Photovoltaic-Installation Performance in Central Europe on the Example of Poland

Ewa Klugmann-Radziemska*

PL 80-233 GDANSK, Narutowicza 11/12, Poland

Abstract: The amount of the electric energy obtained from a photovoltaic (PV) installation depends on the energy of the radiation. Weather conditions differ strongly between various years even in the same season. Depending on the climatic conditions of a given location, fixed PV solar plants as well as one-axis and dual-axis tracking PV solar plants are being installed worldwide. The aim of this work is to analyse the sunlight intensity and PV system performance under the geographic conditions of central Europe. The analysis was made on the basis of multi-month monitoring in Gdańsk, Poland, and by comparison with systems in other locations on the basis of the results of researchat Opole University, West Pomeranian University of Technology, Szczecin, Poznan University of Technology, and AGH University of Science and Technology.The annual irradiation and the electrical PV energy production have been averaged over a time period of several years. Two aspects are explored within this paper: the expected average annual electricity generation of a standard 1-kWp standalone or grid-connected PV system and the theoretical potential of PV electricity generation in the European countries.

Keywords: Photovoltaic modules, energy conversion efficiency, climate influence.

1. INTRODUCTION

Energy generation has a tremendous impact on the environment and is responsible for such negative effects as climate warming and ozone layer depletion. The ozone layer is one of the layers of the atmosphere, and it plays a beneficial role by absorbing most of the biologically damaging ultraviolet sunlight and allowing only a small amount to reach the Earth's surface. After many years of human activity, however, the ozone layer has been depleted by gases such as fluorine, chlorine and carbon dioxide.

Our society and its rapid industrialisation is based on coal, oil and natural gas. Principally as a result of the combustion of these fossil fuels, carbon dioxide levels in the atmosphere have been rising steadily. If they continue to do so, we will be in for a climatic disaster.

Greenhouse gases like carbon dioxide, nitrous oxide and methane trap heat and energy, thus preventing solar radiation from escaping back into space. If the quantity of greenhouse gases in the atmosphere is too high, this will cause too much heat to be retained. As a result, the Earth gets warmer, glaciers start melting, and sea levels start to rise, which could lead to coastal flooding.

The way to improve this situation is to reduce the use of conventional energy resources by households and industry, to eliminate environmental pollution in developed countries and to phase out the use of harmful chemicals.

Renewable energy plays an important role in the supply of energy: when renewable energy sources are used, the demand for fossil fuels is reduced. Unlike fossil fuels, non-biomass renewable sources of energy (hydropower, geothermal, wind, and solar) do not directly emit greenhouse gases.

The use of solar energy releases no CO_2, SO_2 or NO_2 gases and does not contribute to global warming. Photovoltaics is now a proven technology which is inherently safe, as opposed to some dangerous electricity generating technologies. Over its estimated life a photovoltaic module will produce much more electricity than was used in its production. A 100 W module will prevent the emission of over two tonnes of CO_2. Photovoltaic systems make no noise and cause no pollution while in operation.

In 2012, more than 100 GW of PV are installed globally - an amount capable of producing at least 110 TWh of electricity every year. This energy volume is sufficient to cover the annual power supply needs of over 30 million European households [1].

Different countries have different solar energy policies to reduce dependence on fossil fuels and increase domestic solar-energy-powered energy production. In the National Energy Policy – the energy policy of Poland until 2025 (accepted by the Polish Council of Ministers on 4 January 2005, solar energy is treated as a way to produce both heat and electric

*Address correspondence to this author at the PL 80-233 GDANSK, Narutowicza 11/12, Poland; Tel: +48583471874; Fax: 48583472458; E-mail: ewa.klugmann-radziemska@pg.gda.pl

E-ISSN: 2410-2199/14

energy; however it is not considered as being a part of the national grid [2].

Photovoltaics is a dynamically developing branch, and many materials meeting the needs of applications have been discovered. Among this large number of materials, the most popular is silicon, mainly due to its availability all over the world and low prices.

A few essential configurations of photovoltaic (PV) systems are as follows: stationary installation, sun-tracking installation, off-grid installation, and grid-connected installation. In order to obtain the most electric energy from PV modules, the system tracks the movement of the Sun. It regulates the placing of these modules in two planes.

Poland is located in a temperate warm transitional climate zone. Its territory is crossed by air masses from both the Atlantic Ocean and the heart of the Eurasian landmass.

In Poland, the possibilities of exploiting the energy of solar radiation are highly diversified. The Baltic area is the area in which the greatest values of the intensity of solar radiation appear. The highest annual totals for global solar radiation (annual sums of global irradiation>3.8 GJ/m^2) are observed in the centre, as well as in the north and northeast. In the western and southeastern regions, annual totals of global irradiation are less than 3.6 GJ/m^2. Reduced annual sums of global irradiation are also noted in the Warsaw agglomeration. On the other hand, increased annual sums of global irradiation are registered at the tops of mountains [3].

The purpose of this article is to determine potential options for generating electric energy using PV modules in the geographical conditions of central Europe for the example of Poland by estimating the energy of the falling solar radiation in the measurement year for the city of Gdańsk and evaluating the amount of electric energy which it is possible to obtain from an installation of monocrystalline and polycrystalline silicon PV modules with a sun-tracking system in the geographical conditions of Gdańsk and other Polish cities located in various regions of the country.

2. METHODS

Measurements were performed on a custom designed and built test stand, a two-axis sun-tracking station, placed on the roof of the Faculty of Chemistry of the Gdańsk University of Technology building in Gdańsk, Poland (latitude: 54°22' N/longitude: 18°36' E). The PV modules are mounted on the roof of the four-storey building of the Faculty of Chemistry and face to the south. The required values of the angle of slope and the surface azimuth angle of the tracking modules' surfaces have to be calculated continuously.

Some weather conditions, which are continuously monitored by meteorological stations, have a relevant influence on the working parameters of the PV modules: wind velocity [m/s], horizontal component of the wind direction [º], irradiance [W/m^2], and ambient temperature [ºC].

Apart from the data collected from meteorological stations, the data from PV stations are continuously being monitored and stored: the PV cells' temperature, the photocell voltage with variable resistance of load and without load (V_{oc}), the photocell current with variable resistance of load and short circuit current (I_{sc}), the battery voltage, and the charge/discharge battery current.

Based on the above measured data, the following values were calculated separately for both PV modules: module efficiency η, actual I-V curve and instantaneous power.

Solar radiation was analysed for the daily, monthly, and annual cycles. The amount of electric energy which is possible to obtain from modules in the daily, monthly, and annual cycles was calculated.

The steps taken to prepare the analysis were as follows:

2.1. Getting Acquainted with the Experimental Station

The station is a two-axis sun-tracking station (the modules change position in such a way that the highest amount of solar radiation reaches their surfaces) using two different types of PV modules: a polycrystalline one (model: Photowatt PW850), and a monocrystalline one (model: Atersa AP-7105/A-75). Each module is composed of a PV sun-tracking module, computer-controlled (mono- and polycrystalline Si), a meteorological station, making it possible to perform the analysis of the influence of atmospheric conditions (wind velocity, air temperature, light intensity) on the working parameters of PV modules, and an automatic system for acquisition, archiving, and sharing of the data from both stations (mono- and polycrystalline).

To create automatic I-V curves of the examined PV modules it was necessary to develop a variable resistance of the load controlled by a personal computer. The load can take the following values of resistance: 0 Ω, 10 Ω, 20 Ω, 40 Ω, 80 Ω, 160 Ω, 320 Ω, and 40 MΩ. A resistance value of 0 Ω is used to determinate the short circuit current (I_{sc}), and 40 MΩ is used for the open cell voltage (V_{oc}). The remaining resistance values from 10 Ω to 320 Ω can provide up to 63 different combinations of resistance.

Two such devices were made, one for each of the circuits, that is, the mono- and polycrystalline PV modules.

2.2. Data Collection

The data were collected in an automatic manner by the system incorporated into the experimental station. The measurements of light intensity were conducted during the year 2008. The ambient temperature and the temperature of the module itself were also measured. As the latter influences the power (power decreases with increases in temperature), it is important to know both of these values. The data are in the form of time series. The step between each two measurements is about 20 seconds.

2.3. Data Analysis

At the beginning, all the points with solar irradiation values lower than 120 $\frac{W}{m^2}$ were removed. The reason was to avoid analysing values corresponding to non-solar hours (for example dusk or dawn), which would interrupt the analyses. Then, Tables containing all the data and the data averaged over days (each record was a daily average of all the parameters of interest) were prepared. Global irradiation and electrical energy produced in the form of monthly and yearly sums were measured and analysed for the horizontal and optimally inclined modules. For the purpose of comparison, the results of the abovementioned calculations are presented for a nominal power system of 1 kWp.

Figure 1: Analysed systems –locations of the installations on the map of Poland Copyright: Polish Wikipedia http://en.wikipedia.org/wiki/List_of_cities_and_towns_in_Poland.

2.4. Comparison

The obtained results were compared with those obtained by other researchers for different locations (Szczecin, Poland: 53°25' N / 14°35' E; Opole, Poland 50°40' N / 17°57' E; Kraków, Poland 50°3'41" N / 19°56'18" E; Poznan, Poland: 52°24'22"N/ 16°55'30" E) (Figure **1**).

3. RESULTS - SOLAR RADIATION

Statistical analysis of solar radiation allows analysis of system performance as a function of availability and shows how – for a given array size – the availability and its standard deviation varies with storage.

General parameters: ambient temperature, average wind speed, presence of microclimate.

Solar radiation:

- a full description of solar radiation involves measurements of direct and diffuse radiation several times an hour for a statistically significant time period (usually at least 10 years);
- this level of data is expensive to obtain or exists only for a limited number of locations, and because of its volume it also requires a computer program to analyse and use;
- full data sets used for the statistical processing of data – used in calculations to determine the relationship between availability and battery size;
- reduced data sets include monthly averages and TMY; a Typical Meteorological Year (TMY) maintains the variability in the solar resource, while reducing multi-annual data to a single year; TMY solar radiation data is determined by averaging the solar radiation for each month of the year over multiple years; TMY data consists of global, direct and – in some sets – diffuse radiation measurements every hour of the day (the angle at which the global and direct radiation measurements are made must be checked with the data specification).

Solar radiation arriving at the surface of the Earth in a clean atmosphere covers the ultraviolet region, which comprises 9% of the radiation energy, the visible region, which comprises 44%, and the infrared region, which comprises 47%, in a broad range of heat radiation wavelengths (0.75–3.0 μm.). The basic radiation, comprising 98% of the whole radiation energy inside the atmosphere, covers the wavelengths from 0.2 to 3.0 μm.

The annual world average horizontal surface irradiance during daytime is approximately 170 W/m^2, which results in 5.4 GJ being incident on 1 m^2 at ground level per year [4].

Table 1: Maximum and Average Irradiance (*clear sky*) for Locations in Northern and Southern Poland

Value/Localization	Northern Poland	Southern Poland
Maximum irradiance (*clear sky*) [W/m^2]		
May	1060	950
June	1020	924
July	1040	930
August	1040	943
September	949	876
average for localization	1022	925
average for the whole country	974	
difference	9.9%	
Average irradiance (*clear sky*) [W/m^2]		
May	526	496
June	486	463
July	504	476
August	555	514
September	549	497
average for localization	534	490
average for the whole country	512	
difference	8.6%	

Very reliable data can be found in the Photovoltaic Geographical Information System (PVGIS) database (Table **1**).

The application of the PVGIS program in four towns in Poland shows that the yearly sum of global irradiation per square meter received by an optimally inclined plane ranges from 1054 kWh/m^2 (Szczecin) and 1091 kWh/m^2 (Gdańsk, Northern Poland) to 1102 kWh/m^2 (Kraków, Southern Poland) and 1113 kWh/m^2 (Opole).

On this basis, the average annual sum of global irradiation incident on a horizontal surface in Poland is equal to 1100 kWh/m^2 [5], which results in 3.96 GJ being incident on 1 m^2 at ground level per year.

Table **2** shows that the yearly average of solar irradiation on the horizontal plane ranges from 2890 Wh/m^2 (Szczecin) to 3050 Wh/m^2 (Opole); the yearly average of solar irradiation on the optimally inclined plane ranges from 3370 Wh/m^2 (Szczecin) to 3530 Wh/m^2 (Gdańsk); the yearly average of solar irradiation on the vertical plane ranges from 2390 Wh/m^2 (Szczecin) to 2530 Wh/m^2 (Gdańsk); theyearly average of the optimal panel inclination ranges from 35^o(Kraków) to 39^o(Kraków) (the optimum tilt angles were determined by searching for the values of angles for which the total radiation on the PV surface was maximum for the period studied); the yearly average of Linke turbidity ranges from 3.0 (Gdańsk) to 4.6 (Kraków); the yearly average of the ratio of diffuse to global solar irradiation ranges from 0.5 (Gdańsk) to 0.54 (Kraków); the yearly average of the daytime temperature ranges from 9.2°C (Gdańsk) to 10.1°C (Kraków), and the yearly average of the 24-hours-temperature ranges from 8.4°C (Gdańsk) to 9.1°C (Szczecin).

In summary, differences in the yearly average of solar irradiation do not exceed 5% for the whole country, while the values of optimal panel inclination, Linke turbidity, and yearly average of the daytime temperature rise as the location changes from north to south Poland. The value of incident solar radiation can also be locally variable due to temporary air pollution (e.g. dust, smoke), which has an influence on the Linke turbidity factor.

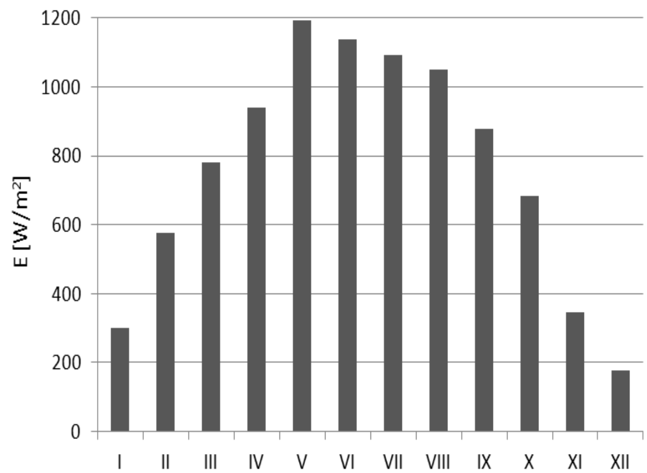

Figure 2: Maximum temporary solar irradiance during the year in Gdańsk (northern Poland) experimental data [6].

Table 2: Geographical Position and the Results of PVGIS Calculation of the Yearly Average Values of the Optimal Panel Inclination, Solar Irradiation on the Horizontal, Optimally Inclined, and Vertical Planes, Linked Turbidity, Ratio of Diffuse to Global Solar Irradiation, Daytime Temperature, and Temperature during 24 Hours for some Cities in Poland [5]

Cities In Poland	Geographical Position	Optimal panel Inclination (°)	Solar Irradiation			Linke Turbidity	Ratio of Diffused and Global Solar Radiation	Average Daytime Temperature (°C)	24 hour Average of Temperature (°C)
			On horizontal plane (Wh/m^2)	On optimally inclined plane (Wh/m^2)	On vertical plane (Wh/m^2)				
Gdańsk	54°22' N/ 18°36' E	39	2990	3530	2530	3.0	0.50	9.2	8.4
Szczecin	53°25' N/ 14°35' E	38	2890	3370	2390	3.5	0.53	10.0	9.1
Opole	50°40' N/ 17°57' E	36	3050	3520	2440	4.4	0.53	10.1	9.0
Kraków	50°3'41" N/ 19°56'18" E	35	3020	3460	2380	4.6	0.54	10.0	8.8
Poznań	52°24'22"N/ 16°55'30" E	37	2970	3450	2420	3.7	0.53	10.1	9.0

The maximum temporary solar irradiance during the year averaged over the measuring periodis presented in Figure **2**.

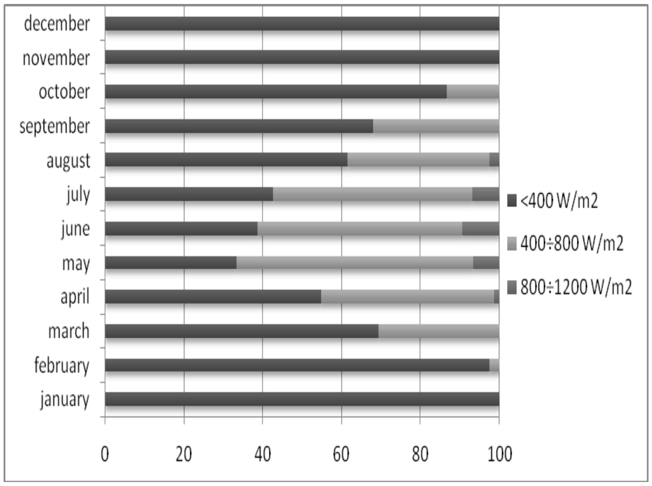

Figure 3: Frequencies of solar irradiance in different ranges (as percentages) – averaged experimental data for the investigated period.

Figure **3** shows the distribution of the irradiance values recorded in each month as percentage values for different ranges. Three intervals were chosen for this analysis: (0, 400) W/m^2, (400, 800) W/m^2 and (800,1200) W/m^2.

In the measurement period, a total radiation energy of 921 kWh/m^2 was received on the horizontal plane per year and 1060 kWh/m^2 was received on the optimally inclined plane per year. It was found that holding the optimum angle made it possible to receive about 13% more solar radiation energy during the year. The solar radiation reaching the surface of the Earth shows not only seasonal, but also monthly, and – in our geographical situation – daily changeability. The solar radiation energy can also be changeable locally because of temporary air pollution.

The comparison of the monthly values (in the plane of the horizon) of the total global solar radiation energy measured in Kraków (Southern Poland) is presented in Figure **4**.

3. ELECTRICITY GENERATION POSSIBILITIES

The amount of energy that can be gained from PV modules depends not only on the climatic conditions but also on the atmospheric composition. The light intensity on a cloudy day is only about 10% of that on a sunny day, with *cumuli* – bulky clouds at low altitudes – being one of the most effective causes of blocking of sunlight [8]. To characterize the effect of a clear atmosphere on sunlight, the concept of air mass (*AM*) was introduced.

Due to the absorption of electromagnetic radiation, heat is produced in a solar module. Apart from heating, radiation entering a solar cell can set free electrons from their atomic bonds, creating electron–hole pairs. In order to generate an electron–hole pair, the proper photon energy must be provided to the cell; it must be at least equal to the material band-gap energy, and by means of a built-in “potential barrier” of the p-n junction the electrons are separated from the holes, generating a photoelectric current and heat in the series resistance of the module and electric power in the load circuit as

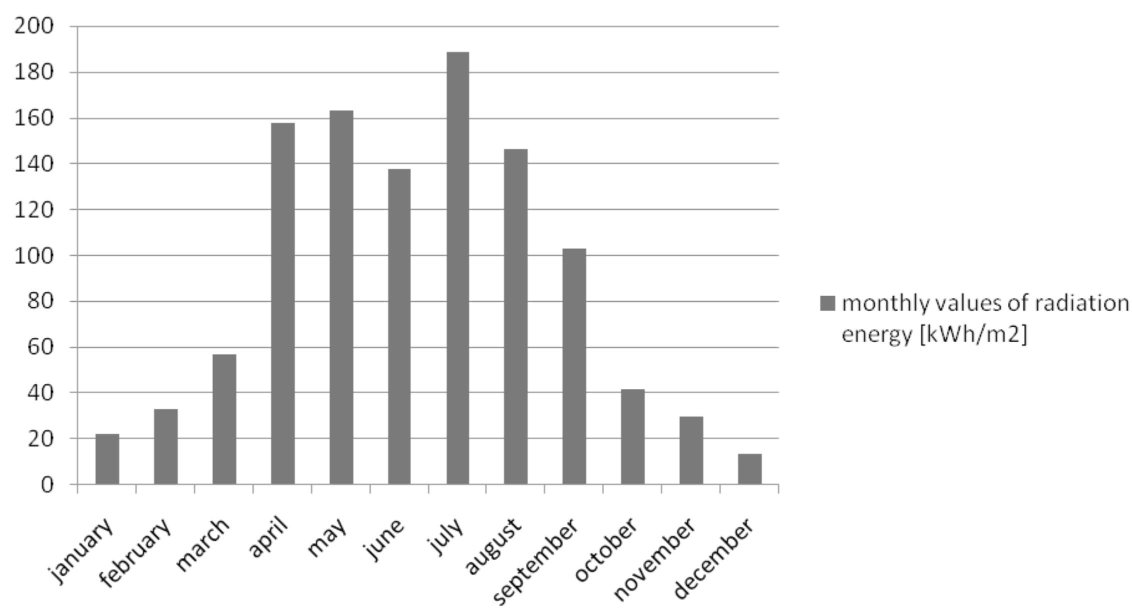

Figure 4: Monthly values of the total global solar radiation energy in the plane of the horizon in Kraków (southern Poland) [7].

Table 3: The Electric Energy Output from the 1-kWp PV Systems in Different Locations in Poland: Summary of the Experimental Results

Localization	Type of Installation/ Technology	Electric Energy Averaged Output from 1 kWp Photovoltaic system		
		June	July	year
Gdańsk University of Technology (current experiment)	two- axis sun tracking/ monocrystalline Si	160.52	147.25	984 kWh
Poznan University of Technology [11]	stationary/ multicrystalline Si	115.36	110.61	N/D
Poznan University of Technology [11]	two- axis sun tracking/ multicrystalline Si	161.36	143.47	N/D
Opole University [7]	stationary/ monocrystalline Si	N/D	N/D	954 kWh
West Pomeranian University of Technology, Szczecin [12]	stationary/ monocrystalline Si	N/D	N/D	886.6 kWh
AGH University of Science and Technology, Kraków [13], [14]	stationary/ multicrystalline Si	80.10*	134.32	N/D

N/D - No Data.

well. In operation with a small load resistance, the photo-cell (solar-cell) represents a photoelectric current source, whereas in operation with a great load resistance, the photo-cell represents a voltage source-electromotive force. Thus the power generated by the solar-cell is affected by the load resistance (a circuit powered by the cell), illumination, and temperature.

The physical consequences that are connected with lower output power and a decrease in PV module conversion efficiency caused by increasing temperature are:

- electron-phonon scattering caused by an increase in thermal lattice vibrations,
- lower mobility of charge carriers,
- lower p-n junction built-in voltage,
- lower junction separation (of electrons from holes) ability [9].

As a result of the loaded module temperature increase, the gap energy E_g width decreases, and the V_{oc} value also decreases. As E_g decreases, the generated current value I_{ph} increases. However, this increase does not compensate for the decrease in the values of V_{oc} and V_{MPP} (maximum power point voltage). From the user's point of view, this generates a limitation in the module use, connected with the charge carriers' thermalization process [10].

The output from the PV system depends on the size of the PV system installed. For comparison, PV modules are rated in kilowatts peak (kWp).

A summary of the experimental results of electric energy output from 1-kWp PV systems in different locations in Poland is presented in Table **3**.

The application of the PVGIS program in four towns in Poland shows that the total yearly electricity production by the optimally inclined fixed 1-kWp PV systems with solar modules of monocrystalline silicon ranges from 945 kWh (Szczecin) to 978 (Kraków), 987 kWh (Gdańsk), and 992 kWh (Opole). Total yearly electricity production by the optimally inclined two-axis tracking PV systems of 1 kWpwith solar modules of crystalline silicon ranges from 1230 kWh (Kraków) to 1240 kWh (Szczecin), 1260 kWh (Opole), and 1340 kWh (Gdańsk) [5].

The results of measurements of the potential electrical energy generation per day and per month carried out in Gdańsk (northern Poland) are presented in Figures **5** and **6**. On the basis of the analysis of several months' measurements, the value of the electric energy that can be obtained from the module, expressed for an installed power of 1 kWp, is equal to 984 kWh/year.

Figure **7** presents the calculated average monthly efficiency. On the basis of the value of electric energy produced, the yearly average value was calculated from the equation:

$$\overline{\eta}[\%] = \frac{\sum E_{el}\left[\frac{kWh}{year \cdot m^2}\right]}{\sum E_{Sun\_year}\left[\frac{kWh}{year \cdot m^2}\right]} \cdot 100\%$$

The annual average efficiency of the monocrystalline module was calculated; a value of 12% was obtained, while the maximum momentary efficiency η_{max}= 17.18%.

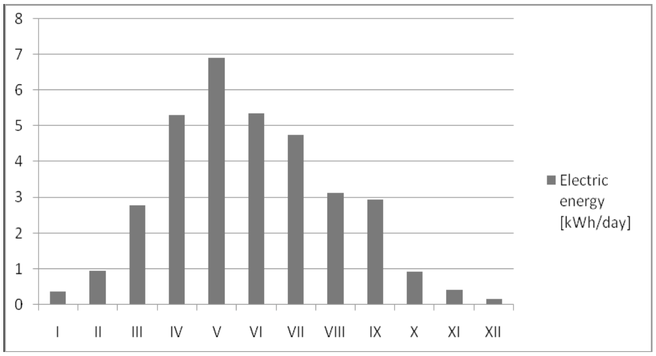

Figure 5: Electrical energy generated by 1-kW_p installation in kilowatt hours per day in each month.

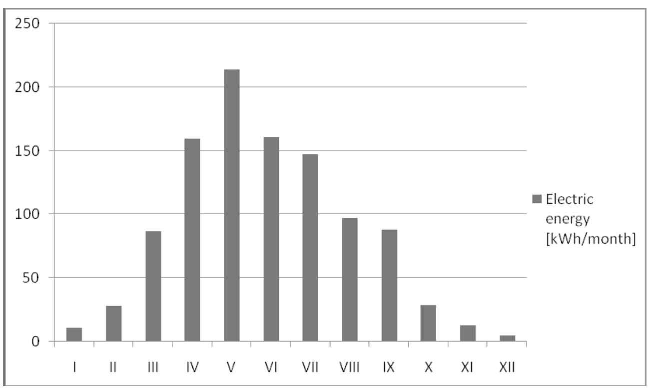

Figure 6: Electrical energy generated by 1-kW_pinstallation in kilowatt hours per month.

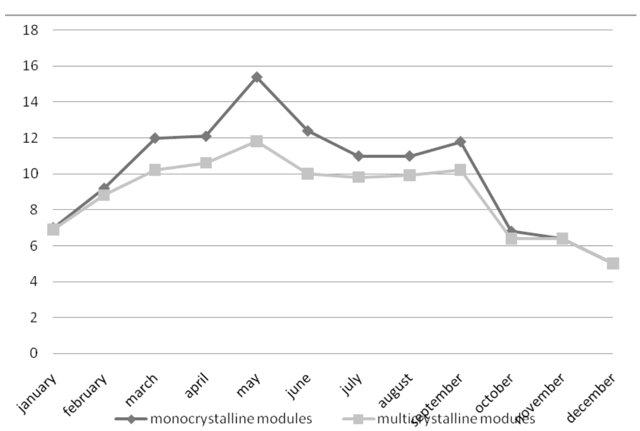

Figure 7: Efficiency of PV modules in individual months of the year-average values.

4. CONCLUSIONS

The potential energy of a PV power generation system is inexhaustible, and it is possible to use it as a source of energy that is reliable and environmentally friendly in the long-term. A PV power generation system can be used as an option to meet the objective of reducing emissions of carbon dioxide and to achieve renewable energy goals.

Conclusions were drawn from the research performed with the main focus on technological aspects of the investigated topic.

Differences in yearly average solar irradiation do not exceed 5% throughout the area of the country of Poland.

Maintaining the optimal angle makes it possible to obtain more solar radiation incident on the illuminated plane than when a horizontal or vertical plane is used.

Maintaining a complete tracking system makes it possible to obtain about 34% more solar energy during the year.

The amount of electricity produced varies slightly depending on the chosen technology (monocrystalline Si orpolycrystalline Si).

The efficiency of the PV system has the highest value in the months which have the highest solar radiation intensity (May–August). The minimum value of efficiency occurs in December.

Although Poland has a favorable climate for the installation and use of PV solar plants, not one PV solar plant has been installed to date and there are rare cases of the use of PV systems elsewhere. The solar energy sector in Poland is not yet developed, although the first large solar farms of Wierzchosławice (1 MWp) and Gryźliny, near Olsztyn (1 MWp), are the hope for the development of PVs in the coming years.

REFERENCES

[1] Masson G, Latour M, Rekinger M, Theologitis IT, Papoutsi M. Global Market Outlook for Photovoltaics 2013-2017; EPIA 2013.

[2] Paska J, Sałek M. Surma T. Current status and perspectives of renewable energy sources in Poland. Renewable and Sustainable Energy Reviews 2009; 13: 142-154. http://dx.doi.org/10.1016/j.rser.2007.06.013

[3] Blazejczyk K. Climate and bioclimate of Poland, Natural and human environment of Poland. A geographical overview, Ed. M. Degórski Polish Academy of Sciences, Inst. of Geography and Spatial Organization Polish Geographical Society, Warsaw 2006, p. 31-48

[4] World Energy Resources 2013 Survey, World Energy Council, London 2013

[5] Photovoltaic Geographical Information System (PVGIS), European Union, 1995-2014

[6] Klugmann-Radziemska E, Grzesiak W. Possibilities of electrical energy generation in photovoltaic systems installed in central Europe. 28th European PV Solar Conference and Exhibition. Paris, France 30.09-04.10. 2013.

[7] Rodziewicz T, Teneta J, Zaremba A, Wacławek M. Analysis of Solar Energy Resources in Southern Poland for Photovoltaic Applications, Ecol Chem Eng S. 2012; 20(1): 177-198

[8] Wenham SR, Green MA, Watt ME, Corkish R. Applied photovoltaics. Second Edition. ARC Centre for Advanced Silicon Photovoltaics and Photonics 2007.

[9] Radziemska E. The effect of temperature on the power drop in crystalline silicon solar cells. Renewable Energy 2003; 28: 1-12. http://dx.doi.org/10.1016/S0960-1481(02)00015-0

[10] Jacobson MZ. Review of Solutions to Global 1 Warming. Air Pollution and Energy Security. Energy and Environmental Science 2009; 2: 148-173. http://dx.doi.org/10.1039/b809990c

[11] Frydrychowicz-Jastrzębska G, Bugała A. Comparison of the efficiency of solar modules operating with two-axis follow-up system and with a fixed mount system. Electrical Review 2014; 90(1): 63-65.

[12] Zapałowicz Z, Rogowska A. PV system evaluation after few years of operation. International Conference: The integration of the renewable energy systems into the building structures. Patra, Greece 7-10 July 2005; 261-266.

[13] Chojnacki J, Teneta J. Independent Photovoltaic System, Opto-electronics Review 2000: 8(4): 368-371.

[14] Teneta J. The temporal characteristics of electricity production in sun tracking photovoltaic systems, 2nd National Conference on Photovoltaics. 12-15 May KrynicaZdrój. Poland 2011; 178-18.

.

Received on 30-08-2014 Accepted on 23-09-2014 Published on 19-11-2014

DOI: http://dx.doi.org/10.15377/2410-2199.2014.01.01.1