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Study on the Effects of Changes of Ambient Temperature and Solar Irradiance on the Efficiency of the Silicon PV Modules

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Summary. This paper presents the results of measurements of the operation of a photovoltaic system, connected to the power grid. The intensity of solar radiation and the ambient temperature in the location of the installation were simultaneously recorded in different weather conditions on selected days throughout the year. For the combined results the analysis of correlation in terms of efficiency of individual exemplary photovoltaic installation was conducted.

Key words: photovoltaics, efficiency, solar radiation, ambient temperature.

INTRODUCTION

Solar radiation is a never-ending source of energy and its use in the conversion process does not influence destructively the energy balance of the Earth [3, 4, 13, 15]. A disadvantage of solar radiation as an energy source is its cyclical daily availability and its dispersion. Photovoltaics (called further – PV) uses a phenomenon that involves direct conversion of solar radiation into electricity, it is not an energy source adapted to supply the power consumers continuously. The main problem in photovoltaics is that the amount of sunlight changes throughout the year, most often in the disproportionate way to the demand. The result is low energy efficiency of PV systems in the Polish climate zone and the need for additional financing of this type of investment [7, 9, 10, 11, 12].

PV generators are modular, and technical data of a single PV module is established and communicated by the producers in strict standard conditions, so-called **STC** (*Standard Test Conditions*), and sometimes even in normal conditions, so called **NOCT** (*Normal Operating Cell Temperature*) (Table 1).

In the climate zone in which the study was conducted (central Poland), **NOCT** are closer to real conditions. Another important factor from the point of view presented in the paper study are the so-called temperature coefficients which determine the effects of temperature changes on the basic parameters of the PV module (usually on the voltage of an unloaded module, short-circuit current and maximum power) [6].

Table 1. Comparison of the conditions for measurement of basic parameters of PV modules, provided by the manufacturers [4, 5, 7]

STC:	**NOCT** :
irradiance: 1000 [W·m^{-2}]	irradiance: 800[W·m^{-2}]
cell temperature of lighted module: 25°C	-
-	ambient temperature 20°
air mass AM 1.5	air mass AM 1.5
-	wind speed: 1 [m·s^{-1}]

In the study the results will be presented of the impact of the changing conditions of ambient temperature and solar radiation on the efficiency of PV modules made of mono- and polycrystalline PV cells.

CONSTRUCTION OF THE TEST BENCH

Studies on the effects of solar radiation and ambient temperature on the efficiency of PV system were carried out on the test bench (Fig. 1), which is a PV mini-system connected to a grid (on-grid), built of two PV generators with attached modular inverters called micro-inverters.

The study involved two, currently most commonly used, types of PV modules made of mono- and polycrystalline silicon PV cells (Fig. 1). The monitoring subsystem of inverters module enables the measurement of the instantaneous power of each PV generator and the temperature of micro-inverter, which is comparable to the temperature of the PV cells (T_c) in PV modules. While there is an empirically determined relationship (Eq. 1) between the ambient temperature (T_{amb}), and the temperature of PV cells, it has only an approximate character [13]. Therefore, during conducting researches, ambient temperature (T_{amb}) was measured independently with a standard thermometer with the accuracy of 1°C.

$$T_c = T_{amb} + \frac{(NOCT - 20) \cdot E}{800} \quad [°C], \qquad (1)$$

where:

T_c – temperature of PV cells in the module [°C],
T_{amb} – ambient temperature of the PV module [°C],
E – intensity of solar radiation [$W \cdot m^{-2}$],
NOCT – module operation temperature under normal conditions [°C].

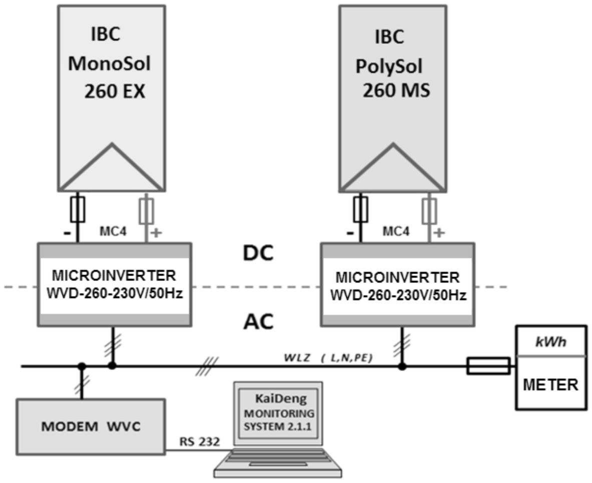


Fig. 1. Diagram of the measuring bench

The intensity of solar radiation (E), measured using a **PL-110SM** device with the accuracy of 1 $W \cdot m^{-2}$. The measuring stand during the test was located in the area with coordinates: 52.48 N and 19.67 E (near the city of Plock – Poland). Based on the manufacturer's data, theoretical value of the instantaneous power (P_i) can be estimated for different temperatures of lighted PV module (Table 2) [7]:

$$P_i = P_{MPP}\left[1 + (T_c - 25)\frac{\gamma_T}{100}\right] \quad [W], \qquad (2)$$

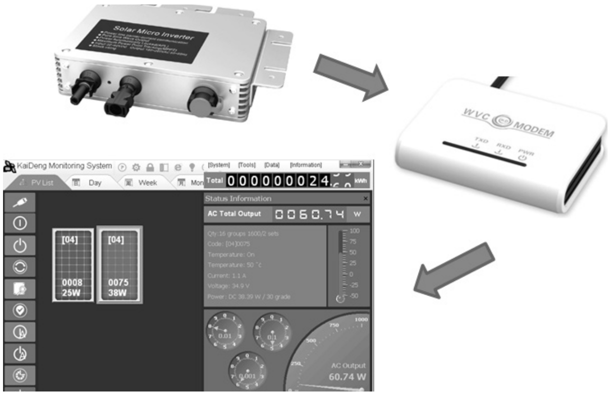
where:

P_{MPP} – maximum power under STC [W] (260 W – for both PV generators).

In real measurement conditions the dependence of instantaneous power on temperature does not have a linear form. The negative temperature coefficient of the power (Table 2) indicates that for both the PV generators temperature rise above 25°C results in a proportional decrease in the instantaneous power.

METHODS OF CONDUCTING MEASUREMENTS

The monitoring of the PV system is implemented by co-operation of micro-inverters with a special modem (Fig. 2). Communication between the devices is performed using PLC technology (*Power Line Communication*), which does not require an installment of a separate communication cabling [2].



Qty:16 groups 1600/2 sets
Code: [04]0075
Temperature: On
Temperature: 50 °C
Current: 1.1 A
Voltage: 34.9 V
Power: DC 38.39 W / 30 grade

Fig. 2. The method of test results registration

The basic premise of the research is parallel measurement of instantaneous power, ambient temperature and radiation. To make this possible, each time two screenshots of the monitoring application were performed, and additionally two independent measurements of the ambient temperature (**T_{amb}**) and radiation (**E**). Registration of one such set of measurements took approx. 30 seconds. The research was conducted on different days and in different weather conditions in the years 2014/2015 in the specified location. For the analysis, 50 items of such sets of measurements were carried out. The results showed an extremely low intensity of solar radiation, below 200 $W \cdot m^{-2}$. The instantaneous power of the generator was recorded based on the monitoring data system with the accuracy of 0.01 W. The efficiency of PV modules was calculated from the equation (assuming that $P_{MPP} » P_i$ – determines the function MPPT of micro-inverter):

$$\eta = \frac{P_{MPP}}{E \cdot S} \cdot 100 \quad [\%], \qquad (3)$$

where:

S – the surface of the PV modules in m^2 (calculated on the basis of data from Table 2).

TEST RESULTS

The results were entered into a spreadsheet *MS Excel 2010* and subjected to the initial statistical processing. For each dependent trend lines for the linear model were de-

Table 2. Selected characteristics of PV modules [1]

Parameter	IBC MonoSol260 EX	IBC PolySol260 MS
NOCT [°C]	48.4	48
Temperature coefficient of power – γ_T [%/°C]	-0.44	-0.48
Power in conditions – P_{NOCT} [W]	189	201.8
PV module dimensions [mm]	990 x 1660	992 x 1650

termined and data analysis was conducted by determining correlations. Dependence was analyzed of the solar radiation intensity (E) on the efficiency for monocrystalline PV module – IBC MonoSol 260 EX (Fig. 3). We achieved quite a poor fit ($R^2 = 0.0753$) for linear trend line model, which does not coincide with the results of simulation studies [8]. Data analysis for this case led to determining the coefficient of correlation with the value of -0.0933 (Table. 3). In a similar way the correlation was analyzed of solar radiation (E) to the efficiency for polycrystalline PV module – IBC PolySol 260 MS (Fig. 5). The statistical coefficient R^2 and correlation for this case were respectively 0.0088 and -0.0936 (Fig. 5) and (Table 3).

Completely different is the relation of ambient temperature (T_{amb}) to efficiency of different PV generators, for which the statistical coefficient R^2 and correlation are respectively 0.0076 and -0.2403 (Fig. 4) and (Table 3) for the monocrystalline PV module and 0.0389 and -0.1973 (Fig. 6) and (Table 3) for polycrystalline PV module. The spread of results is so large that the existence of a linear relationship cannot be concluded on the basis of these measurements.

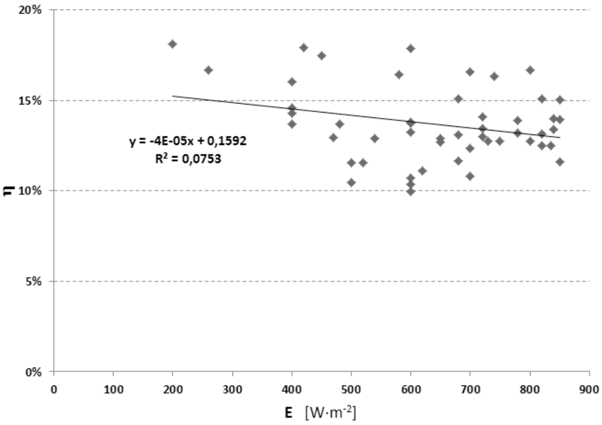


Fig. 3. Effect of solar radiation (**E**) on efficiency (**h**) of monocrystalline PV module – **IBC MonoSol 260 EX**

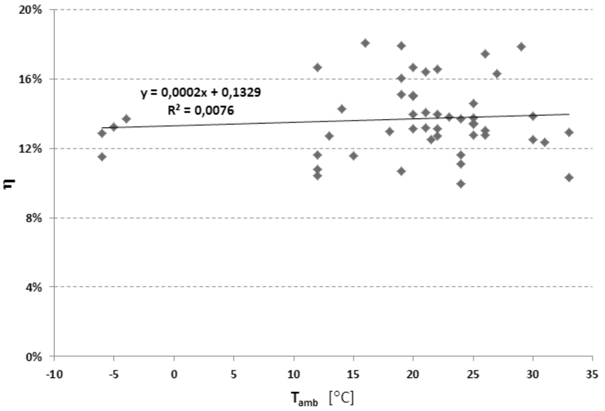


Fig. 4. Influence of ambient temperature (**T_{amb}**) on efficiency (**h**) of monocrystalline PV module – **IBC MonoSol 260 EX**

Separate analysis of data on relationships between efficiency and solar radiation and ambient temperature does not explain exactly what can be calculated theoretically using the temperature coefficients. Factor directly influencing the performance of PV modules is the temperature of PV cells, rather than the ambient temperature and therefore it is essential to take into account the size of the solar radiation.

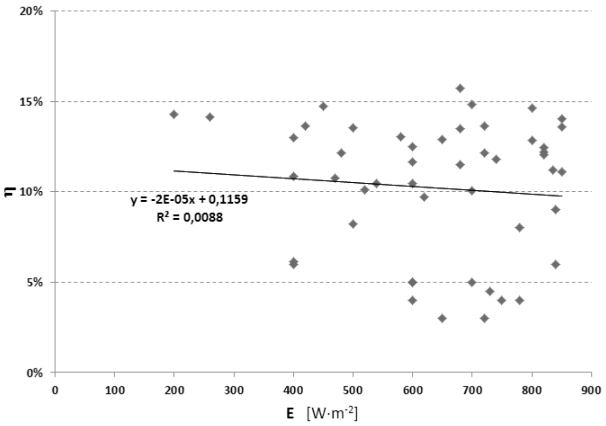


Fig. 5. Effect of solar radiation (**E**) on efficiency (**h**) of polycrystalline PV module – **IBC PolySol 260 MS**

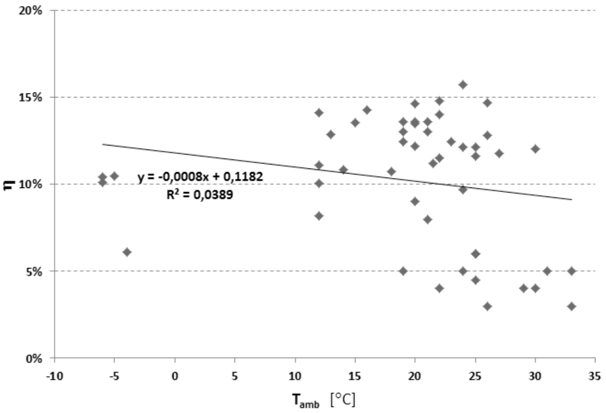


Fig. 6. Influence of ambient temperature (**T_{amb}**) on efficiency (**h**) of polycrystalline PV module – **IBC PolySol 260 MS**

Table 3. The results of data analysis – correlation (by MS EXCEL 2010)

The correlation coefficients	Monocrystalline PV module		Polycrystalline PV module	
	E	T_{amb}	E	T_{amb}
Efficiency of PV modules – η	-0.0933	-0.2403	-0.0936	-0.1973

The analysis of the results of research was completed by calculating the correlation coefficients (Table 3). Linear regression analysis of the obtained results was performed assuming a 95% confidence level. The results of the analysis of correlation between the efficiency of the PV modules and the solar radiation and ambient temperature relative to the **Guillford** scale can be described as "weak". However, in the **Stanisz** scale the correlation between efficiency and the solar radiation is known to be "of dim" and between the efficiency and the ambient temperature "weak" [14].

Fig. 7 shows the dependence of the efficiency of the PV modules on the ambient temperature and solar radiation on the 3D graphs. The highest efficiency was obtained for conditions similar to the STC.

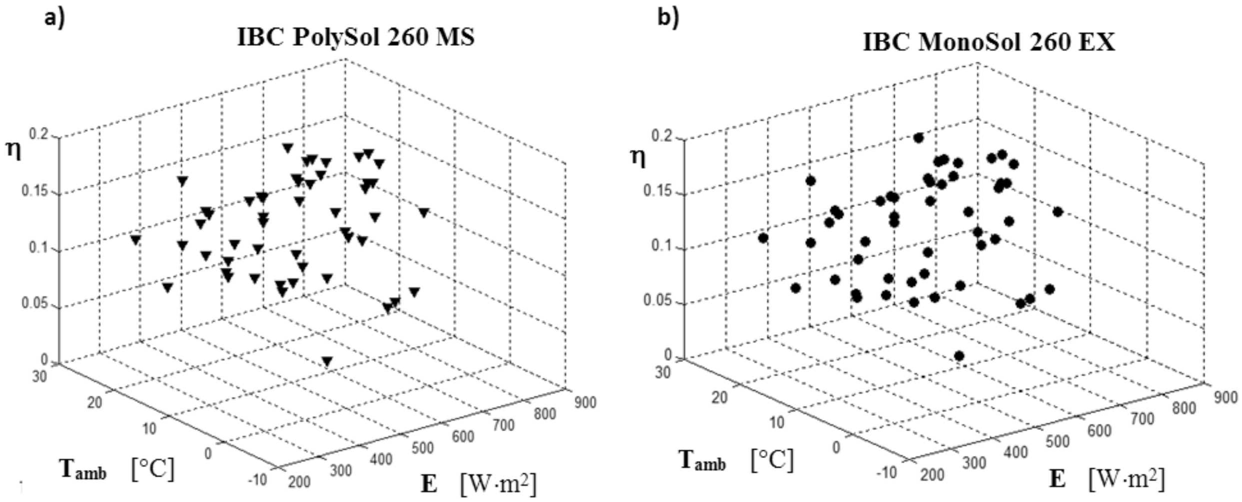


Fig. 7. Cumulative 3D charts efficiency for PV modules: a) polycrystalline and b) monocrystalline (*scatter3 generated function in MatLab*)

CONCLUSIONS

1. For PV generators made of crystalline silicon, independently of technology, a similar to linear dependence has been observed of the efficiency on solar radiation and ambient temperature.
2. Taking into account the parallel measurement of temperature and solar radiation intensity it has been observed that the efficiency in the study of PV installations depends on the technology of PV modules.
3. PV generator consisting of PV modules made of monocrystalline silicon exhibits higher efficiency in the summer months, while considering the efficiency for year-round installation, greater amounts of energy will be generated by PV module made of polycrystalline silicon.
4. The drawback of the study was a relatively small number of measurements made in sub-zero temperatures, which was the result of the mild winter 2014/2015 at the location of the tested PV system.
5. In further studies other environmental factors of PV generator should take into account such factors as wind speed, wind direction and humidity, which can more precisely explain the impact of climatic conditions in a specific location on the performance of the PV generator.
6. Based on the analysis of Fig. 7 it can be hypothesized that multiple correlation will be a better tool for the statistical analysis of this problem.

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BADANIA WPŁYWU TEMPERATURY OTOCZENIA I NATĘŻENIA PROMIENIOWANIA SŁONECZNEGO NA SPRAWNOŚĆ KRZEMOWYCH MODUŁÓW FOTOWOLTAICZNYCH

Streszczenie: W pracy zaprezentowano wyniki pomiarów funkcjonowania systemu fotowoltaicznego, dołączonego do sieci elektroenergetycznej. Równolegle rejestrowano natężenie promieniowania słonecznego i temperaturę otoczenia w lokalizacji instalacji w różnych warunkach pogodowych w wybranych dniach w ciągu całego roku. Dla zebranych wyników przeprowadzono analizę korelacji względem sprawności przykładowej instalacji fotowoltaicznej.

Słowa kluczowe: fotowoltaika, uzysk jednostkowy mocy, natężenie promieniowania słonecznego, temperatura otoczenia, temperatura modułu.