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Power production comparison of photovoltaic modules

***Abstract**. This paper presents an analysis of characteristics of photovoltaic modules. The comparisons between the characteristics provided by the manufacturers and characteristics obtained by measurements, under the real time conditions are accomplished. The temperature dependence of power and the actual energy production are also presented. Measurements are obtained directly from the module without the inverter.*

***Streszczenie.** W artykule przedstawiono analize charakterystyk modułów fotowoltaicznych. Porównania charakterystyk dostarczonych przez producentów i charakterystyk pomierzonych w czasie rzeczywistym zostały wykonane. Przedstawiono zależności temperaturowe mocy i energii. Pomiary wykonano bezpośrednio na modułach bez udziału przekształtnika. (**Porównanie produkcji mocy modułów fotowoltaicznych**).*

Keywords: photovoltaics, energy production, specific energy yield.
Słowa kluczowe: fotowoltaika, produkcja energii, specyficzny zysk energii

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Introduction

European Union's directive, upon increasing the production of electricity from the renewable energy sources till 2020, has contributed to the growth of photovoltaic (PV) systems connected to the electric grid. In comparison to power production using rotational electric machines [1, 2], which can be used as electric generator, PV systems do not make any noise and have no moving parts. The main elements of the PV systems are solar modules, which convert the solar radiation directly into the electricity. Thus, there is a task to increase the efficiency of energy conversion in PV systems, for example, by developing new types of PV modules [3].

In this paper, the analysis of characteristics of four photovoltaic (PV) modules is presented. The comparisons under real conditions are accomplished between characteristics provided by the manufacturers and characteristics obtained by measurements. The temperature dependence of electric power and actual energy production is also presented. Measurements are accomplished on the PV module without the inverter. All sample PV modules are measured at the same time, therefore identical conditions are ensured.

Measuring system and method

Measurements are performed by using an automatic measuring system for characteristics monitoring of PV modules (MSPV01) as shown in Fig.1.

Fig.1. Measuring system for characteristics monitoring of PV modules (MSPV01)

Measuring system [4] is able to measure current-voltage characteristics, total solar radiation on horizontal basis and temperature. From these data the electric power is calculated. Measured results are stored into the personal computer database after each measurement. In order to process measured results the LabVIEW software produced by National Instruments is used. LabVIEW receives data from multiple outputs of the instrument MSPV01 and stores them into the database to enable subsequent analyses and comparisons. MOSFET transistors that withstand intermittent electric load are also part of the measuring system. Current pulses represent the load of the PV modules and on their basis the maximum power point (MPP) of PV modules is achieved [5].

PV modules are measured at three different slopes: 30°, 45° and 60°. The next measuring test is carried out with two partially shaded PV modules at the slope of 30°.

The efficiency given by the manufacturer is additionally verified by using (1).

(1) $$\eta_{STC} = \frac{P_{STC}}{AG_{STC}} \cdot 100\%$$

where: η_{STC} – efficiency calculated at standard test conditions, P_{STC} – power calculated at standard test conditions, A – active surface of the module and G_{STC} – irradiance at standard test conditions.

Equation (2) presents the efficiency calculated on the basis of measured electric power and measured irradiance.

(2) $$\eta_m = \frac{P_m}{AG_m} \cdot 100\%$$

where: η_m – efficiency calculated on the basis of measured power and measured irradiance, P_m – measured electric power, G_m – measured irradiance.

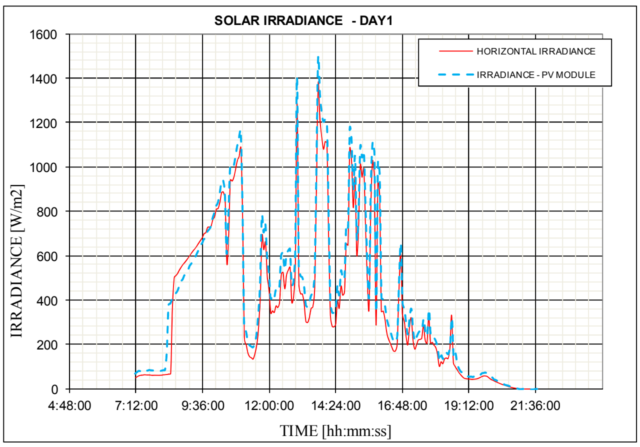

Fig.2. Solar irradiance for day 1

Figure 2 shows the solar irradiance for the first day. The same measurements have been accomplished for the other days as well. The thick line represents the horizontal solar irradiance and the dashed line represents the solar irradiance that falls onto the surface of the PV module.

Analytically calculated electric power is determined by using (3).

$$P_a = P_{STC} \frac{G_m}{G_{STC}} (1 - \gamma (T_m - T_{STC})) \tag{3}$$

where: P_a – analytically calculated power, P_{STC} – power calculated at standard test conditions, G_m – measured radiation, G_{STC} – irradiance at standard test conditions, γ – temperature coefficient of power, T_m – measured temperature of the module, T_{STC} – temperature of the module at standard test conditions.

The comparison between calculated efficiency on the basis of measurements and the efficiency given by the manufacturer is accomplished. These results are also compared with those obtained by shaded PV modules. Two modules of the same manufacturer with the same nominal power are used as measuring objects. The back side the first PV module is thermally insulated with Styrofoam and the second PV module is without additional thermal insulation. Both electrical power and temperature of PV modules are compared as well.

Results

Table 1 shows calculated efficiencies by using (2) and efficiencies obtained by datasheets. The efficiency obtained by the manufacturer (datasheets) is in good agreement with a calculated efficiency by using (2).

Table 1. Comparison of efficiencies

	Efficiency calculated by using (2)			Efficiency given by the manufacturer at STC
Slope	30°	45°	60°	
Module 1	15%	15%	15%	14,3%
Module 2	15%	14%	15%	14,3%
Module 3	15%	15%	15%	14,1%
Module 4	16%	15%	15%	14,4%

Figures 3, 4 and 5 show the difference between calculated electric power of PV module 2 by using (3) and the measured power of PV module 2.

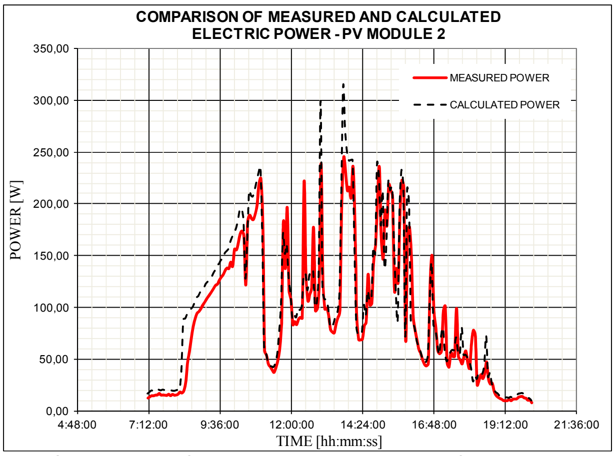

Fig.3. Comparison of calculated electric power of PV module 2 by using (3) and the measured power of PV module 2– day 1

The comparison has been conducted for three days. Figures 3, 4 and 5 are for day 1, 2 and 3. Thick lines in the figures represent the measured electrical power and dashed lines represent the calculated electrical power by using (3). Deviation between calculated electric power and measured power occurs due to the measuring instruments which causes the load in the form of pulses.

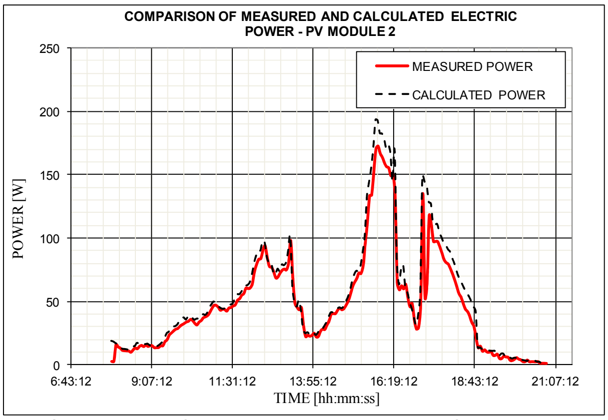

Fig.4. Comparison of calculated electric power of PV module 2 by using (3) and the measured power of PV module 2– day 2

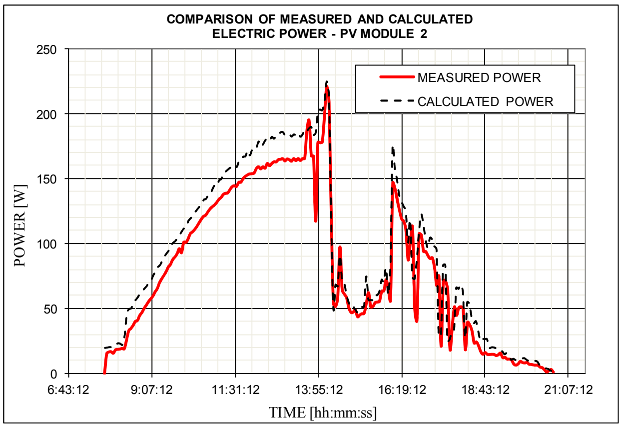

Fig.5. Comparison of calculated electric power of PV module 2 by using (3) and the measured power of PV module 2– day 3

Table 2. Comparison between insulated and non-insulated PV module

	$P1_{average}$ (W)	$P2_{average}$ (W)	*Deviation* (W)	*Deviation* (%)	$T1_{average}$ (°C)	$T2_{average}$ (°C)	*Deviation* (°C)	*Deviation* (%)
Slope: 30								
Day1	80	84	3,6	-4,3	43	34	9,7	23
Day2	85	92	6,5	-7,1	42	36	6,3	15
Slope: 45°								
Day1	46	46	0,3	-0,7	33	28	5,3	16
Day2	76	80	3,9	-4,9	42	33	8,5	21
Slope: 60°								
Day1	73	76	2,7	-3,6	45	37	8,7	19
Day2	54	54	0,9	-1,6	36	30	5,7	16
Slope: 30° with shading								
Day1	12	12	-0,1	0,9	40	31	9,1	23

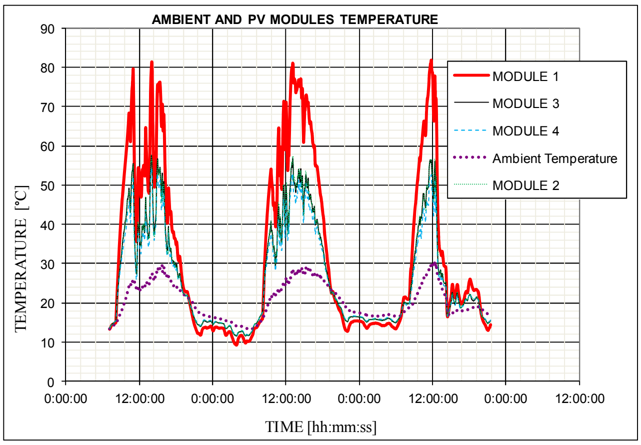

Fig.6. Ambient and PV modules temperature

Figure 6 shows the temperature of PV modules and ambient temperature for three days. Modules are of the same rated power and from the same manufacturer. Module 1 is isolated by Styrofoam. Average electrical power is calculated by summing the individual measured results divided by the number of measured results for different days. The lowest line in the figure represents the ambient temperature, and the highest line represents the temperature of Styrofoam insulated PV module. It is obvious that the temperature of this PV module is much higher than the temperature of other PV modules, hence smaller efficiency is expected.

Figures 7 and 8 show how shaded the PV modules are as well as the operating mode of PV modules. PV modules 1, 2 and 4 are standard ones with three operating sectors (3 bypass diodes), but PV module 3 is a special one, with 9 operating sectors (9 bypass diodes).

Fig.7. Shading of PV modules

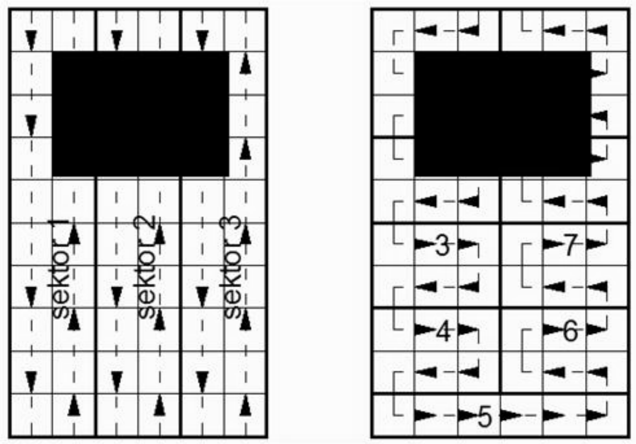

Fig.8. Operating mode of PV modules

Comparison is made between PV modules with 3 and 9 bypass diodes. In order to see the difference between them they have to be shaded. Posters of the same dimensions are used on all PV modules and placed on the same position as shown in Fig. 7. The advantage of PV module with 9 bypass diodes is that it has 9 operating sectors, which are divided as it is shown in Fig.8. Fig. 8 also shows how the operating sectors are divided in PV modules with 3 bypass diodes. The principle is that when some cells of one sector are covered, the whole sectors barely work. As can be seen from Fig. 7 and 8, poster covers all 3 sectors on PV modules with 3 bypass diodes and only 4 on PV module with PV module with 9 bypass diodes. That means that 5 out of 9 sectors operate normally.

Figure 9 shows the specific energy yield of PV modules. The upper line represents the energy yield of PV module 3 which is the one with 9 bypass diodes. When the PV modules are shaded it is obvious that PV module 3 has the biggest energy yield in comparison with the others. It is confirmed with Fig. 10, which shows the daily power diagram of PV modules. Thick line is much higher than other lines. Of course PV module 3 works with less efficiency due to the shading; max power is 150 Wp when it should be around 230 Wp. Other PV modules work with around 15% of their capability because of the shading.

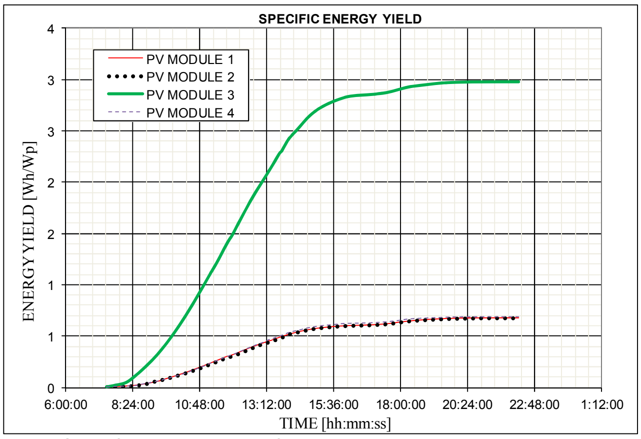

Fig.9. Specific energy yield of shaded PV modules

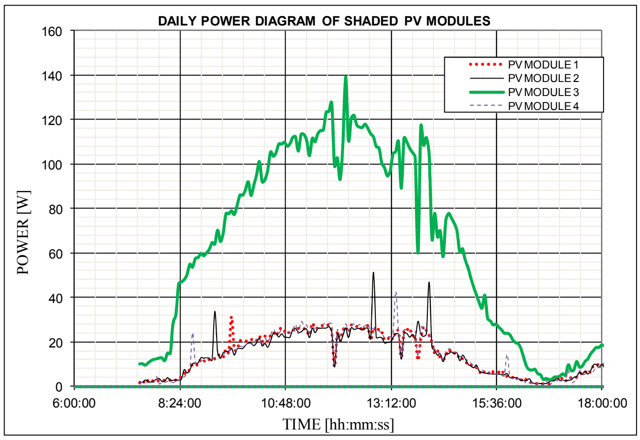

Fig.10. Daily power diagram of shaded PV modules

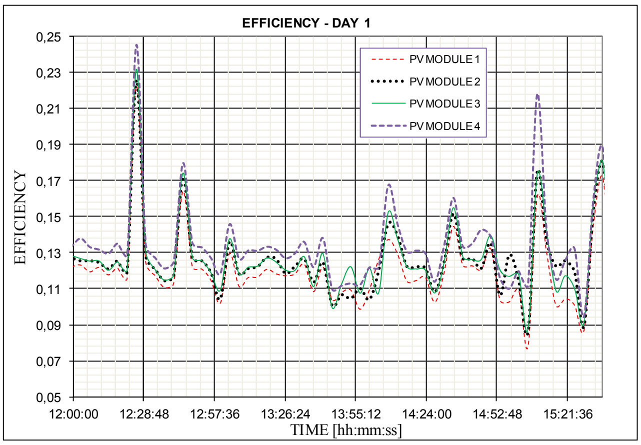

Fig.11. Efficiencies at slope 30°

Measured efficiencies of PV modules

Some of the reasons for the actual efficiency of cells being lower than the theoretical limitation are:

1. Reflection of light from the surface of the cell.
2. Shading of the cell due to current collecting electrical contacts.
3. Internal electrical resistance of the cell.
4. Recombination of electrons and holes before they can contribute to the current [5].

Figure 11 shows the efficiencies of PV modules at the slope of 30°, Fig. 12 at slope 45° and Fig. 13 at slope 60°. The peaks in the characteristics occur due to the measuring errors of the measuring equipment.

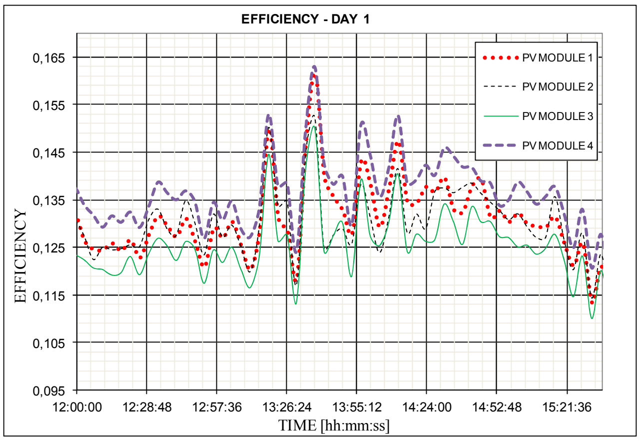

Fig.12. Efficiencies at slope 45°

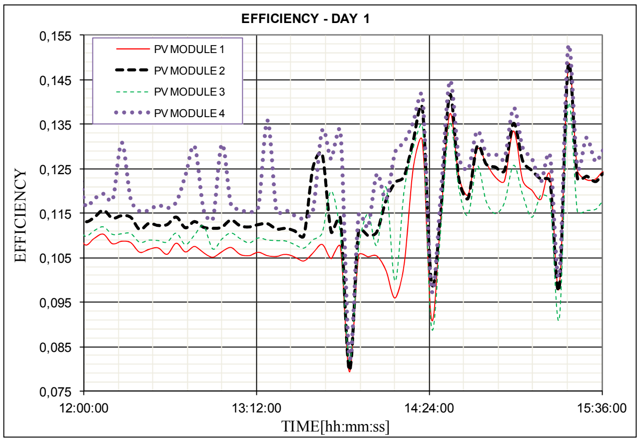

Fig.13. Efficiencies at slope 60°

Conclusion

This paper presents the results of the analysis of characteristics of four photovoltaic modules. The energy yield is directly calculated from meteorological and geographical data with knowing PV module performance and losses in the system.

The exact value of the future annual energy yield cannot be determined because of two factors. Firstly, the equation that can predict weather in the future reliably doesn't exist. It can only be calculated on a base of long-term averages, minimums and maximums. Secondly, some losses also cannot be exactly calculated and have to be chosen on the basis of experience and recommendations. For a more accurate calculation of the energy yield, the PV module characteristics of particular module have to be known.

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