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# Experimental Investigation of the Effect of a Combination of Active and Passive Cooling Mechanism on the Thermal Characteristics and Efficiency of Solar PV Module

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**Abstract:** A photovoltaic (PV) module's electrical efficiency depends on the operating temperature of the cell. Electrical efficiency reduces with increasing PV module temperature which is one of the drawbacks of this technology. This is due to the negative temperature coefficient of a PV module which decreases its voltage significantly while the current increases slightly. This study combines both active and passive cooling mechanisms to improve the electrical output of a PV module. A heat sink made up of aluminum fins and an ultrasonic humidifier were used to cool the panel. The ultrasonic humidifier was used to generate a humid environment at the rear side of the PV module. The cooling process in the study was able to reduce the temperature of the panel averagely by 14.61 °C. This reduction led to a 6.8% improvement in the electrical efficiency of the module. The average power of 12.23 W was recorded for the cooled panel against 10.87 W for the referenced module. In terms of water consumption, a total of 1.5 L was approximately consumed during the whole experimental process due to evaporation. In effect, the proposed cooling approach was demonstrated as effective.

**Keywords:** solar photovoltaic panels; electrical efficiency; aluminum fins; passive cooling; active cooling

## 1. Introduction

Economic development coupled with the increasing population growth has led to an upsurge in primary energy consumption at a rate of about +1.6 percent each year [1]. This necessitates the need to find alternative clean, cheap, and reliable energy sources other than the current fossil fuels that dominate the global energy market. This has become even more necessary now than ever due to the negative effect that is associated with the use of fossil fuels on the environment [2–8]. It is estimated that the world's current primary energy consumption is made up of about 85% of non-renewable sources. If the fight to reduce the negative impact of greenhouse gases on the environment, such as biodiversity loss, climate change and global warming, is to be achieved, then it is important to minimize the use of fossil fuels and replace them with renewable energy (RE). The International Renewable Energy Agency (IRENA) has projected that the percentage of the RE in final energy consumption has to be increased from the 2017 figure of 19% to 65% by 2050 if the 2 °C climate target would be realized [9].

Solar energy is part of the clean energy sources family, and it can be used to generate both electrical and thermal energy. The solar photovoltaic (PV) technology, in particular, is a system that is widely used to generate power globally with virtually no environmental impacts and operating costs compared to the conventional power producing plants that rely on fossil fuels [10]. Although a widely used technology, the PV system has a disadvantage that affects its performance, i.e., its efficiency is dependent on the operating temperature. PV cells which can transform only 10–15% of the solar radiation it absorbs into electricity. Most of it is either absorbed or reflected, and this increases the PV cell's temperature, which can consequently lead to a reduction in the PV module's efficiency [11,12]. The heat in the PV panel can be partially removed by using appropriate cooling mechanisms. There are a number of studies which were conducted along this line, and some of these studies are active, passive or both mechanisms of cooling.

Maleki et al. [11] numerically studied the effect of water flow on the cooling of PV cells. They obtained an enhancement of 17.12% under a solar radiation of 1000 W/m$^2$ and an ambient temperature of 45 °C. Gomaa et al. [13] proposed two cost-effective cooling designs for a PV system. These systems are direct active cooling using water and the second is the use of fins mounted at the rear side of the PV for cooling. They found out that the energy from these PV systems increased by 7% and 10.2% for the fins and backwater cooling, respectively. Tan et al. [14] assessed the electrical and thermal performance of a PV system through a comparison of naturally cooled equivalent and latent heat-cooled PV panel. Their study found out that the PV panel with a fin cooling system had a 15 °C reduction in temperature relative to the naturally cooled panel. The system saw a 5.39% improvement in its electrical efficiency. Also, Hasan et al. [15] replaced the Tedlar layer in the PV panel with micro pin fin from aluminum alloy to serve as a heat sink to increase the conduction of heat transfer. The temperature of the PV module reduced by 14.65% with a 13% electrical performance improvement for the output power. The efficiency also improved by 13.32%.

Finally, Peng et al. [16] investigated the impact of temperature on the output performance of a PV module. The results obtained by the researchers showed that the efficiency of the PV module can be enhanced by 47% using a cooling system. Shmroukh [17] demonstrated through their study that the efficiency of a PV module could increase to an average of 8.5% using a closed-loop free-convection system for the cooling; however, it can reach 10.5% using a closed-loop forced convection system. The system without cooling recorded a daily average efficiency of only 6.2% while the open-loop system recorded 11.3%. Similarly, Bayrak et al. [18] studied the performance of a PV module with 75 W capacity under Turkish weather conditions by applying varying fin parameters. They obtained exergy and energy efficiencies of 10.91% and 11.55%, respectively. Rajvikram et al. [19] assessed the effect of aluminum and PCM on the performance of a PV module. According to the researchers, the PV-PCM with aluminum sheet enhanced the conversion efficiency of the module by an average of 24.4%. The electrical efficiency increased by some 2% for a 10.35 °C drop in temperature. The impact of forced convection on a PV module's performance was investigated by [20]. Data from their study show that the electrical efficiency ranged from 12–12.4% and the thermal efficiency of the system with a mass flow rate of 0.018 kg/s to 0.06 kg/s with 0.05 m channel depth which ranged from 15–31%. Al-Mabsali et al. [21] numerically assessed the possibility to use heat pipes for the cooling of PV modules using computational fluid dynamics. Their results show that the integration of heat pipes could reduce the module's temperature by 9 °C. Agyekum et al. [22] assessed the impact of simultaneously cooling both the rear and front surface of a PV module on its performance. Results from their study show that the temperature of the PV module could drop by 23.55 °C by cooling both surfaces. This resulted in an improvement of 30.3% in the power output of the cooled panel.

It is evident from the reviewed papers that finding of an appropriate mechanism to manage the thermal aspect of PV modules cannot be underestimated, especially during this period when there is much conversation on the need to find alternative sources of energy. Solar PV is identified as one of the solutions to help realize this vision; however, the linear dependence of its performance on the module's temperature was always seen as a minus to this technology. It is for this reason that this study was conducted to provide another alternative to the various cooling mechanisms suggested by various researchers, some of which are reviewed supra. This study combines aluminum fins, water, and ultrasonic humidifier to cool PV panel under real weather conditions. Such a study per the knowledge of the authors is the first of its kind and is expected to add new information to existing literature. The paper is organized as follows: Section 2 presents the materials and methodology used for the study, and the results and discussions are presented in Section 3. The final aspect of the work is the conclusion which is presented in Section 4.

## 2. Materials and Methods

The experiment was conducted under Russian weather conditions in Ural Federal University in Ekaterinburg in July 2021 under clear hot summer days from 8:30 a.m. to 17:00 local time. Ekaterinburg can be found on 56°51′ North latitude and 60°36′ East longitude.

### *2.1. Mathematical Equations for PV Performance Calculations*

The rate of transfer of heat from the back surface of a PV panel is governed by Newton's law of cooling as indicated in Equation (1) [23]

$$\dot{Q}_{conv} = hA_s(T_s - T_a) \tag{1}$$

where the area and temperature of the heat transfer surface are denoted by $A_s$ and $T_s$, and $h$ represents the coefficient of convection heat transfer.

As can be seen from Equation (1), it is clear that the heat transfer rate can be increased in two ways, i.e., either to increase the convection heat transfer coefficient $h$ in the form of active cooling or to increase the area of the heat transfer surface $A_s$, which is passive cooling. It is for this reason that the aluminum fins were used in this study to enhance the heat transfer rate. Equation (2) governs the total heat transfer from fins, this includes the transfer of heat from both the finned and un-finned surface areas, which needs cooling [23].

$$\begin{gathered}\dot{Q}_{total,\ fin} = n\dot{Q}_{unfin} + n\eta_{fin}\dot{Q}_{fin} \\ \dot{Q}_{total,\ fin} = nh_{unfin}A_{unfin}\left(T_{s,\ unfin} - T_a\right) + nh_{fin}A_{fin}\eta_{fin}\left(T_{s,\ fin} - T_a\right)\end{gathered} \tag{2}$$

The number of fins attached to the back of the panel is denoted by $n$, surface temperatures for the finned and un-finned area are also represented with $T_{s,\ fin}$ and $T_{s,\ unfin}$, respectively, the coefficient of the convection heat transfer for the finned and un-finned areas, i.e., $h_{fin}$ and $h_{unfin}$, respectively, will be different as a result of the differences in geometry. $A_{unfin}$ and $A_{fin}$ are the area of one of the fins and un-finned portion of the surface area, respectively. The efficiency of the fin is defined as the ratio of the actual rate of heat transfer from the fin to the rate of heat transfer from the fin, ideally if the whole fin was to be at the back surface temperature of the module.

The efficiency of the PV module is also affected by the temperature of the module as well as the ambient temperature. The maximum PV module power can be estimated using Equation (3) [24]. The effect of temperature on the current, voltage and power of a generic 30 W PV module are presented in Figures 1 and 2, these are figures obtained using the PVsyst software (PVsyst SA, Satigny, Switzerland).

$$P_{mp} = V_{mp} \times I_{mp} = V_{oc} \times I_{sc} \times FF \tag{3}$$

where the maximum power is represented by $P_{mp}$, $I_{mp}$ and $V_{oc}$ are the current and voltage of the module, respectively. The short circuit current and open circuit voltage are also denoted with $I_{sc}$ and $V_{oc}$, respectively, $FF$ is the fill factor.

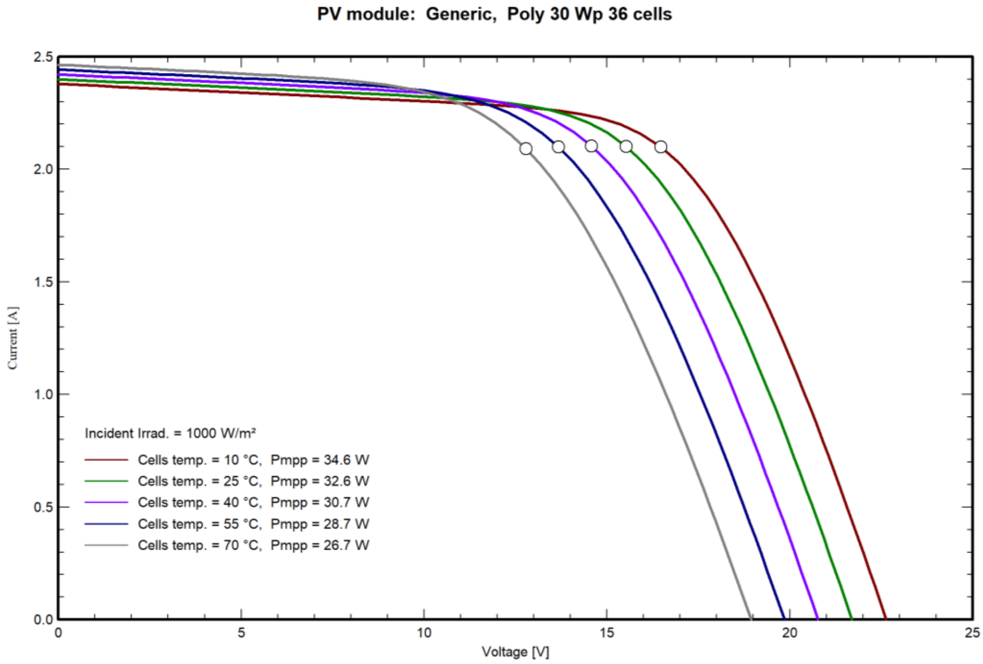



**Figure 1.** Effect of temperature on I-V characteristics of PV.

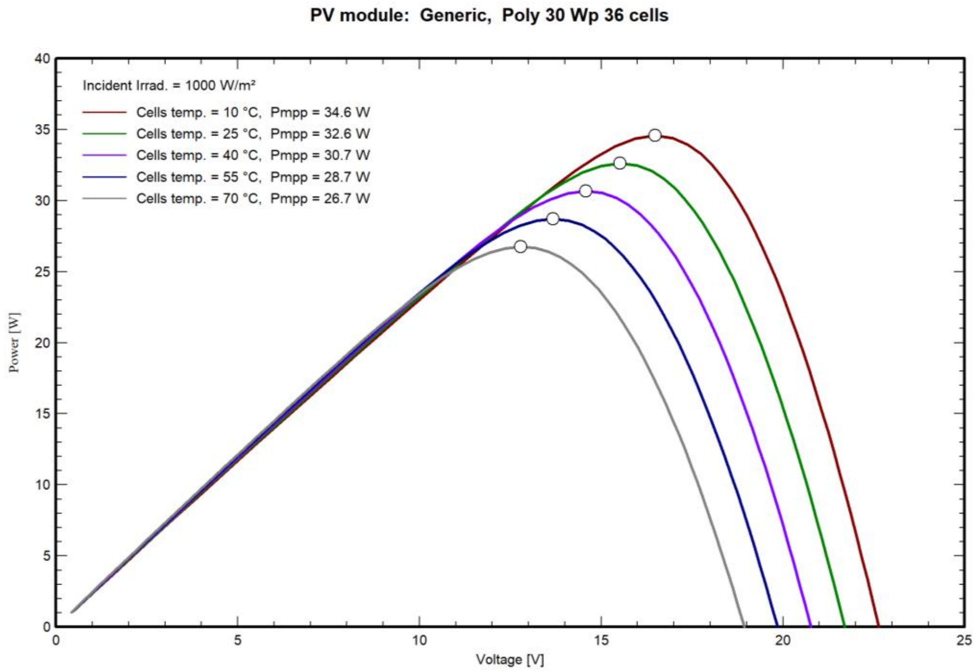



**Figure 2.** Effect of temperature on the P-V characteristics of the PV.

The electrical efficiency of the PV module was calculated using the Evans and Florschuetz equation as presented in Equation (4) after obtaining the temperatures of the PV module within the experimental period. The Evans and Florschuetz equation relates the temperature of the panel with its efficiency [25].

$$\eta_{elec} = \eta_{ref}\left[1 - \beta_{ref}\left(T_{panel} - T_{ref}\right)\right] \quad (4)$$

where the standard efficiency of the PV model under STC is represented by $\eta_{ref}$ which is taken as 15% for this study, $\beta_{ref}$ denote the temperature coefficient which is also 0.004 $C^{-1}$ for this study, the STC temperature is represented by $T_{ref}$ which is 25 °C.

The improvement in the PV module's electrical efficiency as a result of the cooling process can be computed using Equation (5) [26].

$$improvement = \frac{\eta_{cooled\ PV} - \eta_{ref\ PV}}{\eta_{ref\ PV}} \times 100\% \tag{5}$$

### 2.2. Economic Analysis

The cost of energy for the cooled panel was investigated using the levelized cost of energy (LCE) approach as presented in Equation (6). The LCE is one of the most acceptable ways of evaluating the cost of electricity generated from renewable energy power plants [27,28].

$$LCE = \frac{LC_{inv} + LC_{O\&M} + LC_{fuel}}{E_{annual}} \tag{6}$$

$$LC_{inv} = CRF \times C_{inv} \tag{7}$$

$$CRF = \frac{i_{eff} \cdot \left(1 + i_{eff}\right)^{n}}{\left(\left(1 + i_{eff}\right)^{n}\right) - 1} \tag{8}$$

$$LC_{O\&M} = C_{O\&M} \times CELF \tag{9}$$

$$CELF = \left(K_{O\&M} \times \frac{1 - K_{O\&M}^{n}}{1 - K_{O\&M}}\right) CRF \tag{10}$$

$$K_{O\&M} = \frac{1 + r_n}{1 + i_{eff}} \tag{11}$$

where the investment cost is denoted with $C_{inv}$, the capital recovery factor (%) is denoted by $CRF$, $C_{O\&M}$ is the annual cost of operations and maintenance, $CELF$ is the constant-escalation levelization factor, $n$ is the plant's lifetime, $r_n$ is the nominal escalation rate (%) and $i_{eff}$ is the effective discount rate.

### 2.3. Construction of the Cooling System

The use of fins to cool PV panels is an old method that was studied by several researchers as reviewed supra. However, one disadvantage with this mechanism of cooling is the low temperature reduction that is usually associated with it. As a result, the use of fins alone especially in very hot climate areas turn to have a very low effect on the efficiency of the panel compared to other mechanisms that use water or other PCMs as the cooling agent. According to [29] when the ambient temperature exceeds 35 °C, heat dissipation from a PV module that relies on only a heat sink cooling system becomes limited and unable to maintain acceptable PV module temperature. In effect, active cooling is usually preferred in harsher environments. In order to increase the efficiency of the temperature reduction process using fins, this study proposed the addition of an ultrasonic humidifier to create a humid environment at the back surface of the panel to enhance the cooling process. The construction of the setup was achieved with minimal water loss in mind.

The cooling mechanism consist of discontinuous aluminum sheets which were attached at the rear side of the PV module as shown in Figure 3a. A thermal grease was used in order to increase thermal conductivity between the rear side of the panel and the aluminum sheet fins. The universal sealant moment silicone gel (white) was also used to hold the various sheets firmly at the back of the panel. An aluminum basin with a length and width (95 cm × 40 cm) similar to the solar PV panel was used as a basin to host the water and the ultrasonic humidifier. In order to prevent the transfer of heat from the surrounding environment into the water through the aluminum basin, we used an insulator to rap around the basin.

A 30 W solar polycrystalline PV panel was used for the experiment. In order to assess the effect of the cooling mechanism on the efficiency of the PV module, a reference module without any modifications as shown in Figure 3b was also assessed simultaneously with the modified panel. Seven k-type thermocouples were attached at the rear side of each panel to take temperature readings from seven spots in order to find the average temperature of the panel. The temperature range of the thermocouple is −200–1370 °C and a resolution of 0.1 °C. The thermocouples were manufactured by Weewooday and supplied by Amazon.

(a) (b)

**Figure 3.** (**a**) Modified panel with aluminum fins (**b**) referenced module.

The ambient temperature was measured with a GM 1362-EN-01 temperature thermometer (AliExpress BZG Electronics Co., Ltd., China). The Tenmars TM-207 pyranometer (Amazon) was used to measure the solar radiation on the day of the experiment. The specifications for the two ultrasonic humidifiers are presented in Table 1. The voltage and current were measured using the clamp meter (RS Components Ltd., Shanghai, China). Figure 4 shows the image of one of the ultrasonic humidifiers used for the experiment.

**Figure 4.** Ultrasonic humidifier.

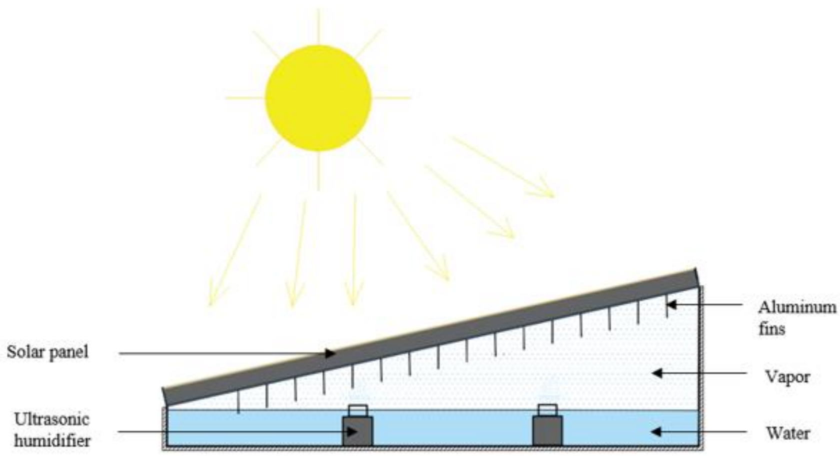
**Table 1.** Specifications for the ultrasonic humidifier.

| Parameter | Value |
|---|---|
| Diameter | 45 mm |
| Atomization amount | 400 cc/har |
| Capacity | 160 mL |
| Voltage | 24 V |
| Power | 14 W |
| Humidification method | Mist discharge |

### 2.4. Experimental Setup

The two panels (i.e., cooled and referenced modules) are a presented in Figure 5a, the cooled panel is on the left while the referenced panel is on the right. An SD logger 88598 (Gain Express Holding Ltd., Hong Kong) was used to record the temperature at various points. The two modules were positioned to face the south of the country. An infra-red thermal imager (testo 875) (testo company, Titisee-Neustadt, Germany) was also used to take temperature distribution of the two panels in the course of the experiment. This was to provide a graphical representation of the effect of the cooling process. The schematic diagram of the test rig is presented in Figure 5b.


(a)




(b)

**Figure 5.** (**a**) Experimental test rig and (**b**) schematic diagram of the proposed system.

Heat is transferred from the rear side of the panel to the heat sink which is dissipated into the environment. Heat dissipation from the fins in most studies is facilitated through the help of natural or forced air; however, in this study, the humid environment created by the ultrasonic humidifier in the basin cools the aluminum fins. The vapor that is generated by the ultrasonic also cools the exposed rear surface of the panel which are not covered by the aluminum fins.

### 2.5. Measurement Error Analysis

The influence of the measurement errors during the experiment is presented briefly in this Section. We measured the various parameters of the quantity in order to estimate the uncertainty associated with the instruments used for the measurement. The accuracies for the various instruments, i.e., thermocouples, a clamp meter for both the current and voltage, pyranometer, and a thermometer for ambient temperature measurement, are all presented in Table 2. The standard uncertainty $u_n$ can be estimated using Equation (12) [30].

$$u_n = \frac{a_n}{\sqrt{3}} \tag{12}$$

where the accuracy of the instrument, as stated by the manufacturer, is denoted by $a_n$. The uncertainty of $z$ can be estimated using Equation (13) when $z$ depends on several inputs [31].

$$u(z) = \left[ \left( \frac{\delta z}{\delta w_1} \right)^2 u^2(w_1) + \left( \frac{\delta z}{\delta w_2} \right)^2 u^2(w_2) + \ldots \right]^{0.5} \tag{13}$$

**Table 2.** Accuracies and uncertainties of various instruments.

| Instrument | Range | Accuracy | Uncertainty | Error |
|---|---|---|---|---|
| GM 1362-EN-01 thermometer | −30–70 °C | ±2% | 1.15% | 2.8% |
| Clamp meter | | ±1.5 | 0.87% | 0.2% |
| Thermocouple | −200–1370 °C | ±0.1 °C | 0.58% | 3.0% |
| Pyranometer | 0–2000 W/m2 | ±5% | 2.87% | 0.1% |

## 3. Results and Discussion

The whole experimental test was conducted under real environmental conditions from 8:30 to 17:00 on 8 July 2021 in Ekaterinburg. The experimental results were taken at 30-min intervals. The progression of the ambient temperature, humidity, and solar irradiation on the day of the experiment is shown in Figure 6. As can be seen from the weather characteristics for the day, the intensity of the solar radiation is highest at 12:30 p.m. with an intensity of 1235 W/m$^2$. The highest ambient temperature of 31.8 °C was also recorded during that same time. The average temperature for the day is 27.79 °C with an average humidity of 28.51%. An average solar irradiation of 991.44 W/m$^2$ was also recorded for the day.

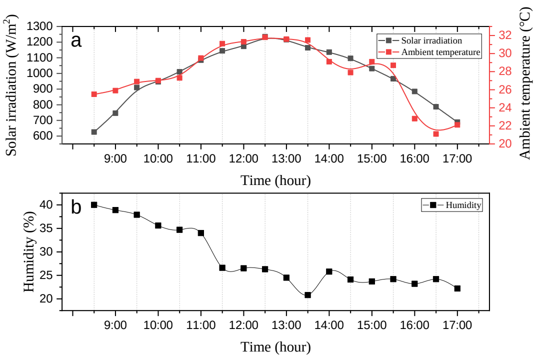



**Figure 6.** (**a**) Solar irradiation and ambient temperature and (**b**) humidity.

### 3.1. Impact of the Cooling Mechanism on Temperature of Panel

The variation in the temperature of the cooled and referenced panels is represented in Figure 7. Clearly, the effect of the cooling mechanism on the temperature of the cooled panel is visible from that figure. The cooling mechanism proposed in this study was able to stabilize the temperature of the panel even under very hot temperatures within the day. The maximum temperature 62.1 °C for the referenced panel occurred at 13:30 while the cooled panel recorded a temperature of 41.59 °C. This shows the positive impact of the cooling process on the temperature regulation of the PV module. The cooling mechanism developed in this study was able to reduce the temperature of the module at its highest peak on the day of the experiment by 20.51 °C. The average temperature of the cooled panel during the entire experimental period is 35.74 °C against 50.35 °C for the referenced module. On the average, the cooling mechanism was able to reduce the temperature of the panel by 14.61 °C. In other studies, Ahmad et al. [32] experimentally assessed the effect of a finned plate aluminum on the thermal management of a PV module. They obtained a temperature reduction of 6.1 °C. Bayrak et al. [18] evaluated the effect of different fin parameters on both the efficiency and temperature of a PV module under natural convection. They were able to obtain the highest temperature reduction of 3.39 °C on the PV rear surface. Popovici et al. [33] also employed air cooled heat sinks to manage the temperature of a PV module. Their results show that the temperature of the PV could be reduced by 10 °C using their proposed model. Hernandez-Perez et al. [34] also used a discontinuous finned heatsink profile to cool the PV module. According to their experimental results, the proposed cooling mechanism led to a mean temperature reduction of about 5 °C. Comparing the results obtained by these researchers to the current study shows that the integration of the ultrasonic humidifier in the cooling process played a significant role in the temperature reduction. As stated earlier in this study, the effect of fin only on the thermal management of PV modules is usually minimal, and this is demonstrated through the reviewed literature that used only fins as way of enhancing heat loss from PV modules.

An infrared thermal image of the front surface for the two panels is presented in Figure 8. This was taken at mid-day, i.e., 12:00 p.m. This is supposed to act as an added backup information to the already obtained results from the thermocouples as presented supra. It gives a graphical presentation of the temperature distribution on each panel. The maximum temperature of the cooled panel is 39.6 °C whiles the referenced panel had a maximum temperature of 50.7 °C. The cooled panel recorded a minimum value of 31.1 °C against 40 °C for the referenced module. In effect, it is clear about the positive effect of the cooling mechanism on the cooled panel, it was able to significantly reduce the temperature of the module.

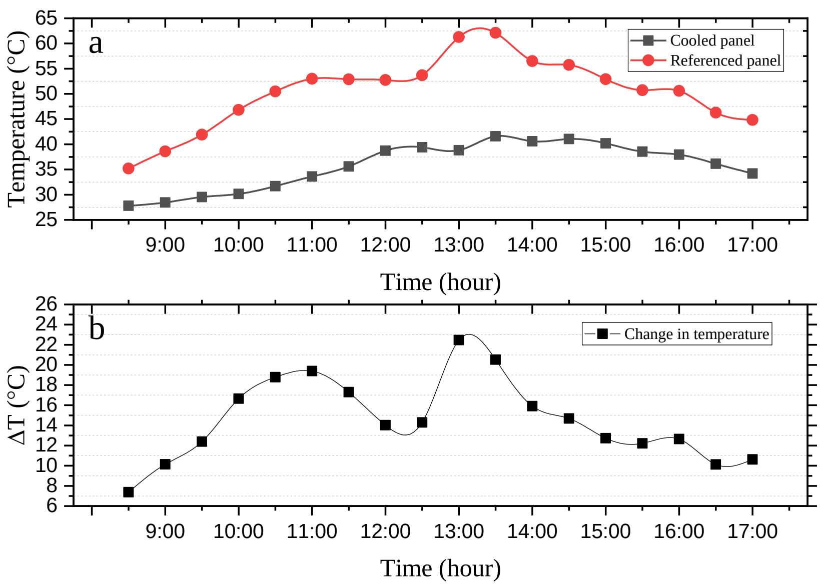



**Figure 7.** (**a**) Temperature (**b**) change in temperature for the two panels.

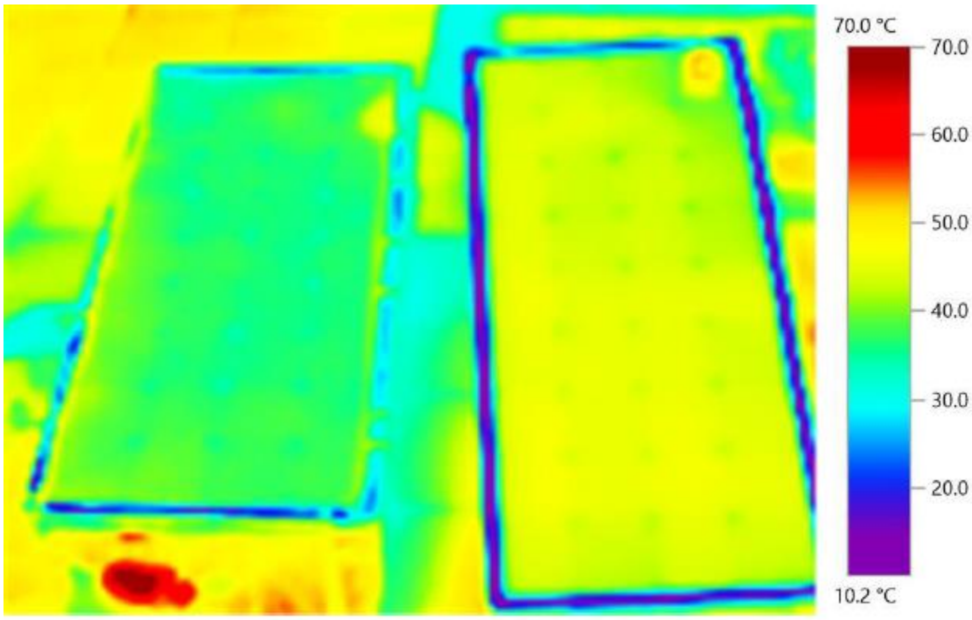



**Figure 8.** Thermal image for both panels, cooled (**left**) referenced (**right**).

### *3.2. Electrical Analysis of both Panels*

The effect of the cooling mechanism on the electrical output is discussed in this Section. The voltages of both panels are presented in Figure 9a. The effect of the cooling process on the output voltage of the cooled panel is very significant. According to the results from the study, the voltage of the uncooled panel, i.e., the referenced panel, decreased considerably with increasing temperature. This confirms what is already known in the literature about the negative effect of temperature on PV cells. The maximum voltage of the cooled panel was 18.89 V which was recorded at around 12:30 p.m. when the intensity of the solar radiation was highest, the referenced module also recorded its maximum voltage of 17.48 V around that same period. It was around this same period that the highest ambient temperature for the day was also recorded. This implies that the effect of the cooling mechanism on the PV module was positive. The average voltage of the cooled panel for the entire experimental period is 18.69 V against 17.27 V for the referenced module. In effect, it can be said that the lack of cooling on the referenced module led to a drop of 1.42 V in its output voltage.

Though the effect of the cooling process on the current of the panel was minimal, this is expected because the change in current with increasing temperature is not as significant as that of voltage. The current for both panels remained almost the same from the beginning of the experiment until mid-day when the ambient temperature and the temperature of the panels increased sharply. The current of the cooled panel remained relatively stable even under high temperatures, but this is not same for the uncooled panel. In general, the cooled panel recorded an average current of 0.65 A against 0.63 A for the referenced panel. The change in current is not significant, the results for the current is illustrated in Figure 9b.

The power output of the two panels is illustrated in Figure 10. An average power of 12.23 W was recorded for the cooled panel against 10.87 W for the referenced module. This represents an improvement of 12.51% in the power output of the module due to the integration of the proposed cooling mechanism. As expected, the highest output power for both panels was recorded when the solar irradiation was highest after mid-day.

Efficiency for both panels is as shown in Figure 11. The average efficiency of the cooled panel is 14.4% while the referenced module recorded 13.48%. This represents an improvement of 6.8% in the electrical efficiency of the module due to the cooling system. The improvement in both the efficiency and power in the current study is comparable to previous studies, as either the results in this study proved to be better or similar to other proposed mechanisms. Ahmad et al. [35] used a technique to cool the rear side of a PV panel by using waste air from an air conditioning system. They obtained an improvement of 8.65% om the generated electrical output. Xu et al. [36] proposed a super thin conductive thermal absorber to manage the temperature of PV modules by retrofitting an existing module into a PV/T system. They recorded an electrical efficiency improvement of 5% for the cooled panel. Gomaa et al. [13] obtained an average improvement of 5.8% and 8.1% for using fins and water, respectively, as coolants for PV modules. Furthermore, Sivakumar et al. [37] used a water immersion cooling approach to cool a PV module. The results of their study show that the immersion of the module in a tap water of 20 mm can increase the efficiency by 9.1%. Their results are expected since this is an immersion. Bevilacqua et al. [38] showed through their study that a simple spray cooling mechanism on a PV module could increase the electrical efficiency up to 1.6%. In a study by Abdolzadeh and Ameri [39] they used water spraying on the PV module's front surface to increase the cell efficiency by 3.26%.

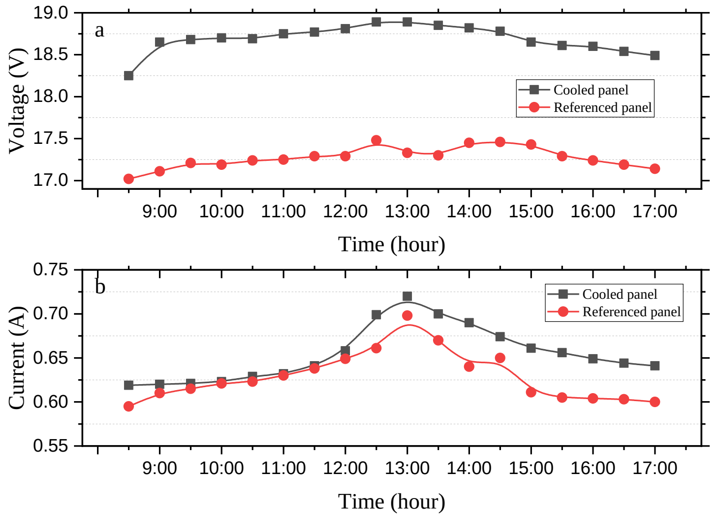



**Figure 9.** (**a**) Voltage (**b**) current.

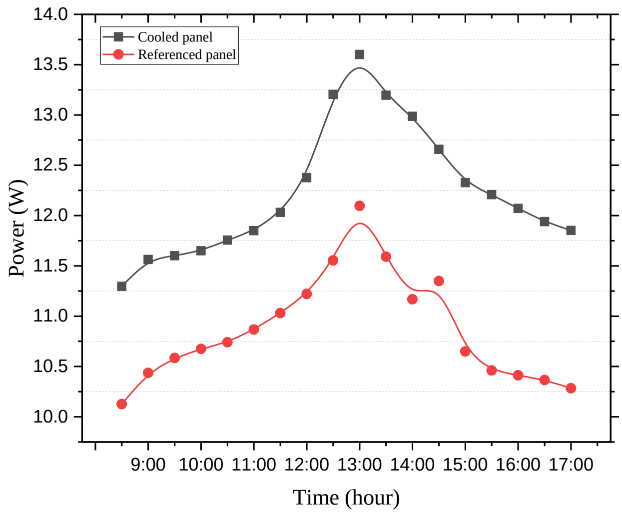



**Figure 10.** Output power for both panels.

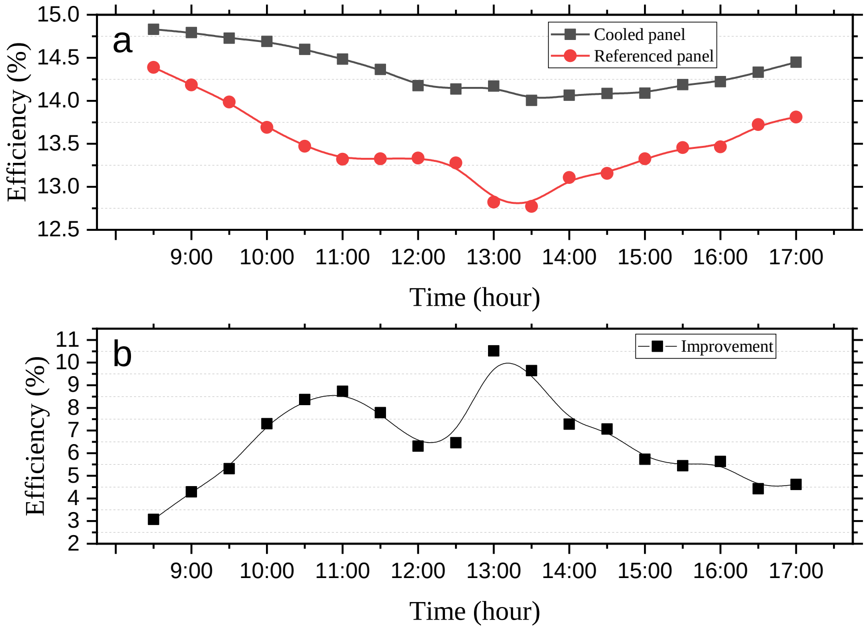



**Figure 11.** (**a**) Efficiency and (**b**) improvement in efficiency.

The results obtained in terms of the temperature reduction in this study are compared to other already published results which used various forms of heat sinks to cool PV modules. The results as presented in Table 3 clearly show that the mechanism proposed in this study is more effective. The reduction in the PV module's temperature in this study is significantly more than virtually all the reviewed literature in Table 3. This shows the significant impact the ultrasonic humidifier had on the cooling process of the cooled PV module.

**Table 3.** Comparison with other published works.

| S.No | Reference No | Technique Used | Temperature without Cooling (°C) | Temperature with Cooling (°C) | Temperature Reduction (°C) |
|---|---|---|---|---|---|
| 1 | [40] | Wind-driven roof top turbine ventilator | 63.5 | 48.7 | 14.8 |
| 2 | [41] | Conjunction fins and cotton wicks | 49.2 | 43.3 | 5.90 |
| 3 | [32] | Finned aluminum plate | 56 | 49.9 | 6.1 |
| 4 | [42] | Aluminum fin | 49 | 48 | 1 |
| 5 | [43] | Aluminum Spreader | 49.2 | 43.3 | 5.9 |
| 6 | [33] | Aluminum with perforated ribs | 56 | 46 | 10 |
| 7 | [44] | Finned container heat sink | 57.9 | 51.8 | 6.1 |
| 8 | [45] | Silicon micro-finned heat sinks | 78.8 | 70.4 | 8.4 |
| 9 | [34] | Discontinuous finned heat sink (Numerical and Experimental) | 49 | 38 | 5–7 |
| 10 | [13] | U shaped Fins cooling | 57 | 55 | 2 |
| 11 | [46] | Finned Heat sinks | 62 | 51 | 11 |
| 12 | Current study | Aluminum fins + Ultrasonic humidifier | 50.35 | 35.74 | 14.61 |

### 3.3. Water Consumption

Water consumption is one of the disadvantages of evaporative cooling, and as a result an appropriate mechanism ought to be put in place to minimize water loss. In this study, portions of water vapor from the ultrasonic humidifier tend to condense on the surface of the fins integrated at the rear side of the panel which then returns to the tank. This minimizes water loss, and this is very important for areas or regions that have severe water scarcity. A total of 15 L of water was poured into the basin in the beginning of the experiment. At the end of the experiment a total of 13.5 L was left, which means about 1.5 L of water was approximately consumed in the course of the experiment, and this is due to evaporation. This translates into a total of 0.015 L/hour water consumption during the experiment. This shows that the proposed cooling mechanism has the potential to save water and minimize the level of water consumption.

### 3.4. Economic Analysis

In assessing the economics of the PV system, it is important to evaluate it at least with a one-year period; however, the poor weather conditions in the greater part of the year in Russia do not allow for such an assessment. To that effect, we assumed that the effective period for the period of operations of the PV system is only during the summer period, i.e., May, June, July, and August, which is equal to 120 days per year. For the purposes of the economic analysis, we also assumed that the power generation from the PV module is equal throughout this period as recorded in this experiment for the cooled module. We also assumed that the panel generated energy for 12 h per day. Then the 12.23 W generated by the cooled panel translate to 17.611 kWh per year. However, if all 12 months in a year are taken into consideration, then a total of 40.175 kWh will be the annual energy yield. The aluminum sheet cost 640 rubles which translates to $8.64; however, only a third of it was used for which also translates to $2.88. The cost of the used panel and its operations and maintenance cost $C_{O\&M}$ were also assumed to be $50 and $3.00, respectively. The ultrasonic humidifier cost 560 rubles each on Amazon which translates to $7.62. The cost of the basin for storing is also 400 rubles equivalent to $5.45 at an exchange rate of 1 rub = $0.0136. Another installation cost of $5 was assigned (this includes the cost of thermal glue, silicone gel, and insulation). This translates into a total of $78.57 invest cost $C_{inv}$. Fuel is not required in PV power plants, so the cost of fuel is zero under this circumstance. An effective discount rate and nominal escalation rate of 5% and 1% were applied in these calculations. By the calculations using the equations presented in Section 2.2, an LCE of 0.478 $/kWh will be the cost of the PV system for the 120 days and 0.210 $/kWh for a 365-day period for a total of 9 h of energy generation each day. These figures are less than the 1.57€/kW h obtained by [27] for their cooled panel.

## 4. Conclusions

A mechanism to manage the temperature of a PV module to enhance its efficiency is proposed in this study. A combination of both active and passive cooling was adopted to cool a PV system. This includes the use of aluminum fins and an ultrasonic humidifier to generate a humid environment behind the rear side of the PV module. The proposed approach worked effectively by helping the PV fins to cool down very quickly. This mechanism of cooling can be used in regions or areas with hot arid weather conditions instead of just using heat sinks which as stated supra have proven to be ineffective under very high weather conditions. The following results were obtained:

- The cooling process in the study was able to reduce the temperature of the panel averagely by 14.61 °C. This reduction led to a 6.8% improvement in the electrical efficiency of the module.
- The average voltage of the cooled panel for the entire experimental period is 18.69 V against 17.27 V for the referenced module. In effect, it can be said that the lack of cooling on the referenced module led to a drop of 1.42 V in its output voltage.

- The difference in the current of both modules were insignificant compared to the voltage, and this is expected.
- An average power of 12.23 W was recorded for the cooled panel against 10.87 W for the referenced module. This represents an improvement of 12.51% in the power output of the module due to the integration of the proposed cooling mechanism.
- By the calculations an LCE of 0.478 $/kWh will be the cost of the PV system for the 120 days and 0.210 $/kWh for a 365-day period for a total of 9 h of energy generation.
- In terms of water consumption, a total of 1.5 L was approximately consumed during the whole experimental process.
- Future studies can take into consideration the effect of the distance between the panel and the ultrasonic humidifier on the temperature variation of the module. Similarly, the effect of the thickness of the aluminum sheet used as fins can also be assessed to obtain the appropriate thickness for future implementation. Additionally, the effect of humidity and wind speed on the cooling process should be looked at during future studies that uses the proposed cooling mechanism. Furthermore, the effect of the arrangement of the aluminum fins and shapes and sizes can also be assessed in future studies.

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## References


1. BP. Statistical Review of World Energy | Energy Economics | Home. 2018. Available online: https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html (accessed on 15 January 2021).
2. Agyekum, E.B. Energy poverty in energy rich Ghana: A SWOT analytical approach for the development of Ghana's renewable energy. *Sustain. Energy Technol. Assess.* **2020**, *40*, 100760. [CrossRef]
3. Agyekum, E.B.; Velkin, V.I. Optimization and techno-economic assessment of concentrated solar power (CSP) in South-Western Africa: A case study on Ghana. *Sustain. Energy Technol. Assess.* **2020**, *40*, 100763. [CrossRef]
4. Adebayo, T.S.; Awosusi, A.A.; Oladipupo, S.D.; Agyekum, E.B.; Jayakumar, A.; Kumar, N.M. Dominance of Fossil Fuels in Japan's National Energy Mix and Implications for Environmental Sustainability. *Int. J. Environ. Res. Public Health* **2021**, *18*, 7347. [CrossRef]
5. Alwan, N.T.; Shcheklein, S.E.; Ali, O.M. Experimental investigation of modified solar still integrated with solar collector. *Case Stud. Therm. Eng.* **2020**, *19*, 100614. [CrossRef]
6. Alwan, N.T.; Shcheklein, S.E.; Ali, O.M. Experimental analysis of thermal performance for flat plate solar water collector in the climate conditions of Yekaterinburg, Russia. *Mater. Today Proc.* **2021**, *42*, 2076–2083. [CrossRef]
7. Amjad, F.; Agyekum, E.B.; Shah, L.A.; Abbas, A. Site location and allocation decision for onshore wind farms, using spatial multi-criteria analysis and density-based clustering. A techno-economic-environmental assessment, Ghana. *Sustain. Energy Technol. Assess.* **2021**, *47*, 101503. [CrossRef]
8. Adebayo, T.S.; Agboola, M.O.; Rjoub, H.; Adeshola, I.; Agyekum, E.B.; Kumar, N.M. Linking Economic Growth, Urbanization, and Environmental Degradation in China: What Is the Role of Hydroelectricity Consumption? *Int. J. Environ. Res. Public Health* **2021**, *18*, 6975. [CrossRef]
9. Benato, A.; Stoppato, A.; De Vanna, F.; Schiro, F. Spraying Cooling System for PV Modules: Experimental Measurements for Temperature Trends Assessment and System Design Feasibility. *Designs* **2021**, *5*, 25. [CrossRef]
10. Agyekum, E.B. Techno-economic comparative analysis of solar photovoltaic power systems with and without storage systems in three different climatic regions, Ghana. *Sustain. Energy Technol. Assess.* **2021**, *43*, 100906. [CrossRef]
11. Maleki, A.; Ngo, P.T.T.; Shahrestani, M.I. Energy and exergy analysis of a PV module cooled by an active cooling approach. *J. Therm. Anal. Calorim.* **2020**, *141*, 2475–2485. [CrossRef]
12. Dimri, N.; Tiwari, A.; Tiwari, G.N. Thermal modelling of semitransparent photovoltaic thermal (PVT) with thermoelectric cooler (TEC) collector. *Energy Convers. Manag.* **2017**, *146*, 68–77. [CrossRef]

13. Gomaa, M.R.; Hammad, W.; Al-Dhaifallah, M.; Rezk, H. Performance enhancement of grid-tied PV system through proposed design cooling techniques: An experimental study and comparative analysis. *Sol. Energy* **2020**, *211*, 1110–1127. [CrossRef]
14. Tan, L.; Date, A.; Fernandes, G.; Singh, B.; Ganguly, S. Efficiency Gains of Photovoltaic System Using Latent Heat Thermal Energy Storage. *Energy Procedia* **2017**, *110*, 83–88. [CrossRef]
15. Hasan, I.A.; Faraj, S.R.; Mohammad, I.A. Performance Improvement of Photovoltaic Module Using an Air-Cooling Micro Finned Heat Sink. *IOP Conf. Ser. Mater. Sci. Eng.* **2020**, *765*, 012021. [CrossRef]
16. Peng, Z.; Herfatmanesh, M.R.; Liu, Y. Cooled solar PV panels for output energy efficiency optimisation. *Energy Convers. Manag.* **2017**, *150*, 949–955. [CrossRef]
17. Shmroukh, A.N. Thermal regulation of photovoltaic panel installed in Upper Egyptian conditions in Qena. *Therm. Sci. Eng. Prog.* **2019**, *14*, 100438. [CrossRef]
18. Bayrak, F.; Oztop, H.F.; Selimefendigil, F. Effects of different fin parameters on temperature and efficiency for cooling of photovoltaic panels under natural convection. *Sol. Energy* **2019**, *188*, 484–494. [CrossRef]
19. Rajvikram, M.; Leoponraj, S.; Ramkumar, S.; Akshaya, H.; Dheeraj, A. Experimental investigation on the abasement of operating temperature in solar photovoltaic panel using PCM and aluminium. *Sol. Energy* **2019**, *188*, 327–338. [CrossRef]
20. Kasaeian, A.; Khanjari, Y.; Golzari, S.; Mahian, O.; Wongwises, S. Effects of forced convection on the performance of a photovoltaic thermal system: An experimental study. *Exp. Therm. Fluid Sci.* **2017**, *85*, 13–21. [CrossRef]
21. Al-Mabsali, S.A.; Chaudhry, H.N.; Gul, M.S. Numerical Investigation on Heat Pipe Spanwise Spacing to Determine Optimum Configuration for Passive Cooling of Photovoltaic Panels. *Energies* **2019**, *12*, 4635. [CrossRef]
22. Agyekum, E.B.; PraveenKumar, S.; Alwan, N.T.; Velkin, V.I.; Shcheklein, S.E. Effect of dual surface cooling of solar photovoltaic panel on the efficiency of the module: Experimental investigation. *Heliyon* **2021**, *7*, e07920. [CrossRef]
23. Khan, S.; Waqas, A.; Ahmad, N.; Mahmood, M.; Shahzad, N.; Sajid, M.B. Thermal management of solar PV module by using hollow rectangular aluminum fins. *J. Renew. Sustain. Energy* **2020**, *12*, 063501. [CrossRef]
24. Elbreki, A.M.; Sopian, K.; Fazlizan, A.; Ibrahim, A. An innovative technique of passive cooling PV module using lapping fins and planner reflector. *Case Stud. Therm. Eng.* **2020**, *19*, 100607. [CrossRef]
25. Abdallah, S.R.; Saidani-Scott, H.; Benedi, J. Experimental study for thermal regulation of photovoltaic panels using saturated zeolite with water. *Sol. Energy* **2019**, *188*, 464–474. [CrossRef]
26. Haidar, Z.A.; Orfi, J.; Kaneesamkandi, Z. Experimental investigation of evaporative cooling for enhancing photovoltaic panels efficiency. *Results Phys.* **2018**, *11*, 690–697. [CrossRef]
27. Baloch, A.A.B.; Bahaidarah, H.M.S.; Gandhidasan, P.; Al-Sulaiman, F.A. Experimental and numerical performance analysis of a converging channel heat exchanger for PV cooling. *Energy Convers. Manag.* **2015**, *103*, 14–27. [CrossRef]
28. Agyekum, E.B.; Adebayo, T.S.; Bekun, F.V.; Kumar, N.M.; Panjwani, M.K. Effect of Two Different Heat Transfer Fluids on the Performance of Solar Tower CSP by Comparing Recompression Supercritical $CO_2$ and Rankine Power Cycles, China. *Energies* **2021**, *14*, 3426. [CrossRef]
29. Al-Amri, F.; Maatallah, T.S.; Al-Amri, O.F.; Ali, S.; Ali, S.; Ateeq, I.S.; Zachariah, R.; Kayed, T.S. Innovative technique for achieving uniform temperatures across solar panels using heat pipes and liquid immersion cooling in the harsh climate in the Kingdom of Saudi Arabia. *Alex. Eng. J.* 2021. [CrossRef]
30. Chandrika, V.S.; Karthick, A.; Kumar, N.M.; Kumar, P.M.; Stalin, B.; Ravichandran, M. Experimental analysis of solar concrete collector for residential buildings. *Int. J. Green Energy* **2021**, *18*, 615–623. [CrossRef]
31. Pichandi, R.; Kulandaivelu, K.M.; Alagar, K.; Dhevaguru, H.K.; Ganesamoorthy, S. Performance enhancement of photovoltaic module by integrating eutectic inorganic phase change material. *Energy Sources Part A Recovery Util. Environ. Eff.* **2020**, *2020*, 1–18. [CrossRef]
32. El Mays, A.; Ammar, R.; Hawa, M.; Akroush, M.A.; Hachem, F.; Khaled, M.; Ramadan, M. Improving Photovoltaic Panel Using Finned Plate of Aluminum. *Energy Procedia* **2017**, *119*, 812–817. [CrossRef]
33. Popovici, C.G.; Hudişteanu, S.V.; Mateescu, T.D.; Chereches, N.-C. Efficiency Improvement of Photovoltaic Panels by Using Air Cooled Heat Sinks. *Energy Procedia* **2016**, *85*, 425–432. [CrossRef]
34. Hernandez-Perez, J.G.; Carrillo, J.G.; Bassam, A.; Flota-Banuelos, M.; Patino-Lopez, L. Thermal performance of a discontinuous finned heatsink profile for PV passive cooling. *Appl. Therm. Eng.* **2021**, *184*, 116238. [CrossRef]
35. Ahmad, F.F.; Ghenai, C.; Hamid, A.K.; Rejeb, O.; Bettayeb, M. Performance enhancement and infra-red (IR) thermography of solar photovoltaic panel using back cooling from the waste air of building centralized air conditioning system. *Case Stud. Therm. Eng.* **2021**, *24*, 100840. [CrossRef]
36. Xu, P.; Zhang, X.; Shen, J.; Zhao, X.; He, W.; Li, D. Parallel experimental study of a novel super-thin thermal absorber based photovoltaic/thermal (PV/T) system against conventional photovoltaic (PV) system. *Energy Rep.* **2015**, *1*, 30–35. [CrossRef]
37. Sivakumar, B.; Navakrishnan, S.; Cibi, M.R.; Senthil, R. Experimental study on the electrical performance of a solar photovoltaic panel by water immersion. *Environ. Sci. Pollut. Res.* **2021**, *28*, 42981–42989. [CrossRef] [PubMed]
38. Bevilacqua, P.; Perrella, S.; Cirone, D.; Bruno, R.; Arcuri, N. Efficiency Improvement of Photovoltaic Modules via Back Surface Cooling. *Energies* **2021**, *14*, 895. [CrossRef]
39. Abdolzadeh, M.; Ameri, M. Improving the effectiveness of a photovoltaic water pumping system by spraying water over the front of photovoltaic cells. *Renew. Energy* **2009**, *34*, 91–96. [CrossRef]

40. Valeh-E-Sheyda, P.; Rahimi, M.; Parsamoghadam, A.; Masahi, M.M. Using a wind-driven ventilator to enhance a photovoltaic cell power generation. *Energy Build.* **2014**, *73*, 115–119. [CrossRef]
41. Chandrasekar, M.; Senthilkumar, T. Passive thermal regulation of flat PV modules by coupling the mechanisms of evaporative and fin cooling. *Heat Mass Transf.* **2016**, *52*, 1381–1391. [CrossRef]
42. Selimefendigil, F.; Bayrak, F.; Oztop, H.F. Experimental analysis and dynamic modeling of a photovoltaic module with porous fins. *Renew. Energy* **2018**, *125*, 193–205. [CrossRef]
43. Chandrasekar, M.; Senthilkumar, T. Experimental demonstration of enhanced solar energy utilization in flat PV (photovoltaic) modules cooled by heat spreaders in conjunction with cotton wick structures. *Energy* **2015**, *90*, 1401–1410. [CrossRef]
44. Wongwuttanasatian, T.; Sarikarin, T.; Suksri, A. Performance enhancement of a photovoltaic module by passive cooling using phase change material in a finned container heat sink. *Sol. Energy* **2020**, *195*, 47–53. [CrossRef]
45. Micheli, L.; Senthilarasu, S.; Reddy, K.S.; Mallick, T.K. Applicability of silicon micro-finned heat sinks for 500× concentrating photovoltaics systems. *J. Mater. Sci.* **2015**, *50*, 5378–5388. [CrossRef]
46. Johnston, E.; Szabo, P.S.B.; Bennett, N.S. Cooling silicon photovoltaic cells using finned heat sinks and the effect of inclination angle. *Therm. Sci. Eng. Prog.* **2021**, *23*, 100902. [CrossRef]