Annual analysis of the performance of a PV module with a cooling system

Całoroczna analiza pracy modułu fotowoltaicznego z systemem chłodzenia

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This paper presents an analysis of the influence of weather conditions on the temperature of PV cells and the impact of that change of temperature on energy conversion's efficiency and electrical energy generation. This paper also shows an analysis of performance of PV modules with a cooling system and the energetical benefits of usage of such systems. The analysis of cooling PV modules by extended finned heat exchange surface on the module's back side and air-flow based cooling system is presented.

The analyzed modules' parameters are as follows: power of 410 W, efficiency in Standard Test Conditions of 21.5%, temperature coefficient of power of – 0.34%/°C for one module and – 0.5%/°C for second analyzed module. The weather conditions are based on data provided by a meteorological station in Wroclaw. It was established that the maximum temperature of PV cell without cooling equaled 57°C, maximum efficiency equaled 24.4% and minimum efficiency 19.2% for module with temperature coefficient of – 0.34%/°C, however for the module with temperature coefficient of – 0.5%/°C those efficiencies vary from 25.8% to 18.1%.

Extended heat exchange surface as a cooling system on the back side of the module decreases the maximum cell temperature to 35.2°C (at a ribbing degree of 10). Relative increase of generated electricity was calculated as 3.1% for module with temperature coefficient of – 0.34%/°C and 4.6% for module with temperature coefficient of – 0.5%/°C.

Air-flow based cooling system of the back side of a module decreases the maximum cell temperature to 41.2°C (at a heat transfer coefficient of 50 W/m^{2}K). Relative increase of generated was calculated as 2.1% for module with temperature coefficient of – 0.34%/°C and 3.1% for module with temperature coefficient of – 0.5%/°C.

Calculated relative increase of generated energy applies to only one year of module's functioning. It is significant that cooling PV modules has an impact on decreasing the amplitude of change of PV cell temperature which causes a decrease in thermal loads. It results in prolonged life span of such module, what suggests that generated power of a cooled module in its whole life could be significantly larger.

Keywords: photovoltaic module, cooling systems for PV modules, finned surface, air-flow based cooling system

W pracy przeanalizowano wpływ warunków atmosferycznych na temperaturę ogniwa PV oraz wpływ jej zmiany na sprawność konwersji energii i generację energii elektrycznej. Analizie poddano również pracę modułów PV z systemem chłodzenia oraz oceniono efekty energetyczne wynikające z zastosowania takich systemów. Uwzględniono chłodzenie przy pomocy rozwinięcia powierzchni wymiany ciepła na dolnej powierzchni modułu oraz powietrznego systemu chłodzenia dolnej powierzchni modułu.

Analizie, na podstawie danych meteorologicznych dla stacji meteorologicznej we Wrocławiu, poddano moduł o mocy 410 W, sprawności w warunkach STC wynoszącej 21,5% oraz dwóch wartościach współczynnika temperaturowego mocy wynoszących – 0,34%/°C oraz – 0,5%/°C. Oceniono, że maksymalna temperatura jaką osiąga ogniwo bez chłodzenia wynosi 57°C, a maksymalna i minimalna sprawność modułu wynosi odpowiednio 24,4% i 19,2% dla modułu o współczynniku temperaturowym mocy wynoszącym – 0,34%/°C oraz 25,8% i 18,1% dla modułu o współczynniku – 0,5%/°C.

Zastosowanie chłodzenia przy pomocy ożebrowania dolnej powierzchni modułu pozwala na obniżenie maksymalnej temperatury ogniwa do 35,2°C (przy stopniu ożebrowania wynoszącym 10) i względny przyrost generacji energii elektrycznej wynoszący 3,1% dla modułu o współczynniku temperaturowym – 0,34%/°C i 4,6% dla modułu o współczynniku temperaturowym – 0,5%/°C.

Zastosowanie chłodzenia powietrznego dolnej powierzchni modułu pozwala na obniżenie maksymalnej temperatury ogniwa do 41,2°C (przy współczynniku przejmowania ciepła z dolnej powierzchni wynoszącym 50 W/m^{2}K) i względny przyrost generacji energii elektrycznej wynoszący 2,1% dla modułu o współczynniku temperaturowym – 0,34%/°C i 3,1% dla modułu o współczynniku temperaturowym – 0,5%/°C.

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Określone przyrosty ilości generowanej energii dotyczą tylko jednego roku eksploatacji. Należy mieć na uwadze, że chłodzenie modułów przyczynia się do zmniejszenia amplitudy wahań temperatury ogniwa, a tym samym zmniejszenia obciążeń termicznych. Powoduje to zwiększenie czasu pracy takiego modułu, a ilość wygenerowanej energii przy wykorzystaniu modułu chłodzonego w ciągu całego cyklu życia może być znacznie większa.

Słowa kluczowe: moduł fotowoltaiczny, chłodzenie modułu, ożebrowanie powierzchni, chłodzenie powietrzne

Nomenclature

A – surface, m^2
C – circumference, m
d_h – equivalent diameter, m
E – energy generated in a year, kWh/year
G – solar irradiance, W/m^2
h – height of a fin, m
m – temperature coefficient of a fin, 1/m
Nu – Nusselt number, –
P – power, W
$\dot{Q}$ – heat flux, W
Re – Reynolds number, –
T – temperature, °C
v – velocity, m/s

Greek:

α – heat transfer coefficient, W/m^{2}K
γ – temperature coefficient of power at Maximum Power Point, %/°C
δ – fin thickness, m
Δ – change in value,
ε – efficiency, –
η – efficiency, %
λ – thermal conductivity, W/mK
ν – kinematic viscosity coefficient, m^2/s
ρ – density, kg/m^3
τ – time, h
φ – finning degree, –

Subscripts:

a – ambient
ad – air duct
bs – module's back side
c – PV cell
cl – cooling
el – electrical energy
f – fin
fs – module's front side
fsf – finning surface
m – module
T_STC – temperature in STC
w – wind

Introduction

In Poland, the amount of electrical energy generated by photovoltaic installations in the national energy production is gaining more significance. Installed capacity of PV systems at the end of May 2023 was estimated at 13.9 GW and energy production reached 8 TWh in 2022, which constituted to 4.48% generated electrical energy in that year and 22% of electrical energy which was generated in Poland in 2022 from all renewable energy sources based systems [1].

The efficiency of solar irradiance conversion for modern PV modules in STC (Standard Test Conditions, i.e., cell temperature of 25°C, solar irradiance of 1000 W/m^2, air mass AM=1.5) is estimated at 20-22%. It depends on cells' temperature, which in Polish weather conditions can even reach up to 70°C. The PV cells' temperature is influenced by weather conditions such as solar irradiance, ambient temperature, wind speed, humidity or air pollution with dust [2]. It is possible to define an impact of every one of these factors on the cells' temperature based on given models and experiments. Ambient temperature causes linear change of cell's temperature and its increase is estimated at 1°C for every 1°C increase in ambient temperature. Linear dependency is also observed in solar irradiance's influence on cell's temperature, its increase of 100 W/m^2 causes temperature rise of 1.75-3.10°C depending on the type of PV module and the selected calculation formula. One of the weather factors causing a positive outcome on a PV module operating condition (by cooling it) is wind. It is estimated that 1 m/s increase in wind speed results in PV cell temperature decrease of 0.6-2,0°C (depending on the type of PV module) and the selected formula [3].

Influence of cells' temperature on working conditions is calculated with temperature coefficients (temperature coefficient of short-circuit current (α), open circuit voltage (β), temperature coefficient of power at Maximum Power Point (MPP) (γ)), given in %/°C in relation to temperature in STC [4]. Temperature coefficient of power at MPP for modernly manufactured PV modules ranges from – 0.5 to – 0.3%/°C, which means that for every 10°C increase in cell's temperature its efficiency decreases from 3 to 5%.

In this paper the influence of weather conditions on PV module's performance and electrical energy production was analyzed as well as the impact of module cooling by extended heat exchange surface (i.e. fins) and forced air flow. An annual analysis based on statistical hourly meteorological data was conducted for an installation located in Wroclaw. The modules taken into consideration in the analysis were featuring the temperature coefficient of – 0.5%/°C and – 0.34%/°C, power of 410 W and efficiency in STC of 21.5%.

Calculation model

In the calculation model, the influence of weather conditions on cells' temperature with hourly time step was taken into account. Consequently, change of module efficiency in relation to STC and generated hourly average power was considered. Establishing cells' temperature is possible by usage of several models available in the literature [5]. In this analysis, Kurtz et al formula was used [5], in which the temperature of photovoltaic cell is dependent on ambient temperature, solar irradiance and wind speed:

$$T_c = T_a + G \cdot e^{-3,473 - 0,0594 \cdot v_w} \qquad (1)$$

Meteorological data in model was chosen for Wroclaw as an exemplary city representing climatic conditions in Poland. It was assumed that the PV module is in a south direction at an angle inclination equal 30 degrees. Meteorological data from Wroclaw meteorological station including solar irradiance and wind speed [6] used for the calculations model is shown in Fig. 1 and 2, comparison of calculated PV cells' temperature and ambient temperature for a typical year is shown in Fig. 3 and the difference of temperature of PV cell and ambient is presented in Fig. 4.

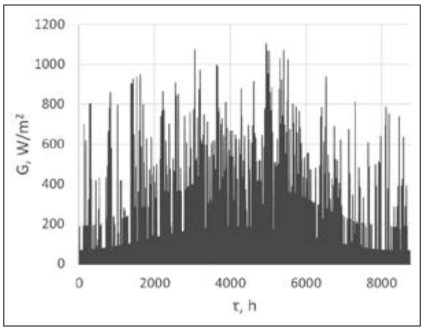

Fig. 1.
Solar irradiance for the meteorological station in Wroclaw (direction – south, angle of inclination – 30°)
Rys. 1. Natężenie promieniowania słonecznego dla stacji meteorologicznej we Wrocławiu (orientacja południowa, kąt nachylenia – 30°)

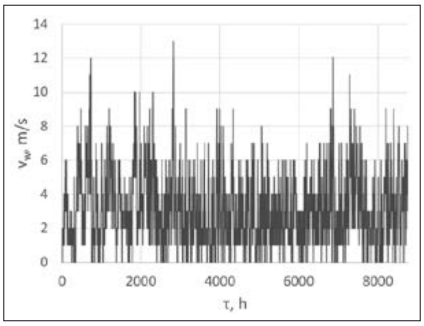

Fig. 2.
Wind speed for the meteorological station in Wroclaw
Rys. 2. Prędkość wiatru dla stacji meteorologicznej we Wrocławiu

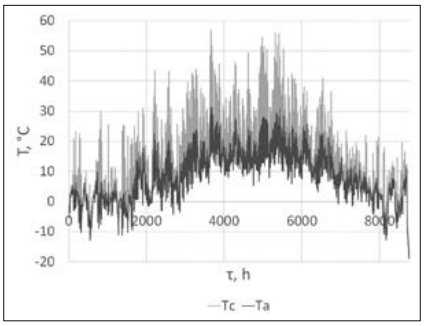

Fig. 3.
Ambient temperature for the meteorological station in Wroclaw and photovoltaic cell temperature determined according to the model of Kurtz et al.
Rys. 3. Temperatura otoczenia dla stacji meteorologicznej we Wrocławiu oraz temperatura ogniw fotowoltaicznych określona wg modelu Kurtza i in

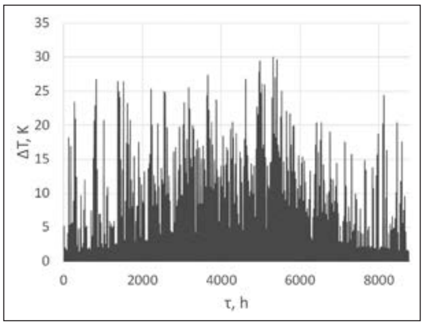

Fig. 4.
Temperature difference between the photovoltaic cell and the ambient
Rys. 4. Różnica temperatury ogniwa fotowoltaicznego i otoczenia

The sun's rays that reaches the PV module is only partly used in the energy conversion process in the module. Part of solar irradiance is reflected from the module's glass cover. Reflection losses can be as much as 10% of perpendicularly incident solar radiation [7]. The model includes influence of partial reflection of sun's rays from module's glass cover. It was assumed that ΔG = 5% is reflected from the glass surface, the rest is assumed to be absorbed by the module.

Based on the selected model, temperature and module's parameters it can be observed that for Wroclaw meteorological station maximum temperature of the PV cell reached 57°C and the biggest difference between cell's and ambient temperatures was 29.9°C.

Electrical power of module for cells' temperature of 25°C defined by STC was calculated from equation:

$$P_{T_{STC}} = \frac{\eta_{STC} \cdot A \cdot (G - \Delta G)}{100} \qquad (2)$$

The difference of module's power including change of cells' temperature in relation to STC temperature was established using equation:

$$\Delta P = P_{T_{STC}} \frac{\gamma}{100} \qquad (3)$$

Based on above, it was possible to establish a generated power by a module in a particular hour in a year:

$$P = A \cdot \frac{\eta_{STC}}{100} \cdot (G - \Delta G) \cdot \left(1 + \frac{\gamma}{100} \cdot \left(T_m - T_{STC}\right)\right) \qquad (4)$$

With hourly average generated power by a module, an hourly average efficiency was determined including the change of cells' temperature in relation to STC temperature.

$$\eta = \frac{P}{A \cdot \left(G - \Delta G\right)} \qquad (5)$$

The change in energy conversion's efficiency throughout the year and change in cell's temperature is shown in Fig. 5.

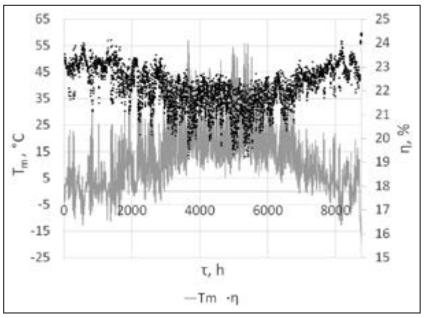

Fig. 5
Change in module temperature over the year for γ = –0.34 %/°C and module efficiency
Rys. 5. Zmiana temperatury modułu w ciągu roku dla współczynnika γ = –0.34 %/°C oraz sprawność modułu

Solar energy absorbed by the module, which is not converted into electrical energy, is transferred into the ambience. It was assumed that the heat is carried out only by convection and radiation. The heat flux was calculated from an energy balance:

$$\dot{Q} = (G - \Delta G) \cdot A - P \qquad (6)$$

With given heat flux it was possible to determine the heat flux coefficient taking into account convection as well as radiation:

$$\alpha = \frac{\dot{Q}}{2 \cdot A \cdot (T_m - T_a)} \qquad (7)$$

Taking into consideration that the analysis was done with a time step of 1 hour, the hourly average electrical power and heat flux were also defining the electrical energy generated by the module and the thermal energy carried out of the PV module:

$$E_{el} = P \cdot \tau \qquad (8)$$

$$Q = \dot{Q} \cdot \tau \qquad (9)$$

Using meteorological data and the calculations model above, annual electrical energy production and heat loss was determined.

Daily electrical energy production and heat loss for a module with temperature coefficient at maximum working point equaling γ = –0.34 %/°C based on data from Wroclaw meteorological station is shown in Fig. 6. Daily percentage of solar energy converted to electricity for the module with γ = –0.34 %/°C is shown in Fig. 7.

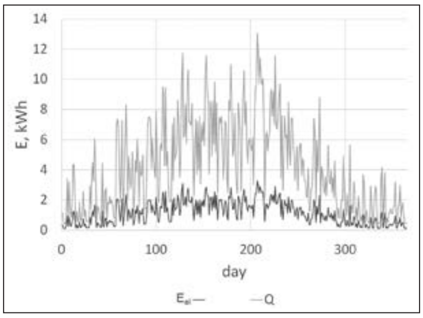

Fig. 6.
Electricity generation and heat loss for the module with γ = –0.34 %/°C
Rys. 6. Generacja energii elektrycznej oraz straty ciepła dla modułu o γ = –0.34 %/°C

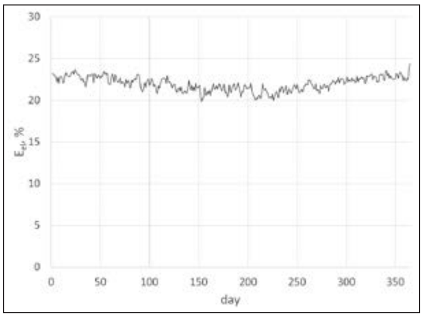

Fig. 7.
Daily percentage of solar energy converted to electricity for the module with γ = –0.34 %/°C
Rys. 7. Dzienny procentowy udział energii słonecznej konwertowanej na energię elektryczną dla modułu o γ = –0.34 %/°C

Yearly generated electrical energy equaled 421 kWh and was not dependent on temperature coefficient of power. Maximum generated power reached 397 W in the module with temperature coefficient of – 0.34%/°C and 388 W for the one with temperature coefficient of – 0.5%/°C. The heat carried out of the module in both cases was calculated to be around 1.54 MWh. Maximum and minimum efficiencies for module with $\gamma = -0.34$ %/°C were 24.4% and 19.2% respectively and for module featuring by $\gamma = -0.5$ %/°C those efficiencies varied from 25.8% to 18.1%.

Intensification of modules' cooling

As can be observed, efficiency of energy conversion as well as the amount of generated energy being a result of the latter, changes significantly with the module's temperature. Additionally, with the solar irradiance reaching the highest level and during the days with the highest number of hours of sunlight, photovoltaic cells heat up the most, causing lower efficiency.

Increasing the intensification of heat transfer throughout the module into the ambience is considered to be a solution to that problem. There are many ways to intensify modules' cooling [2]. An analysis of the possibility of that and the effect of extended heat exchange surface as well as the heat dissipation by air flow through a duct located at the back side of a module is presented below.

Extended heat transfer surface

In order to conduct the analysis the following assumptions were made: C-profiled fins will be applied which are made of aluminum with geometry presented on Fig. 8. and dimensions of A = 21 mm, B = 25 mm, G = 1.2 mm. It was assumed that fins are arranged along the long edge of the module. Thermal conductivity of aluminum equals $\lambda = 209$ W/m^{2}K.

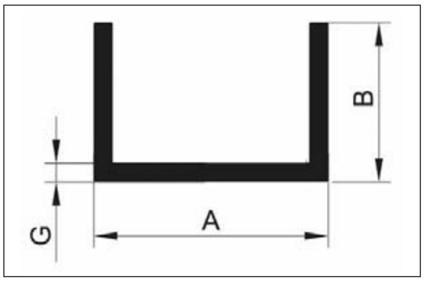

Fig. 8.
Geometry of a fin
Rys. 8. Geometria żeber

With assumed above parameters, the temperature coefficient, efficiency of a fin and finning surface efficiency were calculated based on the following equations:

$$m = \sqrt{\frac{2 \cdot \alpha}{\delta \cdot \lambda}} \qquad (10)$$

$$\varepsilon_f = \frac{\tanh(m \cdot h)}{m \cdot h} \qquad (11)$$

$$\varepsilon_{fsf} = 1 - \frac{A_f}{A_{fsf}}(1 - \varepsilon_f) \qquad (12)$$

Heat flux carried out of module's surface without fins was calculated as follows:

$$\dot{Q} = 2 \cdot A \cdot \alpha \cdot (T_m - T_a) \qquad (13)$$

And for the module with fins:

$$\dot{Q} = A \cdot \alpha \cdot (\varphi \cdot \varepsilon_{fsf} + 1)(T_{m,f} - T_a) \qquad (14)$$

With finning degree based on the formula below:

$$\varphi = \frac{A_{fsf}}{A} \qquad (15)$$

It was assumed that the maximum number of C-profiled fins is 26, which resulted a finning degree equal 3.2.

Based on above calculations, the temperature of a cell in a PV module with extended heat exchange surface on its back side was established with the assumption that heat flux carried out of the module was equal to the one in a module without fins. It allowed to form the formula to calculate a cell's temperature:

$$T_{m,f} = \frac{2 \cdot (T_m - T_a)}{\varphi \cdot \varepsilon_{fsf} + 1} + T_a \qquad (16)$$

Based on that formula, the results presented in Fig. 9 were obtained. Fig. 9 shows an influence of cell's temperature without fins and finning degree of a module on cell's temperature with fins applied on module's back side. Calculations were made for an ambient temperature of 20°C.

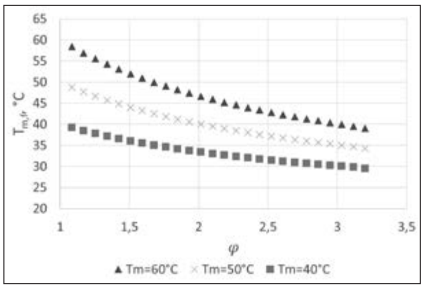

Fig. 9.
The temperature of the module with a finned lower surface as a function of the temperature of the module without fins and the degree of finning
Rys. 9. Temperatura modułu z ożebrowaną dolną powierzchnią w funkcji temperatury modułu bez żeber oraz stopnia ożebrowania

The prepared general formula was implemented into an annual analysis of influence of finning on lowering the cell's temperature, generated power and the sum of yearly produced electrical energy. Because of negligible impact of fins' efficiency (rated above 0.98) on the module's parameters, in the full-year analysis the fins' efficiency was assumed to be 1. Relative increase of annual energy production by analyzed modules was determined using the following equation:

$$\delta E = \frac{E_{cl} - E}{E} \cdot 100\% \qquad (17)$$

The results of the analysis considering an influence of finning degree on yearly sum of generated energy by the module as well as relative increase of energy production for two analyzed temperature coefficients are shown in Fig. 10 and 11.

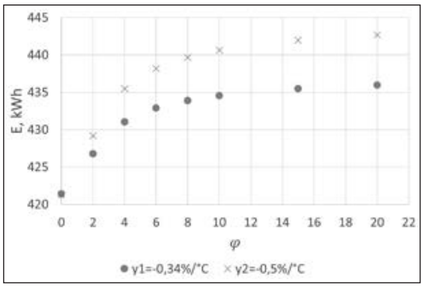

Fig. 10.
Annual electricity production from the module as a function of the finning degree
Rys. 10. Roczna produkcja energii elektrycznej z modułu w funkcji stopnia ożebrowania

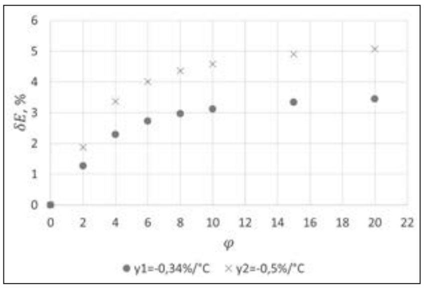

Fig. 11.
Relative increase in annual electricity production from the module as a function of the finning degree
Rys. 11. Względny przyrost rocznej produkcji energii elektrycznej z modułu w funkcji stopnia ożebrowania

Air-flow based cooling system

In order to conduct an analysis of module air cooling it was assumed that air flows through a rectangular duct located under back side of the module. The duct have following dimensions: height of 0.02 m and width equal to the width of the analyzed module, which was 1.1 m. With this assumed geometry, a mass flow rate of air was determined by a formula:

$$\dot{m} = \rho \cdot v \cdot A_{ad} \qquad (18)$$

Based on that, Reynolds number was calculated according to the formula:

$$Re = \frac{v \cdot d_h}{\nu} \qquad (19)$$

Taking into consideration that the air flow in the duct was turbulent, Nusselt number was determined from equation [8]:

$$Nu = 0{,}018 \cdot Re^{0{,}8} \qquad (20)$$

Convective heat transfer coefficient was calculated using a formula below. The change of its value depending on the air flow velocity is shown in Fig. 12:

$$\alpha = \frac{Nu \cdot \lambda}{d_h} \qquad (21)$$

where equivalent diameter is determined from equation:

$$d_h = \frac{4 \cdot A}{C} \qquad (22)$$

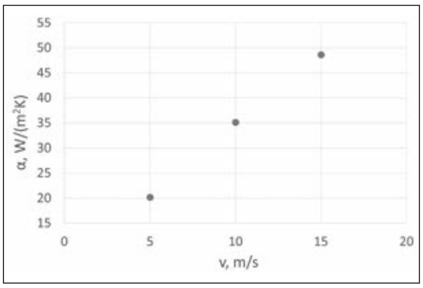

Fig. 12.
The value of the heat transfer coefficient as a function of the air velocity in the air duct
Rys. 12. Wartość współczynnika przejmowania ciepła w funkcji prędkości przepływu powietrza w kanale

Heat flux carried out of module's surface was determined by a formula:

$$\dot{Q} = 2 \cdot A \cdot \alpha \cdot (T_m - T_a) \qquad (23)$$

For a module with an air duct used to intensify the heat dissipation the formula to calculate the heat flux can be written in the following form:

$$\dot{Q} = A \cdot (\alpha_{fs} + \alpha_{bs})(T_{m,ad} - T_a) \qquad (24)$$

Based on that formula, the temperature of a PV cell with back side cooling using an air flow was determined with an assumption of the heat flux being equal to the heat flux carried out of the module without forced air flow. The following formula for the cell's temperature was applied:

$$T_{m,ad} = \frac{2 \cdot \alpha \cdot (T_m - T_a)}{\alpha_{fs} + \alpha_{bs}} + T_a \qquad (25)$$

Based on that equation, the results which are presented in Fig. 13 were obtained. Fig. 13 shows an influence of cell's temperature with no forced air flow and air flow in the duct on cooling cell's temperature.

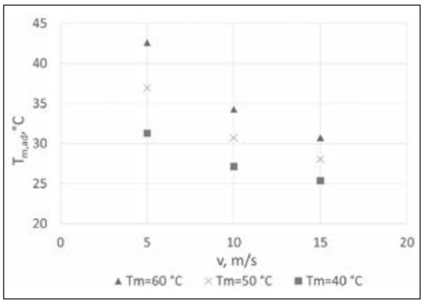

Fig. 13.
Temperature of the air flow cooled PV module as a function of the air velocity
Rys. 13. Temperatura modułu PV chłodzonego powietrzem w zależności od prędkości powietrza

The prepared general formula was implemented to an annual analysis of the influence of forced air flow on lowering a cell's temperature, generated electrical power and the sum of yearly energy production.

The results of the analysis considering the influence of heat transfer coefficient during forced air flow in the duct on yearly sum of energy generated by the module for two analyzed temperature coefficients are presented in Fig. 14. The relative increase in yearly generated power by a cooled module in comparison to a module without cooling is presented in Fig. 15. Negative values of relative energy production's increase for heat transfer coefficient equaling 10 W/m^{2}K at the module's back side are a result of the fact, that average value of the coefficient in the analyzed year is 14.5 W/m^{2}K for a module without any cooling systems.

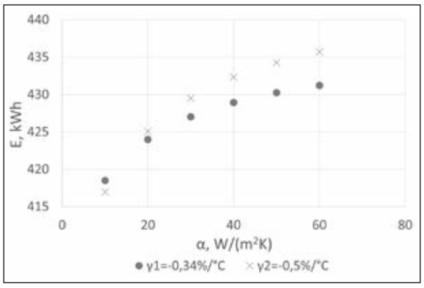

Fig. 14.
Annual electricity generation of the air flow cooled PV module as a function of the heat transfer coefficient value
Rys. 14. Roczna generacja energii elektrycznej przez moduł PV z powietrznym systemem chłodzenia w zależności od wartości współczynnika przejmowania ciepła

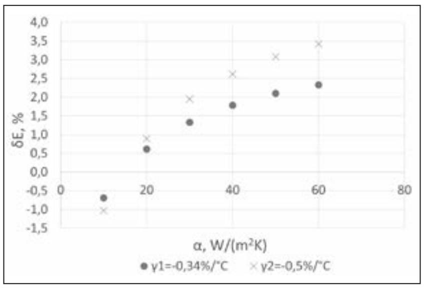

Fig. 15.
Relative increase in annual electricity production of air flow cooled PV module as a function of the heat transfer coefficient
Rys. 15. Względny przyrost rocznej produkcji energii elektrycznej przez moduł PV z chłodzeniem powietrznym w zależności od wartości współczynnika przejmowania ciepła

Summary and conclusions

Installed capacity of PV modules in Poland is growing, which results in systematically increasing electrical energy production by photovoltaic installations. However, the efficiency of this form of energy conversion is not the highest and ranges between 20 and 22%. Additionally, factors such as high solar irradiance and high ambient temperature cause the temperature of a PV cell to rise, resulting in decreased efficiency. In Poland, for data from the example meteorological station in Wroclaw [6], the maximum calculated temperature of photovoltaic cells is 57°C. This is 32°C higher than the STC temperature. This temperature difference results in a drop off 2.3 percentage points in the efficiency of a module with a power temperature coefficient of γ=-0.34%/°C. For a module with a power temperature coefficient of γ=-0.5%/°C, the efficiency drop off is 3.4 percentage points. The efficiency decreases are related to the module efficiency in STC condition which is equal 21.5%. A solution to reduce cells' temperature and increase efficiency is an addition of cooling systems of PV modules.

In this paper the impact of cooling systems such as extended heat transfer surface and forced air flow on PV modules was examined. The energetical benefits of cooling systems were determined. As a result of conducted analysis it can be observed, that cooling systems have the ability to decrease cells' temperature, what causes better efficiency as well as increased electrical energy production.

In the case of cooling based on extended heat exchange surface on the module's back side, a dynamic increase in energy production can be observed while the finning degree stays on the lower levels. As finning degree increases, the dynamic is less noticeable. With finning degree of 10, relative increase of generated electrical energy is 3.1% for a module featuring temperature coefficient of –0.34%/°C, and 4.6% for the module with temperature coefficient of – 0.5%/°C.

In the case of air-flow cooling system working at conditions in which heat transfer coefficient equaled 50 W/m^{2}K, what corresponds to air velocity in the duct of 15 m/s, the relative increase of generated electrical energy is 2.1% for a module featuring temperature coefficient of – 0.34%/°C, and 3.1% for the module with temperature coefficient of – 0.5%/°C.

Because of relatively low solar irradiance and sunshine duration in Poland resulting in low insolation (in polish weather conditions average is equal to 1000 kWh/(m^2year)), increase of generated power is not impressive. The electrical benefits may not cover the investment and operating costs of such cooling systems. However, regions with higher insolation would present conditions in which the effects would be more significant.

It should be taken into consideration that an analysis of difference of energy production of modules with cooling systems concerning only one year is not reliable considering long term benefits. Cooling systems cause decreased amplitude of PV cell temperatures as well as the frequency of cells' temperature changes. This has implications for reduced thermal loads, what has an impact on limiting degradation of a cell, which is a direct factor leading to increased life span of such a modules [9].

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