Research Article/Mechanical Engineering, Mechatronics, and Materials Science http://doi.org/10.15446/ing.investig.106383

Determining the Effect of Photovoltaic Module Surface Temperature on Generation Efficiency

Determinación del efecto de la temperatura superficial de los módulos fotovoltaicos en su eficiencia de generación

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ABSTRACT

It is imperative to consider the environmental impact of energy production and its cost in deciding how to meet future energy needs. In this regard, it is possible to harness the power of the sun by using photovoltaic (PV) cells. However, when the temperature of a PV cell increases, its generation efficiency is negatively affected. The open-circuit voltage of PV modules is the most sensitive parameter to temperature changes. As the temperature rises, this parameter decreases, and the short-circuit current increases. The circuit's resistance also rises as the electrons' speed is reduced. Temperature also affects the lifespan of PV cells, increasing the rate of thermal decay in their materials. On the other hand, when solar radiation is absorbed at lower temperatures, the system's efficiency, power capacity, and useful life increase. PV module surface temperatures can be reduced in a variety of ways, e.g., the surface can be cooled using water. This work studied hybrid PV-thermal modules under the climate conditions of the Hatay province (Turkey) in order to assess the effect of water cooling on their generation efficiency. The results allow stating that up to 52.6% more electricity can be generated by cooling the module's surface. Additionally, it was found that, in order for PV modules to perform efficiently in Hatay's climate, they must operate at a maximum surface temperature of 55 ˚C.

Keywords: solar PV-T module, PV surface temperature, PV efficiency

RESUMEN

Es imperativo considerar el impacto ambiental de la producción de energía y su costo al decidir cómo satisfacer las necesidades energéticas futuras. A este respecto, es posible aprovechar el poder del sol utilizando células fotovoltaicas (PV). Sin embargo, cuando la temperatura de una célula PV aumenta, su eficiencia de generación se ve negativamente afectada. El voltaje en circuito abierto de los módulos PV es el parámetro más sensible a los cambios de temperatura. A medida que la temperatura aumenta, este parámetro disminuye, y la corriente de cortocircuito aumenta. La resistencia del circuito también se eleva a medida que la velocidad de los electrones se reduce. La temperatura también afecta la vida útil de las células PV, incrementando la tasa de degradación térmica en sus materiales. Por otro lado, cuando la radiación solar se absorbe a temperaturas más bajas, la eficiencia del sistema, la capacidad de potencia y la vida útil aumentan. Las temperaturas superficiales de los módulos PV pueden reducirse de varias maneras, e.g., la superficie puede enfriarse utilizando agua. Este trabajo estudió módulos híbridos PV-térmicos bajo las condiciones climáticas de la provincia de Hatay (Turquía) con el fin de evaluar el efecto del enfriamiento con agua en su eficiencia de generación. Los resultados permiten afirmar que se puede generar hasta un 52.6 % más de electricidad enfriando la superficie del módulo. Además, se encontró que, para que los módulos PV funcionen eficientemente en el clima de Hatay, deben operar a una temperatura superficial máxima de 55 ˚C.

Palabras clave: módulo solar PV-T, temperatura superficial PV, eficiencia PV

Received: December 12th, 2022
Accepted: January 19th, 2024

Nomenclature

P_e: Electrical power (W)
V_i: Instant voltage value (V)
I_i: Instant current value (A)
η_e: Electric conversion efficiency (decimal)
G: Solar radiation on the normal surface (W/m²)
A_p: Module surface area (m²)

Introduction

Energy, a key factor for human socio-economic and sustainable development, as well as for improving quality of life, is one of the most important resources in sustaining our lives (Meinshausen *et al.*, 2009). Although the world has been seriously harmed as a result of the misuse of natural resources, there is an ongoing search for ways to obtain clean and sustainable energy (Zanlorenzi *et al.*, 2018), as the majority of today's energy comes from fossil fuels and nuclear sources.

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Solar generation is popular, allowing the energy provided by the sun to be used in different ways by converting it into electrical power (Tiwari *et al*., 2006). Solar cells operate on the photovoltaic (PV) principle for power generation, *i.e.*, they generate electricity when they receive light. When solar radiation in the form of photons hits the surface of semiconductor materials such as silicon, electrons are released from atoms, entailing an electric voltage. Solar energy is free and available in abundance. Many applications based on this resource have been developed, including different types of concentrated solar thermal power technologies, solar PV generation, hybrid solar PV and thermal techniques, solar desalination, solar hydrogen production, solar-assisted heat pump technologies, *etc.* (Wang *et al*., 2021).

It is the type of PV employed that has the most bearing on electrical performance. Power generation from solar cells ranges from 6 to 20% depending on weather conditions and the type of cells used in a typical PV module. The remaining incident solar radiation is transformed into heat, which raises the temperature of the PV module and reduces its efficiency (Dubey *et al*., 2013). As PV cells have spectrum-dependent characteristics, ineffective solar radiation increases the cell temperature after it is absorbed, causing a decrease in photoelectric conversion efficiency. Solar PV-thermal (PV-T) technologies employing beam splitting can solve this problem to a certain degree (Wang *et al*., 2023). PV-T collectors can be used to gather this heat from flowing water or air beneath the PV module.

Increases in intrinsic carrier concentrations at higher temperatures lead to increases in the dark saturation current of the p-n junction, which reduces PV cell efficiency. Due to excessive doping, the intrinsic carrier concentration rises as a result of a reduced band gap. The open-circuit voltage drops linearly as the dark saturation current rises, resulting in a temperature change of 2.3 mV/°C for silicon at 300 K, as stated by Peng *et al*. (2017).

At temperatures ranging from 20 to 100 °C, it is estimated that the reduction in the solar cell's band gap increases the short circuit current by 0.1%. Despite this increase in current, reductions in the open-circuit voltage cause a noticeable decrease in the maximum electrical power, as seen in the characteristic curves of PV modules at different operating temperatures (Figure 1) (Andreev *et al*., 1997).

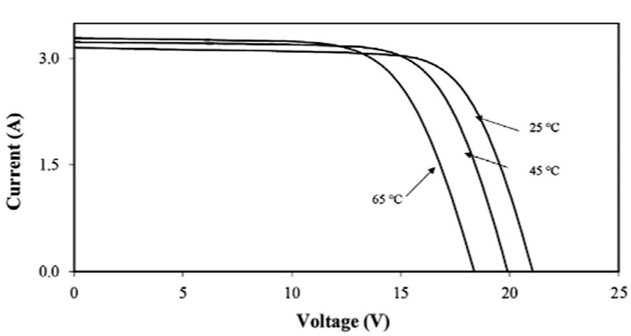

Figure 1. Influence of temperature on a PV module I-V curve
Source: Andreev *et al*. (1997)

A study by Radziemska (2003) determined that the power and voltage produced by monocrystalline silicon solar cells and the maximum power vary at different temperatures (Figure 2).

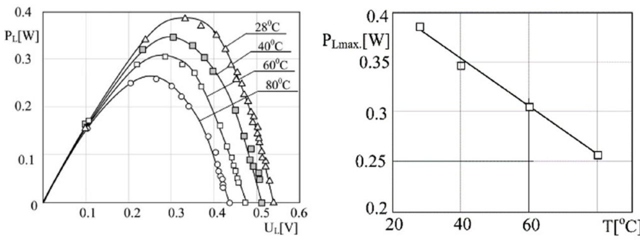

Figure 2. a) Voltage-output power and b) maximum output power-temperature relationships in a monocrystalline silicon cell at different surface temperatures
Source: Radziemska (2003)

One of the advantages of using a solar PV and thermal hybrid system is that it simultaneously generates electricity and thermal energy from the sun. The use of PV-T systems leads to the production of both useful heat energy and electrical power. The solar PV cells currently on the market have a comparatively low efficiency (less than 15%). After PV conversion, more than 80% of the solar energy absorbed is lost as heat into the environment. Cooling PV systems is important, as their efficiency decreases when the temperature goes above a certain point. In order to boost performance, it is critical to keep PV modules cool (Rawat and Dhiran, 2017).

While the short-circuit current of PV cells increases with temperature, the open-circuit voltage decreases. The resistance that reduces the speed of electrons in the circuit also increases with temperature. Therefore, high operating temperatures have a negative impact on power and efficiency in PV systems. With an effect on the thermal degradation of the module's material, temperature also reduces the effective efficiency of the cells. Therefore, lowering the operating surface temperature is an effective way to increase the efficiency of a PV module and reduce its thermal degradation rate. This can be achieved by cooling the module and lowering the heat stored in the PV cells during operation. There are several methods for reducing PV module surface temperatures, including water cooling systems.

The goal of this study is to determine how the efficiency of PV modules changes when cooled via the liquid fluid approach in a PV/T system in the province of Hatay. We expect our results to aid in determining the surface temperature values for the most efficient operation of PV systems, as well as in identifying the efficiency losses regarding electricity production that are caused by temperature in similar hot climate conditions. It is also stated in the studies mentioned above that the panel surface temperature affects the electricity generation efficiency of PV systems. This study aims to determine the extent of this effect and the efficient operating temperature ranges to be used in similar regions. In this vein, a PV-T experimental setup, which can be operated with or without water cooling, is used to take measurements.

Methodology

Materials

Today, hybrid PV-T solar systems are one of the most popular methods for cooling PV modules. These hybrid systems consist of solar PV modules combined with a cooling system. To cool the surface of the PV modules, water or air is pumped over them, boosting their efficiency.

In the experimental setup, (except PV modules) parts such as a pump circulating the cooling water in the cooling system, a water tank, a solar radiation meter, temperature sensors, data recorders, current and voltage recorders, a charge controller, a light bulb, a mini meteorological station, PE pipe components were used (Figure 3).

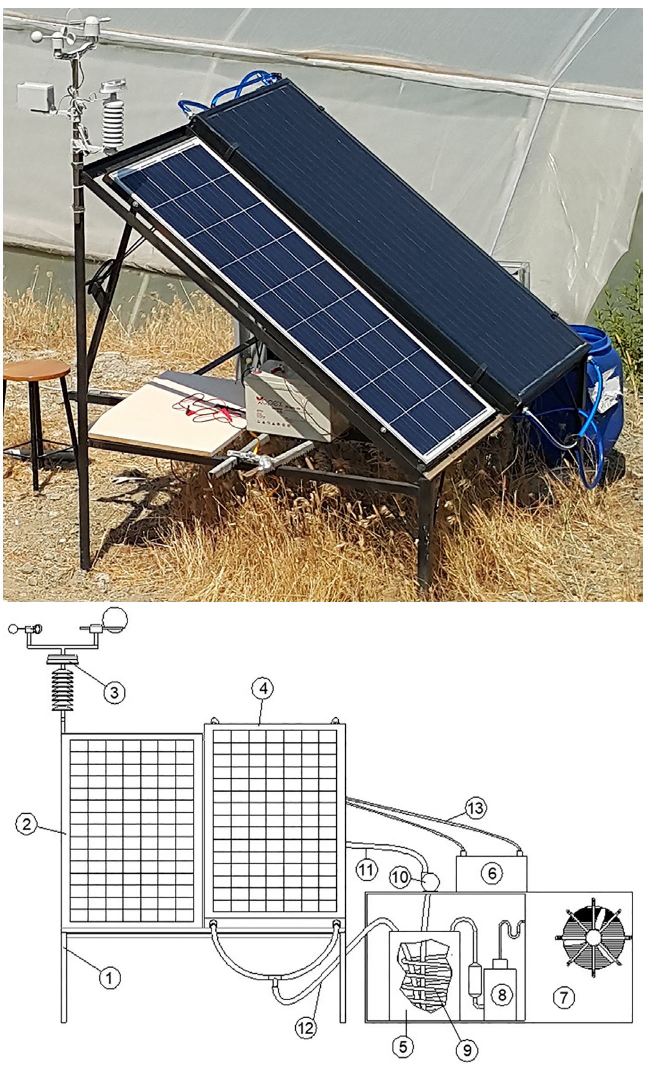

Figure 3. Experimental setup and its parts: 1) scaffold, 2) PV module, 3) weather station, 4) PV-T module, 5) water tank, 6) battery, 7) fan, 8) compressor, 9) serpentine, 10) pump, 11 and 12) PE pipes
Source: Authors

A PV/T module was used, whose features are presented below (Table 1, Figure 4).

Table 1. PV-T module specifications

Properties	**Values**
Dimensions (mm)	1601 x 828 x 90
Mass (kg)	24.4
Nominal power (W)	190
Specific power (W/m²)	143.4
Nominal current (A)	5.2
Short circuit current (I_{SC})(A)	5.6
Nominal voltage (V)	36.4
Open circuit voltage (V_{OC})(V)	45.2
Module	monocrystalline

Source: Authors

The PV-T module was cooled using water, which was in turn cooled with a compressor cooling system. An evaporator in the form of a spiral copper pipe immersed in the tank was entrusted with water cooling. The cooling system was managed with a digital temperature controller that can be set to a minimum temperature of 18 °C (Figure 3, no. 5, 7, 8, 9).

The measurement involved a PWM charge controller; a 12 V, 100 Ah gel-type battery to measure the power produced by the system; and a mini meteorological station to record climate data including wind speed and direction, temperature (ambient, perceived, and dew), and relative and absolute pressure. These data were measured in 5 min intervals (Figure 3, no. 3).

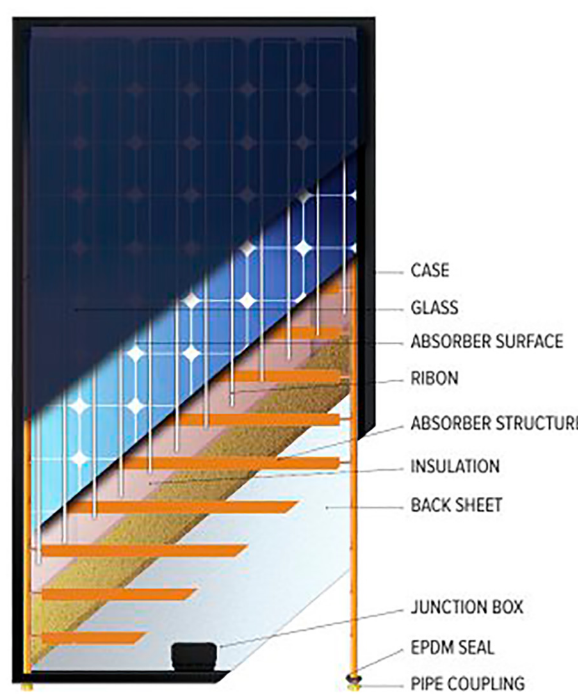

Figure 4. PV/T module
Source: Solimpeks (n.d.)

Method

The electricity generation efficiency of the PV/T module was determined in two ways: with and without cooling. To this effect, as shown in Figure 5, the current and voltage values produced by the module were measured in 5 min intervals by connecting two multimeters. In both experiments, in addition to these measurements, module surface temperature, solar radiation levels, and climate parameters were measured. Measurements were taken between 10:00 a.m. and 3:00 p.m., when the sun was at its most intense.

The water cooled via the compressor system was used to reduce the temperature of the PV/T module. With the help of a 12/24 V DC pump, water at a temperature of around 20 ˚C was pushed through the PV/T module and discharged back into the water tank, providing perpetual circulation.

Moreover, for the sake of comparison, the current, voltage, and surface temperature values of the PV module were measured in the experimental setup.

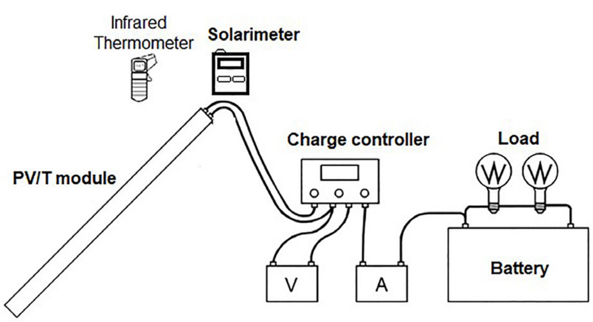

Figure 5. Connection diagram of the experimental setup's measurement system
Source: Authors

The power produced by the solar modules was calculated using Equations (1) and (2), aiming to determine the efficiency of the modules. The power consumed by the cooling water system was not considered.

$$P_e = I_i V_i \tag{1}$$

$$\eta_e = \frac{P_e}{G\,A_p} \tag{2}$$

The results of these measurements were graphed. This includes the evolution of the surface temperature of the PV-T module with and without cooling as well as the module's efficiency, aiming to determine their relationship. The temperature changes were calculated by taking the differences between the two measurement points, and the efficiency change was determined by calculating the percentage of the difference between the two measurement points.

Results

Current-voltage, solar radiation-module power, and temperature-efficiency graphs for a day of operating the PV-T cooling module. A total of six days was plotted. The data for June 24th, 2019, are presented in Figures 6, 7, and 8.

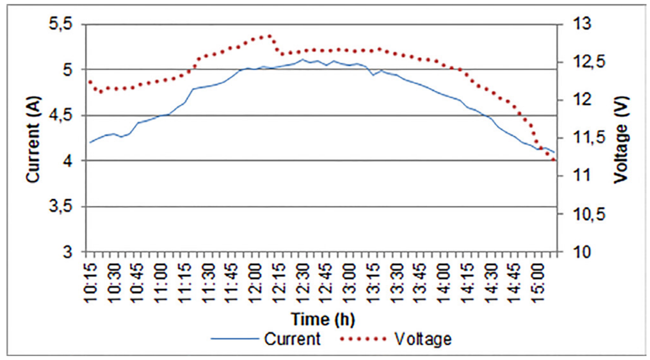

Figure 6. PV-T module with cooling, current-voltage graph (24 June 2019)
Source: Authors

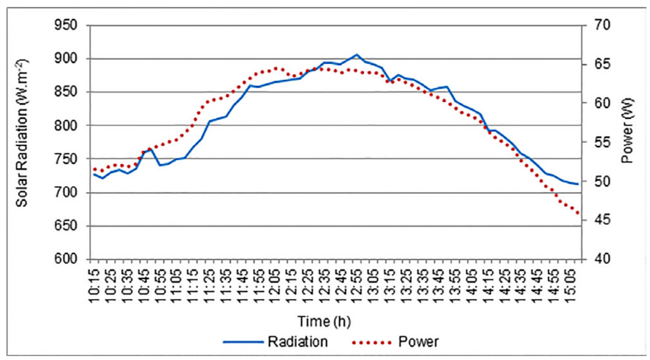

Figure 7. PV-T module with cooling, solar radiation-module power generation graph (24 June 2019)
Source: Authors

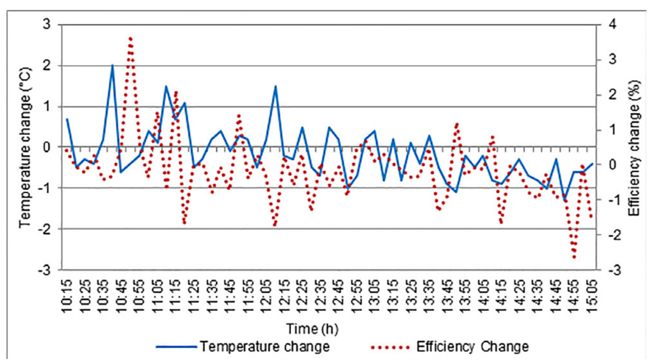

Figure 8. PV-T module with cooling, temperature-efficiency graph (24 June 2019)
Source: Authors

The results showed that the current ranges from 4.0 to 5.11 A, while the voltage ranges from 11.0 to 12.90 V. It was determined that the highest current and voltage values of the PV-T module are reported between 11:45 a.m. and 1:30 p.m. (Figure 6).

Regarding the solar radiation-module power graph, it was observed that the radiation ranges from 711.6 to 905.2 W/

m², and the electrical power generated ranges from 45.92 to 64.53 W. The highest values occurred between 11:45 a.m. and 1:30 p.m. (Figure 7).

The module's surface temperature value ranged from 46.0 to 60.7 ˚C, and its electricity generation efficiency ranged from 4.98 to 5.84%. At many measurement points, temperature increases caused a decrease in efficiency (Figure 8). The temperature between the measurement points went from -1.3 to 2.0 ˚C, and the electricity generation efficiency of the module increased when surface temperature decreased. According to the calculations, the module's efficiency varied between -2.63 and +3.69% with regard to variations in surface temperature.

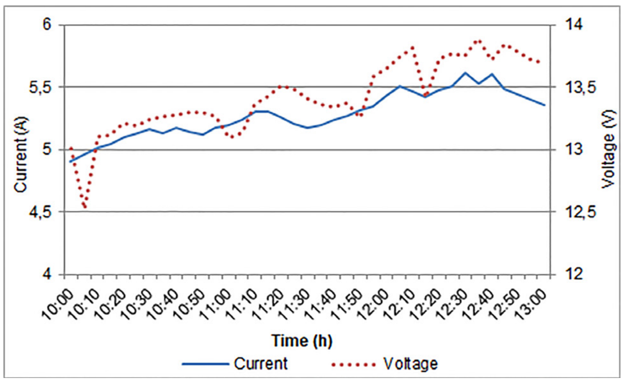

Figure 9. PV-T module without cooling, current-voltage graph (30 June 2019)
Source: Authors

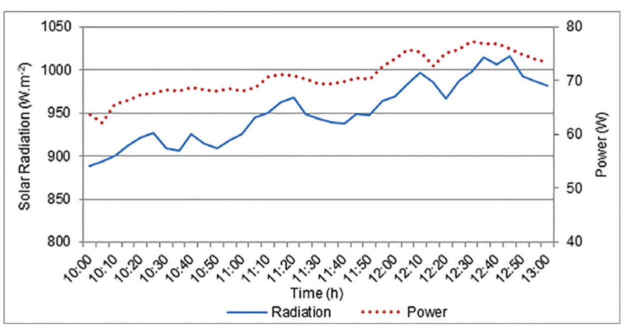

Figure 10. PV-T module without cooling, solar radiation-module power generation graph (30 June 2019)
Source: Authors

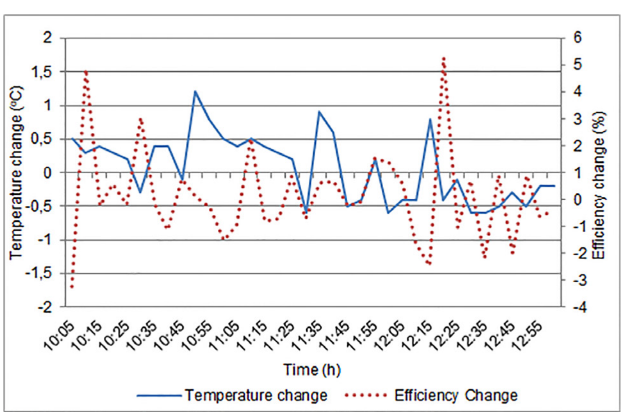

Figure 11. PV-T module without cooling, temperature-efficiency graph (30 June 2019)
Source: Authors

On June 30th, 2019, the current ranged from 4.9 to 5.6 A, while the voltage went from 12.52 to 13.89 V. The highest current and voltage values of the PV-T module occurred between 11:45 a.m. and 1:30 p.m. (Figure 9).

Solar radiation ranged from 888.3 to 1 016 W/m², and power generation ranged from 62.1 to 77.3 W. The highest values were reported between 11:45 a.m. and1:30 p.m. (Figure 10).

The module surface temperature value ranged from 46.0 to 60.7 ˚C, and the electricity generation efficiency went from 4.3 to 6.0%. At many measurements points, temperature increases also caused a decrease in efficiency (Figure 11). Temperature changes between measurement points ranged from -0.6 to 1.2 ˚C. The efficiency of the module increased when the surface temperature decreased. According to the calculations, the changes in generation efficiency are between -3.2 and +5.29% with regard to surface temperature.

The overall variation ranges for all days of measurement are presented in Table 2.

Table 2. Variations in temperature and efficiency in the system with and without cooling

	With cooling	**Without cooling**
Highest temperature change (˚C)	4,20	2,60
Lowest temperature change (˚C)	-5,20	-2,10
Highest efficiency change (%)	3,54	0,55
Lowest efficiency change (%)	-3,45	-0,57

Source: Authors

For all measurements, the temperature change interval of the system without cooling was 7.7 ˚C, and that of the system with cooling was 9.2 ˚C. In light of this, the efficiency change intervals were 1.12 and 6.99%, respectively. Based on these results, it can be stated that an efficiency increase and decrease of 3.5% is generated by changes in the module surface temperature.

Table 3 presents the descriptive statistics of the module surface temperature and efficiency values for all measurement days in both scenarios (with cooling and without cooling).

Table 3. Temperature and efficiency values with and without cooling

Descriptive statistics	**With cooling**		**Without cooling**	
	Temperature (˚C)	Efficiency (%)	Temperature (˚C)	Efficiency (%)
Minimum	33.30	4.42	52.80	4.52
Maximum	61.50	9.31	75.20	6.10
Mean	52.02	5.95	64.28	5.57
Standard error	0.381	0.056	0.334	0.022

Source: Authors

For the PV-T module without cooling, the module surface temperature reported values of up to 75.20 °C. With cooling, the lowest value was 33.30 °C. The efficiency of the system without cooling reached a maximum of 6.10% depending on the surface temperature. Moreover, the highest efficiency value was 9.31% with cooling. By comparing both scenarios, an efficiency increase of 52.62% was observed with the use of the cooling system.

Several studies have been carried out in various applications to reduce the surface temperature of PV panels. Some of these are reviewed below. These works have aimed to increase panel efficiency and generation by reducing the surface temperature.

The efficiency increase achieved with our cooling system is similar to that of Akbarzadeh and Wadowski (1996), who measured water cooling in a hybrid PV-T solar system, with the purpose of increasing the output power by almost 50%. They also determined that the module's cooling process prevents the surface temperature of the solar cells from going above 46 °C for a period of 4 h.

As reported by Teo *et al*. (2012), when a module with no active cooling only exhibits an 8-9% efficiency. However, when it is cooled, the temperature drops significantly, and its efficiency increases to 12-14%.

Abu-Rahmeh (2017) compared three different PV panel cooling methods: water, nanofluid TiO_2 (0.04% by weight), and rectangular aluminum fins. With regard to a non-cooled system, this study reported efficiency increases of 5.37, 2.62, and 1.34% for the TiO_2, water, and fin cooling methods, respectively. In comparison with our study, this work showed that TiO_2 cooling is more effective than using water, while rectangular aluminum fins reported the lowest efficiency improvements.

In the study by Peng *et al*. (2017), which compared the ice cooling method applied behind the PV panel against a non-cooled system, the highest value reported by the latter was 4.98%. The cooled system, however, reached a 7.32% efficiency, which represents a 47% improvement.

Haidara *et al*. (2018) set out to determine the decrease in panel temperature and the changes in panel efficiency while using an evaporative cooling system that involved wetting a fabric and placing it on the back surface of the PV panel. They stated that a 14% increase in electricity generation efficiency was achieved, in response to a temperature drop of more than 20 °C in the PV panel.

In a study conducted by Gül and Akyüz (2019), the electrical and thermal performances of a hybrid PV-T system were evaluated. These authors observed a thermal efficiency range of 49.9-52.11% in measurements taken at fluid velocities of 0.015, 0.044, and 0.069 kg/s. A comparison of the module's electrical performance with and without cooling showed a 12.9% increase in the electrical output's maximum power point, and the electrical efficiency was calculated as 12%.

In the study carried out by Luboń *et al*. (2020), which aimed to reduce the module temperature by pouring cold tap water in the form of a water film on the surface of the PV module, a power increase of up to 20.2 W/m² was observed. These authors determined that a 20% increase in the total power generation can be obtained by continuously cooling the module's surface.

The effect of the water flow rate on PV panel performance was determined in the study by Govardhanan *et al*. (2020), used a uniform water flow on the PV panel surface for cooling. It was determined that cooling the PV module increases the output power by 15% when compared to the conventional approach. The cooling water flow rate that yielded the highest PV module power was 5.3 kg/min.

In a study that experimentally evaluated the effect of simultaneous dual-surface cooling on the output performance of a PV module, where both surfaces were cooled using a water flow on the panel surface and an absorbing cotton wick mesh on the rear surface, an improvement of approximately 30.3% in the output power of the panel was obtained. In addition, it was stated that the average efficiency of the non-cooled panel was 12.83%, against an average efficiency of 14.36% in the cooled system (Agyekum *et al*., 2021).

Zubeer and Ali (2022) set out to determine the changes in panel performance as a result of water cooling in concentrator photovoltaic (CPV) panels. They stated that the surface temperature decreased from 64.1 to 365 °C with this approach. This temperature drop increased the panel's electricity generation efficiency from 14.2 to 17%. In addition, in the water-cooled CPV system, the open circuit voltage and the short circuit current increased by 9 and 5.2%, respectively.

Shalaby *et al*. (2022) employed water passing through PVC pipes placed behind a PV panel for cooling. Their results showed an improvement of 14.1% in the power generation of the cooled PV panel. In addition, they stated that the electrical efficiency of the PV module with cooling reached 19.8% *vs.* the 17.4% value achieved without cooling.

The aforementioned studies show changes in panel surface temperature and electricity generation efficiency depending on the method applied. While the panel surface temperature decreases by over 20 °C with cooling applications, increments of up to 50% in power generation have been observed. According to the cooling method, increments in panel electricity generation efficiency ranging from 12 to 47% have been reported. In our study, it was determined that a maximum temperature difference of 13.7 °C is obtained by cooling the panel surface. Moreover, an efficiency increase of 52.6% was achieved in scenarios involving cooling. These data are similar to those obtained in previous studies.

When analyzing the surface temperature and efficiency graphs for the PV-T module in both scenarios, it was observed that decreases in surface temperature entail increased efficiency. By examining the measurements separately, we noticed a partial decrease in efficiency with increasing surface temperature. This parallel increase in efficiency and temperature could be a result of increased solar radiation. Above a certain temperature, the electricity production of PV modules becomes heat loss, reducing their efficiency. The main reason for this is that, as the temperature of the cell rises, the voltage produced by it decreases, resulting in thermal resistance.

Figure 12 provides a clearer graph of the relationship between the module's surface temperature and electricity generation efficiency throughout the analysis period.

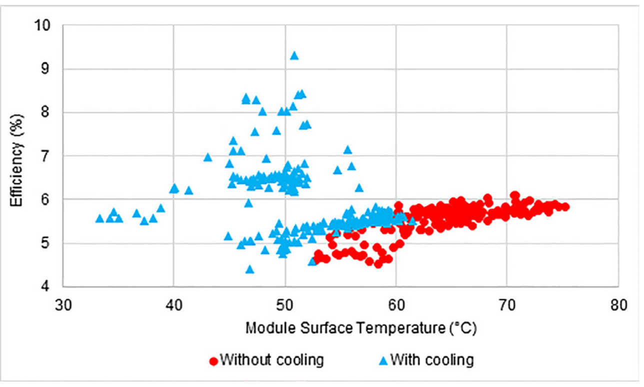

Figure 12. PV-T module with and without cooling, overall surface temperature-efficiency graph
Source: Authors

By evaluating all measurements together, a relationship between surface temperature and generation was observed (Figure 12). In all measurements taken without the cooling system, we noticed an efficiency mostly below 6%. Furthermore, the panel surface temperature did not fall below 50 °C. With cooling however, the surface temperature remained below 60 °C. For this scenario, the calculated efficiency values increased by up to 9%. It was determined that a panel surface temperature of 45-55 °C is necessary to achieve the highest PV module efficiency in summer, as losses were reported at higher temperatures.

The climate data (ambient temperature, humidity, and wind speed) on the days of the experiment were also recorded. The climate parameters for all days were approximately the same. Only on June 30th, 2019, was the air humidity very low in comparison. This day showed the highest values, especially regarding solar radiation (888-1 016 W/m^2).

Conclusions

This section summarizes the results obtained during our, which aimed to determine the effect of PV panel surface temperature on electricity production efficiency while using a water-cooled PV-T system.

- Solar radiation was observed to be in the range of 600-1 000 W/m^2 throughout the analyzed period.
- The highest power generation value was 77.3 W without cooling and 95.7 W with cooling.
- The module surface temperature was between 51.6 and 75.2 °C in the system without cooling and between 33.3 and 61.5 °C in the one with cooling.
- The module generation efficiency was 6.10% without cooling and 9.30% with cooling. This represents an increase of 52.62%.
- According to the scatterplot showing the relationship between module surface temperature and electricity generation efficiency, the most suitable module surface temperature is 45-55 °C, which yields a high efficiency in PV panels operating during the summer months in the Hatay province. This is also valid for regions with similar climate conditions.
- Furthermore, air humidity was shown to have a negative impact on direct solar radiation levels.

CRedit author statement

This article was elaborated within the framework of MSc studies and supported by Hatay Mustafa Kemal University, Coordinatorship of Scientific Research Projects (project no. 18.YL.053).

Conflicts of interest

The authors declare no conflict of interest.

Author contributions

All authors have participated in a) conception and design or data analysis and interpretation; (b) drafting the article or revising it critically for important intellectual content; and (c) approving of the final version of the manuscript.

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