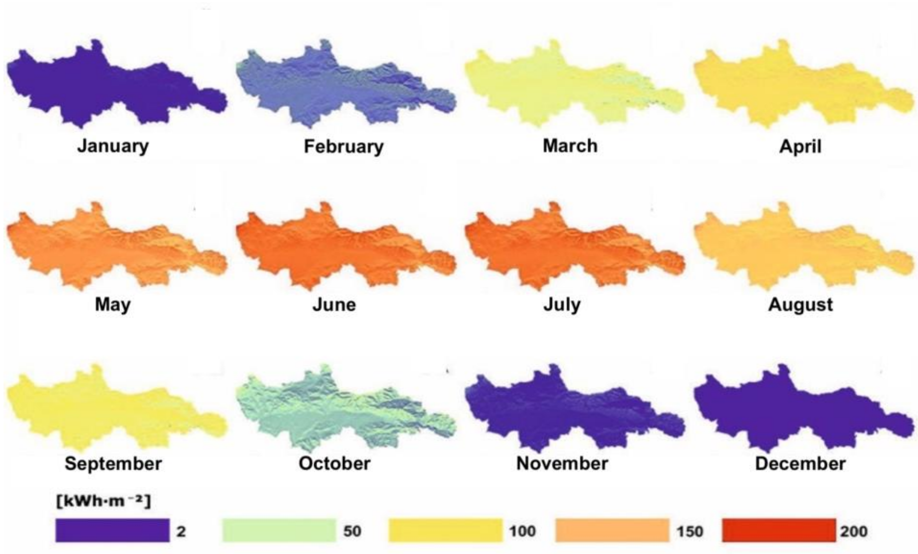


Fig. 4. Insolation potential in the tested area for each month

### 3.3. Actual energy generated by the photovoltaic systems

The highest value of solar radiation that could be converted into energy in the tested area occurred in June and totalled 26.2 (Figure 5). The lowest solar radiation occurred in December and February and yielded 2.4 and 2.3 kWh·m$^{-2}$, respectively (Table 3). The spatial distribution for the tested area of the total actual solar radiation per year ranged from 18 to 203 kWh·m$^{-2}$. Most of the area, however, ranged from 110 to 160 kWh·m$^{-2}$ (see Appendix, section A, Figure A3).

### 3.4. Calculation of the correction coefficient

The coefficients of PV System No. 1 ranged from 0.08 in May to 0.76 kWh·m$^{-2}$ in December and January. The PV System No. 2 had the lowest coefficient of all. It was 0.05 in May, and also the lowest coefficients out of 7 PV systems in summer months. The calculated coefficients for the PV System No. 3 ranged from 0.07 to 0.45. The PV System No. 4 had the lowest coefficient in September at the level of 0.05. With regard to the PV System No. 5, the coefficients ranged from 0.09 to 0.41. In February, the lowest correction factor was recorded for PV System No. 6, which was only 0.08. For the PV System No. 7, the coefficients ranged from 0.10 to 0.64. The calculated average value of the correction factor in May was 0.08. It was at similar levels during summer months, reaching the value of 0.12 in June, the value of 0.11 in July and the value of 0.13 in August (Table 4).

Table 3. Monthly energy total volumes generated by the tested PV systems

| | Month | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Research object** | **II** | **III** | **IV** | **V** | **VI** | **VII** | **VIII** | **IX** | **X** | **XI** | **XII** | **I** |
| | kWh·m$^{-2}$ | | | | | | | | | | | |
| 1 | 10.3 | 14.1 | 17.6 | 12.9 | 20.8 | 18.9 | 19.7 | 16.0 | 16.7 | 7.8 | 6.3 | 9.2 |
| 2 | 5.3 | 7.9 | 9.7 | 7.8 | 12.1 | 10.6 | 10.4 | 8.7 | 8.1 | 3.6 | 2.4 | 3.5 |
| 3 | 8.0 | 13.4 | 16.0 | 12.1 | 19.9 | 17.8 | 17.2 | 13.6 | 12.3 | 5.1 | 3.8 | 5.6 |
| 4 | 7.7 | 13.2 | 14.7 | 12.0 | 19.2 | 17.1 | 16.0 | 3.9 | - | - | 2.7 | 5.0 |
| 5 | 8.1 | 14.1 | 17.0 | 15.0 | 23.1 | 21.1 | 18.9 | 15.1 | 11.5 | 5.5 | 3.3 | 5.0 |
| 6 | 2.3 | 11.0 | 14.8 | 12.2 | 20.3 | 17.2 | 17.5 | 15.2 | 13.5 | 6.9 | 4.4 | 7.4 |
| 7 | 6.6 | 17.8 | 20.0 | 15.9 | 26.2 | 23.7 | 22.5 | 18.7 | 17.2 | 8.3 | 5.7 | 8.3 |

## 3.5. Total of underutilised solar radiation

The volume of underutilized solar energy in the tested area was illustrated spatially. The total underutilised solar energy was a huge value and ranged from 97 to 1111 kWh·m$^{-2}$. In percentage terms, it was, approximately 80% of the total incoming solar energy. In addition, the radiation losses ranged from 605 to 860 kWh·m$^{-2}$ for most of the area (see Appendix, section A, Figure A2).

Table 4. Mean correction coefficient at the research area

| | Month | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Research object** | **II** | **III** | **IV** | **V** | **VI** | **VII** | **VIII** | **IX** | **X** | **XI** | **XII** | **I** |
| | kWh·m$^{-2}$ | | | | | | | | | | | |
| 1 | 0.36 | 0.20 | 0.15 | 0.08 | 0.12 | 0.11 | 0.15 | 0.19 | 0.42 | 0.51 | 0.76 | 0.76 |
| 2 | 0.18 | 0.11 | 0.08 | 0.05 | 0.07 | 0.06 | 0.08 | 0.10 | 0.20 | 0.23 | 0.28 | 0.28 |
| 3 | 0.27 | 0.18 | 0.13 | 0.07 | 0.11 | 0.10 | 0.13 | 0.16 | 0.30 | 0.33 | 0.44 | 0.45 |
| 4 | 0.28 | 0.19 | 0.13 | 0.08 | 0.11 | 0.10 | 0.12 | 0.05 | - | - | 0.34 | 0.43 |
| 5 | 0.29 | 0.20 | 0.15 | 0.09 | 0.13 | 0.13 | 0.14 | 0.18 | 0.29 | 0.37 | 0.40 | 0.41 |
| 6 | 0.08 | 0.15 | 0.13 | 0.08 | 0.12 | 0.10 | 0.13 | 0.18 | 0.34 | 0.46 | 0.54 | 0.61 |
| 7 | 0.22 | 0.24 | 0.17 | 0.10 | 0.15 | 0.14 | 0.16 | 0.21 | 0.42 | 0.52 | 0.64 | 0.64 |
| Average | 0.24 | 0.18 | 0.13 | 0.08 | 0.12 | 0.11 | 0.13 | 0.15 | 0.28 | 0.35 | 0.49 | 0.51 |

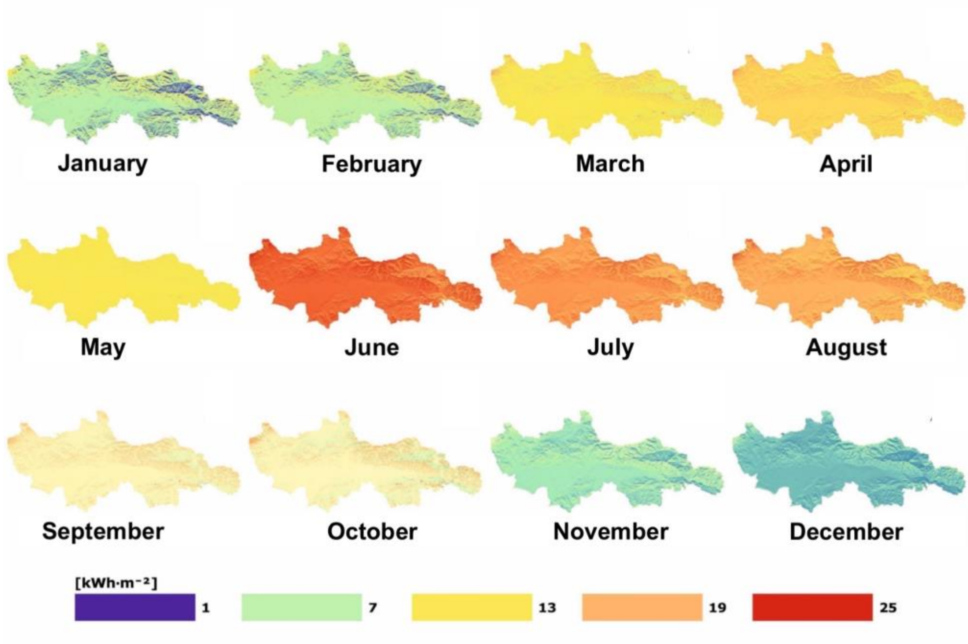


Fig. 5. Energy gained by the PV systems in the tested area

# 4. DISCUSSION

## 4.1. Evaluation of the solar radiation level

Based on the results of the solar radiation modelling, we can conclude that the selected heliocentric region has favourable insolation conditions for the construction of photovoltaic systems. The annual value of potential solar radiation ranges from 113 to 1314 kWh·m$^{-2}$ (Appendix , section A, Figure A1). On the other hand, Stachura [27] report that for a locality located in the vicinity of the tested area, the value of potential radiation was in the range of 760 to 1200 kWh·m$^{-2}$. The difference is due to, inter alia, to the orography and exposure of the slopes around the valley. Another reason includes also the height difference. For the City of Cracow, located in the Carpathian Foredeep and in the Vistula River valley, according to Wojkowski [28], the total solar radiation volumes per year range from 425 to 1193 kWh·m$^{-2}$, so the maximum value is lower than that found in the tested area, while the minimum value is higher. The correction factors for PV System No. 1 ranged from 0.08 in May to 0.76 kWh·m$^{-2}$ in December and January. This was the largest difference between the minimum and maximum coefficient of all the data analysed (Table 4).

In December, all tested PV systems recorded the highest fall in the energy yield. This could be caused, besides the low position of the Sun above the horizon, by the location of the PV systems, since the tested area is adjacent to the mountainous area (Appendix , section B, Figure B1).

According to the approved criteria developed in the study's methodology, single-family house No. 6 can receive surplus energy for an estimated amount of PLN 2991 per year. Contrary, the solar energy demand of single-family house No. 1, PV will not allow it to meet its energy requirements. The owner of installation No. 1 would have to purchase extra electricity in the equivalent of about PLN 660.

## 4.2. Determination of sites of potential PV systems in the valley surrounded by the mountain ranges

The tilt angle and orientation play a pivotal role in maximizing the solar energy yield generated by the photovoltaic panels using the GIS technique [29]. In the paper, Guo [30] used the ergodic technique to model mathematically the extra-terrestrial solar radiation. The purpose of the testing technique was to determine the monthly optimal tilt angles and azimuth angles in six Chinese cities with various weather conditions. The results of the ergodic method served as the reference group for this study. In most cases, the best orientation in the northern hemisphere is the southern exposure (optimal azimuth angle, 180°). Note that extra-terrestrial solar radiation declines with the tilt angle going up [31] or the analysed photovoltaic plant site in the valley surrounded by mountain ranges, it was shown that the radiation distribution is fairly uniform in summertime. On the other hand, in winter months, a greater variation of irradiance was observed in the tested area (Figure 5).

The correction factor for the average monthly radiation in January was 0.51, and for December 0.49. Based on the data, we can notice that temperature is depended to a certain extent on the correction factor level. It can be assumed that as the air temperature increases, the value of the correction factor decreases, and when the temperature decreases the factor increases (Table 4).

The optimal tilt angle for PV systems varies in winter season and in summertime. To enhance the energy volume stored by the PV system, if possible, the tilt angle of the panels should be changed once a month. This can improve the energy efficiency of buildings and the replacement of heat sources [32]. Despite the theoretically favourable location of the tested area in southern Poland, energy yields will not be satisfactory. This is due to the fact that the optimal areas for PV systems are covered by the legal protection of the Polish part of the Western Carpathians (southern slopes of Gorce and Pieniny Mountain Ranges, or Babia

Góra Mount). On other sites the operational conditions for solar photovoltaic systems are not so favourable (Appendix , section A, Figure A2).

### 4.3. Modelling of potential solar radiation

Considering the results of the potential solar radiation modelling, it can be concluded that the tested area has hypothetically favorable insolation conditions. The value of potential radiation obtained for most of the tested area during the year ranges from 1000 to 1300 kWh·m$^{-2}$ (Appendix, section A, Figure A1). Merrouni [33] assigns annual solar radiation for western Morocco, where the sum of total radiation during the year is one of the highest values. The Global Horizontal Irradiation (GHI) for this area ranges from 1816 to 2304 kWh·m$^{-2}$ per year. This is mainly due to latitude and high photovoltaic potential. For Mexico, on the other hand, the daily radiation ranges from 5 to 6 kWh·m$^{-2}$/day and for Germany it is 3.2 kWh·m$^{-2}$/day. Mexico's radiation exceeds Poland's potential− this is due to its location and more favorable insolation conditions [34]. Germany, on the other hand, has a photovoltaic potential similar to Poland. Empirical data obtained from 7 PV systems located in the tested area was analysed, and the solar energy volume that can be absorbed and the potential solar radiation volume (Table 2) that can be harvested by the PV systems were calculated (Table 3).

For the tested area, the June to September period is quite homogeneous in terms of energy yield from the PV systems. On the other hand, in the November-January period the values were down, mostly ranging from 1 to 7 kWh·m$^{-2}$, but more differentiated in spatial terms (Figure 5). Similarly with potential radiation, values varied depending on slope, exposure, and height above sea level (orographic and topographic conditions). On the southern slopes the radiation was higher than on the northern slopes, and the valley itself is surrounded by the mountain ranges, and the insolation was therefore in this area at the same level and hovered around 1000 kWh·m$^{-2}$ (Appendix, section A, Figure A1). The subsequent studies in recognizing insolation parameters should be expanded to include [35-40]: land development and infrastructure, and distances from road network and power grid.

The presented results indicate that it will not be a priority to invest in the development of PV systems in the valleys surrounded by mountain ranges and protected areas (Appendix, section A, Figure A2). The energy yield may not be satisfactory for individual users in the scattered development area.

## 5. CONCLUSIONS

Based on the tests and analysis of solar energy generation by the photovoltaic panels in the tested area, we can conclude that a Geographic Information System (GIS) is a valuable tool for modelling solar conditions. In this paper purposes, maps were developed for the tested area (valleys surrounded by the protected

National Parks) to illustrate the spatial variation of total solar radiation. Total solar radiation depends on temporal and spatial variability. The carried out analyses show that in spring and summer months (May to August), the irradiance distribution was uniform. On the other hand, in winter season (from the last decade of November to the end of February), the irradiance distribution was more differentiated in the tested area. The angle of incidence of sunlight also varied during these seasons. This relationship suggests that the PV system with a variable tilt angle of panel surface should be selected. Spatial variation of modelled potential solar radiation was also noted. Thus, it can be concluded that the best locations for photovoltaic investment projects are on the southern slopes of the mountains. A certain constraint for the construction of photovoltaic systems on the indicated most favourable sites in the tested area are the organizational and legal factors related to the protection of these areas by the national parks. Despite the continuous development of photovoltaic technology, only approximately one-fifth of the available total solar radiation energy is acquired. Therefore, investment in more efficient photovoltaic systems should be considered when constructing such PV systems in the valleys surrounded by the mountain ranges.
The results of this paper may become handy when selecting the optimal site for photovoltaic investment projects, which in the future may play a significant role in the implementation of energy conversion policy. Despite the relatively low efficiency of energy acquisition, this type of solution can be successfully applied on a small scale in the mountain tourism and agritourism sectors, on sites with difficult access.

## ADDITIONAL INFORMATION

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Supplementary Materials: Figure A1.: Total potential solar radiation per year for the whole valley, Figure A2.: A map of underutilised solar radiation in the tested area., Figure A3.: Total energy volume per year in the whole valley from photovoltaic panels. Figure B1.: Average horizon and sunpath for study area. Source [14]., Figure B2.: Global horizontal irradiation (GHI) in Poland. Source [14].

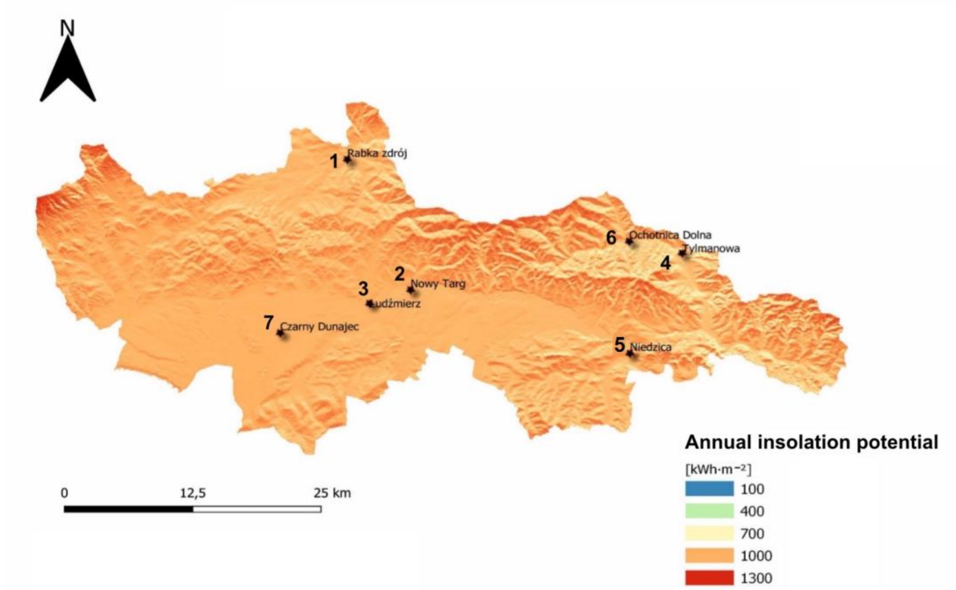


Fig A1. Total potential solar radiation per year for the whole valley

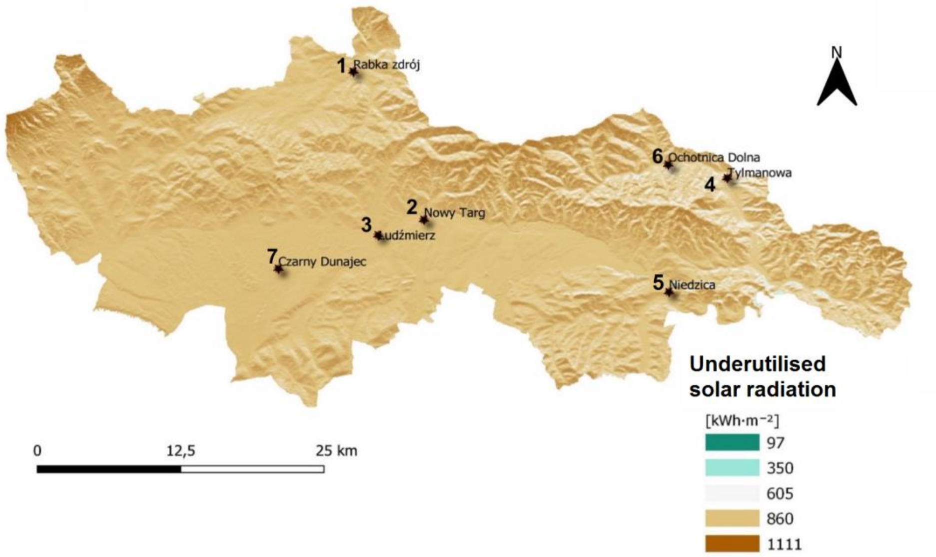


Fig. A2. A map of underutilised solar radiation in the tested area

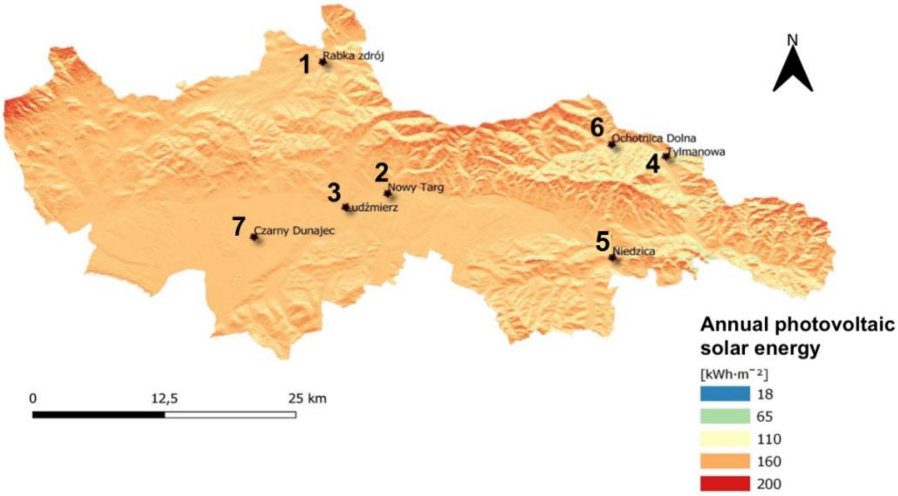


Fig. A3 Total energy volume per year in the whole valley from photovoltaic panels.

## Appendix B

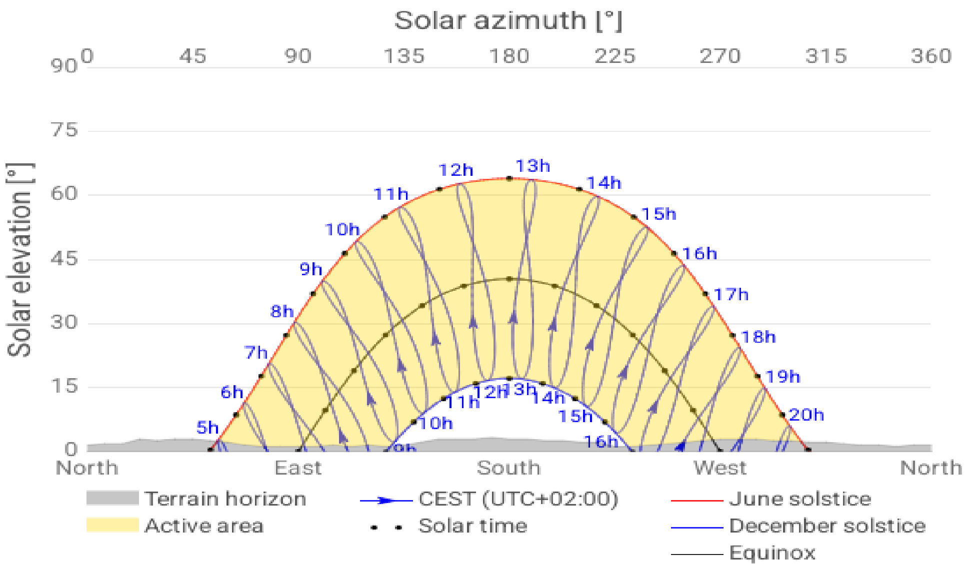


Fig. B1. Average horizon and sunpath for study area. Source [14].

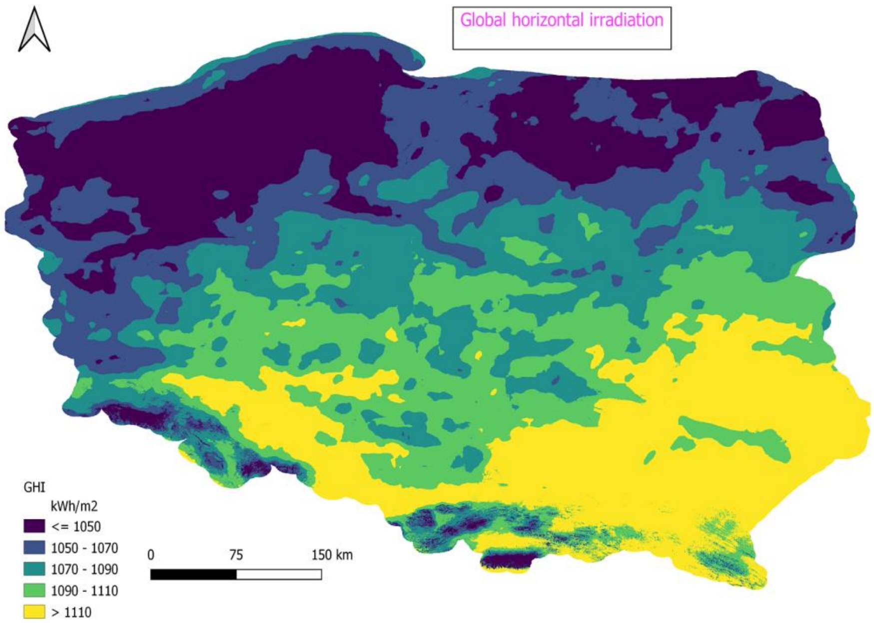


Fig. B2. Global horizontal irradiation (GHI) inPoland. Source [14]

## REFERENCES

1. Re Font Vivanco, D, Wang, R and Hertwich, E 2018. Nexus strength: A novel metric for assessing the global resource nexus *Journal of Industrial Ecology **22(6)***, 1473-1486.
2. Bertoldi, P, Economidou, M., Palermo, V, Boza-Kiss, B and Todeschi, V 2022. How to finance energy renovation of residential buildings: Review of current and emerging financing instruments in the EU. Wiley Interdisciplinary Reviews: *Energy & Environmental Science* **10(1**), e384.
3. Olczak, P, Żelazna, A., Stecuła, K, Matuszewska, D and Lelek, Ł 2022. Environmental and economic analyses of different size photovoltaic installation in Poland. *Energy for Sustainable Development* **70,** 160-169.
4. Tan, X, Sun, Q, Wang, M, Cheong, TS, Shum, WY and Huang, J 2022. Assessing the effects of emissions trading systems on energy consumption and energy mix. *Applied Energy* **310**, 118583.
5. Li, G, Li, M, Taylor, R, Hao, Y, Besagni, G and Markides, CN 2022. Solar energy utilisation: Current status and roll-out potential. *Applied Thermal Engineering* **209**, 118285.

6. Asgharian, H and Baniasadi, E 2019. A review on modeling and simulation of solar energy storage systems based on phase change materials. *Journal of Energy Storage* **21**, 186-201.
7. Naveenkumar, R, Ravichandran, M, Mohanavel, V, Karthick, A, Aswin, LSRL, Priyanka, SSH and Kumar, SP 2021. Review on phase change materials for solar energy storage applications. *Environmental Science and Pollution Research*. 1-42.
8. Dobrzycki, A and Ambrozik, P 2017. [Analysis of the impact of a photovoltaic power plant on the electricity grid]. *Electrical Engineer* **89**, 322–332.
9. Takshi, A, Aljafari, B, Kareri, T and Stefanakos, E 2021. A critical review on the voltage requirement in hybrid cells with solar energy harvesting and energy storage capability. *Batteries & Supercaps* **4(2)**, 252-267.
10. Cader, J, Olczak, P and Koneczna, R 2021. Regional dependencies of interest in the "My Electricity" photovoltaic subsidy program in Poland. *Energy Policy*, **24**, 97-116.
11. Kulpa, J, Olczak, P, Surma, T and Matuszewska, D 2021. Comparison of support programs for the development of photovoltaics in Poland: My Electricity Program and the RES Auction System. *Energies* **15(1),** 121.
12. Szkliniarz, K, Walencik-Łata, A, Kisiel, J, Polaczek-Grelik, K, Jędrzejczak, K, Kasztelan, M and Gola, S 2021. Characteristics of Natural Background Radiation in the Polkowice-Sieroszowice Mine, Poland. *Energies* **14(14),** 4261.
13. Kulesza, K and Bojanowski, JS 2021. Homogenization of incoming solar radiation measurements over Poland with satellite and climate reanalysis data. *Solar Energy* ***225,*** 184-199.
14. Global Solar Atlas "*Global horizontal irradiation*" Attribution 4.0 International (CC BY 4.0). https://globalsolaratlas.info/map?c=53.468431,17.270508,6&s=49.525208,20.039063&m=site.
15. Prieto, JI and García, D 2021. Global solar radiation models: A critical review from the point of view of homogeneity and case study. *Renewable and Sustainable Energy Reviews* , 111856.
16. Pfeifroth, U, Sanchez-Lorenzo, A, Manara, V, Trentmann, J and Hollmann, R 2018. Trends and variability of surface solar radiation in Europe based on surface-and satellite-based data records. *Journal of Geophysical Research: Atmospheres* **123(3),** 1735-1754.
17. Goel, N, Taylor, RA and Otanicar, T 2020. A review of nanofluid-based direct absorption solar collectors: design considerations and experiments with hybrid PV/Thermal and direct steam generation collectors. *Renewable Energy* **145,** 903-913.

18. Gürtürk, M, Benli, H and Ertürk, NK 2018. Effects of different parameters on energy–Exergy and power conversion efficiency of PV modules. *Renewable and Sustainable Energy Reviews* **92,** 426-439.
19. Klepacka, AM, Florkowski, WJ, Meng, T **2018**. Clean, accessible, and cost-saving: Reasons for rural household investment in solar panels in Poland. *Resources, Conservation & Recycling* **139,** 338-350.
20. Wolniak, R and Skotnicka-Zasadzień, B 2022. Development of photovoltaic energy in EU Countries as an alternative to fossil fuels. *Energies* **15(2),** 662.
21. Wciślik, S, Kotrys-Działak, D 2021. Thermal building upgrade with off-grid PV system: a Polish case. *Energy Efficiency* **14(7)**, 1-22.
22. Lichograj, P and Zdyb A 2016. Effect of insolation and wind on the performance of silicon polycrystalline modules. *Ecological Engineering* **50**, 58-62.
23. Kumari, P and Toshniwal, D 2021 Deep learning models for solar irradiance forecasting: A comprehensive review. Journal of Cleaner Production **318**, 128566.
24. Degefa, MZ, Sperstad, IB Sæle, H 2021. Comprehensive classifications and characterizations of power system flexibility resources. *Electric Power Systems Research* **194,** 107022.
25. Assadi, MR, Ataebi, M, sadat Ataebi E and Hasani, A 2022. Prioritization of renewable energy resources based on sustainable management approach using simultaneous evaluation of criteria and alternatives: A case study on Iran's electricity industry. *Renewable Energy* **181**, 820-832.
26. Stachura, T and Krzyś, M 2017. GIS-based assessment of the feasibility of solar energy applications, in the case of Łazy village. *Geomatics, Landmanagement and Landscape,* 51-63.
27. Stachura, T 2016. Assessment of the possibility of using solar energy with the use of GIS tools on the example of Krauszow village. *EPISTEME-CZASOPISMO NAUKOWO-KULTURALNE* **2**, 435-447.
28. Wojkowski, J 2006. Modeling of solar inflow using GIS on the example of the area of the Ojców National Park. *Annales Universitatis Mariae Curie-Sklodowska, sectio B – Geographia* **1**, 1 -10.
29. Choi, Y, Suh, J, Kim, SM 2019. GIS-based solar radiation mapping, site evaluation, and potential assessment: A review. *Applied Sciences* **9(9***)*, 1960.
30. Guo, M, Zang, H, Gao, S, Chen, T, Xiao, J, Cheng L, Sun, G 2017. Optimal tilt angle and orientation of photovoltaic modules using HS algorithm in different climates of China. *Applied Sciences* **7(10***)*, 1028.
31. Khatib, T and Deria, R 2022. East-west oriented photovoltaic power systems: model, benefits and technical evaluation. *Energy Conversion and Management*, **266**, 115810.
32. Yilmaz, A and Şimşek, C 2022. Calculation of the Optimum PV Panel Incline Angle for Mediterranean Climate. *European Journal of Science and Technology* **(35),** 322-329.

33. Merrouni, AA, Elalaoui, FE, Mezrhab, A, Mezrhab, A, Ghennioui, A 2018. Large scale PV sites selection by combining GIS and Analytical Hierarchy Process. Case study: Eastern Morocco. *Renewable Energy* **119**, 863-873.
34. Mundo-Hernández, J, de Celis Alonso, B, Hernández-Álvarez, J, de Celis-Carrillo, B 2014. An overview of solar photovoltaic energy in Mexico and Germany. *Renewable and Sustainable Energy Reviews* **31**, 639-649.
35. Terfa, H, Baghli, L, Bhandari, R 2022. Impact of renewable energy micro-power plants on power grids over Africa. *Energy* **238**, 121702.
36. Nazaripouya, H 2022. Integration and control of distributed renewable energy resources. *Clean Technologies* **4(1**), 149-152.
37. Lin, B, Chen, J, Wesseh Jr, PK 2022. Peak-valley tariffs and solar prosumers: Why renewable energy policies should target local electricity markets. *Energy Policy* **165**, 112984.
38. Mohamad, F, Teh, J, Lai, CM 2021. Optimum allocation of battery energy storage systems for power grid enhanced with solar energy. *Energy* **223**, 120105.
39. Hashimoto, J, Ustun, TS, Suzuki, M, Sugahara, S, Hasegawa, M, Otani, K 2021. Advanced grid integration test platform for increased distributed renewable energy penetration in smart grids. *Institute of Electrical and Electronics Engineers* **9**, 34040-34053.
40. Al-Shetwi, AQ, Hannan, MA, Jern, KP, Mansur, M, Mahlia, TM, I 2020. Grid-connected renewable energy sources: Review of the recent integration requirements and control methods. *Journal of Cleaner Production* **253**, 119831.

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