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Development and Tests of the Water Cooling System Dedicated to Photovoltaic Panels

Krzysztof Sornek *, Wojciech Goryl, Rafał Figaj, Gabriela Dąbrowska and Joanna Brezdeń

Department of Sustainable Energy Development, Faculty of Energy and Fuels, AGH University of Science and Technology, Mickiewicza Ave. 30, 30-059 Krakow, Poland
* Correspondence: ksornek@agh.edu.pl

Abstract: Among all the energy production technologies based on renewables, the photovoltaic panels are the ones with the highest rate of development and applications worldwide. In this context, significant efforts are put into research on innovative materials in order to improve the performance of photovoltaic cells. Nevertheless, possibilities available to enhance the energy yield of existing technologies also exist and are explored, such as the cooling of photovoltaic modules. This approach can decrease the mean operation temperature of photovoltaic cells, leading to an increase in efficiency and energy produced. In the present paper, this method is investigated by developing and testing a dedicated water cooling system for photovoltaic panels. In order to investigate the performance of the cooling system, two market-available monocrystalline photovoltaic panels with a power of 50 and 310 Wp were tested under laboratory and real operation conditions, respectively. Based on the results obtained under laboratory conditions, the most promising variant of the cooling system was selected and assessed under real operation conditions. For this system, the maximum temperature of the water-cooled 310 Wp panel was lower by approx. 24 K compared to an uncooled panel, as pointed out by a measurement performed during a typical sunny day when solar irradiation was approximately 850 W/m^2. This improvement of the cell temperature led to a 10% increase in power generated by the water-cooled photovoltaic panel compared to the uncooled one. The economic analysis revealed that the estimated simply payback time for installing the cooling system in typical domestic photovoltaic installations can be less than 10 years, while from the point of view of net present value, the introduction of the water cooling system can be a profitable option for a 10-year period when a discount rate of 5% is considered.

Keywords: solar energy; photovoltaics; PV; electricity generation; renewable energy; cooling photovoltaic panels

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1. Introduction

Currently, the most dynamically developing sector of renewable energy is photovoltaics in centralized or decentralized systems [1]. In addition to building applications, photovoltaic (PV) panels are increasingly used, e.g., in the electromobility sector to supply cars, aircraft, and boats [2–4]. Independently from the application, the possibilities to obtain energy from various types of PV panels are mainly related to two aspects: (i) availability of solar irradiation and (ii) operating temperature [5]. The most important parameter that directly affects the energy yield of PV panels is the availability of solar irradiation in a given area. Solar irradiation reaching the Earth's atmosphere is not completely transmitted; it is partly dispersed or absorbed by the Earth's atmosphere. These phenomena are strongly dependent on the location and seasons of the year [6].

The amount of electricity produced from a photovoltaic installation is affected not only by the location but also by its operating conditions, including aspects related to the heating PV of panels and the accumulation of dirt or particles which obstruct or distract light energy from reaching the solar cells [7]. Accumulation of dirt or particles (dust, water, sand, and moss) depends on such environmental factors as wind, temperature, moisture, humidity, rainfall, dust properties, or bird droppings [8–10]. On the other hand, the heating of PV panels results mainly from their thermal balance, which includes the following heat flows:

- Solar radiation energy falling on the solar cells;
- Conductive heat transfer to the roof sheet, and to the mounting frame, convective heat transfer, and radiative heat transfer to the surrounding environment (see Figure 1).

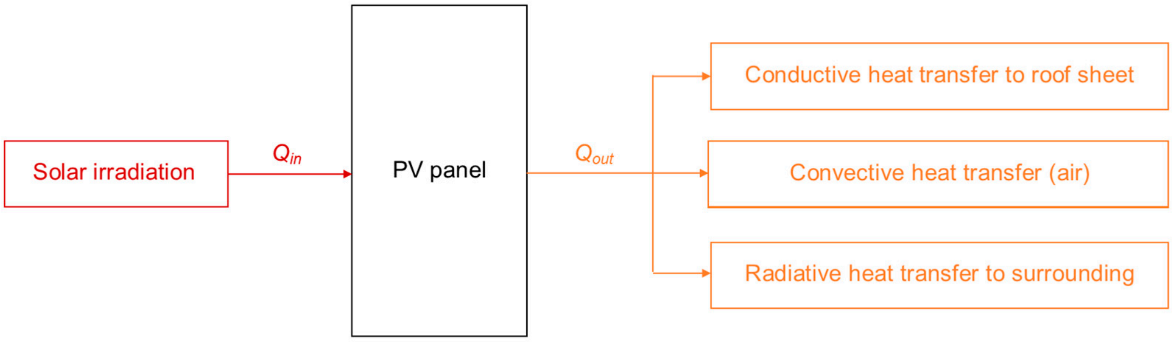


Figure 1. Thermal balance of the PV panels.

The higher the module surface temperature, the higher short-circuit current, and the lower the open-circuit voltage. The negative effect of lowering the open-circuit voltage is dominant and consequently, this lowers the power of the PV panel compared to standard testing conditions [11]. The impact of temperature on the operating characteristic of PV panels is illustrated in Figure 2.

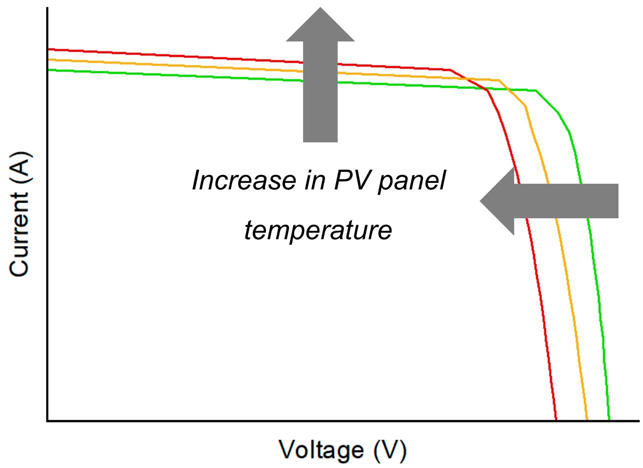


Figure 2. The impact of temperature on the operating characteristic of PV panels.

To minimize the negative effect of temperature on the operation of the PV panels, it is necessary to use modules with a reduced impact on the power drop as a function of increasing temperature. Moreover, hybrid systems in the form of photovoltaic/thermal collectors (PV/T) can be used to decrease the panel temperature and to obtain higher efficiency with respect to normal PV module operation conditions because of simultaneous heat and electricity generation [12].

In PV/T systems there exist numerous possibilities to increase the overall efficiency: systems with glass coating [13], use of unglazed units [14], a different arrangement of water channels [15], adoption of collectors completely or partially covered with solar modules [16], use of semitransparent solar cells [17], or the use of phase change materials (PCM) [18]. In [19] the operation of various cooling variants of a PV/T system was investigated. The highest efficiency was obtained for the water flow of 0.014 kg/s and for the water inlet temperature of 15 °C. For such operating conditions, the authors obtained combined efficiency of 93.92%, of which the electrical efficiency was 17.79% and the thermal efficiency was 76.13%.

In the case of photovoltaic installations, active or passive water or air cooling systems of PV panels could be used [20]. In [21] the authors examined the possibilities of using various types of passive cooling for a 50 W polycrystalline PV panel. The proposed cooling systems were compared with a panel without cooling. The best results were obtained for the panel with the coir pith cooling system. In this type of passive cooling, the power increased by 11.34%.

Authors in [22] tested three different PV cooling techniques, based on air cooling, water cooling, and combined air and water cooling systems. Under Egyptian climate conditions, the best technic was the water cooling system which was characterized by a 7%, 18%, and 29% higher efficiency compared to combined air and water system, air system, and conventional PV panel, respectively. Whereas in [23] in Iraqi climate conditions the efficiency of PV systems increased from 10.23% for a system without cooling to 10.32%, 11.58%, and 11.69% for air cooling, water cooling, and combined water and air cooling, respectively. In [24] the cooling of a PV panel by using a solar collector attached to the rear side of the PV panel was presented. In Saudi Arabia's climate conditions, the temperature of the enhanced PV panel dropped by 20% with respect to the unmodified unit, which translated into a 9% electrical higher efficiency. Baloch et al. investigated a converging channel cooling system to achieve a low and uniform temperature of the PV panel surface. The introduced system cooled down the PV panel meanly from 71.2 °C and 48.3 °C to 45.1 °C and 36.4 °C in under June and December operation conditions, respectively. Compared to uncooled PV systems the efficiency increased by 35.5%, and simultaneously the levelized cost of energy (LCE) decreased from 1.95 EUR/kWh to 1.57 EUR/kWh [25].

Apart from water cooling systems, there are possibilities to use nanofluids to increase the overall efficiency of solar PV systems. Xu and Kleinstreuer presented in their paper that using nanofluids could increase the efficiency by 24.1% compared to system without cooling. At the same time, power generation was 57% and 25.6% higher than in PV alone and PV only water-cooled systems, respectively [26].

Another way of PV performance improvement is the use of water spraying systems since it is promising due to the possibility of simultaneous cooling from contamination of the front of the PV panel. Such a system was described in [27]. The authors using a cooling system achieved a temperature of 24 °C in front of the PV panel compared to 44 °C in a reference non-cooled module. The power and efficiency were 30% higher compared to a PV panel without any cooling system. Whereas in [28] the authors investigated the possibility of water cooling on the back side of a PV panel for two identical PV panels: one with cooling and the other without cooling. The system with a cooling system achieved a power increase compared to the panel without cooling by 14.1% with an electrical efficiency of 19.8%. The electrical efficiency of the panel without cooling was 17.4%.

There are also technological solutions for PV panels that increase the yield in photovoltaic installations. For example, using bifacial PV panels, where solar cells are located on the front and rear side of the PV panel, could increase from 10% to 28% the production of energy compared to traditional monofacial photovoltaic installations [29]. Another way to increase the performance of PV panels is using solar concentrators, including parabolic dish concentrators [30], Fresnel lenses [31], nanofluid optical filters [32], and other solutions. Moreover, hybrid systems, such as photovoltaic/thermal systems (PV/T) [33], photovoltaic/wind systems [34], ground/photovoltaic/wind systems [35], and PV panels integrated with thermoelectric generators (PV/TEG) [36] are considered in the frame of increasing the performance of solar systems. It is also possible to use CPV (concentration photovoltaic) systems to increase energy yield. In [37] energy yield from three types of PV systems was investigated: conventional PV panel, concentrated PV system, and water-cooled concentrated PV system. Compared to the conventional PV panel, the authors obtained a power increase of 10.65% and 24.4% for the concentrated PV system and water-cooled concentrated PV system, respectively.

When analyzing the available literature data, it may be concluded that cooling systems can play an important role in ensuring the high efficiency and reliability of PV panels. On the other hand, many of the existing solutions require further improvements to provide effective work with low investment and operating costs. In fact, the main problems of ad hoc developed systems for the improvement of PV performance are related to their integration into conventional panels, which lead to significant costs for the adopted technology. Therefore, the main goal of solving the problem of the adoption of cooling systems is the achievement of the best improvement with minimum installation complexity as well as the investment needed to build the system. Conversely, the adoption of the ways mentioned in the previous paragraph to improve PV yield involves the adoption of expensive technologies, which may overcome the cost of the sole PV installation.

Thus, the aim of this paper is to develop a cooling system dedicated to PV panels, which will be characterized by low investment costs, simple construction, and safe operation for PV panels. Such a system should eliminate the problem significantly affecting solar panels' efficiency: the relatively high temperature during their operation. Taking into account these assumptions, a prototype of the cooling system has been developed and described. This prototype consists of a water pipeline on the front sides of PV panels (header), which helps to decrease the temperature of solar cells. The system is also equipped with a thermostat with a temperature sensor for measuring the temperature of the panel. The spraying system is designed to operate and spray water only when the panel temperature rises to relatively high levels. From the hydraulic point of view, the system consists of a non-pressurized water cooling circuit to cool down the PV panels. The system is investigated in both laboratory and outdoor conditions in terms of temperature distribution on the PV panels surface and electrical parameters achieved by the device in order to assess the effect of cooling on the PV panels performance.

The contribution of this work is threefold: (i) the proposed cooling system was innovatively designed as a system, in which water is both a cooling medium and a layer limiting the heat flux from solar radiation; (ii) cooling water can be used also as a cleaning medium, (iii) heated water can be used to preheat domestic hot water when dedicated heat exchanger will be applied. Furthermore, the developed water cooling system can be adapted depending on the type of PV panels and the size of the photovoltaic installation. In addition, the system configuration allows rainwater to be collected and used.

The further part of the paper is structured as follows: the Section 2 includes information regarding the experimental rigs and the main parameters of the components used during the presented studies; the Section 3 presents results obtained under laboratory and real conditions as well as the analysis of economic aspects of introducing a water cooling system, and finally, Section 4 includes a summary of the main findings resulting from the discussed studies.

2. Materials and Methods

The investigations were divided into two parts: the first part was carried out using 50 Wp PV panels tested under laboratory conditions, while the second part of the study was carried out using 310 Wp panels tested under real conditions. The detailed information regarding the configuration of the experimental rigs has been included below.

2.1. Experimental Rig with 50 Wp PV Panels (Experimental Rig No. 1)

The experimental rig no. 1 was developed to test PV panels under laboratory conditions. As can be observed in Figure 3, the rig is equipped with a PV panel, artificial light source, water tank, water cooler, water pump, air fan, electrical load, pyranometer, temperature sensors, flowmeter, modular PLC controller with a set of I/O modules, computer with installed CoDeSys software, and other electric and hydraulic components (valves, pipes, elbows, tees, filter, connectors, etc.). Additionally, an infrared camera was used to assess temperature distribution on the front surface of the tested PV panel. During the tests, cooling water is supplied through a header (*HE*) located on the front part of the PV panel. The header has holes through which water is sprayed onto the surface of the panel. After receiving heat from the surface of the panel, water is collected by a water collector (located on the bottom part of the panel), cooled down in a water cooler (*WC*), and flows to the water tank (*WT*). The water is then pumped again to the header and the whole process starts from the beginning. It is worth noting that the entire process is organized in a closed loop, so there is no need to supply fresh water. Actually, the operation of the system can be controlled manually using specially developed visualization: the operator can turn on and turn off artificial light, water pump, and air fan. Furthermore, it is possible to observe and archive measured values of temperatures, water flow, as well as voltage, current, and power generated by the tested PV panel.

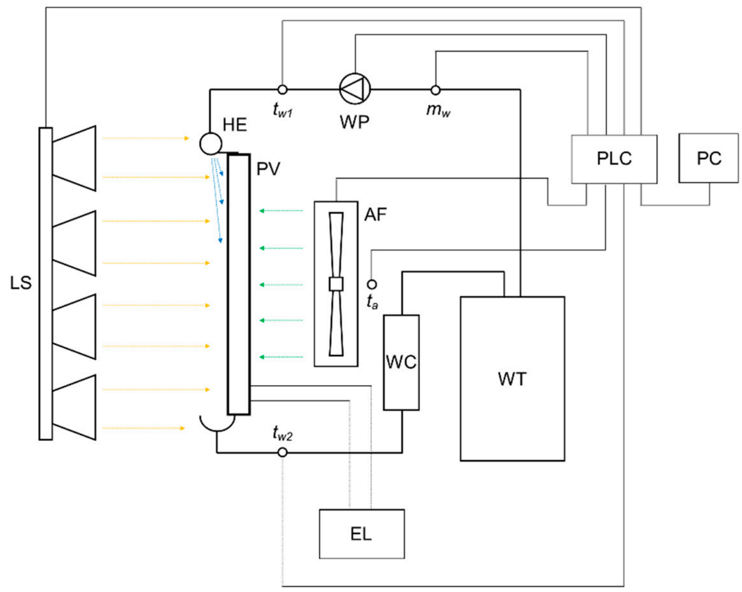
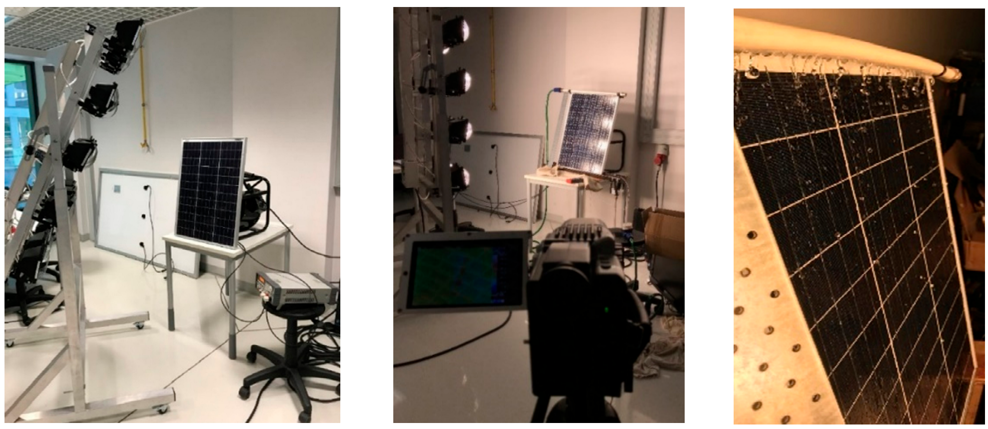


Figure 3. General scheme of the experimental rig (PV: PV panel, LS: light source, AF: air fan, WT: water tank, HE: header, WP: water pump, WC: water cooler, EL: electronic load, PLC: programmable logic controller, PC: computer, t_{w1}, t_{w2}, t_{air}: temperature sensors, m_w: water flowmeter).

The configuration of experimental rig no. 1 is shown in Figure 4. During described tests, the rig was located in the Laboratory of Energy Conversion at AGH UST in Krakow.

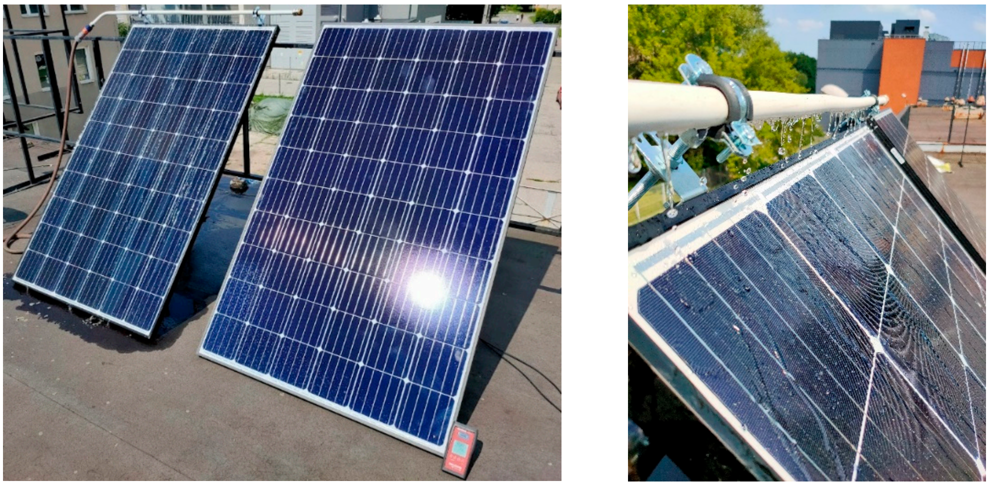


(**a**) (**b**) (**c**)

Figure 4. Experimental rig no. 1: (**a**) general view of the experimental rig no. 1, (**b**) experimental rig during tests with an infrared camera, (**c**) a part of the water cooling system (header) installed on the tested 50 Wp PV panel.

2.2. Experimental Rig with 310 Wp PV Panels (Experimental Rig No. 2)

The experimental rig no. 2 was located on the roof of the building of the Faculty of Energy and Fuels at AGH UST in Krakow. Measurements were carried out during summer using the following equipment: two identical PV panels, cooling water loop, electrical load, pyranometer, temperature sensors, flowmeter, modular PLC controller with a set of I/O modules, computer with installed CoDeSys software, and other electric and hydraulic components. The results obtained from the water-cooled PV panel were compared with the operational parameters of the uncooled PV panel. The part of the experimental rig no. 2 (including elements located on the roof) is shown in Figure 5.



(**a**) (**b**)

Figure 5. Experimental rig no. 2: (**a**) the general view of the experimental rig no. 2 with shown elements located on the roof, (**b**) a part of the water cooling system (header) installed on the tested 310 Wp PV panel.

2.3. The Main Parameters of the Components Used

The detailed parameters of the components used during tests are the following:

- The 50 Wp polycrystalline PV panels characterized by a maximum power P_{MAX} of 50 W, a nominal MPP current I_{MPP} of 2.77 A, a nominal MPP voltage V_{MPP} of 18.00 V, a short circuit current I_{SC} of 2.96 A, an open circuit voltage V_{OC} of 21.60 V, and dimensions of 680 × 510 × 30 mm [38];
- The 310 Wp monocrystalline PV panels characterized by a maximum power P_{MAX} = 310 W, a nominal MPP current I_{MPP} of 9.31 A, a nominal MPP voltage V_{MPP} of 33.30 V, a short circuit current I_{SC} of 9.70 A, an open circuit voltage V_{OC} of 39.99 V, and dimensions of 1640 × 992 × 35 mm [39];
- Artificial light source equipped with 15 halogen lamps characterized by the electrical power of 7.5 kW (500 W each lamp);
- Electronic load with the following input ratings: current 0–40 A (accuracy 0.05% + 8 mA), voltage 0–80 V (accuracy 0.1% + 8 mV), and power 0–400 W (accuracy 0.1% + 600 mW);
- Programmable logic controller with a set of I/O modules, including analog modules to measure temperature and flow, as well as digital modules to control the operation of pump, air fan, and light source;
- Pt100 resistance sensors with a measuring range from −50 °C to 400 °C and tolerance of ±0.3 + 0.005 × [t];
- Water flowmeter with pulse transmitter (1 L = 1 impulse) (accuracy ±3.0%).

The assessment of the performance of tested PV panels was realized on the basis of the measured values of current, voltage, and power by means of an electronic load. Another parameter, which can be used to assess the PV panels' operation, is fill factor (*FF*). It was calculated using the following equation:

$$FF = \frac{P_{MAX}}{I_{SC} \cdot V_{OC}} \quad (1)$$

where:

P_{MAX}—the matched power, W
I_{SC}—short circuit current, A
V_{OC}—open circuit voltage, V

The economic model used to investigate the performance of the proposed solution was based on investment costs of the cooling system, and energy savings. It was assumed that operation of pump, cooler and controller requires electric power, which will be taken from the PV panels. The cost of water has not been included in the analysis because water used in proposed installation is the rainwater and any water losses are replaced by stored rainwater. Moreover, the yearly maintenance costs were assumed at a level of 10% of the initial costs. Simple payback time of the installation (SPBT) was calculated as a function of initial cost, maintenance costs, and energy savings on the basis of the following equation:

$$\text{SPBT} = \frac{I_C}{E_s} \quad (2)$$

where:

I_C—initial costs, EUR
E_S—energy savings, EUR/year

Net Present Value (NPV) after the period of 10 and 15 years is calculated with the use of discount rates (α) of 5% and 10%. This economic parameter was calculated on the basis of the following equation [40]:

$$\text{NPV} = \sum_{t=1}^{n} \frac{CF_t}{(1+\alpha)^t} - I_C \quad (3)$$

where:

I_C—initial costs, EUR
CF_t—net cash flow during a single period t, EUR/year
A—discount rate, -
T—number of time periods, years

3. Results and Discussion

The tests described below were divided into four measurement series. Series 1–3 were carried out using a 50 Wp PV panel under laboratory conditions. The impact of temperature on the performance of the PV panel was analyzed and different cooling methods were compared. Based on results obtained in Series 1–3, Series 4 was carried out using a 310 Wp PV panel under real conditions. The impact of temperature on the performance of the PV panel on sunny days was analyzed. Finally, the economic premises regarding the introduction of a water cooling system to PV panels were assessed.

3.1. Series 1—Study of the Impact of Temperature on the Performance of the 50 Wp PV Panel

Temperature is one of the crucial factors affecting the performance of photovoltaic panels. As can be observed in Figure 6 the average temperature of the tested 50 Wp PV panel increased from 298 K (measured at the beginning of the experiments) to approximately 327.3 K (in minute 7.5) and approximately 349.1 K (in minute 15). These values were observed when irradiance was at an average level of approximately 750 W/m^2. The most significant increase in PV panel temperature occurred in the first part of the tests (approximately 3.9 K/min between the initial phase and 7.5 min), while in the second part temperature increase was quite lower (approximately 2.9 K/min). Variations in the temperature of the PV panel can be described by the polynomial function $y = -0.051 \cdot x^2 + 4.656 \cdot x + 298.892$, where y—the temperature in K and x—time in minutes. The coefficient of determination R^2 is 0.995.

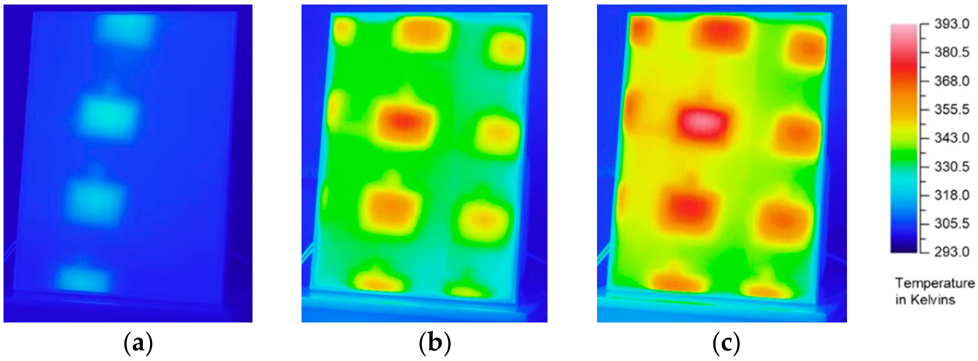


Figure 6. Temperature distribution on the front side of the 50 Wp PV panel during experiment: (**a**) beginning of the experiment, (**b**) after 7.5 min, (**c**) after 15 min (visible areas with higher temperatures are a result of the configuration of the light source).

Hot spots visible on thermal images come from a halogen light source which turned out to be problematic in the analysis of temperature distribution on the front surface of the tested PV panels. However, as part of laboratory work, it did not significantly affect the results obtained in the initial phase of the study. The comparative results did not show an excessive influence on the occurrence of visible hot spots in the thermograms.

The temperature of the PV panel significantly impacts its performance. As can be observed in Figure 7, the maximum power generated in the tested PV panel varied from 29.4 ± 0.6 W (at the beginning of the experiment, when the average panel temperature was approx. 298.0 K), to approximately 27.3 ±0.6 W (after 7.5 min, when the average panel temperature was approx. 327.3 K) and approximately 25.9 ± 0.6 W (after 15 min, when the average panel temperature was approx. 349.1 K). The decrease in PV panel performance was calculated as −0.28%/K, while a value of −0.35%/K was declared by the manufacturer. Finally, after 15 min, the performance of the tested PV panel was lower by approximately 12.0% compared to the initial phase of the experiment. On the other hand, the obtained values were lower than the nominal matched power, which resulted, e.g., from testing conditions.

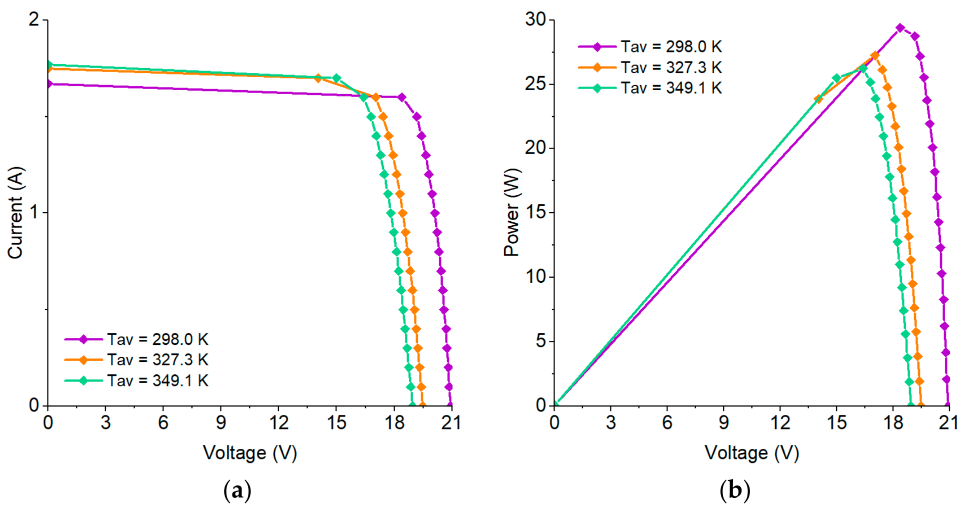


Figure 7. Variations in the performance of the 50 Wp PV panel depend on its temperature (without any cooling system): I-V characteristic (**a**) and P-V characteristic (**b**).

3.2. Series 2—Study of the Impact of Cooling on the Performance of the 50 Wp PV Panel

To reduce the negative effect of temperature on the performance of the tested PV panel, two cooling methods were analyzed: air cooling and water cooling systems. In the first case, the air fan was cooling the rear side of the tested PV panel, while in the second case water was used to cool its front side. In this case, the front side of the panel was sprayed manually with water. As is shown in Figure 8, the average temperature of the panel surface was the lowest in the case of using a water cooling system. After 15 min of the experiment, the PV panel had reached a temperature of 327.8 K when the water cooling system was used, compared to 334.5 K when the air cooling system was used, and 349.1 K without any cooling system.

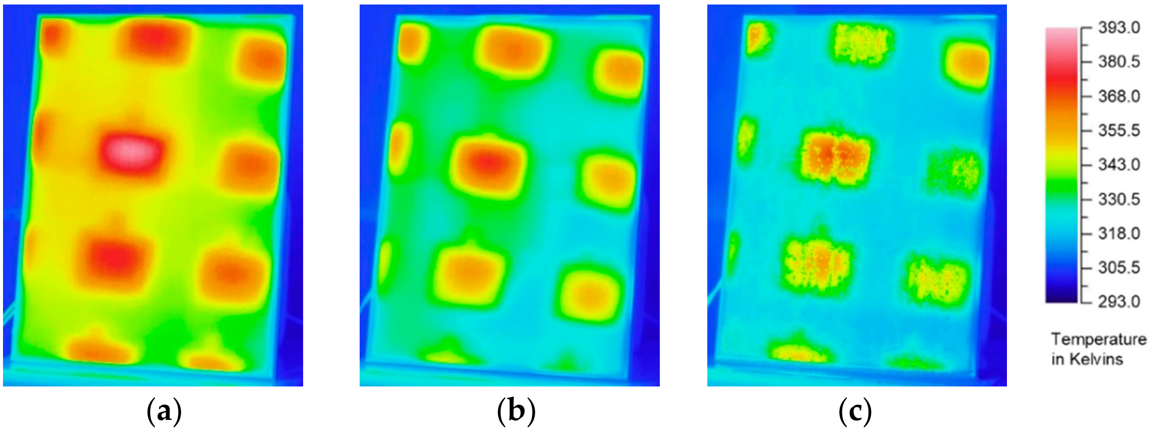


Figure 8. Temperature distribution on the front side of the 50 Wp PV panel after 15 min of the experiment: (**a**) without cooling, (**b**) with air cooling, (**c**) with a water cooling system (visible areas with higher temperature result from the configuration of the light source).

The maximum power generated in the tested panel with a water cooling system was 28.3 ±0.6 W at the 15th minute. This value was higher by 2.5% compared to the configuration when the air cooling system was used (27.6 ± 0.6 W) and higher by 9.3% compared to the configuration without any cooling system (25.9 ± 0.6 W). The temperature coefficient was calculated as −0.16%/K, −0.22%/K, and −0.28%/K, respectively. It can be stated that by using a water cooling system, the performance of the tested 50 Wp PV panel can be increased by approx. 7.9% compared to solar panels operating without cooling. It is worth noting that this result was achieved under only a simple manual cooling system. Variations in the performance of the PV panel as a function of the cooling method used are shown in Figure 9.

3.3. Series 3—The Impact of Water Cooling on the Performance of the 50 Wp PV Panel

Considering the fact that manual water cooling was characterized by the highest positive impact on solar panel performance during the test conducted in Series 2, the prototypical cooling system was introduced and tested. The distribution of water flow through the front side of the PV panel tested achieved with the laboratory-scale developed water cooling system is shown in Figure 10. As can be observed in Figure 11, by implementing the dedicated water cooling system, the performance of the tested PV panel increased by approx. 11.6% compared to uncooled panel (28.9 ± 0.6 W compared to 25.9 ± 0.6 W) under the same experimental conditions adopted in Series 2.

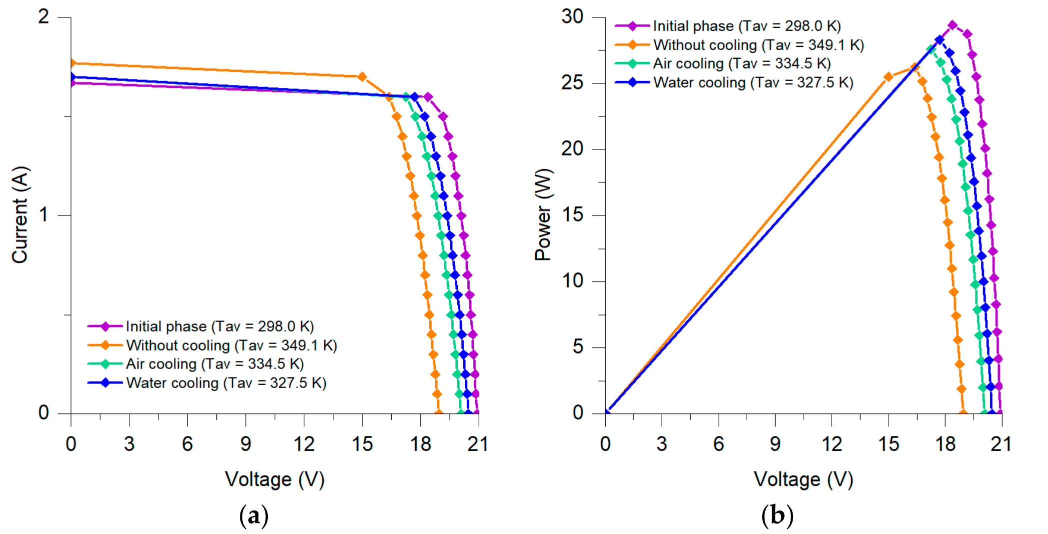


Figure 9. Variations in the performance of the 50 Wp PV panel depend on its temperature (resulted from the cooling method used): I-V characteristic (**a**) and P-V characteristic (**b**).

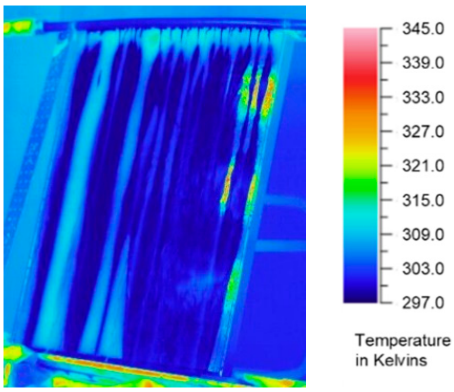


Figure 10. Temperature distribution on the front side of the 50 Wp PV panel after 15 min of the experiment (when dedicated water cooling system was used).

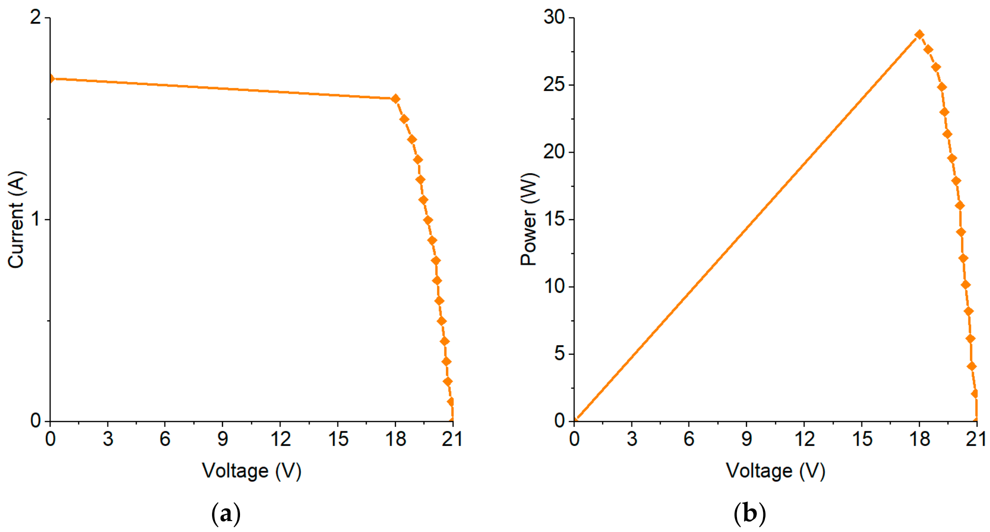


Figure 11. Variations in the performance of the 50 Wp PV panel depend on its temperature (when the prototype of water cooling system was installed and used): I-V characteristic (**a**) and P-V characteristic (**b**).

3.4. Series 4—The Impact of Temperature on the Performance of the 310 Wp PV Panel

The results obtained in laboratory conditions during Series 1–3 were taken into account to construct the prototypical version of water cooling system dedicated to normal size PV panels. The tests performed in Series 4 were conducted under real conditions during typical sunny day when solar radiation was approx. 850 W/m^2. Temperature of ambient air was approx. 300 K, while temperature of the cooling water was approx. 293 K. As is shown in Figure 12, the average temperature of the water-cooled PV panel was lower by 29.1 K compared to the uncooled panel (the temperatures were 297.8 K and 326.9 K, respectively). The consequence of the implementation of the water cooling system and the reduction in panel temperature was the increase in power generation (see Figure 13). When water cooling was installed, the maximum power generated in the solar panel no. 2 was 281.8 ± 0.9 W, while in the case of the uncooling panel the maximum power was at a level of 255.1 ± 0.9 W, (i.e., lower by 9.5%).

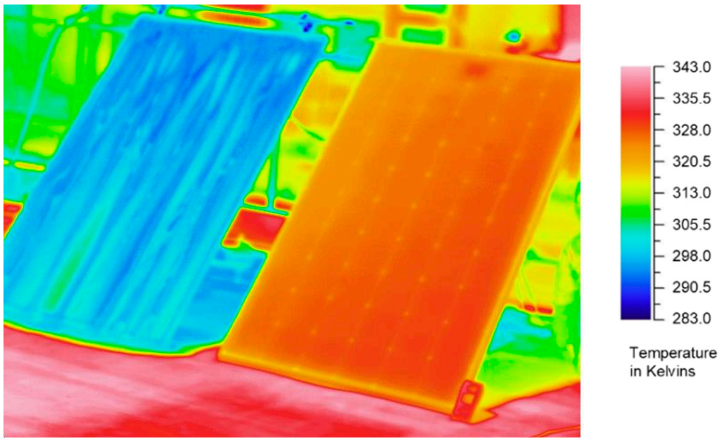


Figure 12. Thermal images show the temperature on the front surface of the tested 310 Wp PV panel without cooling (**right** panel), and with a water cooling system (**left** panel).

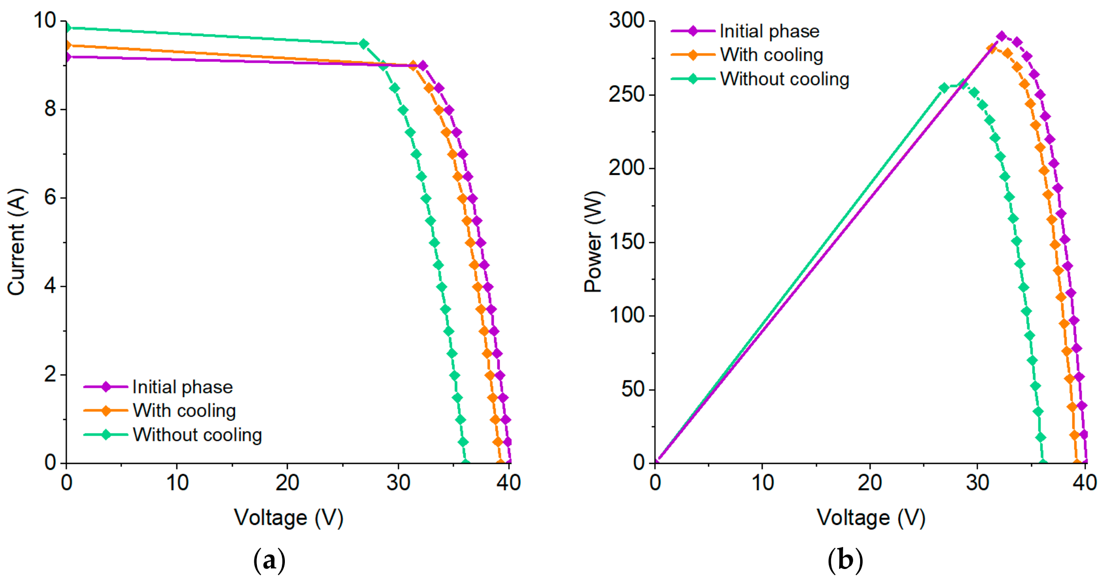


Figure 13. Variations in the performance of the 310 Wp PV panel depending on its temperature: I-V characteristic (**a**) and P-V characteristic (**b**).

3.5. Summary of the Results Obtained in Series 1–4

Measured values of the maximum power, short circuit current and open circuit voltage were used to calculate the fill factor (according to Equation (1)). Table 1 shows variations in the operating parameters of the tested 50 Wp PV panel depending on the cooling method (Series 1–3). As can be observed, FF is the highest in time 0 (when it is 0.88), and in the further part of the experiment it is lower due to the temperature increase in the panel. Indeed, the value of FF strongly depends on the temperature of the tested PV panel, which results from the cooling method. In Series 1, when cooling was not used, FF dropped to 0.77 (decrease of 12.5%), while in Series 2 the calculated decrease in FF value was lower, since it was 8.0% in the case of water cooling and 9.1% when air cooling was used. Finally, in Series 3 the value of FF after 15 min of experiment was 0.82, with a decrease of 6.8% compared to the initial phase. The lowest reduction in the performance of PV panel and in the value of FF confirm the importance of using water cooling systems to increase the amount of power generated in photovoltaic installations. Power generated in the case of water cooling PV panel was 28.9 ± 0.6 W, and it was approx. 94.0% of the power generated by the PV panel at the initial phase of the experiment.

Table 1. Variations in the operating parameters of the tested 50 Wp PV panel depending on the cooling method.

Cooling Method	**V_{MPP} V**	**I_{MPP} A**	**P_{MPP} W**	**V_{OC} V**	**I_{SC} A**	**FF -**
			Initial phase (t = 0 min.)			
N/A	18.4	1.6	29.4	21.6	1.7	0.88
			Final phase (t = 15 min.)			
No cooling (Series 1)	16.2	1.6	25.9	18.5	1.8	0.77
Air cooling (Series 2)	17.3	1.6	27.6	20.1	1.7	0.80
Water cooling (Series 2)	17.7	1.6	28.3	20.5	1.7	0.81
Water cooling (Series 3)	18.0	1.6	28.9	20.9	1.7	0.82

In Series 4, the fill factor ranged from 0.72 to 0.76 in the case of no cooling and water cooling system, with a decrease of 8% and 3% compared to the initial phase. Variations in the operating parameters of the tested 310 Wp PV panel are presented in Table 2.

Table 2. Variations in the operating parameters of the tested 310 Wp PV panel.

Cooling Method	**V_{MPP} V**	**I_{MPP} A**	**P_{MPP} W**	**V_{OC} V**	**I_{SC} A**	**FF -**
Initial phase	32.3	9.0	289.9	40.1	9.2	0.78
No cooling (Series 4)	28.3	9.0	255.1	36.1	9.9	0.72
Water cooling (Series 4)	31.3	9.0	281.8	39.2	9.5	0.76

3.6. The Economical Aspects of Introducing a Water Cooling System

In addition to the technical aspects of the operation of the tested 310 Wp PV panels, the economic premises of the proposed water cooling system should be taken into account. Based on the obtained results, some general conclusions can be drawn. However, since the only prototypical version of the cooling system was tested (which will be further developed), some additional assumptions were introduced to the analysis concerning, i.e., a typical domestic photovoltaic installation with installed power at a level of 5 kWp and 10 kWp. An investment cost of a water cooling system was estimated to be approx. EUR 750, considering a photovoltaic installation with an installed power of 5 kWp, and approx. EUR 1200 for a photovoltaic installation with an installed power of 10 kWp. These costs include, i.e., header, water tank, water pump, cooler, pipes, filter, controller, and other fittings. Moreover, it was assumed that the operation of the pump, cooler, and controller requires electric power, which will be taken from the PV panels. Considering Polish climatic conditions, characterized by insolation around 1000–1100 kWh/(m^2·year) [41] and an electrical energy generation potential of approx. 1000 kWh/year from each 1 kWp of installed power under real operation conditions, the yearly electricity generation can be increased by approx. 10% taking into account the results of the presented tests. To calculate SPBT and NPV, Equations 2 and 3 were used, respectively. It was assumed that the actual price of electricity was EUR 0.2134 per kWh (based on the average price in the EU-27 area for the second half of 2020) [42]. The results of the conducted analysis are presented in Table 3.

Table 3. Economic aspects of introducing the colling system.

Parameter	PV Installation 5 kWp	PV Installation 10 kWp
Estimated investment costs, EUR	750	1200
Estimated increase in generated energy, kWh	500	1000
Estimated economic benefits, EUR per year	90	180
SPBT, years	8.3	6.7
NPV (10 years, α = 5%), EUR	−55.0	189.9
NPV (10 years, α = 10%), EUR	−197.0	−94.0
NPV (15 years, α = 5%), EUR	184.2	668.3
NPV (15 years, α = 10%), EUR	−65.5	169.1

The SPBT for the installation of the water cooling system to the PV panels ranges from 6.7 to 8.3 years depending on its size. The values of NPV are worse. Assuming a 10-year period, NPV ranges from EUR −55.0 to EUR 189.9 (when the discount rate is 5%) and from EUR −197.0 to EUR −94.0 (when the discount rate is 10%). On the other hand, when a 15-year period is considered, the NPV ranges from EUR 184.2 to EUR 668.3 (when the discount rate is 5%) and from EUR −65.5 to EUR 169.1 (when the discount rate is 10%). Thus, from an economic point of a view, the introduction of the water cooling system to 10 kWp photovoltaic installation is a profitable option, when: (i) a 10-year period and discount rate of 5% is considered or (ii) when a 15-year period is considered regardless of the discount rate.

4. Conclusions

This paper deals with the problems associated with the heating of the surface of PV panels which reduces the efficiency of electricity generation. This problem can be solved by introducing a dedicated water cooling system into PV panels. Such a system has been developed by the authors. During the described tests cooling, water was supplied through a header located on the front part of the PV panel. The adopted configuration of the water cooling system has advantages such as direct cooling, with fluid as a heat transfer barrier.

The measurements carried out were divided into four series. Series 1–3 were performed under laboratory conditions, while Series 4 was performed under real conditions. In the case of tested PV panel no. 1, the maximum generated power was 29.4 ± 0.6 W when the average panel temperature was approx. 298.0 K (at the beginning of measurements). Generated power decreased from 29.4 ± 0.6 W to 25.9 ± 0.6 W after 15 min of the experiment, when the average panel temperature was approx. 349.1 K. This means that the performance of the heated panel was lower by approx. 12.0% compared to the panel operated with the initial temperature. When the prototypical water cooling system was introduced, the power generated by the tested PV panel was lower by approx. 1.7% compared to the value obtained when the temperature was approx. 298 K. On the other hand, the generated power was higher by approx. 11.6% compared to the situation when the panel operated without any cooling system. Finally, the tests were carried out under real conditions. When water cooling was installed, the maximum power generated in the 310 Wp PV panel was approx. 281.8 ± 0.9 W, while in the case of the uncooled panel the maximum power was approx. 255.1 ± 0.9 W which gives a 10% power increase. It is estimated that the efficiency of the PV cooling system increases the efficiency by 2% compared to the non-cooled system. It is comparable with the data obtained in the literature, e.g., [23,28]. This allows for the conclusion that the chosen path to improve the efficiency of PV panels is correct and should be further developed in the future. The authors provide that the introduction of additional cooling modifications and their optimization will allow for additional efficiency increases.

The results presented confirm that the proposed solution can be a really interesting option from the standpoint of increasing the efficiency and reliability of PV panels. The introduction of such a system may affect not only the performance of PV panels but also the economic aspects of their operation. As was calculated, the estimated SPBT varies from 6.7 to 8.3 years. On the other hand, the introduction of the developed water cooling system to a 10 kWp photovoltaic installation can be a profitable option, when a 10-year period and discount rate of 5% are considered or when a 15-year period is considered regardless of the discount rate.

Future works will be focused on the further examination of the proposed water cooling system in real conditions. Then, based on the actual observations, the required modification will be introduced to the prototype and the prototype will be installed on the experimental photovoltaic installation. Furthermore, collected data will be used to create and validate a mathematical model describing the performance of the PV panels equipped with the water cooling system. This model will be used to perform dynamic simulations and assess the impact of the introduction of water cooling to photovoltaic installations.

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Abbreviations

AF	Air fan
EL	Electronic load
EUR	Euro
CPV	Concentration photovoltaic
FF	Fill factor
HE	Header
I/O	Input/output
LCE	Levelized cost of energy
LS	Light source
NPV	Net present values
PC	Computer
PCM	Phase change materials
PLC	Programmable logic controller
PV	Photovoltaic
PV/T	Photovoltaic thermal
SPBT	Simple pay-back time
WC	Water cooler
WP	Water pump
WT	Water tank
TEG	Thermoelectric generator

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