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Impact of water cooling on photovoltaic modules performance in Polish climate conditions – a case study

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Abstract

Atmospheric conditions, such as for example ambient temperature, may have the influence on temperature of a photovoltaic (PV) module. The greatest impact is exerted by solar radiation intensity, leading to an increase in the temperature of photovoltaic cells. As the temperature of the module increases, the efficiency and thus the generated power decreases. The cooling systems capable of lowering the temperature of the module, thus improving its efficiency may be promising solution to this problem. This paper presents the results of a study on the effect of water cooling of a photovoltaic module. The experiments were conducted in Poland using the test stand composed of two photovoltaic modules. One module was equipped with a water cooling system at its front surface while the second module was treated as the reference. Thanks to such a test setup design it was possible to study the influence of atmospheric conditions on the change of photovoltaic module temperature, power output and amount of energy generated by the cooled and reference module. Two cooling methods concerning the timing of cooling water flow activation/deactivation were investigated. The first method involved a fixed cooling time and intervals, while the second method adjusted the cooling water flow activation and deactivation time based on the surface temperature of the module. As a result of the conducted research, a maximum decrease of 17.6 K of photovoltaic module temperature and a maximum power increase of ca. 5%, using the cooling system, was achieved. Furthermore, a correlation between cooling efficiency and cloud cover was described, as well as a method for determining cooling water flow. It was found that better cooling results are obtained when employing a cooling activation and deactivation method based on temperature dependence.

Keywords: Photovoltaic module; PV cell temperature; PV cooling system; PV module efficiency

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1. Introduction

Climate change, partly caused by the use of conventional fossil fuel-based energy systems for electricity generation, can be mitigated by incorporating a greater share of renewable energy sources into the electricity generation system [1]. One of the most important sources of renewable energy that can potentially be used to change the energy mix and thus decarbonise the energy systems is solar radiation. Photovoltaic installations are one of the possible technologies that can be applied for solar radiation harvesting [2,3]. In recent years, there has been a significant increase in the installed power of photovoltaic installations observed worldwide (an average annual increase was equal to ca. 25%), reaching the power of 1.05 TW in 2022 [4]. In Poland, an even more rapid growth of installed photovoltaic (PV) power is observed, which reached the power of 16.9 GW at the end of 2023 [5]. Such a rapid growth of PV installations power in Poland is largely caused by the increasing number of prosumer PV

Nomenclature

A – surface area, m^2
E – energy, Wh
G – solar irradiance, W/m^2
P – power, W
q – flow rate, l/min
T – temperature, K
U – voltage, V

Greek symbols

γ – temperature coefficient at the maximum power point, %/K
δ – relative difference
Δ – change in value
η – efficiency, %

Subscripts and Superscripts

a – ambient
c – photovoltaic cell
el – electrical energy
v – volumetric

Abbreviations and Acronyms

A – cooled module
B – comparison module
PV – photovoltaic
STC– standard test conditions

microinstallations, whose share in installed power at the end of 2022 was equal to 72% [6]. Figure 1 shows the change in installed photovoltaic power on a global, European and Polish scale. An increase in installed PV power directly translates into an increase in the amount of electricity generated from such installations. Figure 2 shows the change in the amount of electricity generated by PV installations in Poland and its share in the total electricity amount generated from all sources.

The maximum efficiency of commercially available photovoltaic modules is nowadays equal to ca. 20−22% [6]. In real operating conditions, the PV module efficiency varies and depends on different variables, such as e.g. atmospheric conditions, which may affect the operating temperature of the PV cells and the amount of harvested solar radiation. The most important parameters related to atmospheric conditions include solar irradiance, ambient temperature, wind speed, precipitation and air pollution (i.e. content of dust and other pollutants) [6−8]. The intensity of solar radiation is an important factor on which the power generated by a PV module directly depends. What is more, at the same time, the intensity of solar radiation is causing the PV cell heating, which results in a decrease of its efficiency. An increase in ambient temperature also heats the cells (i.e. to the ambient temperature level). At the same time, due to ambient temperature increase, the cooling intensity of the modules decreases, which results in a negative effect of increasing temperature of PV cells. Wind also influences the operation of photovoltaic modules. On the one hand, it positively influences and helps in better heat removal from the module surface, thus lowering the cell temperature. On the other hand, wind influence can be negative, because it can carry pollutants such as dust or leaves, which may partially cover PV modules and consequently reduce their efficiency. Wind-borne volatile pollutants such as dust, sand, pollen and others may stick to the surface of the module, causing it to be shaded and thus reducing the generated power. In this aspect, the wind can also have a positive effect by removing contaminants from the module surface. Rainfall can also have a positive effect on the operation of photovoltaic modules. Water may remove contaminants from the module surface, allowing more solar energy to reach the cells. At the same time, water acts as a coolant, which reduces the cell temperature and thus increases efficiency.

A number of models that can be used for determining PV cell temperature as a function of various atmospheric conditions can

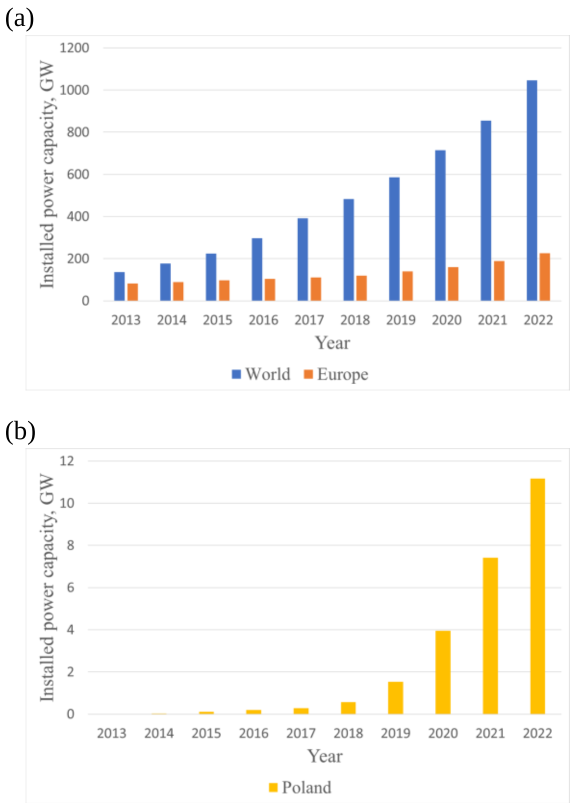

Fig. 1. Installed power of photovoltaic systems: (a) data for World and Europe; (b) data for Poland. Own elaboration based on [4].

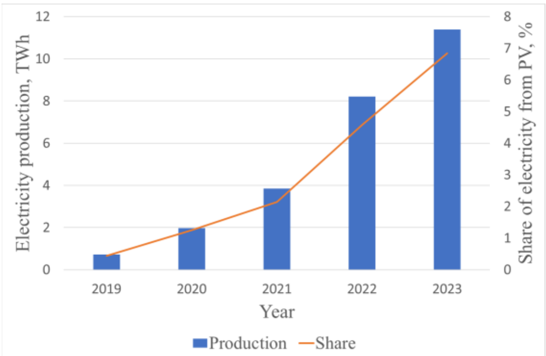

Fig. 2. Electricity production from PV and its share in Poland energy production. Own elaboration based on [5].

be found in the literature [6,9−11]. On the basis of these models, it is possible to determine the influence of individual atmospheric conditions on the cell temperature. These models are different depending on the module and installation type. Solar irradiance has a linear effect on the change in cell temperature. An increase of solar irradiance by 100 W/m^2 at a constant ambient temperature results in an increase of cell temperature by 3.1 K according to the Mondol et al. model [6] and by 1.75 K if the cell temperature is determined using the Tselepis model [6]. The change in the cell temperature as a function of the change in solar irradiance depends on the type of module and usually ranges between 1.8 K and 4.93 K [9]. Also, a change in ambient temperature causes a linear change in cell temperature. Ambient temperature increase by 1 K results in an increase of cell temperature by ca. 1 K, however, it depends on the type of PV module [9]. Using the Mondol et al. model, this increase can be determined as 1 K, while using Tselepis model a value of 1.1 K is obtained [6]. Wind has a positive effect on the cell temperature, causing an intensification of PV module cooling. Models that take wind speed into account can deviate from a linear character and cause large discrepancies in the obtained modelling results, due to the very strong influence of the module's position and thus the intensity of cooling. Based on selected models (i.e. Markvart [9], Kurtz et al. [9], Chenni [9], Skoplaki and Palyvos [6]), an average decrease of cell temperature of 0.6 K to 2 K per 1 m/s of wind speed can be determined at constant solar irradiance and ambient temperature. The most rapid decrease in cell temperature is observed at low wind speeds, which can be clearly seen from the Skolpaki and Palyvos model [6].

In Polish climatic conditions, the temperature of PV cells can reach 70°C [12], and depends on the temperature coefficient of maximum power and the way of the PV system installation (i.e. roof-top or ground-mounted installation). Figure 3 shows the change of ambient (T_a) and cell temperature (T_c), which were determined from the Kurtz et al. model using the annual variation of ambient temperature for Wrocław. Figure 4 shows the variation of module efficiency (η) resulting from the change in the cell temperature. Presented data were obtained for a PV module featuring a temperature coefficient of power at maximum power point of γ = −0.340 %/K, i.e. the module used in this study. This means that the achievable power and thus the efficiency of this module decrease by 3.4% for each increase of cell temperature by 10 K. The efficiency of the module was determined using the following formula:

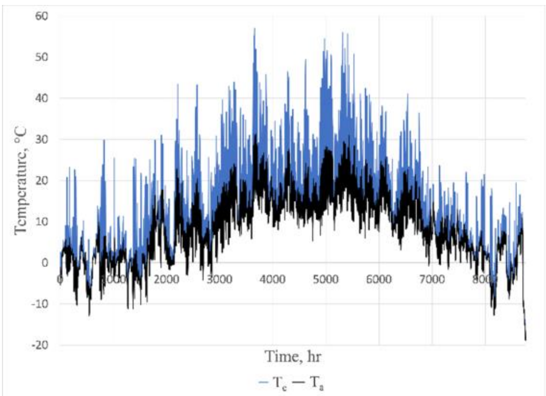

Fig. 3. Annual variation of ambient temperature in Wroclaw and photovoltaic cell temperature determined from Kurtz et al. model. Own elaboration based on [13,14].

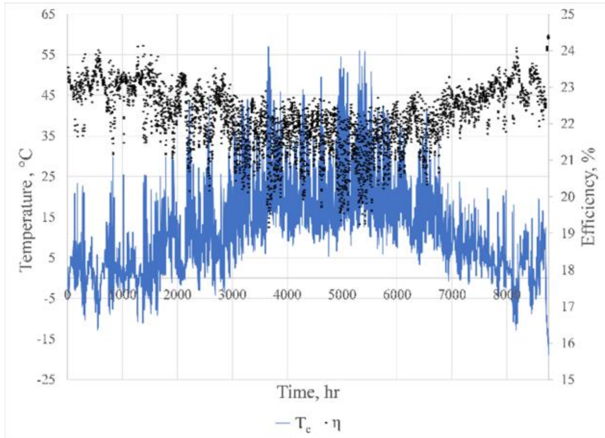

Fig. 4. Annual variation of PV cell temperature and module efficiency determined for γ =−0.340 %/K. Own elaboration based on [13,14].

$$\eta = \eta_{STC}\left[1 + \frac{\gamma}{100}(T_c - T_a)\right], \quad (1)$$

where η_{STC} is the efficiency under STC conditions (i.e. standard test conditions defined as: cell temperature of 25°C, solar irradiance of 1000 W/m^2 and air mass factor of AM1.5), T_c is the photovoltaic cell temperature and T_a is the ambient temperature, and γ is the temperature coefficient of power at maximum power point.

From the above analysis, it can be seen that by lowering the operating temperature of photovoltaic cells, it is possible to increase the energy conversion efficiency of the module and thus increase the module power and electricity production. It should also be noted that application of module cooling may contribute to reducing the amplitude and frequency of cell temperature fluctuations, reduce the cell thermal load, limit their degradation and extend their operating time [15].

2. Review of methods applied for photovoltaic modules cooling

There are many methods that can be applied for photovoltaic modules cooling, i.e. active, which require a power supply for their operation, and passive, which do not need additional energy input [15−21].

Water is one of the substances which can be used to cool PV modules. As a cooling medium for PV modules, it has many advantages over air. These include a higher value of the thermal conductivity coefficient and specific heat, thanks to which the modules can be cooled in a shorter time. It also has the ability to clean the PV module against dust accumulation, which is particularly important in deserts, agricultural and polluted areas.

It can be applied for passive cooling by immersing the modules in water or placing the modules on the water surface. In active cooling methods, water can be directly applied as a coolant to cool the top or bottom surface of the module. The top surface can be cooled by forcing a film of liquid to flow down on the module surface or by spraying it on the module surface to mimic rainfall. The bottom surface can also be cooled by direct water sprinkling or by forcing the water flow through a heat exchanger (cooler) adjacent to its surface. A comprehensive description of water cooling methods can be found in the review [22].

Water (or other fluids) can also be used to cool photovoltaic modules in photovoltaic/thermal (PV/T) systems. In [23], the authors highlighted the positive features of PV/T systems and their great application potential. They presented an innovative thermal collector for a PV/T system and presented the obtained research results. It was estimated that, at a sufficiently matched water flow rate and inlet temperature, the tested system achieves an electrical efficiency of 17.79% and a thermal efficiency of 76.13%, which is significantly better than in the case of other solutions available in the literature. A study of module cooling in a PV/T system was also carried out in [24]. The study showed that, as a result of the cooling system used, energy production increased by 14.1% and electrical efficiency increased to 19.8% compared to 17.4% for the module without the applied cooling system. Experimental results related to the cooling of a monocrystalline and polycrystalline PV module were presented in [25]. It was observed that there is a linear relationship between the module efficiency and its temperature. As a result of the applied cooling, the average temperature was 13.6% lower (for the monocrystalline module) and 7.2% lower (for the polycrystalline module) compared to the case without cooling. The decrease in average temperature of the modules resulted in increased modules' efficiency (by 13% and 6.2%, respectively). In [26], the numerical research aimed at determining the influence of atmospheric conditions (i.e. ambient temperature, solar irradiance and wind speed) on the cooling of the back surface of the PV module using water flowing in a channel was carried out. The obtained results proved that water cooling is an effective method, and that the best results are achieved at high ambient temperatures and high irradiance values. It was also observed that the influence of wind on the cooling process is less important than the influence of ambient temperature and irradiance. The maximum increase of module efficiency by 52% (compared to a PV module without cooling) was found during the study. The results of a numerical study on the PV module cooling were also published in [27]. It was observed that the modelled cooling system was able to reduce the module temperature by 6 K. In [28], the authors presented the results of a study on cooling the front and back surfaces of the PV module. The research was carried out in India. The front surface was drip-cooled by water flow, while the back surface was cooled by the application of wet grass. The research results showed that the average temperature drop of the PV module was 21.23%, which resulted in a 28.60% increase in module power. The researchers also found that cooling the front surface of the module gives a more noticeable effect.

High impact in lowering the PV modules temperature is achieved by cooling their front surface. Therefore, many researchers are dealing with this type of cooling. In [29], the authors presented a mathematical model describing the heat transfer mechanism in a module with cooling applied to its front surface and validated this model using a test stand located in India. The validation showed good agreement between modelled and experimentally obtained data, and the study showed that the application of the cooling system resulted in a reduction of module surface temperature (from 56.67°C to 39.44°C) and an increase of its efficiency (from 12.74% to 14.29%). In [30], the authors conducted a study on cooling the front surface of a PV module by sprinkling water on it with the help of nozzles and made an attempt to optimise the number, geometry and position of the nozzles. It was found that a cooling system consisting of 3 nozzles with a 90-degree opening angle, which are supplied with water at a pressure of 1.5 bar reduces the module temperature by 24 K and improves its efficiency from 11.18% to 13.27% if the cooling system is operated in 30 s spray and 180 s pause time sequences. A study of spray cooling of a photovoltaic module is also reported in [31]. The applied cooling technique was based on the simultaneous cooling of both the front and back surfaces of the PV module. The tests were conducted in a Mediterranean climate location. The experimental results showed that by cooling both the front and back surfaces simultaneously, it was possible to reduce the module temperature from 54°C to 24°C, which resulted in a 16.3% increase of maximum module power and a 14.1% increase of module efficiency. In [32], a mathematical model was developed to determine the optimal cooling cycle of the modules' front surface through water flow. The model was validated by performing an experiment carried out in Egypt. Based on the model of the heating and cooling rate of the module, it was found that the panels achieve the highest energy output if the panel temperature reaches the maximum allowable temperature of 45°C. In [33], the results of a study and exergy analysis on cooling monocrystalline modules by cooling water flow were reported. The obtained results are valid for Laos climate and showed an increase in the exergy efficiency of the module from 2.91% (in the case of the module without an applied cooling system) to 12.76% (in the case of the module with an applied cooling system). The results of tests on cooling the front surface of a module equipped with reflectors, which focus solar radiation, are presented in [34]. The tests were carried out in Iraq and it was observed that the temperature of the cooled module decreased to 36.5°C compared to the temperature of 64.1°C observed for the module without the applied cooling system. An increase in power output by 24.4% and electrical efficiency from 14.2% to 17% due to the use of focusing reflectors and cooling was observed. In [35], the authors presented the results of the simulation of water cooling of PV modules using single nozzles. The influence of the nozzle position on the obtained results was analysed. It was assessed that the droplet size is a key parameter that plays a very important role in the contact effectiveness of the sprayed liquid stream. In [36], researchers from Poland presented their findings on cooling the front surface of the PV module by liquid film flow and by sprinkling water to mimic rain. A decrease of module temperature from 45°C to 25°C was achieved. Better results were achieved by cooling the module with a water film, and continuous cooling led to a 20% increase in power output.

The above literature review shows that the problem of photovoltaic module cooling is vital and has been addressed by many researchers. Unfortunately, most of the research is carried out in regions where climate conditions significantly differ from Central European regions where climate conditions significantly differ from Central European climate or carried out only in laboratory conditions using low-power photovoltaic modules. Specific differences in Polish climate conditions compared to other regions of the world where experimental investigations on PV module cooling have been conducted include lower ambient temperatures (resulting in a lower maximum temperature reached by the modules), fewer sunny hours per year (leading to a shorter requirement for module cooling), and consequently, fewer opportunities to increase the amount of energy produced. Despite the fact that Poland experiences continental climatic conditions, and consequently, there may be significantly fewer days characterised by high temperatures compared to, for example, Mediterranean countries, thus reducing the need for module cooling, it may still be necessary. However, it is worth noting that in Poland, during the summer months, ambient temperatures do not differ much from those in Mediterranean countries; only the duration of their occurrence is shorter. The application of module cooling is not only related to a possible increase in the amount of energy generated by modules, but also to increasing their longevity. The application of cooling reduces the amplitude and frequency of cell temperature fluctuations, decreases thermal loads, and consequently contributes to limiting cell degradation, thereby extending cell operational lifespan.

The authors decided to fill the research gap related to PV module cooling analysis in Poland. Therefore, the present study is aimed at investigating the effect of drip cooling of 410 W monocrystalline PV modules, which are operating in Polish climate conditions. The research is aimed at assessing the temperature reduction rate of PV modules in a temperate climate and investigating the feasibility of real benefits from the application of a drip cooling method.

3. Description of experimental set up and mathematical model

3.1. Description of experimental test stand

The experimental test stand was commissioned in the Renewable Energy Laboratory, which is located on the flat roof of the campus building of Wrocław University of Science and Technology in Poland. The photovoltaic modules used for the analyses were inclined at an angle of 30° to the roof surface and facing south. A scheme of the test stand is presented in Fig. 5. The main components of the stand are two photovoltaic modules of the same type, whose catalogue data are presented in Table 1. These modules are made in half-cut technology and are assembled on concrete blocks (6). On one of the modules, the cooling system is installed. This module is further referred to as module *A* (2). The second module does not have a cooling system installed and is treated as a reference module to compare measurement results. This module is further referred to as module *B* (1). The test stand is equipped with water cooling system, which is composed of a pump (5) (used for pumping water from a tank (4) to a dispenser (7), which is assembled on the front surface of the module), a tank (4), a dispenser (7) (made of PVC pipe featuring a diameter of 1", in which a set of 68 holes, each featuring a diameter 2.5 mm and spaced by a pitch of 15 mm are drilled) and a trough (3), which directs the cooling water flowing out from the cooling system back to the tank. A bucket (9) and scale (8) are used to measure the cooling water mass flow. Each module is connected to an optimiser (10) and an inverter (15) for direct current (DC) to alternating current (AC) conversion. The experimental data from the measuring system is collected by a National Instruments data acquisition (DAQ) system equipped with an NI 9212 card (13), working with a laptop (14) equipped with LabVIEW software. Seven T-type (Cu-CuNi) thermocouples with a measurement accuracy of ±0.5 K (12) were used to measure temperature at different points of the system. Locations of thermocouples are marked with blue numbers (01−07) in

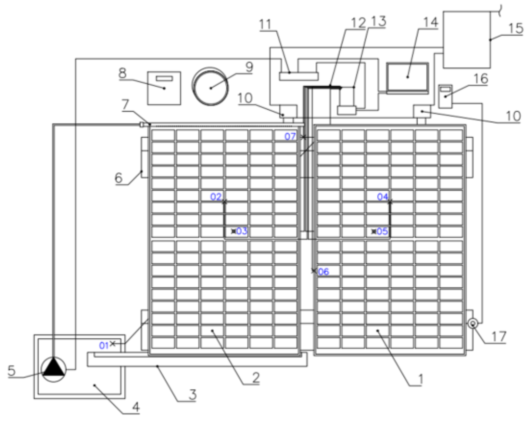

Fig. 5. Test stand scheme: 1 – comparison module (*B*) Longi LR5-54HPH-410M; 2 − cooled module (*A*) Longi LR5-54HPH-410; 3 – trough; 4 − water tank; 5 − diaphragm pump; 6 − concrete blocks; 7 – dispenser; 8 – scales; 9 – bucket; 10 − power optimizer SolarEdge S500; 11 − power supply; 12 − T-type thermocouples; 13 − measuring system National Instruments (basis USB - cDAQ-9174, measurement card NI 9212, compact cassette NI TB-9212); 14 − computer; 15 − inverter SolarEdge SE5K-RW0TEBNN4; 16− universal meter DT-30B; 17 − pyranometer Kipp & Zonen SP Lite.

Table 1. Catalogue data of the photovoltaic modules used in the experiment.

Name	Catalogue data
Type of module	Silicon, mono-crystalline
Manufacturer	Longi Group
Model	LR5-54HPH-410M
Rated power	410 W
Performance in STC	21%
Temperature coefficient of the current short circuit	α = 0.050 %/K
Temperature coefficient of the voltage of an open circuit	β = -0.265 %/K
Temperature coefficient of maximum power	γ = -0.340 %/K
Surface area	1.953 m^2

Fig. 5. The first (01) was immersed in water in the tank, the second (02) was attached to the front surface of the cooled module, the third (03) was attached to the back surface of the cooled module, the fourth (04) was attached to the front surface of the comparison module, the fifth (05) was attached to the back surface of the comparison module, the sixth (06) was used to measure the ambient temperature in front of the surface of the modules, and the seventh (07) was used to measure the ambient temperature in the shade. The maximum measuring error of the NI 9212 temperature measuring system is equal to ±0.02 K. Measurement of the solar irradiance was possible by application of a Kipp & Zonen SP Lite pyranometer (17), which was transmitting a voltage signal to the DT-830B type universal multimeter (16). A solar irradiance value was then calculated from the measured voltage (U) using the following formula:

$$G = \frac{10^6 \cdot U}{71}. \tag{2}$$

The maximum measuring error of the solar irradiance measuring system is equal to ±2.4%. The pump, laptop and NI data acquisition (DAQ) system were connected to the power supply (11).

(a)

(b)

Fig. 6. Photograph of the test stand: (a) front view; (b) back view.

(a)

(b)

Fig. 7. Photograph of the test stand: (a) water-washed module; (b) water outflow from the dispenser.

Photographs of the test stand front and back are presented in Figs. 6a and 6b, respectively. Figure 7a shows the general view of a water-washed PV module, while Fig. 7b visualises the water outflow from the dispenser.

3.2. Experimental procedure

Experiments were carried out in the summer of 2023 and lasted three days. A description of the weather conditions, the times of the experiments and their duration are summarised in Table 2.

Table 2. Experimental conditions.

	Day 1 29.06.2023	Day 2 30.06.2023	Day 3 08.07.2023
Weather conditions	Maximum temperature in the shade: 30.3°C, sky partly covered by clumped clouds (further referred to as cloudy sky conditions)	Maximum temperature in the shade: 28.6°C, sky completely covered by stratus clouds (further referred to as completely overcast sky conditions)	Maximum temperature in the shade: 37.6°C, cloudless sky (further referred to as cloudless sky conditions)
Experiment start time	11:10 a.m.	10:20 a.m.	10:10 a.m.
Experiment end time	2:30 p.m.	12:25 p.m.	3:15 p.m.
Duration of experiment	3 hr 20 min	2 hr 5 min	5 hr 5 min

The temperature measurements were recorded automatically by a data acquisition system. Voltage readings were taken at five-minute intervals on a universal multimeter connected to the pyranometer. These results were then converted into a solar irradiance value using Eq. (2). The mean value of the cooling water flow rate was obtained after converting the mass flux values measured by the weighing method and was equal to 6.27 l/min, 14.33 l/min, 15.33 l/min for the following days, respectively.

On each experimental day, the cooling water flow occurred under different conditions. During experiments, which were performed in cloudy sky conditions (i.e. day 1), the condition for switching on the cooling water pump was that the temperature difference between the temperature of the back surface of the cooled PV module and the ambient temperature in the shade was equal to at least 10 K. Cooling water pump was switched off when the temperature difference reached 5 K. During experiments which were performed in completely overcast sky conditions (i.e. day 2), experiment on module cooling was started at 10.35 a.m. and ended at 12.05 p.m. That day, the cooling water flow was switched on and off periodically (i.e. 1 min water flow once every 30 min of experimental time). During experiments, which were performed in cloudless sky conditions (i.e. day 3), the experiment on module cooling was started at 10.20 a.m. and ended at 3.05 p.m. That day, the cooling water flow was also switched on and off periodically (i.e. 1.5 min water flow once every 15 min of experimental time). The detailed information on the cooling water flow during experiments is presented in Table 3.

Table 3. Cooling water flow during experiments.

	Day 1 29.06.2023	Day 2 30.06.2023	Day 3 08.07.2023
		q_v, l/min	
	8.77	14.54	15.91
	5.96	14.63	14.65
	4.08	13.95	15.43
		14.21	
Average	6.27	14.33	15.33

By connecting a SolarEdge optimiser to each module, it was possible to access the software, which provides detailed data for PV modules. Therefore, it was possible to read data about the power generated by each module and the daily amount of electricity generated by each module. The accuracy of electrical power measurement using the SolarEdge system is ±5%.

3.3. Description of mathematical model

The power of the module, defined for a cell temperature specified in STC (i.e. 25°C), is calculated from the formula

$$P_{T\_STC} = \frac{\eta_{STC}}{100} A \times G, \tag{3}$$

where A is the surface area of the module and G is the solar irradiance.

The change in PV module power is related to the change in cell temperature (relative to the STC temperature) and was calculated using the formula

$$\Delta P = P_{T\_STC} \frac{\gamma}{100}, \tag{4}$$

The power generated by the module can be calculated using the formula

$$P = P_{T\_STC} + \Delta P (T_c - T_{STC}) \tag{5}$$

where T_{STC} is the cell temperature specified in STC.

If it is not possible to directly measure the temperature of photovoltaic cells, it is possible to calculate it using the temperature models. Temperature models that take into account meteorological variables and/or material variables, or system configuration, are used for this purpose. The models used in this paper are presented below. Equation (6) is the Mondol et al. temperature model [9]:

$$T_c = T_a + 0.031G. \tag{6}$$

Equation (7) is the Tselepis temperature model [9]:

$$T_c = 30 + 0.0175(G - 150) + 1.14(T_a - 25). \tag{7}$$

The relative difference in the sum of the daily electricity produced by the modules is calculated using the following formula:

$$\delta E_{el} = \frac{E_{el\_B} - E_{el\_A}}{E_{el\_B}}, \tag{8}$$

where E_{el_A} is the amount of electricity generated by module A and E_{el_B} is the amount of electricity generated by module B.

4. Results and discussion

The results of the temperature and solar irradiance measurements, which were made during three series of experiments, are presented in Figs. 8–10. The curves show the variation of the temperatures of the back surface of the cooled module (T_{A_back}), the back surface of the comparison module (T_{B_back}), the ambient in the shade (T_{a_shadow}) and the cooling water in the tank (T_{H2O}). The solar irradiance values (G) were highlighted on the graphs by yellow points. The purple bars show the time of cooling water flow on the module surface during the experiments (the cooling water flow rates are reported in Table 3).

4.1. Results of experiments performed in cloudy sky conditions

The first part of the experiments was performed in cloudy sky conditions, which caused varied solar irradiance conditions (see Fig. 8). Due to the partial cloud cover, the lowest irradiance was equal to 148 W/m^2, while the highest was equal to 1183 W/m^2. Significant variations in this value affect the shape of the curve corresponding to the temperature of the back surface of the comparison module (B), which is also characterised by a large difference between the values of the highest and lowest temperature (i.e. 28.3°C and 51.2°C). The proportional dependence of the module temperature on the solar irradiance is apparent. In the case of the cooled module (A), its lowest temperature was

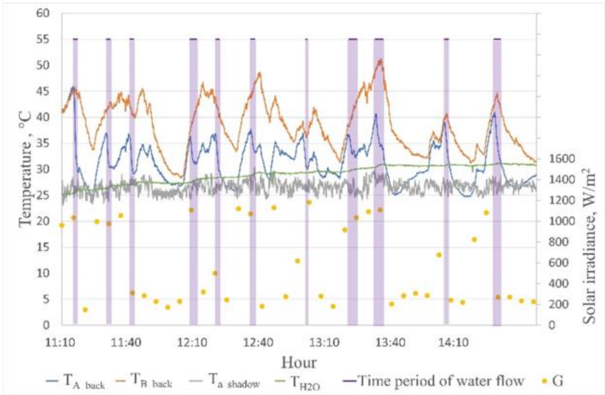

Fig. 8. Variation of PV panel, cooling water and ambient temperature, and solar irradiance, for experiments performed in cloudy sky conditions.

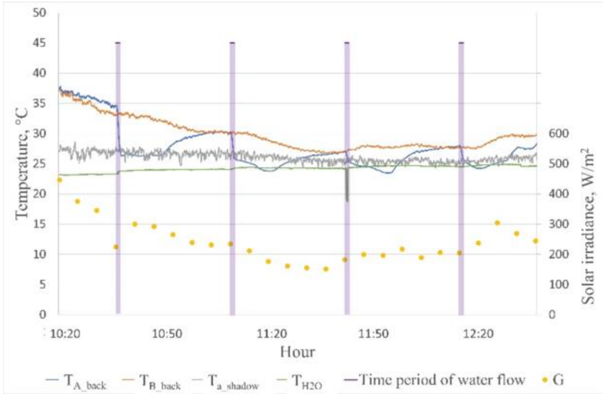

Fig. 9. Variation of PV panel, cooling water and ambient temperature, and solar irradiance, for experiments performed in completely overcast sky conditions.

equal to 24.7°C, while the highest temperature (observed after the first cooling) was equal to 41.0°C. The maximum temperature difference between the modules was equal to 17.6 K, which clearly shows the positive effect of water cooling. At the beginning of the experiment, the cooling water temperature was equal to 25.2°C, while at the end of the experiment it increased to 30.8°C. The maximum observed cooling water temperature was equal to 31.2°C. In addition to the increase of cooling water temperature, which was caused by the absorption of heat from the back of the PV module, the cooling water may also be warmed up due to absorption of heat from solar radiation falling on the black water tank. A steeper rise in the temperature is noticeable in the cooling water temperature curve during the time of water flow, just after the flow, and then during the absence of water flow. The average ambient temperature during the experiment was equal to 26.6°C.

4.2. Results of experiments performed in completely overcast sky conditions

The second part of the experiments was performed in completely overcast sky conditions. For this reason, less dynamic variations in the solar irradiance and thus of the temperature of the reference module were observed (see Fig. 9) compared to experiments, which were performed in cloudy sky conditions. The irradiance value changes between 151 W/m^2 and 445 W/m^2, while the temperature of the reference module (*B*) varies between 26.7°C and 37.3°C. The maximum temperature of the cooled module (*A*) after the first cooling cycle was equal to 30.5°C, while the minimum was equal to 23.5°C. Compared to the cooling method used during the experiments performed in cloudy sky conditions (when the water flow was regulated depending on the difference between the PV module temperature and the ambient temperature), during the experiments performed in completely overcast sky conditions, the cooling water flow was periodic and not temperature-dependent. The maximum observed difference between the temperatures of the modules was equal to 7.6 K. Due to the low solar activity during the experiments, which were performed in completely overcast sky conditions, the module did not reach as high a temperature as in the experiments performed in cloudy sky conditions. This is also caused by the lower amount of heat absorbed by the cooling water. The observed increase of water temperature in this case was equal to 1.5 K. The sharp drop in cooling water temperature during the time of the third flow is due to a measurement error. The average ambient temperature during the experiments, which were performed in completely overcast sky conditions, was equal to 26.1°C.

Considering the experiments, which were conducted in cloudy and completely overcast sky conditions, a significant difference is noticeable in the maximum temperature reached by the comparison module (*B*). The maximum value of the module temperature observed for the experiments performed in cloudy sky conditions was equal to 51.2°C, while for experiments performed in completely overcast sky conditions, this temperature was equal to 37.3°C, despite comparable average ambient temperatures during both experiments (i.e. 26.6°C and 26.1°C, respectively). Therefore, it can be concluded that not the ambient temperature, but the solar irradiance is mainly influencing the module temperature. During the experiments carried out in cloudy sky conditions, solar irradiance reached much higher maximum values (equal to 1183 W/m^2) compared to the maximum value of solar irradiance observed during the experiments performed in completely overcast sky conditions (equal to 446 W/m^2).

4.3. Results of experiments performed in cloudless sky conditions

The third part of the experiments was performed in cloudless sky conditions. Temperature variations of PV panel, cooling water and ambient, as well as solar irradiance for these experiments are presented in Fig. 10. At the beginning of the experiment, the solar irradiance value of 777 W/m^2 was observed and it reached a maximum value of 989 W/m^2 at 12:25 p.m. The lowest irradiance value was equal to 763 W/m^2 and was observed at the end of the experiment. It is worth to note that the maximum observed solar irradiance for experiments performed in cloudless sky conditions (08.07.2023) was 194 W/m^2 lower than the solar irradiance value observed during experiments performed in cloudy sky conditions (29.06.2023). The temperature of the reference module (*B*) varied between 38.3°C and 53.3°C. During experi-

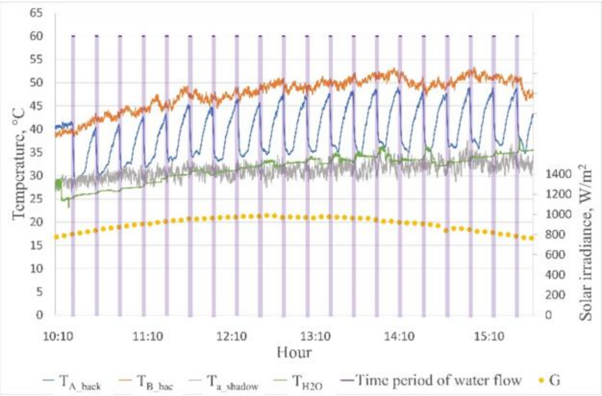

Fig. 10. Variation of PV panel, cooling water and ambient temperature, and solar irradiance, for experiments performed in cloudless sky conditions.

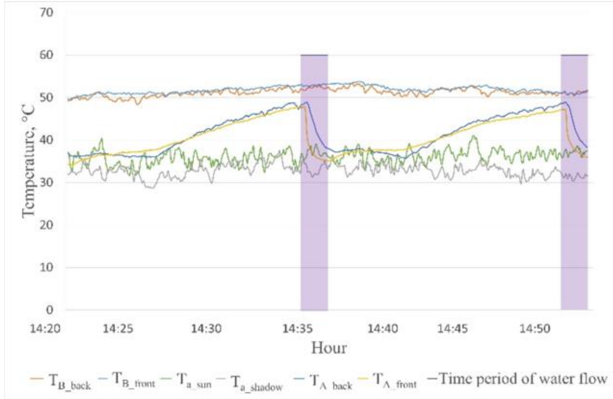

Fig. 11. Variation of PV panel and ambient temperature during experiments performed in cloudless sky conditions (data presented for 30 min of experiment time).

ments, which were performed in cloudless sky conditions, the maximum module temperature during the entire experimental research was observed. The cooling water flow during these experiments was periodic and not dependent on the observed temperatures. The lowest temperature of 28.7°C and the highest temperature of 49°C were observed for the cooled module. The maximum temperature difference between the modules was equal to 16.1°C. The temperature of the cooled module (*A*) fluctuated considerably and the maximum temperature reached by the cooled module was very high (due to the applied periodic cooling water flow). The temperature of the cooling water increased from 27.1°C to 35.4°C at the end of the experiment due to the heating of the cooling water during flow on the PV module surface, the direct heating of the water tank by solar radiation and the need of refilling the tank by adding a fresh, colder water. The average ambient temperature during experiments conducted in cloudless sky conditions was equal to 31.1°C.

When the experimental results obtained for different water flow condition are compared, it is worth to pay attention to the maximum temperature of the cooled module (*A*). During the experiments, which were performed in cloudy sky conditions, the cooling water flow was dependent on the temperature difference between the temperature of the cooled module (*A*) and the temperature of the ambient. For these experimental conditions, the difference between the maximum temperature of the cooled module (*A*) and the comparison module (*B*) was equal to 10.2 K. During the experiments, which were performed in completely overcast and cloudless sky conditions, the temperature differences were considerably smaller, and in certain cases the temperature of the cooled module (*A*) was comparable to the temperature of the reference module (*B*). The main aim of PV module cooling is to keep its temperature at a relatively low and constant value. Therefore, obtained experimental results prove that it may be preferable if the cooling water flow on the PV module surface will be temperature temperature-dependent, not switched on and off periodically. This aim could also be achieved if the water flow sequences were more frequent, but in order to minimise the water losses and limit the consumption of energy needed to drive the feed pump, it may be beneficial to regulate the length and frequency of flow sequences depending on the module temperature.

Figure 11 visualises variations of the module and ambient temperature during the experiments, which were performed in cloudless sky conditions. This graph summarises the temperature measured on the front and back surfaces of the modules, as well as the ambient temperature in the shade (i.e. at the back of the modules) and in front of the modules. To make the results more readable, selected measurement data (i.e. for 30 min of experiment time) is presented in Fig. 11. The average ambient temperature behind and in front of the modules during the experiments performed in cloudless sky conditions was equal to 31.3°C and 33.7°C, respectively. A discrepancy of measured values can also be seen for the temperature of the front and back sides of the modules. In the case of the comparison module, most of the time the temperature of its front side is higher than the temperature of its back side. This may be due to the effect of direct radiation falling on the front thermocouple. For the cooled module (*A*), the temperature ratio between the front surface and the back surface is influenced by the cooling water flow on the PV module surface and thus changes periodically. Before the first cooling water flow, the temperature of the front surface of the cooled module was higher than the temperature of its back surface, which can be explained similarly as in the case of the comparison module. After the first and each subsequent cooling process, the temperature of the back side of the module was higher than the temperature of its front side. Water, which is flowing down on the front surface of the PV module, firstly cools this surface. Each component of the PV module is characterised by specific thermal conductivity, as well as thermal inertia, which have the influence on the response time to the applied cooling. Once the water flow on the surface ends, the temperatures of the front and back surfaces of the module equalise. The front surface temperature then rises steadily, at one stage reaching a higher value than the value of the back surface temperature. Then the drop in this temperature is observed. The steady increase in the front surface temperature may be due to the fact that a certain volume of water remains in the vicinity of the thermocouple and affects the measured value. The front surface of the PV module is constantly exposed to sunlight, which probably causes that this surface reaches a higher temperature than the back surface. It should also be taken into account that a certain amount of liquid remains on the surface of the module after the cooling water flow is stopped. This water evaporates, which mainly intensifies the cooling of the front surface, but it also may result in a higher temperature of the back surface of the module at the end of the cycle, before the next cooling water flow. In addition, the drop of the cooled module (*A*) temperature occurs with some delay from the start of the cooling water flow, due to the time needed to fill the dispenser and reach the module surface.

Figure 12 shows the measured and modelled temperature variations of the comparison module (*B*). The green line shows the mean value of the measured front and back temperatures of the module. The orange line shows the module temperature calculated from the Mondol et al. model (see Eq. (5)) [9], while the dark blue line shows the temperature calculated from the Tselepis model (see Eq. (6)) [9]. These models are based on two variables, i.e. ambient temperature and solar irradiance. This figure shows that the Tselepis model better approximates the obtained experimental results. The maximum difference between the modelled value and the measured value is 14.4%, while for the Mondol et al. model this difference is equal to 33.7%. The mean difference between the measured and calculated values is equal to 5.3% (for the Tselepis model) and 23.1% (for the Mondol et al. model).

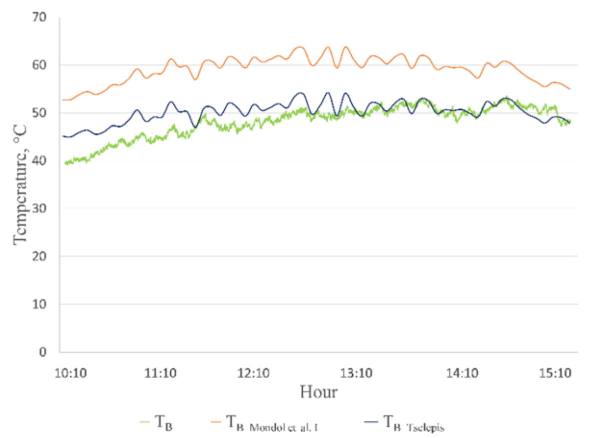

Fig. 12. Measured and modelled temperature variations of comparison module (*B*) during experiments performed in cloudless sky conditions.

4.4. Analysis of the amount of electricity generated by modules during the experiments

In order to assess the effect of the cooling system application on the generated electricity, the daily sum of electricity (E_{el}) generated by the comparative (*B*) and cooled (*A*) modules was analysed. This data was collected over 49 days (from April 1, 2023, to July 23, 2023) and visualized in Fig. 13 with blue (E_{el_B}) and yellow (E_{el_A}) dots, representing the comparative and cooled modules, respectively. The data is arranged from highest to lowest values relative to the comparison module (*B*). The SolarEdge application was utilized for data collection, facilitated by optimizers installed on the modules.

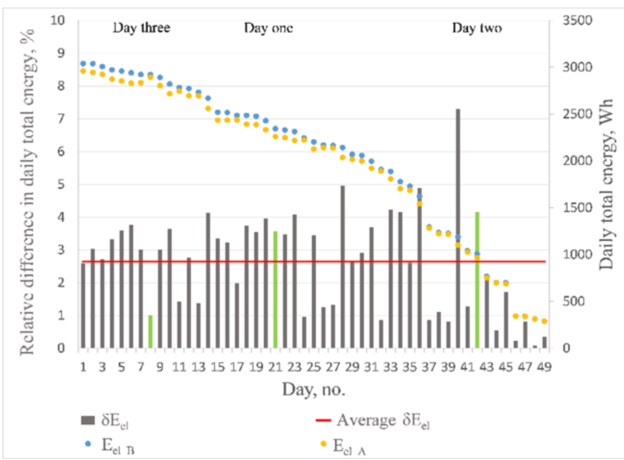

Fig. 13. The amount of electricity generated daily by the modules and the relative difference in the obtained values.

Despite both modules being of the same type and manufactured by the same company, it is observed that each day, the comparison module (*B*) generated more electricity than the cooled one (which may be attributed to internal differences). Additionally, Fig. 13 illustrates that the daily electricity generated by the cooled module (*A*) is, on average, 2.64% lower than that generated by the comparison module (*B*), as indicated by the red line. Smaller differences are noticeable when daily electricity gains are low. The relative difference in the sum of generated electricity is described by Eq. (8). These differences were calculated for each day of the experiment, visualized by grey bars, and considered in the analysis of the module cooling efficiency.

Experimental days during which water cooling was actively applied to module *A* are denoted by green bars in Fig. 13. It can be observed that during the experiments which were performed in cloudless sky conditions, when module *A* was cooled, the relative difference in the sum of generated electricity dropped to 1%, significantly lower than the average value. Conversely, during the experiments, which were performed in completely overcast and cloudy sky conditions, the values are higher than the average. This effect can probably be explained by the presence of a cooling water film on the PV module surface. Besides reducing the module temperature, water flow may also restrict the absorption of solar radiation by the module. In case of experiments, which were conducted when the sky was cloudless and solar radiation intensity was relatively high, the positive effect of module cooling by water flow and the reduction of its temperature outweighed the effect of limited absorption of solar radiation caused by the presence of the cooling water film on the module surface. However, on other experimental days when the sky was cloudy, the limited absorption of solar radiation caused by the cooling water film might have resulted in the cooled module (*A*) generating less electricity. In such cases, the positive effect of cooling may not be as visible.

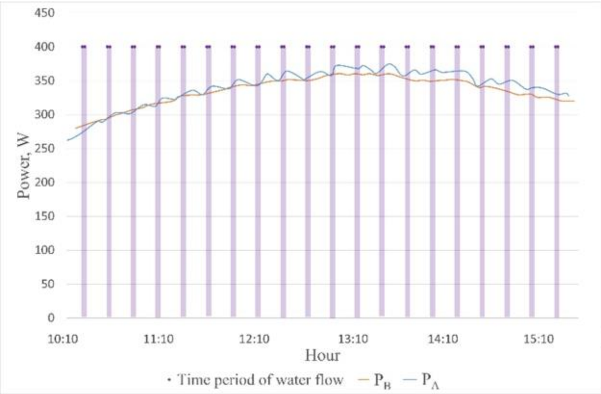

Fig. 14. The variation of measured module power during experiments performed in cloudless sky conditions (power values were obtained from the SolarEdge application).

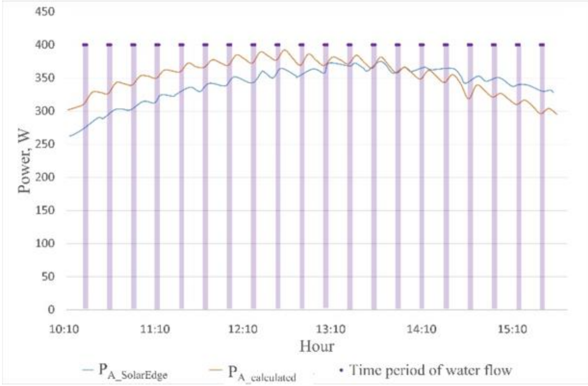

Fig. 16. Variation of the measured and calculated power of the cooled module during experiments performed in cloudless sky conditions.

4.5. Analysis of photovoltaic module power during the experiments

Module power analysis was carried out during experiments, which were performed in cloudless sky conditions using SolarEdge software. The variation of measured module power is presented in Fig. 14. Differences are noticeable between the power of the comparison module (B) and the cooled module (A). The cooled module achieves higher power values (maximum difference of ca. 15 W is observed), which represents a power increase by 4% compared to the comparison module power (B). A direct correlation can be seen between the power achieved by the PV module and the cooling water flow.

Figure 15 shows the variation of modules power calculated using Eqs. (3), (4) and (5). These calculations could be made using measured solar irradiance and the temperature of the modules. Compared to measured values of power, which are presented in Fig. 14, there are higher power values obtained for the cooled module (*A*) and the dependence of a calculated power value on the cooling water flow.

A comparison of the measured and calculated power values for the cooled module (*A*) is presented in Fig. 16. The maximum difference between the measured power value and the calculated value is about 40 W, thus a relative error is equal to 15%. The shape of the two presented characteristics is similar. The differences in the measured and calculated values may be due to the assumption adapted in calculations (i.e. it was assumed that the solar irradiance was perpendicular to the inclined module surface, while the solar irradiance perpendicular to a flat surface was measured experimentally).

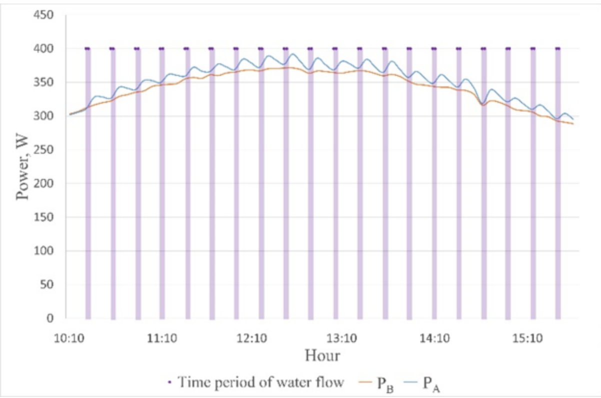

Fig. 15. The variation of module power during experiments performed in cloudless sky conditions (power was calculated using the calculation model presented in Section 3.3).

5. Summary and conclusions

The research was aimed to assess the impact of temperate climate atmospheric conditions on the temperature and on the electrical parameters achieved by the PV module, as well as evaluating the possibility of improving the energy conversion efficiency of the PV module by the application of a water cooling of its front surface.

The study showed that solar irradiance has the greatest influence on the PV module temperature. During the experiments, which were performed in cloudy and completely overcast sky conditions, the average ambient temperature differed. The solar radiation intensity during experiments, which were performed in cloudy sky conditions, reached values exceeding 1000 W/m^2, while during experiments performed in completely overcast sky conditions it reached nearly 500 W/m^2. The maximum temperature of the comparison module (*B*) for these experiments reached 51.2°C and 37.3°C, respectively.

The effect of the water cooling of the module was observed during the tests. During cooling, the temperature of the module was reduced to values close to the cooling water temperature. The maximum differences between the temperature of the comparison module (*B*) and the cooled module (*A*) reached values of 17.6 K, 7.6 K and 16.1 K for consecutive experiments.

The type of system used to determine water flow influences the maximum temperature reached by the cooled module. The application of temperature-dependent cooling water flow system (which was used during experiments performed in cloudy sky conditions) resulted in reaching lower maximum module temperature compared to the maximum temperature of comparison module. Thus, by application of this type of water cooling system it is possible to limit the modules operational temperature range. A different effect was observed for the periodic cooling water flow during the other experiments.

There is a noticeable difference in the temperature of the front and back surfaces of the module. For the cooled module (*A*), most of the time the back surface temperature was higher than the temperature of the front surface, and during cooling water flow, the cooling of the back surface is delayed. For the comparison module (*B*), the front surface temperature was higher than the back surface temperature.

The gains in the daily amount of electricity generated by the cooled module (*A*) are dependent on the weather conditions (mainly on the cloud cover and the solar irradiance). For a cloudless sky conditions, there is a noticeable growth observed in the amount of electricity generated by the cooled module. For cloudy sky conditions, cooling is not efficient or even may have negative influence on the module operating conditions.

During the experiments, which were performed in cloudless sky conditions, there was an increase in the cooled module (*A*) power observed compared to the comparison module (*B*). The maximum increase of ca. 4% was obtained. This is relatively low value compared to the data presented for installations tested in warmer climates than Polish. In Table 4, a comparison of the obtained research results with data published in literature is presented, illustrating differences between the results obtained in different climatic conditions.

The output power of PV modules can be clearly compared based on the results obtained during experiments, which were performed in cloudless sky conditions. The maximum output power of the cooled module was 374.5 W, while the output power of comparative module was equal to 360.7 W at the same time (i.e. an increase in output power by 3.83% was obtained). The maximum power increase of the cooled module was 5.64%, while the average power increase of the cooled module between 11 a.m. and 3 p.m. was equal to 7.6 W.

From the obtained research results, it can be concluded that to achieve a better cooling effect, the water cooling installation should be designed and regulated to enable periodic activation and deactivation of the cooling water flow based on the PV module temperature. In a large PV installation, a good solution appears to be the utilization of an underground water tank, which can dissipate the heat contained in the cooling water to the ground and utilize rainwater to replenish any water losses in the cooling system. It is worth to note that the application of module cooling is not only related to a possible increase in the amount of energy generated by modules, but also to increasing their longevity. The application of cooling reduces the amplitude and frequency of cell temperature fluctuations, decreases thermal loads, and consequently contributes to limiting their degradation, thereby extending their operational lifespan.

Further work could focus on determining and optimizing the periods of time during which the PV module cooling system would be activated, as well as the optimal cell temperature.

Based on the work carried out, the following most important conclusions can be drawn:

1. Solar irradiance has the greatest influence on the photovoltaic module temperature;
2. The maximum module temperature reduction was 7.6−17.6 K (depending on atmospheric conditions);
3. The maximum electrical output power increased by 5.65%;
4. To achieve a better cooling effect, the water cooling installation should be designed and regulated to enable periodic activation and deactivation of the cooling water flow based on the photovoltaic module temperature

Table 4. Comparison of the obtained research results with data published in the literature.

Reference	Cooling method	Location	Results
Kumar et al. [29]	Water flow	India, Chennai	• Decrease of the daily average module temperature from 56.67°C to 39.44°C • Increase of the average daily module electrical efficiency to 14.29%, compared to 12.74% (without cooling)
Moharram et al. [32]	Water flow	Egypt, Cairo	• Highest energy output is obtained if the panel temperature reaches the maximum allowable temperature of 45°C • Module temperature reduction by 10 K • Increase of module electrical efficiency of 12%
Chanphavong et al. [33]	Water flow	Laos	• Decrease of the highest module temperature from 65.7°C to 36.5°C • Increase of the average exergy efficiency of module to 12.76% compared to 2.91% (without cooling)
Zubeer et al. [34]	Water flow (with solar concentration system)	Iraq, Duhok	• Decrease of the module temperature from 64.1°C to 36.5°C • Increase of the module electrical efficiency to 17% compared to 14.2% (without cooling) • Increase of electric power output of 24.4%
Benato et al. [30]	Spraying the upper surface of the module	indoor test	The ON/OFF cycle in which water is sprayed for 30 s and remains turned off for 180 s constitutes the best compromise among mean surface temperature reduction and PV efficiency improvement: • Module temperature reduction – 24.31 K • Increase of module electrical efficiency to 13.27% compared to 11.18% (without cooling) • Increase of the amount of generated electricity from 178.88 W to 212.31 W
Nizetic et al. [31]	Spraying both sides of the module	Croatia, Split	• Decrease of the average module temperature from 54°C to 24°C • Increase of module electrical efficiency of 16.3% • Increase of electric power output of 14.1%

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