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*RESEARCH ARTICLE - MECHANICAL ENGINEERING*

# Study the Impact of Active Cooling Systems on Solar Cell Efficiency

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**Abstract**

The performance development of photovoltaic systems has become crucial with the increasing demand for renewable energy sources. Cooling systems play a crucial role in maintaining solar cell temperatures within optimal ranges, thereby improving their overall efficiency. This study presents an experimental investigation into the effectiveness of fan-based cooling systems aimed at enhancing the efficiency of solar cells. In this experiment, a cooling system was tested under limited environmental conditions to assess its impact on solar cell performance. It was concluded from the results that reducing the temperature using the air-cooling system did not significantly impact the efficiency of the solar cell when the temperature was below 50 degrees Celsius; however, the proposed cooling system was effective in reducing the temperature of the solar cell by 18 °C relative to the reference solar cell.



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**Keywords**: Renewable Energy; Photovoltaic Cells; Temperature; Cooling System; Efficiency.

## 1. Introduction

Many countries use renewable energy on a large scale, as photovoltaic cells are considered one of the most important and most widespread renewable energy technologies, as solar energy is a widespread and abundant source of renewable energy on our planet. Solar cells, also called photovoltaic cells, are used to convert solar energy into electrical energy. The efficiency of solar cells is relatively low with the high abundance of solar radiation on Earth, and this is due to many different influencing factors, the most important of which is the effect of cell temperature. Solar cells convert part of the solar radiation directly into electricity, which is subsequently utilized to power different electrical appliances, during the operation of the solar modules, while dissipating the remaining energy into heat. The efficiency of the photovoltaic cells begins to decrease as the operating temperature of the photovoltaic cells increases [1].

Enhancing the efficiency of a solar photovoltaic (PV) power system requires a range of strategies to boost energy output and system performance. The growing global demand for clean and sustainable energy has intensified the focus on optimizing solar power systems. Achieving high performance in these systems depends on several critical factors, including the optimal placement and orientation of solar panels, the use of high-quality photovoltaic modules, and regular maintenance to ensure operational efficiency. Moreover, managing temperature effects, incorporating advanced technologies, and applying thoughtful system design contribute significantly to overall effectiveness. The integration of energy storage solutions and continuous system monitoring further enhances reliability and energy availability, particularly in variable environmental conditions [2].

The performance of solar cells tends to decrease with increasing temperature, and this is due to the higher rates of internal carrier recombination resulting from higher carrier concentrations. Operating temperature plays a crucial role in the PV conversion process, affecting both the electrical efficiency and power output of the photovoltaic (PV) module linearly, the efficiency of photovoltaic (PV) modules declines with rising temperatures, with the power output of a PV module typically diminishing by 0.4-0.5% for each degree Celsius increase in temperature [3]. In a solar cell, the open circuit voltage is the parameter most affected by temperature increases, as shown in Fig. 1. [4]. Overheating of solar cells during normal operation significantly reduces their energy harvesting efficiency and leads to additional issues such as thermal cycling and performance degradation of the modules [5-7]. Employing an underground heat exchanger for cooling can significantly boost the efficiency of photovoltaic solar modules. Specifically, the power generation of cooled solar modules increased by up to 12.4% with a coolant flow rate of 1.84 liters per minute per square meter of the solar panel [5]. Meanwhile, investigated monocrystalline silicon photovoltaic cells' I–V (current-voltage) characteristics across a broad temperature spectrum, ranging from -170 °C to +100 °C [6].

**Nomenclature & Symbols**

| | | | |
|---|---|---|---|
| $v_{oc}$ | Normalized Voltage (without units) | n | The Factor (without unit) |
| $V_{oc}$, | Open Circuit Voltage (Volt) | $\gamma$ | Constant Value |
| $I_{sc}$ | Short Circuit Current (Amp.) | $E_g$ | The Energy Band Gap |
| e | The Electron Charge | $T_{cell}$ ($T_c$) | Solar Panel Temperature (°C) |
| $I_o$ | The Reverse Saturation Current | $\eta$ | Cell Efficiency (%) |
| $\varepsilon$ | The Silicon Solar Cell Constant | F | The Thermal Conductivity Coefficient Between the Solar Panel and the External Environment |
| K | Boltzmann Constant (joule/Kelvin) | $T_a$ | Environmental Temperature |
| T | Temperature (Kelvin) | A | Area of Collector ($m^2$) |
| q | Elementary Charge (Coulomb) | $y^n$ | The Factors Related to the Difference of X |
| $L_n$ | The Minority-Carrier (Electron) Diffusion Length in the n-Region (meter) | $L_p$ | The Minority-Carrier (Hole) Diffusion Length in the p-Region (m) |
| E (G) | Incident Radiation flux ($W/m^2$) | | |

This study is noteworthy because similar measurements over this temperature range are rare. Additionally, [7] reported that under hot weather conditions, their experimental setup achieved a temperature reduction of 20°C and a 14.75% increase in efficiency. Lastly, [8] found that the temperature coefficient of a solar panel is -0.258% per degree Celsius, indicating that the maximum power output decreases by 0.258% for every degree Celsius increase in temperature.

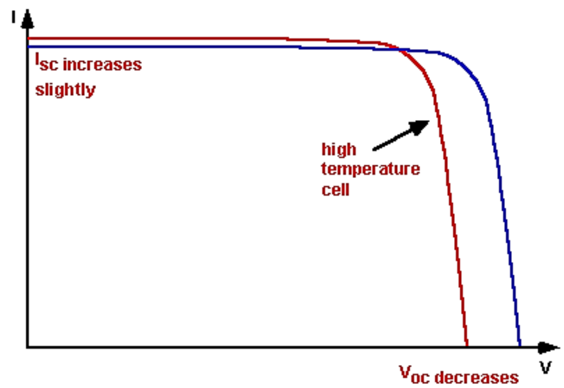


Fig. 1. The effect of temperature on the IV characteristics of a solar cell [4]

Solar panels encounter various problems, some common across different regions and others specific to the installation location. Common issues observed in solar panels include micro-cracks, hot spots on the panels, potential induced degradation (PID) effect, internal corrosion and delamination, and snail trail contamination. As temperatures rise, the panels produce less voltage and become less efficient in generating electricity.

There is a common misconception that stronger sunlight results in greater power generation by solar panels, but this is not accurate. Like all electronics, solar panels are affected by temperature.

The temperature coefficient of a solar panel is 0.258% per degree Celsius. This means that for every degree increase in temperature, the maximum power output of the solar panel will decrease by 0.258%, and conversely, for every degree decrease, the power output will increase by the same percentage. Therefore, regardless of location, solar panels are affected by seasonal variations, and they operate more efficiently in cooler temperatures [8]. This paper identifies a gap in the effectiveness of fan-based cooling systems for solar cells when temperatures are below 50°C. Although the cooling system successfully lowered the temperature of the solar cells by 18°C compared to reference cells, it did not substantially improve their efficiency at these lower temperatures. This indicates that, despite achieving temperature reductions, the cooling system's ability to enhance solar cell performance is limited under the conditions tested. The effects are consistent with literature that finds the efficiency of solar panels generally decreases with increasing temperature, but this effect does not occur within a small temperature range.

## 2. Experimental Work

An experimental setup was devised to investigate the impact of a cooling system on the performance of a photovoltaic panel in terms of heat dissipation and electricity generation. The experiment aimed to analyze how temperature variations affect the efficiency and energy output of a polycrystalline solar module. The panel features key electrical characteristics such as an open-circuit voltage (Voc) of 21.6 V, a short-circuit current (Isc) of 1.21 A, a voltage at maximum power (Vmp) of 17.8 V, a current at maximum power (Imp) of 1.12 A, and a rated output power of 20 W during operation.

Air duct channels were constructed using wood, measuring 2 cm thick, 14 cm long, 38 cm wide, and 49 cm high, with two holes' radius 2.5 cm on the sides of the duct, Figs. 2 and 3. A 12 V DC fan, with a radius of 4.5 cm, powered by batteries, was incorporated into the system to extract air from the environment and cool the solar units. This airflow was channeled through the air duct to enhance the heat transfer rate of the PV panel. Care was taken in designing the manifold inlet to ensure uniform distribution of airflow.

The devices utilized in this experiment included a digital temperature measuring device, an avo-meter device, a solar radiation intensity measuring device, and an air velocity measuring device. The devices utilized in this experiment included a digital temperature measuring device, an avo-meter device, a solar radiation intensity measuring device, and an air velocity measuring device. This cooling system offers several advantages, including environmental friendliness and low investment cost. Fig. 4 and Table 1 illustrate the designed cooling module and its specifications.

A B

Fig. 2. A) Front, and B) Side view of a solar panel with the air-cooling system (Cell-1) and the solar panel reference (Cell-2)

A B

Fig. 3. A) Back view of a solar panel with the air-cooling system (Cell-2), and (B) the solar panel reference (Cell-1)

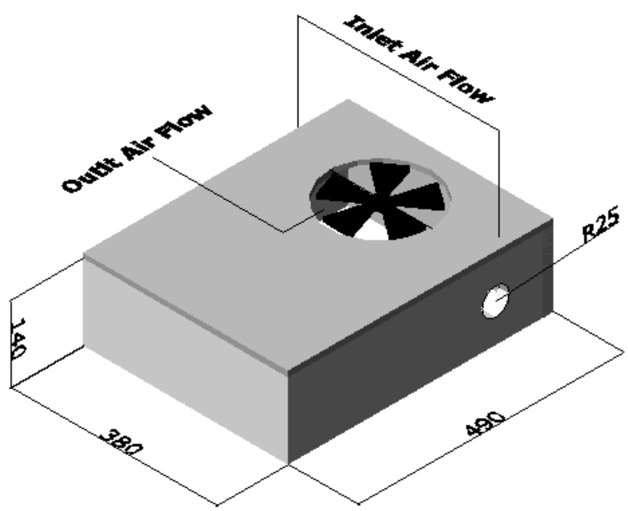


Fig. 4. The cooling solar cell fan duct, dimensions in mm

Table 1. Specifications of the designed model

| Equipment | Description |
|---|---|
| Collector's location | Baghdad- Iraq, (33.33 °N and 44.43 °E) |
| Collector's Dimensions | 49 cm×38 cm× 14 cm |
| Orientation & Slope | South, 40°. |
| Pyranometer | RK200-03, SN:R18021068, Range: 0-2000 W/m$^2$. |
| Fan | 12 V DC, radius 4.5 cm. |
| Hot Wire Anemometer | HT-9829, 60-90 mA. |
| Temp. Data-logger (EXTECH) | Accuracy of ± (0.4 % + 1°C), model SDL200 |

### 3. Solar Collector Thermal Performance

The solar cell's performance is evaluated based on key factors using the following equations:

*3.1. Fill factor (FF)*

The fill factor (FF) is a key parameter used to evaluate the performance of a solar cell. It represents the ratio of the maximum obtainable power to the theoretical power and provides insight into the quality of the cell. Assuming the photovoltaic cell behaves like an ideal diode, the fill factor can be expressed as a function of the open-circuit voltage using the following relation [9, 10]:

$$FF = \frac{v_{oc} - ln(v_{oc} + 0.72)}{v_{oc} + 1} \quad (1)$$

$$v_{oc} = \frac{V_{oc} \times q}{KT} \quad (2)$$

*3.2. Cell efficiency ($\eta$)*

Cell Efficiency is defined as the performance efficiency of a photovoltaic cell is determined by the ratio between the electrical power it produces and the amount of solar energy it receives. The output power is obtained through the conversion of visible sunlight into electricity, while the input energy is calculated by multiplying the solar irradiance (E) by the cell's surface area (A): [4]. Efficiency can be calculated by Equation (3).

$$\eta = \frac{P_{out}}{P_{in}} = \frac{V_{OC} \times I_{SC} \times FF}{E \times A} \quad (3)$$

### 4. Uncertainty Analysis

Holman's method is used to calculate the uncertainty ωη of solar efficiency [11]. This method accounts for errors associated with daily experimental measurements. The uncertainty results can be determined using equation (4), where $\omega x$ represents any physics parameter, and $\omega x$ is the uncertainty associated with these parameters.

$$\omega x = \left[ \left( \frac{\partial X}{\partial y1} \omega y1 \right)^2 + \left( \frac{\partial X}{\partial y2} \omega y2 \right)^2 + \cdots + \left( \frac{\partial X}{\partial yn} \omega yn \right)^2 \right]^{\frac{1}{2}} \quad (4)$$

The fractional efficiency with its contributing variables can be formulated as the following Eq. 5:

$$\frac{\omega \mu}{\mu} = \left[ \left( \frac{\omega\, Voc}{Voc} \right)^2 + \left( \frac{\omega\, Isc}{Isc} \right)^2 + \left( \frac{\omega\, E}{E} \right)^2 \right]^{\frac{1}{2}} \quad (5)$$

The factors were calculated for cells with and without cooling. The average values of these variables were then used to determine the fractional uncertainty of cell efficiency. The mean values measured during the experimental work are presented in Table 2.

Table 2. The total average values for five days' experiment

| Average value | E /W/m$^2$ | $T_{cell}$/°C | $V_{oc}$/volt | $I_{sc}$/Amp | η/% |
|---|---|---|---|---|---|
| Cell 1/ Reference | 1036.5 | 46.2 | 21.26 | 0.689 | 9.2 |
| Cell 2/ With a cooling system | 1036.5 | 28.2 | 21.61 | 0.644 | 8.5 |

The calculated uncertainty of cell efficiency is 0.183 for Cell 1/ Reference and 0.217 for Cell 2/ with the cooling system. The uncertainty of thermal efficiency is associated with ωVoc= ±5%, temperature differences, ωIsc= ±5%, solar intensity, ωE= ±7%, and collector area, ωA= ±0.2%.

### 5. Results and Discussion

The two solar cells were examined under identical working days and environmental conditions. The cell temperatures and solar radiation intensity were recorded during midday hours from 11:00 a.m. to 12:30 p.m. with data recorded every ten minutes. All experiments were carried out in clear sky conditions with low wind speeds in April, at Middle Technical University, Al-Za'franiya city, Baghdad- Iraq, 33.33 °N and 44.43 °E.

Solar radiation directly affects the temperature of the solar cell, as an increase in the cell temperature reduces the cell's performance and efficiency. So the study involved adding a cooling system to reduce the temperature of the solar cell.

The values of solar radiation, cell temperature, voltage, and current were recorded to study the effect of using a cooling system on the performance of the cell. Solar radiation, temperature, efficiency, and other factors values of solar panels are presented in Tables 3 and 4.

*5.1. Solar intensity and solar cell temperature*

The results showed an increase in temperatures in the two cells; Cell 1 operated without any cooling mechanism, whereas Cell 2 was equipped with a fan cooling system. The reason is due to the effect of the intensity of solar radiation on the temperature of the voltaic cell, which in turn affects the performance of the voltaic cell, as the temperature of the solar panel increases in general as a result of the increase in the intensity of solar radiation, according to Equation 6 [12]. In Cell 1, the maximum temperature reached 49 °C, while in Cell 2 reached a 31 °C at a maximum solar radiation intensity of 1112 W/m$^2$ as shown in Fig. 5.

$$T_s = T_a + F \times G \quad (6)$$

Table 3. The parameters of the solar cell without a cooling system vs. time

| Cell 1/ Reference | | | | | | | |
|---|---|---|---|---|---|---|---|
| Time | E, Intensity W/m$^2$ | $T_{cell}$ °C | $V_{oc}$ | $I_{sc}$ | $V_{oc}$ | FF | η, Efficiency% |
| 11:00 | 997 | 44 | 21.4 | 0.64 | 782.13 | 0.99021 | 9.09 |
| 11:10 | 1010 | 45 | 21.3 | 0.67 | 776.03 | 0.99014 | 9.35 |
| 11:20 | 1013 | 45 | 21.3 | 0.66 | 776.03 | 0.99014 | 9.18 |
| 11:30 | 1004 | 44 | 21.3 | 0.63 | 778.47 | 0.99017 | 8.84 |
| 11:40 | 1070 | 46 | 21.2 | 0.70 | 769.96 | 0.99008 | 9.17 |
| 11:50 | 1080 | 46 | 21.1 | 0.73 | 766.33 | 0.99004 | 9.43 |
| 12:00 | 1100 | 47 | 21.4 | 0.72 | 774.80 | 0.99013 | 9.27 |
| 12:10 | 1102 | 48 | 21.2 | 0.75 | 765.16 | 0.99002 | 9.54 |
| 12:20 | 1112 | 49 | 21.3 | 0.71 | 766.39 | 0.99004 | 9.00 |
| 12:30 | 1103 | 48 | 21.1 | 0.71 | 761.55 | 0.98998 | 8.98 |

Table 4. The parameters of the solar cell with cooling system vs. time

| Cell 2/ With a cooling system | | | | | | | |
|---|---|---|---|---|---|---|---|
| Time | E, Intensity W/m$^2$ | $T_{cell}$ °C | $V_{oc}$ | $I_{sc}$ | $V_{oc}$ | FF | η, Efficiency % |
| 11:00 | 997 | 26 | 21.7 | 0.58 | 840.84 | 0.990812 | 8.36 |
| 11:10 | 1010 | 27 | 21.6 | 0.62 | 834.17 | 0.990748 | 8.78 |
| 11:20 | 1013 | 27 | 21.4 | 0.63 | 826.45 | 0.990673 | 8.81 |
| 11:30 | 1004 | 26 | 21.7 | 0.57 | 840.84 | 0.990812 | 8.15 |
| 11:40 | 1070 | 28 | 21.6 | 0.64 | 831.40 | 0.990721 | 8.55 |
| 11:50 | 1080 | 28 | 21.6 | 0.67 | 831.40 | 0.990721 | 8.87 |
| 12:00 | 1100 | 29 | 21.8 | 0.68 | 836.32 | 0.990768 | 8.92 |
| 12:10 | 1102 | 30 | 21.6 | 0.70 | 825.91 | 0.990667 | 9.08 |
| 12:20 | 1112 | 31 | 21.6 | 0.68 | 823.20 | 0.990641 | 8.74 |
| 12:30 | 1103 | 30 | 21.5 | 0.69 | 822.09 | 0.990630 | 8.90 |

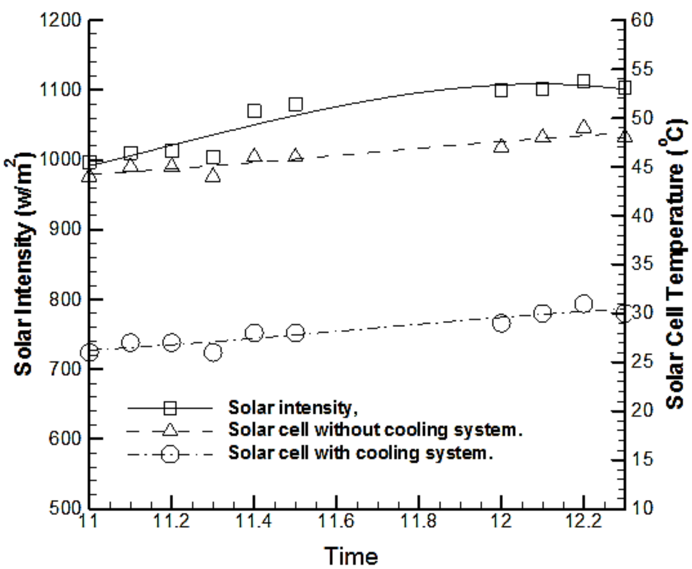


Fig. 5. This graph shows the solar intensity and the solar cell temperature with and without a cooling system as a change in time

*5.2. $I_{sc}$, $V_{oc}$ and solar cell temperature*

It was observed from the results that the value of the short circuit current increases with the increase in radiation intensity, and the reason is that the value of the short circuit current increases with the increase in radiation intensity in general, as the intensity of solar radiation affects the current of the solar panels indirectly, so the short circuit current increases with the increase in the intensity of solar radiation (Eq. 7) [13, 14], and the values of short circuit current Isc increase with increasing temperature and vice versa. In cell 1, the Isc reached 0.71-0.75 Amp at a temperature of 48-49°C, while in cell 2, the $I_{sc}$ reached 0.69-0.7 Amp, at a temperature of 30-31°C. This variation may be attributed to the fact that for many semiconductors, the energy gap between electronic states becomes narrower as the temperature increases [15].

$$I_{sc} = qnG\ (L_n + L_p) \tag{7}$$

Additionally, it is noticed that the open circuit Voc values increase slightly with a rise in temperature (Eq. 8), then its values decrease with higher temperatures, the reason for this is attributed to a saturation current density $I_o$, rises speedily with temperature faster than $I_{sc}$ (Eq. 9) [2].

$$V_{oc} = \frac{kT}{e} \ln \left(\frac{I_{SC}}{I_o} + 1\right) \tag{8}$$

$$I_o = \varepsilon n T^{\gamma} e^{\left(\frac{-E_g}{KT}\right)} \tag{9}$$

*5.3. Solar cell efficiency*

Cell efficiency depends on several factors, including the values of Isc, Voc, and solar radiation; as a result, the efficiency η generally decreases with increasing temperature and it also rises with cooling, however such a rise is not noticeable within the small range of temperature, and this is what was observed from the data in Tables 2 and 3, as shown in Fig. 6.

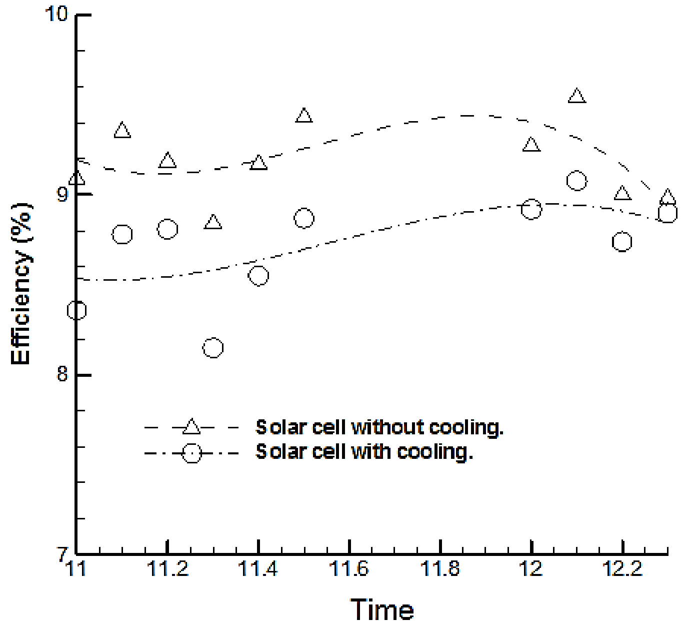


Fig. 6. This graph shows the efficiency of the solar cell with and without a cooling system as a change in time

As noticed in Tables 2 and 3 and Fig. 6, the best efficiency of the reference solar cell, without a cooling mechanism, is about 9 - 9.5% at 48-49°C, while the best efficiency of the solar cell with a cooling system is about 8.9 - 9% at 30 - 31°C, this indicates that the proposed cooling system has shown effectiveness in cooling the solar cell; the drop in temperature reached up to 18°C, although its effect in increasing the efficiency of the solar cell has not been achieved. The effects are consistent with literature that finds that the efficiency of solar panels generally decreases with increasing temperature, but this effect does not occur within a small temperature range [16].

The scientific reasons for the low efficiency of photovoltaic cells despite cooling [17-19]: 1- Cooling might reduce the temperature of photovoltaic cells, but this doesn't always lead to improved efficiency. The efficiency of solar cells is influenced by their temperature coefficient, which varies among different materials. Although efficiency typically drops with rising temperatures, the gains from cooling might diminish once the temperature reaches a certain level. 2- Thermal resistance and heat transfer: Effective cooling requires overcoming thermal resistance between the solar cell and the cooling system. If heat transfer is not efficient or if the system cannot address all heat sources, cooling might not significantly enhance performance.

## 6. Conclusion

In this study, the impact of temperature on solar cell performance was investigated with the use of a cooling system. The experimental findings revealed the following:

- The temperature of the solar cell without cooling ranged from approximately 44 to 49 degrees Celsius, whereas the temperature of the solar cell with the cooling system decreased to a range of 26 to 31 degrees Celsius. So, the proposed cooling system showed effectiveness in cooling the solar cell by reducing the temperature of the solar panel by approximately 18 degrees Celsius compared to the solar panel without the cooling system.
- The efficiency of the solar cell without cooling was approximately 9-9.5%, while the efficiency of the solar cell with the cooling system was around 8.4-9%. The solar radiation intensity during the experiment ranged from 990 to 1100 watts/m².
- The conclusions drawn from the study indicate that while the fan-based cooling system effectively reduced the temperature of the solar cells by 18°C compared to the reference cells, it did not significantly enhance the efficiency of the solar cells when temperatures were below 50 °C. Therefore, the use of such a cooling system did not result in a notable improvement in photovoltaic performance under the tested conditions. This suggests that while cooling can lower the temperature of the cells, its impact on increasing overall efficiency may be limited when temperatures are already within a certain range.

Based on these results, it was concluded that the proposed cooling system was effective in cooling the solar cell, although reducing the temperature using the cooling system did not significantly affect the efficiency of the solar cell when the temperature was less than 50 °C.

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