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Enhancing the performance of photovoltaic panels by controlling external climatic parameters: An experimental study

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ABSTRACT

The global energy crisis presents itself as an ongoing problem which photovoltaic (PV) panels address effectively by converting renewable solar power into electricity. The performance of PV panels suffers from operating temperature increases causing important decreases in electrical efficiency. A reliable cooling system needs implementation to preserve thermal stability along with maximizing energy conversion performance. A laboratory investigation evaluates the implementation of distilled thermoelectric heat sinks aimed at reducing PV panel surface temperatures for better overall performance enhancement. The laboratory experiment used closed-loop cooling with parallel-installed thermoelectric modules below and above PV panels to measure various configuration performances under controlled indoor testing. Tests took place at the college of technical engineering at University of Thi-Qar to identify the best thermal energy (TE) module layout which produced the minimum achievable base temperature of the PV panel. The study conducted a systematic analysis of different cooling setup configurations which helped identify the top performing design that simultaneously reduced energy losses and achieved maximum power output. The study's findings show that proper positioning of TE modules creates substantial improvements for PV system thermal regulation. The best arrangement yielded substantial temperature reduction alongside enhanced energy efficiency which demonstrated TE-assisted cooling can be an effective solution for future solar power systems.

Keywords: photovoltaic panels, climatic parameters, solar cells, heat generation

INTRODUCTION

People's lifestyles in any nation are typically determined by the infrastructure which keeps up with the advancements in some areas, including technology and energy. Individuals constantly strive to do so, life is more comfortable due to energy utilization and accessibility. Most energy sources that are utilized by the nations are fossil fuels, which include oil, coal, and gas. They are not easily obtainable, though. In addition to that, in the case when such types of raw fuels aren't transformed into products that can be used, they can't be used. Pollution from fuel conversion processes damages the environment and contributes to global warming. One of the most harmful man-made occurrences is the global warming (Abdellatif et al., 2013). More emissions will be produced and released into the atmosphere, making the weather extremely polluted. Because of the pollution issue, scientists are always searching for new energy sources that emit no emissions while in use. Another factor is that it is forcing the energy sector to look for sustainable energy sources. The greatest potential energy source to supply power to all consumers worldwide is the sun. Many researchers and scientists were drawn to work on solar energy since it is an environmentally friendly energy source (Ozgoren et al., 2013). With the use of solar light, two types of energy could be produced. First, there is the electrical energy that is generated by using photovoltaic (PV) cells for converting light into electricity, and second, there is the thermal energy (TE) generated through turning sunlight into heat (Ust et al., 2017). Diagram of the ground mount array is shown in **Figure 1**.

Problem Statement

The temperature of cells in which the PV module operates (25 °C and 1,000 W/m^2) determines the panel's performance. The productivity related to the PV cell for electrical power reduces as the cell's temperature increases, leading to a reduction in module efficiency. The percentage related to solar radiation that is converted into electrical energy falls in the range of 13% to 20%, and most solar radiation that is absorbed through the cell is converted to unwanted TE, which raises the temperature of the cell and reduces the degree of efficiency. The primary issue with PV panels is the decline in cell performance and efficiency brought on by an increase in cell

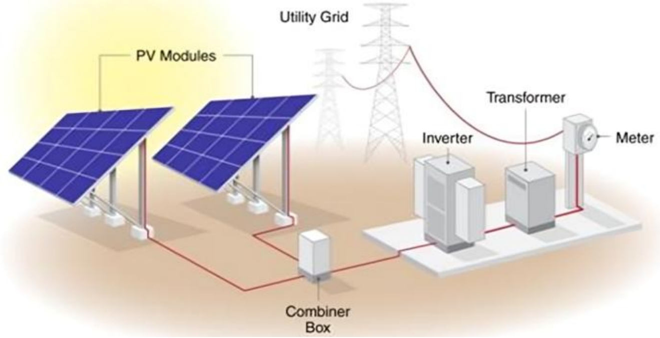


Figure 1. Main components of a solar energy system (ground-mounted array diagram) (Yazdanpanahi et al., 2015)

base temperature. The most straightforward and quickest way to decrease cell base temperature through heat transfer and disposal techniques is highly motivated in order to get around this restriction.

Table 1 shows the summary of existing PV cooling approaches, limitations, and research gaps.

Research Objectives

The aims of this study are through the immersion of PV panels in water, in which the process of immersion takes place; PV cooling systems can be used to improve PV performance in the following ways: Lowering the PV cell's overall surface temperature, which increases its absorption of sunlight. Assessing the PV cooling system's performance using thermos-electric leg. In comparison with typical solar panels, high-production solar panels require less area to install. Significance of the study: As was previously indicated, maintaining PV module efficiency at its optimum or maximum value–that is, meeting the requirements in practical applications for obtaining the expected efficiency–is a significant difficulty. The presented work aims to determine whether or not it is economically feasible to use a cooling system for cooling PV modules in order to maintain the highest potential performance. Numerous theoretical and experimental investigations have been carried out on the subject of cooling PV panels in order to boost their production efficiency. It's critical to comprehend the many scientific perspectives regarding the cooling system of PV panels for understanding the different cooling techniques. The most widely used and significant technologies are those that combine the use of air and water or both.

COOLING METHODS OF THE PHOTOVOLTAIC CELLS

Here, a variety of approaches were evaluated as well as summarized to give readers an overview of the types of approaches that are currently being researched for highlighting research on cooling systems for PV cells. The PV's ability to generate power will rise as the cooling systems operate better. Therefore, it is worthwhile to highlight a few of those significant studies, which are listed below.

PV Cooling Systems Utilizing Water as Coolant

A water-spraying approach was employed by Yazdanpanahi et al. (2015) to reduce the amount of water that is consumed in PV panel cooling facility. The 45 °C temperature dropped to 35 °C. Examine how spraying water on the front face of PV can clean it and lower its surface temperature (Rosa-Clot et al., 2014). The results demonstrated that PV performance may be increased by 9.5% by employing a thin layer of water for extracting the heat. Three PV cooling methods were verified by experimental studies carried out by Gakkhar et al. (2016). It has been discovered that surface temperature of solar cells had dropped to 16 °C when the first membrane of water-cooling technique was put to their front surfaces. The second method involves attaching direct contact back water to cool. It has been discovered that solar cells' surface temperature had dropped to 18 °C, while the third method combined back and film cooling. The cells' surface temperature was discovered to have dropped to 25. An infrared camera was utilized to get the results of experiment. It demonstrates that, in comparison to non-cooled PV modules, the daily energy production regarding PV cooling increased by a ratio as high as 22%, 29.80%, and 35%, respectively for film, back, and combined film-back cooling modules.

On the rear and back of the coolant, Wu and Xiong (2014) built an absorber and a collector. There are ways to improve the electric efficiency by 8.50, 12-14, and 8%. Han et al. (2013) have immersed silicon monocrystalline panel in a pool of water at varying depth levels. When put to comparison with PV panels without any cooling devices, data analysis reveals that electrical efficiency had increased (by 11%) to a 4 cm depth and just increased by 15% at a 40 cm water depth. For addressing the increase in operating cell temperature, Raad (2014) improved a PV module's electrical performance by using water cooling. Prior to the cooling procedure, it has been noted that

Table 1. Summary of existing PV cooling approaches, limitations, and research gaps

Category	Examples	Advantages	Limitations	Research gaps
Passive cooling	Heat sinks, extended fins, natural ventilation, phase-change materials (PCMs)	Simple, no external energy consumption, low maintenance	Limited cooling effect under high irradiance, performance drops in hot climates	Often evaluated under narrow conditions; not sufficient in high-irradiance climates
Active air cooling	Forced convection using fans	Effective in reducing surface temperature, relatively low cost	Requires electricity for fans; effectiveness depends on wind distribution	Few studies quantify net energy gain (extra power-fan consumption)
Active liquid cooling	Water circulation, hybrid PV/T systems	Strong cooling capacity, can provide thermal energy for secondary uses	Higher complexity, risk of leakage, pump energy cost, maintenance required	Limited comparative field experiments vs. air cooling under the same conditions
Hybrid strategies	PV with shading devices, nanofluids, or combined cooling	Potentially higher overall performance	System complexity, cost-effectiveness not proven in real conditions	Lack of systematic testing of combined strategies with energy balance

electrical efficiency was not higher than 8%. The cell temperature dropped at the ideal water flow rate of 0.2 L/s, increasing electrical efficiency by no less than 9.6% and thermal efficiency to 12.3%. The water-cooling method of immersion was examined by Hosseini et al. (2011). The PV have been immersed in water and monitored under real condition with cell surface temperature of (31 °C-39 °C). At 1 cm depth, efficiency has been enhanced by 17%.

Three distinct water-cooling techniques were employed by Kordzadeh (2010): rear, front, and double cooling. With regard to front cooling, spray technology has been employed, and for the rear cooling, the direct contact water technology has been utilized. In order ascertain the performance regarding PV module in various water-cooling techniques and to identify optimal module, the findings have been put to comparison with a non-cooling PV panel. The outcome showed that the front cooling method is better than the rear cooling method in terms of its ability to lower the PV module's temperature on a broader scale.

Ust et al. (2020) and Nashee et al. (2025) have utilized COMSOL program in order to study heat transfer on absorb plate system under the PV thermal photovoltaic/thermal (PV/T). Impacts of the level of irradiation from 200W/m2 to 1,000 W/m^2, a flow channel depth (0.020 m, 0.015 m, and 0.010 m), and various other parameters, like Prandtl No. from 4 to 6.50 and Reynolds No. from 200 to 1,600 on electrical and heat transfer performance have been developed then studied.

Cell temperature had dropped to 10.2 °C and the heat transfer rate had increased to 25.50% by increasing the channel depth and renumber, respectively. Water spray technique was employed by Revati and Natarajan (2016) and Rawat et al. (2014) to provide single-side cooling, which was administered to both the front and back sides. Power output has been 40.1 W for front side only and 39.9 W for the rear side. Water cooling technology was employed by Enasel et al. (2023) from both the solar panel's back and top. Direct water cooling was used for cooling the front panel, while pipes connected to a water reservoir cooled the rear of the panel. According to the data, the temperature of the cell decreased from 50 °C to 39 °C, according to the data. The impact of cooling on the plate's front surface throughout India's winter and summer was investigated by Sainthiya et al. (2018). The findings demonstrated that the electricity efficiency reaches (11-14%) in the winter and (9-12%) in the summer. The impact of reducing cell surface temperature on efficiency and conversion tool was investigated by Rashwan et al. (2016). A total of four distinct nozzle types with varying diameter values (2, 3, 4, and 5 mm) have been utilized in the water spray method. The findings demonstrated that utilizing a 2 mm diameter nozzle lowered the cell temperature to half of its original value.

PV Cooling Systems That Use Air as Coolant

As Rawat et al. (2014) applied forced air to PV cells, they discovered that the level of the voltage dropped the first time the cell was exposed to solar radiation without any cooling. When the PV was exposed to sunlight and cooled, the voltage rose. The study discovered that PV's temperature increases in response to solar radiation, which has a detrimental effect on the PV's performance.

Revati and Natarajan (2016) investigated how temperature affected PV cell performance in a variety of settings, including solar cells on grass field, air-cooled solar cells, and solar cells without any type of cooling mechanism. There were displays of the temperature of the panel, temperature of the cell surface, open circuit voltage and short circuit current. In the case when air cooling was employed, high open circuit voltage and short circuit current values have been attained because temperature of solar cells had decreased.

Alsayah (2020) and Maghrabie et al. (2017) have investigated the impact of air forced cooling on the PV cells utilizing air blower to rectangular channel that is mounted on the back of the PV module. Findings have indicated that in the case where the air passes over the back of the PV unit, the temperature regarding the cell decreases by 11%, and in the case where the air passes over the front of PV, PV temperature decreases by 10%. PV efficiency is rising at rate of 3.7%. The effectiveness of a PV/T air collector was examined by Farshchimonfared et al. (2015) and Teo et al. (2012) in relation to several parameters, including optimized channel depth and air mass flow rate/unit area. The suggested model considered various collector areas and ratios of length to width assuming a constant increase in temperature of 10 °C. It was shown that raising length to width ratio and the collector area led to increasing collector's optimal depth.

Tonui and Tripanagnostopoulos (2007) investigated the effectiveness of solar PV collectors that take out heat by using force or regular air motion. The air conduit has been enhanced by two techniques that increase heat conversion from the pipe wall to airflow. The first placed the thin metallic layer in the middle of the tube, and the other one connected the rectangular fin at the back of channel.

PV Cooling Systems That Use an Air and Water Combination as Coolant

Four PV cells were used by Mansour and Al-Hamdani (2024a), two of which had air cooling and the other 2 had water cooling. The results show that the water-based cooling systems are more efficient in comparison with the air-based cooling systems. Temperature had increased to 9 °C, and the previous cooling method's efficiency increased by a ratio of 9.27%. For studying the effects of cooled PV panels, Mansour and Al-Hamdani (2024b) used both air and water at the same time. Water has been passed in front of PV panel and air was passed through a channel that was constructed at its back. After using ANSYS simulation tool to examine the data, it has been found that cooling water had reduced the temperature of air cooling by 53% and by 19%.

Two investigations were carried out by Najm and Mansour (2024) to investigate and analyze PV cells that use an air and water cooling system. A water-cooling system has been built on front surface of PV cells, and an air-cooling system utilizing a DC fan with a 3.07 m/sec wind speed has been installed on the cells' back. Solid-Work application was used for designing an engineering model, while the ANSYS program was used for thermal analysis. In the case when utilizing the water cooling systems, the temperature increased to 31.15 °C, whereas the air cooling system was able to lower it to 53.6 °C.

Observations From Previous Studies

It is clear from this chapter's demonstration of the most relevant studies utilizing cooling systems that the researchers aimed to improve the PV panels' overall performance through boosting their electrical efficiency through using various cooling systems. Furthermore, it may be said that cooling systems that run on water are more efficient compared to those that run on air because of their greater effectiveness. This encourages us to focus on enhancing PV panels through the immersion in water. Water cooling systems are being used by researchers for a variety of reasons, including their affordability, simplicity, and the availability of water everywhere.

THEORETICAL STUDY

This study's technique will be further developed through experimentation and numerical analysis. This chapter solely addresses the numerical part. The approach's primary objective is to maximize heat transfer in PV thermal collectors by considering the depth of water flow in their channels. This chapter will discuss the approaches used for carrying out the research technique, giving readers a thorough understanding of what is happening in this research project.

Assumptions

There are various geometries that could be utilized for the purpose of achieving the PV/T system's thermal channel collector. The suggested thermal collector's rectangular channel can be modified by varying the water flow's depth; Figure 3-1 illustrates this process, in which PV module's upper and lower parts are pushed for circulating distilled water for use as a working fluid. The next assumptions have been made in the simulation and analysis:

1. A channel's outer surface is totally insulated, with the exception of PV/T system's top surface that is exposed to solar radiation.
2. Laminar flow.
3. Heat transfer with the fluid flow.

NOCT varies throughout modules based on manufacturing technology and manufacturer. However, NOCT often has a value between 45 and 48 °C (Mansour & Ugla, 2024). This value has been utilized for calculating cell temperature.

Coefficients of Temperature For the Power, Current, and Voltage (HP, HI, and HV)

The temperature coefficients of each solar cell, also known as PV module, are different. Those coefficients are crucial for calculating how a change in temperature affects a PV module's voltage, power, and current. Voltage temperature coefficient (HV): evaluates changes in the open circuit voltage regarding PV module because of changes in the degrees of temperature.

Usually,

$$HV = -3.7 \times 10 - \frac{3mV}{1}{}^{\circ}C. \quad (1)$$

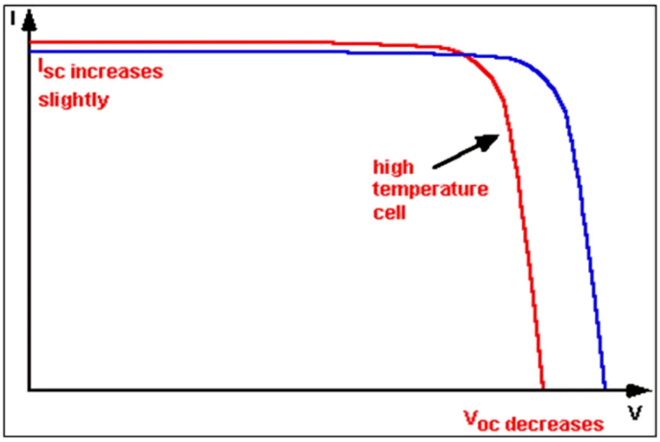


Figure 2. Effects of temperature degree on IV characteristics of the solar cell (Tonui & Tripanagnostopoulos, 2007)

Temperature coefficient of current (HI): evaluates changes in the short circuit current of PV module because of changes in its degree of temperature (Lafta et al., 2025).

$$HI = 6.4 \times 10 - \frac{4mA}{1}{}^{\circ}C. \quad (2)$$

Temperature coefficient of power (HP): evaluates changes in the power because PV changes in the degree of temperature. This coefficient could be calculated with the use of voltage temperature coefficient HV, based on the next equation (Lafta & Mansour, 2025), where HV represents temperature coefficient of open-circuit voltage [V/°C], V_{mp} represents voltage at maximal power point under the standard testing conditions [V]. Since it is the primary (and initial) coefficient impacted by cell temperature, voltage temperature coefficient is typically supplied together with the module's data sheet from the manufacturer (Abdulhasan et al., 2022).

The Way That Temperature Affects the Solar Cells

As it is well known, a number of factors, majorly due to the cell temperature, cause PV module output in the field to vary from that at the STC or in the lab. However, why is the temperature of the cell rising? And how does that impact the PV module's output and performance? The temperature affects all semiconductor devices, such as solar cells. A semiconductor's band gap narrows with temperature, which has an impact on the majority of semiconductor material properties. It is possible to think of reduction in semi-conductor's band gap with increasing degree of temperature as increase in electron energy within a material. Thus, a smaller amount of energy is required in order to break the bond. A reduction in the bond energy results in a corresponding decrease in the band gap in the semiconductor bond model (Shkarah, 2021). Thus, the band gap is lowered by raising the temperature. Open-circuit voltage in a solar cell represents the metric that is most affected by temperature rise. Figure 2 illustrates how rising temperatures affect open circuit voltage.

Table 2. Sunlight combinations (Mansour & Doos, 2025)

Spectrum	Wavelength range	Percentage of sunlight
Ultraviolet	10 nm-380 nm	46%
Violet	380-450 nm	7%
Blue	450-495 nm	
Green	495-570 nm	
Yellow	570-590 nm	
Orange	590-620 nm	
Red	620-750 nm	
Infrared	750-1,000,000 nm	47%

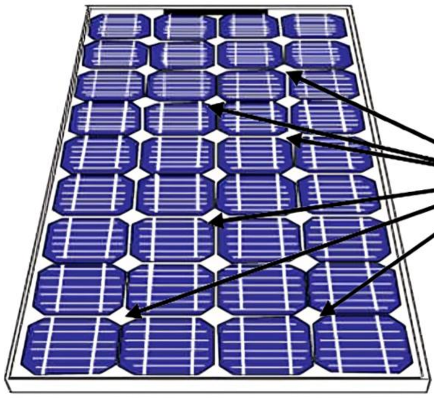


Figure 3. Empty PV module regions (Tonui & Tripanagnostopoulos, 2007)

Correlation Between Cell Temperature and Solar Radiation

A portion of sun's energy is bounced back to space before it enters the atmosphere, leaving the remaining portion that powers our lives behind. The only energy source that PV module receives is solar radiation, and it receives this energy from the sun. The module will absorb some radiation, or solar light, and convert it to heat and electricity. The remaining light will be reflected. The sun's configurations are displayed in **Table 2**.

The most common semiconductor material for solar cells is silicon, along with p- and n-type materials. Solar cells use visible light for generating electricity. The material is exposed to solar radiation with wave-lengths that range between 380 nm and 750 nm, or violet to red, with sufficient energy for knocking electrons from their weak bonds and creating electric current. Because they lack the energy to excite the electrons, unused wavelengths (UV and infrared) have been absorbed as heat.

Heat Generation and Losses in Photovoltaic Modules (i.e., Solar Cells) Heat Generation

Just 10% to 15% of the incident sunlight is converted to electricity in typical commercial PV module that works at its maximal power point; the rest of the percentage is transferred into heat.

Thus, a PV module that is exposed to the sunlight produces heat in addition to electricity. There are some factors affecting heat generation (module heating):

1. IR light absorption (i.e., low energy) by the solar cells.
2. Electrical operation of the cells (means that the current flows through the shunt and series resistance).
3. The reflection from the top surface.
4. Sun-light Absorption by the empty regions. There are regions which aren't covered by the solar cell in module as that has been shown in **Figure 3** (Mansour, 2024).
5. The solar cells' packing material.

Table 3 shows the measured parameters, instruments, and accuracy.

PRESENTATION OF RESULTS & ANALYSIS

The findings in **Figure 4** display the steady state temperature in degrees Celsius at the cooling application's area or center.

Table 3. Measured parameters, instruments, and accuracy

Parameter	Purpose	Instrument/sensor	Measurement range	Accuracy/resolution
Module voltage (V)	Compute instantaneous power, Voc	Digital multimeter/data logger channel	0-100 V	±0.1 V/0.01 V
Module current (I)	Compute instantaneous power, Isc	Shunt resistor + DAQ/current sensor	0-10 A	±0.01 A
Module surface temperature (T_module)	Assess effect of cooling on module	K-type thermocouple or PT100 sensor	-20 °C to 100 °C	±0.5 °C
PV cell temperature (T_cell)	Determine efficiency and temperature coefficient	Embedded thermocouple or sensor on backsheet	-20 °C to 100 °C	±0.5 °C
Plane of array irradiance (G)	Normalize power to standard test conditions	Pyranometer/reference cell	0-1,200 W/m²	±5 W/m²
Ambient temperature (T_ambient)	Environmental context	Thermocouple/weather station	-20 °C to 60 °C	±0.5 °C
Wind speed (u)	Quantify convective cooling potential	Cup or ultrasonic anemometer	0-20 m/s	±0.1 m/s
Relative humidity (RH)	Assess atmospheric impact on PV performance	Hygrometer	0-100%	±2%
Cooling device energy consumption	Compute net energy gain/loss	Inline power meter for fan/pump	0-1,000 W	±1 W
Time/date	Synchronize measurements	Data logger timestamp	N/A	1 s

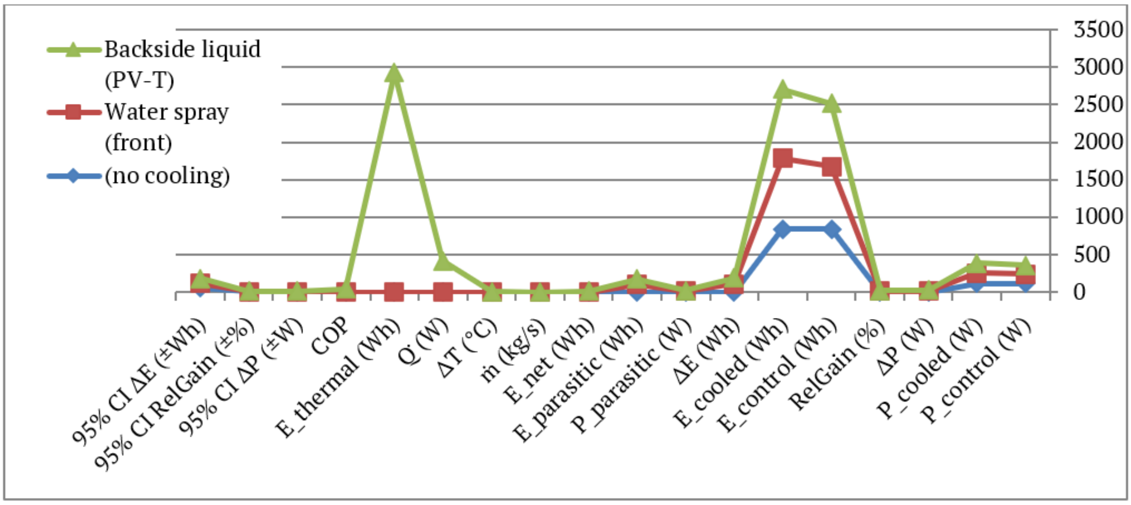


Figure 4. Comparison table: PV cooling methods validation values (validation equations for PV panel cooling methods: Absolute power gain (W): ΔP = P_cooled-P_control; relative efficiency gain (%): RelGain% = (ΔP/P_control) × 100; energy yield gain (%): ΔE = E_cooled-E_control\nEnergyGain% = (ΔE/E_control) × 100; parasitic power & net energy: E_parasitic = P_parasitic × t_op\nE_net = ΔE-E_parasitic; thermal recovery (W): Q = m × c_p × (T_out-T_in); thermal energy (Wh): E_thermal = Q × t; coefficient of performance (COP): COP = Q/P_parasitic) (Source: Authors' own elaboration)

Figure 5. How to install thermoelectric heat sink on the solar panel (Source: Field study)

Additionally, it shows the matching power output for that specific cooling technique. The baseline is located at the top of histogram, in which cooling is most efficient, and no cooling occurs at the bottom. It's evident that the active water-cooling approach worked well. Furthermore, the outcomes of the numerous passive conduction cooling techniques that made use of heat sinks and pipes are comparable. The module temperature was just marginally lowered by such findings compared to water cooling.

Ultimately, all configurations significantly decreased the module's operating cell temperature from the first tests conducted without any cooling. Given the variety of cooling methods that have been tested, a universal value which characterizes cooling must be defined for comparing cooling effects. It is challenging to compare the obtained results because so few works have done comprehensive measurements as well as computations of gained power, total and relative efficiency increases, and detailed descriptions of cooling methods. A particular power gain per surface could be determined for every one of the experiments by considering the maximum power gain and dividing it by the PV cell's effective surface. Tests cannot be considered without such details. Furthermore, this method of comparison is merely qualitative since it leaves out important details from a number of works from which just logical conclusions could be drawn (e.g., the effective area could be roughly inferred from overall area).

Thermoelectric Heat sink

Figure 5 depicts how to install thermoelectric heat sink on the solar panel. For evaluating value of power, each thermoelectric sink 3.8 V and 2.5 A. Power for each TE leg = 2.5 + (2 × 3.8) = 9.5 W and multiply with five (numbers of TE leg is used). TE leg is 2 × 9.5 = 19 W.

Each fan consumed 4 watt:

$$Total\ power = (4 \times 2) + 19 = 8 + 19 = 27\ watt. \qquad (3)$$

This means that the power needs an approximate value of 27 watts to operate the solar panel.

Figure 6 shows the configuration and specifications thermoelectric heat sink.

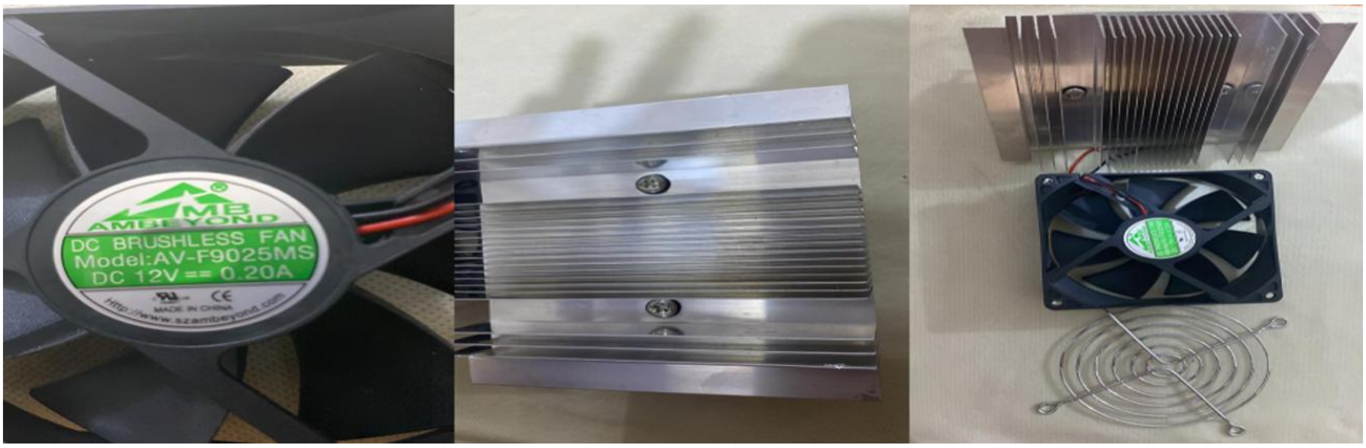


Figure 6. Configuration and specifications thermoelectric heat sink (Source: Field study)

Figure 7. Using the sensor to read the temperature on the solar panels (Source: Field study)

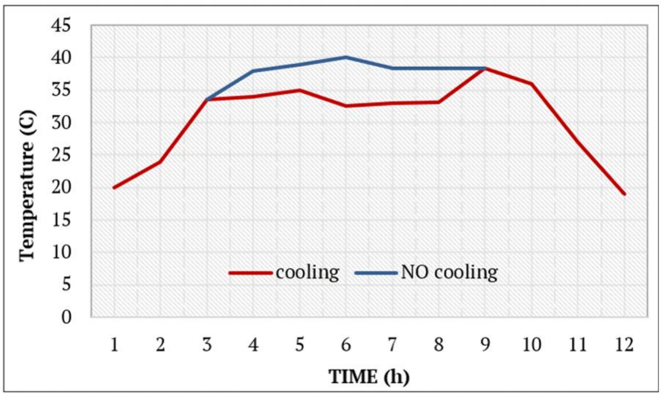
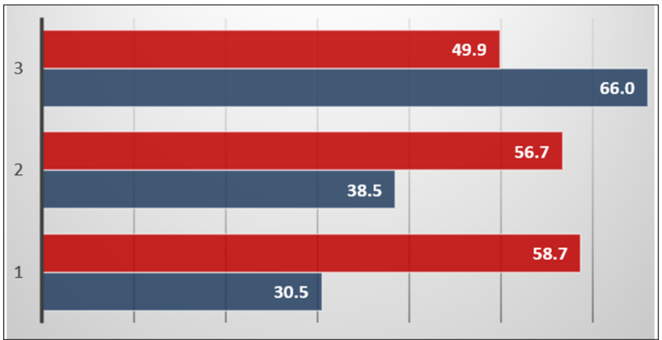


Figure 8. Temperature vs. time graph of PV module without cooling and when cooling is done (Source: Authors' own elaboration)



Legend: Red: Power output; Blue: Temperature; 1: Thermoelectric heat sink; 2: Water cooling; & 3: No cooling

Figure 10. Temperature and power for each cooling method test (Source: Authors' own elaboration)

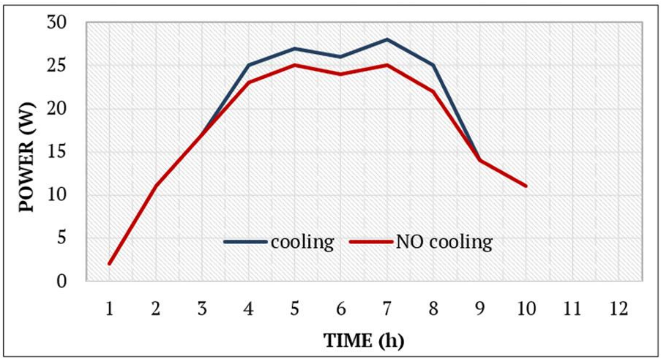


Figure 9. Power vs. time graph of PV module without cooling and when cooling is done (Source: Authors' own elaboration)

Figure 7 shows the using the sensor to read the temperature on the solar panels.

Figure 8 depicts the temperature vs. time graph of PV module without cooling and when cooling is done.

Figure 9 shows the power vs. time graph of PV module without cooling and when cooling is done.

The findings are displayed in **Figure 10**, which displays the steady state temperature in degrees celsius at the cooling application's area or center.

Additionally, it shows the corresponding power output for that specific cooling technique. The baseline is located at the top of histogram, in which cooling is most efficient, and there is no cooling at the bottom. It's evident that the active water-cooling approach worked well.

Table 4. Performance of PV before and after cooling by water

Parameter	Before cooling	After cooling
Panel temperature (°C)	81.0	34.6
Voc (V)	16.64	19.30
Reduction in Voc (%)	22.62%	10.00%
Output power (W)	58.9	97.0
Reduction in output power (%)	27.40%	5.00%
Electrical efficiency (%)	10.62%	11.63%
Thermal efficiency (%)		50.05%
Total efficiency (%)		61.68%

Table 5. Performance of PV before and after cooling by open cycle system

Parameter	Before cooling	After cooling
Panel temperature (°C)	82	35
Voc (V)	36.5	42.0
Reduction in Voc (%)	17.50%	5.00%
Output power (W)	120	167
Reduction in output power (%)	32.00%	5.00%
Electrical efficiency (%)	11.70%	13.09%
Thermal efficiency (%)		51.54%
Total efficiency (%)		64.63%

Furthermore, the outcomes of the numerous passive conduction cooling techniques that made use of heat sinks and pipes are comparable. The module temperature was just marginally lowered by such findings compared to water cooling. Ultimately, every setup significantly decreased the module's operating cell temperature from the first tests conducted without any cooling.

Table 4 shows the performance of PV before and after cooling by water.

Table 5 depicts the performance of PV before and after cooling by open cycle system.

CONCLUSIONS

This research demonstrates that integrating PV/T solar technology presents a favorable opportunity for Thi-Qar residential applications. A sustainable solution of PV/T technology shows promise for the region since its climate and geology make it ideal for such implementation. Using underground TE for cooling has shown itself to be a successful technique for sustaining PV module operations and improving system efficiency throughout. PV/T systems generate electrical power while simultaneously delivering heat energy for residential hot water preparation and home heating requirements. The dual-energy generation capacity enhances system efficiency while improving domestic viability for such integrated PV/T units. The cooling system proves its capability to serve as a thermal sink when used with ground source heat pump (GSHP) systems which creates a comprehensive solution for building temperature control. The temperature condition of PV modules serves as a fundamental element which controls the amount of electricity generated by PV systems. The open circuit voltage together with output power shows direct correspondence to temperature fluctuations. Any efforts to enhance PV module energy output require effective thermal regulation systems. The enhanced thermal operations and electrical capabilities of PV/T systems provide utility companies with the chance to control peak winter electricity consumption levels. The systems play a dual role by capturing waste heat and contributing to both energy conservation and more sustainable energy supply infrastructure operation. PV/T technology alongside combined underground cooling systems with GSHP represents a sustainable energy solution that delivers maximum efficiency to the region.

Future Works

While the current study validates the effectiveness of different cooling methods for PV panels under controlled climatic parameters, several avenues remain for future investigation.

1. **Integrated PV/T for domestic use:** Create a PV/T system which employs a self-contained water circulation system and cooling mechanism to provide both heating for spaces and hot water services effectively.
2. **PV/T with phase change materials (PCM):** Construct PV/T systems which integrate PCMs as storage elements and temperature controllers for optimizing system performance.
3. **Economic and sustainability assessment:** Perform a techno-economic analysis of different cooling technologies to determine cost-effectiveness over the lifecycle of PV panels.Assess the environmental footprint of cooling methods in terms of embodied energy, water use, and recyclability of cooling materials.
4. **Concentrated PV/T systems:** Further research should be conducted into CPV/T systems alongside optical concentrators as this combination decreases array footprint while generating equal or enhanced power outputs.
5. **Integration with GSHP systems:** A combined PV/T technology with GSHPs allows users to access heating and cooling functions throughout the entire year.
6. **Advanced cooling materials:** Explore the integration of nanofluids, phase change composites, and aerogels to enhance heat transfer and thermal storage capacity. Investigate how thermoelectric modules with improved materials (e.g., skutterudites, half: Heusler compounds) can achieve higher
7. **Climatic performance evaluation:** A series of experimental research projects together with simulations should be conducted under different Thi-Qar weather patterns to verify the system's reliability and performance efficiency.

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