

Influence of module temperature on the operating parameters of photovoltaic modules

Wpływ temperatury modułu na parametry pracy modułów fotowoltaicznych

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This paper shows the results of investigation of the effect of operating temperature on the performance of a photovoltaic module. Two modules made in different technologies were experimentally studied, i.e., monocrystalline and polycrystalline. The experiments were performed in the temperature range of $-20\text{ }^{\circ}\text{C}$ – $60\text{ }^{\circ}\text{C}$ and for each measurement point, the electrical parameters of the module were measured and from this data the generated power and solar energy conversion efficiency were calculated. As a result of the tests, a decrease of power and efficiency of the module was observed with increasing operating temperature. In the tested temperature range, the observed decrease in efficiency was about 20%. Higher efficiency values were obtained for the monocrystalline module. However, this module was also characterized by a higher dynamics of efficiency decrease with operating temperature increase. The obtained value of the temperature coefficient of power loss for an irradiance of about 500 W/m^2 for the polycrystalline module was equal to $0.26\text{ } \%/K$ and for the monocrystalline module it was equal to $0.28\text{ } \%/K$.

Keywords: efficiency of PV module, temperature coefficient of power, PV module performance characteristic

W pracy zbadano wpływ temperatury modułu na parametry pracy modułu fotowoltaicznego. Badano dwa moduły wykonane w różnych technologiach: monokrystaliczny i polikrystaliczny. Pomiarów wykonywano w zakresie temperatury $-20\text{ }^{\circ}\text{C}$ do $60\text{ }^{\circ}\text{C}$ i dla każdego punktu pomiarowego mierzono parametry elektryczne modułu oraz obliczano generowaną moc oraz sprawność konwersji energii promieniowania słonecznego. W wyniku przeprowadzonych badań zaobserwowano spadek mocy i sprawności modułu wraz ze wzrostem temperatury. W badanym zakresie temperatury spadek sprawności wyniósł około 20%. Wyższe wartości sprawności otrzymano dla modułu monokrystalicznego, jednakże cechował się on również wyższą dynamiką spadku sprawności wraz ze wzrostem temperatury. Wartość temperaturowego współczynnika spadku mocy dla natężenia promieniowania wynoszącego około 500 W/m^2 dla modułu polikrystalicznego wyniosła $0,26\text{ } \%/K$, a dla modułu monokrystalicznego $0,28\text{ } \%/K$.

Słowa kluczowe: sprawność modułu fotowoltaicznego, temperaturowy współczynnik mocy, charakterystyka modułu

Nomenclature

- A – active surface area of the module, m^2
- I – radiation intensity, W/m^2
- I_{mpp} – current of the maximum power point, A
- I_{sc} – short circuit current, A
- P_{max} – maximum power, W
- P_{ob} – power, W
- PMPP – temperature coefficient of power, $\%/K$
- TCPL – temperature coefficient of power loss, $\%/K$
- T_{range} – temperature range, K
- U_{max} – max system voltage, V
- U_{mpp} – voltage of the maximum power point, V
- U_{oc} – open-circuit voltage, V

Abbreviations

- PV – photovoltaic
- STC – standard test conditions

Greek Letters

- δP – relative power decrease, %
- ΔT – temperature difference, K
- η – efficiency of the PV module, %

Introduction

The ongoing energy transformation, which necessity is resulting from climate change and rising energy prices, forces an increase in the share of renewable energy sources in the energy mix. For this purpose, both at the European Union and Polish levels, specific targets were set for the share

of renewable sources in gross energy consumption. Poland has declared to achieve a 23% share of RES by 2030 and, according to the Polish Nuclear Power Program, the target share of RES in electricity generation in 2045 will amount to 37–58% while the installed capacity of such sources will be 36.5–52 GW [1]. According to experts, in the coming years, one of the most dynamically developing sectors of energy conversion systems based on renewable sources will be photovoltaics. At the end of 2020, the installed capacity of photovoltaic installations in Poland was equal to 3.94 GW, and according to the Institute of Renewable Energy, by the end of 2025 it may reach the level of 15 GW [2]. Prosumer micro-installations are particularly popular, and

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the operating effects of such installations which were described in publications [3, 4] show that they meet the expectations of prosumers.

With such a large installed capacity of photovoltaic systems, the efficiency of converting solar energy into electricity plays an important role. In practical applications, this efficiency is about 20%. According to the IEC 60904-3 standard, each photovoltaic module dedicated to the European market needs to be tested in reference conditions called STC (Standard Test Conditions), which assume a cell temperature of 25 °C, solar radiation intensity of 1000 W/m² and air mass of AM 1.5. In real conditions, the cells may operate in significantly different conditions. Especially important is the temperature of the cells, the increase of which significantly affects their efficiency. This is due to the fact that, under the influence of solar radiation, the semiconductor used in the cell heats up, which results in a voltage drop on the module. This happens because silicon, as a result of temperature increase, loses its ability to absorb solar radiation.

The development of the photovoltaic market will also result in the research for new technologies and the improvement of existing ones, which will contribute to higher efficiencies. One of the future modules may be those based on n-TOP-Con technology, which is characterized by efficiencies exceeding 20%, low degradation rates (1% in the first year and 0.4% in subsequent years), and a low temperature coefficient (-0.32 %/K) [12].

The presented introduction shows that solar energy will play an increasingly important role in the energy balance. For this reason, you should strive to operate photovoltaic modules in optimal conditions, and thus increase their efficiency.

The aim of this work is to determine the operation characteristics of the photovoltaic modules for different module temperatures and radiation intensity. These tests are preliminary and comparative tests for further research for the newly designed module temperature limitation systems.

Energy conversion efficiency

Considering the fact that the influence of atmospheric factors on the operating temperature of the modules, and thus on the energy conversion efficiency, is very important, many researchers have conducted research in this area. In the paper [5], Lichoraj and Zdyb presented the results of laboratory tests aimed at investigating the influence of radiation intensity and

wind speed on the electrical parameters of polycrystalline modules. In their results, they confirmed the correlation of temperature influence on voltage change. At the same time, they proved that the air flow (i.e., wind) near the modules causes cooling of their surfaces, thus increasing the voltage. The authors of [6] developed a simple model of a photovoltaic module based on a mathematical model of a photovoltaic cell and analyzed the effect of atmospheric conditions on electricity production on its basis. They presented the module characteristics determined from the model for an actual photovoltaic module. For the analyzed module, the authors obtained a temperature power coefficient value of - 0.33 2%/K. In the work [7], Santiago et al. collected and analyzed 20 models of a photovoltaic installation located in southern Spain to determine the cell temperature as a function of environmental parameters such as ambient temperature, wind speed, irradiance, and others. Aly et al. in their work [8], based on the developed numerical model, studied the effects of environmental factors such as ambient temperature, irradiance, and wind speed on the electrical performance of a photovoltaic module. They observed that the electrical efficiency of the modules is inversely proportional to operating temperature. However, the temperature of the module is linearly dependent on the ambient temperature, and an increase of 1 K in the ambient temperature causes an increase of about 1 K in the module temperature. An increase in irradiance also causes an increase in cell temperature, although the effect deviates slightly from linearity, with an average increase in module temperature of 1 K for every 30 W/m² of irradiance. The authors also noted that the effect of wind speed on module temperature is the opposite to that of ambient temperature and irradiance. As the wind speed increases, the module temperature decreases. The most dynamic temperature decrease is observed at low wind speeds, i.e., during the transition from free convection to the forced convection conditions. Mars et al. [9] conducted a comparative analysis of the effects of module tilt angle, ambient temperature, and irradiance for climatic conditions in Tunisia. The analyses were performed for different types of photovoltaic panels. Based on the analysis results, it was estimated that the highest panel efficiency occurs at temperatures between 17 and 25 °C, and the best technology is polycrystalline panel. In [10], the authors presented a review of 33 models published in the literature and used for

determining the operating temperature of modules and discussed the parameters that have the greatest influence on the temperature of modules.

The presented literature review shows how important issue is the influence of the temperature of photovoltaic cells on the obtained power and efficiency of modules. Evaluation of the influence of temperature on the operating parameters of modules will allow scientists and engineers for improving the design of photovoltaic systems and thus reduce its negative impact.

Methodology of research

The research was aimed at determining the effect of module temperature on the performance of photovoltaic modules. Two modules were tested, i.e. a monocrystalline module with a power of 50 W (see, Fig. 1) and a polycrystalline module with a power of 60 W (see, Fig. 2). PV modules electricity performance parameters were shown in table 1. The measurements were carried out in laboratory conditions with the use of artificial light source in the form of 4 halogen lamps of total power 1600 W in 2x2 arrangement (see, Fig. 4) emitting warm white light of 3000 K temperature. As indicated in the literature



Fig. 1.
Monocrystalline module
Rys. 1. Moduł monokrystaliczny



Fig. 2.
Polycrystalline module
Rys. 2. Moduł polikrystaliczny

Tab. 1. PV modules electricity performance parameters

Tab. 1. Parametry elektryczne modułów

	Monocrystalline module	Polycrystalline module
P_{max} , W	50	60
V_{mpp} , V	18.6	18.2
I_{mpp} , A	2.69	3.32
V_{oc} , V	22.9	22.6
I_{sc} , A	2.85	3.52
V_{max} , V	600	600
T_{range} , °C	-45 – +80	-40 – +80

[11], halogen light is suitable for reproducing the characteristics of photovoltaic modules. However, due to its low power in relation to the power of solar radiation, it does not allow to experimentally obtain the maximum power output of the module. The tests were carried out under steady-state conditions. The module temperature was stabilized using a thermal chamber within a temperature range of - 20 and 60 °C. Measurements were made with a temperature step of 10 K for two irradiance values. During the experiments the open circuit

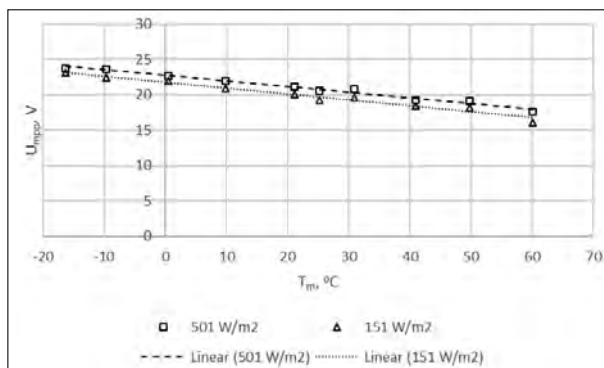
voltage, short circuit current, voltage, current, and power of the maximum power point and module surface temperature were measured. A schematic diagram of the test stand is presented in Figure 3, and a general view of the system during the experiment is presented in Figure 4.

Radiant intensity was determined by the indirect (current-voltage) method based on STC conditions. For polycrystalline module it was equal to 501 and 151 W/m² while for monocrystalline module it was equal to 533 and 166 W/m².

obtained in the form of graphs. Figures 5 and 6 show the variation of voltage of the maximum power point as a function of the maximum power point as a function of module temperature. With increasing module temperature, both modules show a linear voltage drop, and the dynamics of the voltage drops were similar for the modules built with different technologies as well as for both evaluated irradiance levels.

On the basis of the obtained measurement data, using the equation (1), the power obtained from the modules was determined:

Fig. 5. Voltage of the maximum power point for polycrystalline modules as a function of temperature
Rys. 5. Napięcie maksymalnego punktu pracy w funkcji temperatury dla modułu polikrystalicznego



$$P_{ob} = U_{mpp} \cdot I_{mpp} \quad (1)$$

where:

U_{mpp} – voltage of maximum power point, V

I_{mpp} – current of maximum power point, A and, according to equation (2), the efficiency energy conversion of light radiation to electrical energy was calculated:

$$\eta = \frac{P_{ob}}{I \cdot A} \cdot 100 \quad (2)$$

where:

η – efficiency of the PV module, %

P_{ob} – power of the PV module, W

I – radiation intensity, W/m²

A – active surface area of the module, m²

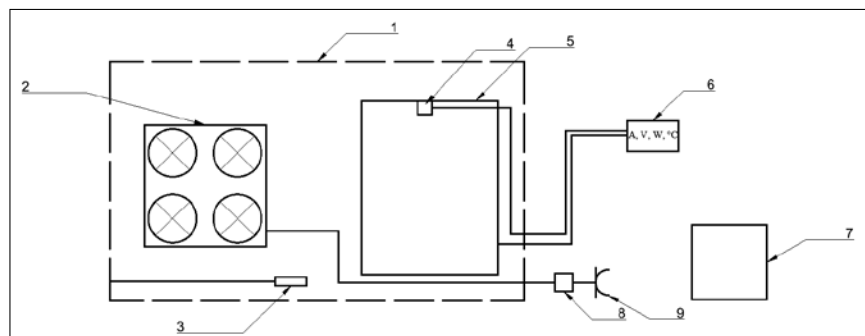


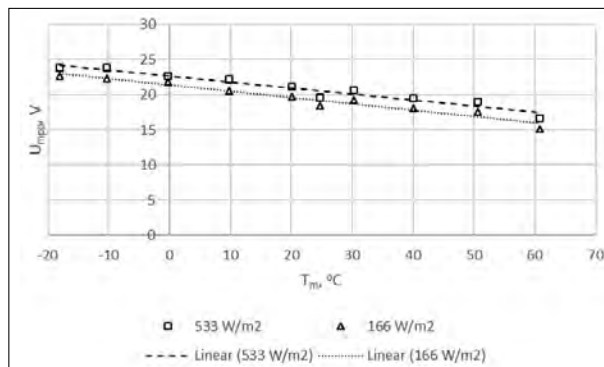
Fig. 3. Scheme of the research test stand for measuring photovoltaic cell parameters: 1 – thermal chamber, 2 – lighting system to simulate solar radiation, 3 – thermocouples measuring ambient temperature, 4 – thermocouple measuring module temperature, 5 – photovoltaic module, 6 – control and measuring apparatus, 7 – computer, 8 – autotransformer, 9 – power source

Rys. 3. Schemat stanowiska badawczego do pomiaru parametrów ogniw fotowoltaicznych: 1 – komora termiczna, 2 – instalacja oświetleniowa do symulowania promieniowania słonecznego, 3 – termopary mierzące temperaturę otoczenia, 4 – termopara mierząca temperaturę modułu, 5 – moduł fotowoltaiczny, 6 – aparatura kontrolno-pomiarowa, 7 – komputer, 8 – autotransformator, 9 – źródło zasilania



Fig. 4. General view on research test stand for testing photovoltaic modules parameters
Rys. 4. Stanowisko do badania parametrów modułów fotowoltaicznych

Fig. 6. Voltage of the maximum power point for monocrystalline module as a function of temperature
Rys. 6. Napięcie maksymalnego punktu pracy w funkcji temperatury dla modułu monokrystalicznego



Results and Discussion

As a result of the measurements, the characteristics of the tested modules were

Figures 7 and 8 show the variation of power generated from the modules as a function of module temperature change. As can be observed, the value of generated

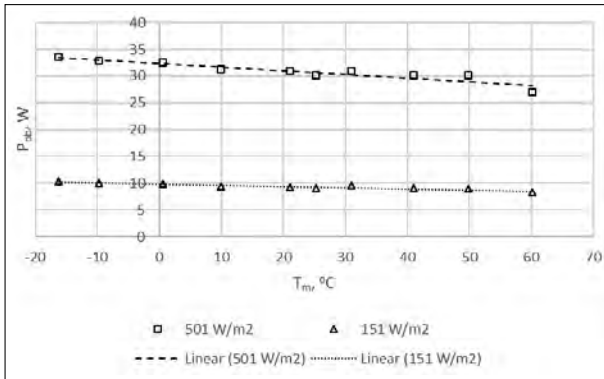


Fig. 7.
Module power as a function of temperature for polycrystalline module
Rys. 7. Moc modułu w funkcji temperatury dla modułu polikrystalicznego

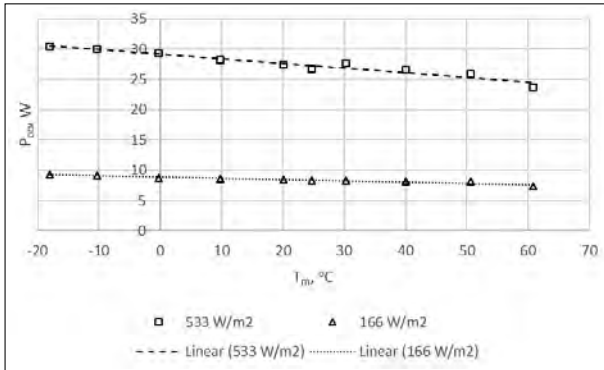


Fig. 8.
Module power as a function of temperature for monocrystalline module
Rys. 8. Moc modułu w funkcji temperatury dla modułu monokrystalicznego

power decreases with increasing temperature for both monocrystalline and polycrystalline modules. This decrease is a linear function and is more dynamic for the monocrystalline module.

Figures 9 and 10 show the change in energy conversion efficiency for the studied modules as a function of module temperature. They show a clear decrease of effi-

ciency with increasing module temperature. As can be observed, the monocrystalline module is characterized by a higher efficiency than the polycrystalline module, but at the same time, a higher dynamics of efficiency decline with increasing temperature can be observed in this case.

The average power loss ΔP [W/K], average efficiency loss $\Delta \eta$ [p.p/K], and

temperature coefficient of power loss TCPL [%/K] were determined using the calculated values of the power obtained from the modules for different irradiance and module temperature. The value of this parameter is very important due to the fact that the temperature of photovoltaic cells is usually higher than specified in STC conditions. The smaller the value of the temperature power coefficient (PMPP) is, the better, and it is assumed that well designed and fabricated cells should have a value of this coefficient of less than -0.42 %/K. Temperature coefficient of power loss was determined from the equation:

$$TCPL = \frac{\delta P}{\Delta T}$$

where:

TCPL – temperature coefficient of power loss, %/K

δP – relative power decrease, %

ΔT – temperature difference, K

As a result of the analysis, for an irradiance of about 500 W/m² for the polycrystalline module, an average power drop value of 0.084 W/K was obtained, which gave a value of temperature coefficient of power loss of 0.26 %/K, and for the monocrystalline module these parameters were equal to 0.08 W/K and 0.28 %/K, respectively. These values are not temperature power coefficient because the efficiency and power drop above STC temperature were not determined. This parameter specifies the average power drop over the measurement temperature range (-20 to $+60$ °C) which means that at temperatures lower than the STC temperature, the power obtained from the module will be higher than at STC conditions.

Summary

This paper reports the results of experimental analysis on the influence of temperature on the electrical parameters of photovoltaic modules, including generated power. Two modules were experimentally tested, i.e. monocrystalline module featuring a power of 50 W and polycrystalline module featuring a power of 60 W. As a result of the experiments carried out, it was confirmed that an increase in operating temperature has a negative effect on the obtained voltage and results in a decrease of module power and efficiency. The obtained values of temperature power drop coefficient of 0.26 and 0.28 %/K for polycrystalline and monocrystalline modules, respectively, show that these modules are good quality. However, it is worth noting that for the tested

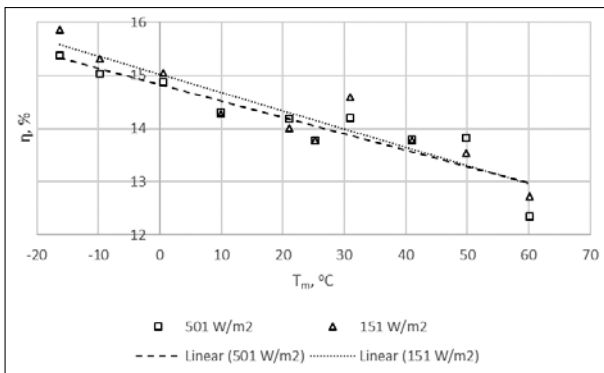


Fig. 9.
Module efficiency as a function of temperature for polycrystalline module
Rys. 9. Sprawność modułu w funkcji temperatury dla modułu polikrystalicznego

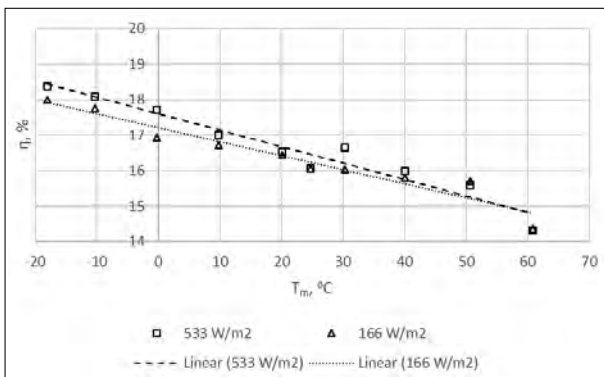


Fig. 10.
Module efficiency as a function of temperature for monocrystalline module
Rys. 10. Sprawność modułu w funkcji temperatury dla modułu monokrystalicznego

polycrystalline module a lower value of power drop coefficient was obtained, which indicates that the generated power decreases less with increasing temperature, and as a result, for the same power given under STC conditions, it can produce more energy at a higher temperature than the monocrystalline module. In Polish conditions, photovoltaic modules can heat up to the temperatures of 60–70 °C. With a difference in temperature power coefficient of 0.02 p.p./K and assuming a reference temperature of 25 °C, this results in 0.9% less power. This value may seem small, but in the case of photovoltaic farms with capacities of the order of 1 MW, each decrease in performance, even by less than a percent, translates into a real loss of energy, and thus profit and payback time. Therefore, it is crucial to properly select photovoltaic modules with the lowest possible temperature coefficients.

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