



Experimental comparative study on using different cooling techniques with photovoltaic modules

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Abstract

Overcoming the issue of photovoltaic (PV) module productivity at high temperatures is one of the most critical obstacles facing its use. PV cells are made of silicon, which loses its properties at high temperatures, degrading the PV module work. The present research compares cotton wicks integrated with rectangular aluminium fins (CWIRAFs) submerged in water as passive cooling with an absorbing plate and copper pipes attached at the PV module backside as active cooling. Compared with the PV module without cooling, CWIRAFs have better performance with the PV module than active cooling owing to evaporative cooling and increased heat dissipation area represented by wet cotton bristles integrated. The PV module is exposed to significant performance degradation without cooling in hot climate conditions. As a result, using CWIRAFs with the PV module had reduced the temperature by 31.4%, increased the power by up to 66.6%, and increased the electrical efficiency from 3.12 to 8.6%. Active cooling methods have reduced the PV temperature by 20.8%, increased the power by 56.7%, and enhanced electrical efficiency by 7.9%. Removing excess heat from the backside of the PV module via circulating water has improved the thermal efficiency and overall efficiency of the PVT system by about 26.3 and 34.2%, respectively.

Keywords Evaporative cooling · Active cooling · Electrical efficiency · Output power · PV Thermal behaviour · PV performance

Abbreviations

A_c	Surface area of the PV modules m^2
CWIRAFs	Cotton wicks integrated with rectangular aluminium fins
CWs	Cotton wicks
C_p	Specific heat $J g^{-1}K^{-1}$
I	Current A
\dot{m}	Mass flow rate $kg s^{-1}$
P	Power W
PV	Photovoltaic
Q_u	Energy gain W
S	Solar radiation $W m^{-2}$
T_o	Outlet temperature $^{\circ}C$
T_i	Inlet temperature $^{\circ}C$

V	Voltage V
η_{th}	Thermal efficiency %
η_{ov}	Overall efficiency

Introduction

Modern economies mainly depend on long-term energy availability for future economic growth. The energy sector has manifested significant concerns due to the unavailability of sufficient energy resources and increasing conventional energy demands due to human activities. Although fossil fuels are a significant energy source for power generation, burning fossil fuels increases air pollution and greenhouse gas emissions. Fluctuating fossil fuel prices and significant environmental damages encourage renewable energy sources to be an alternative to conventional energy sources in various applications. Solar energy is one of the abundant clean energy sources, reduces environmental impact and is applicable in various fields [1, 2]. Photovoltaic (PV) is amongst solar energy technologies that consist of semiconductor materials and work to convert sunlight (i.e. short-wavelength energy) to electricity [3]. Given that PV modules work

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outdoors, they are constantly affected by weather conditions, such as temperature, solar radiation and wind [4]. Generally, below 20% of solar radiation is converted into electricity by PV modules, and the remainder is converted into heat causes long- and short-term problems for PV modules. Environmental factors, such as ultraviolet intensity, temperature and water, ingress into PV cells and cause performance degradation of PV modules (i.e. long-term problem).

Meanwhile, increasing PV cell temperature negatively affects cell conversion efficiency, decreasing PV modules electrical power yield (i.e. short-term problem) [5]. Increasing PV cell temperature decreases open-circuit voltage and 0.4–0.5% in PV cell efficiency compared with the standard test condition [6]. Thus, the reliability and lifetime of PV modules are affected [7]. Different cooling techniques used help to reduce productivity losses and enhance PV module efficiency at high temperatures. Passive and active cooling techniques have been commonly used to maintain PV module performance at high operating temperatures. Passive cooling does not require external power for cooling the PV module, whereas active cooling needs it [8]. In this regard, different configurations of passive and active cooling were applied to decrease operating temperature and enhance the PV module performance. Figure 1 shows the progress of PV cooling techniques in the recent decade.

Numerous research works have been made to investigate different cooling techniques for PV module improvement. Amongst others, Nasrin et al. [9] proposed a passive cooling technique consisting of phase change material (PCM) consisting of different oils placed in a container designed as a zig-zag geometry to increase the heat transfer surface at the PV modules backside. Natural water circulation removes heat from the PCM container without any pump system.

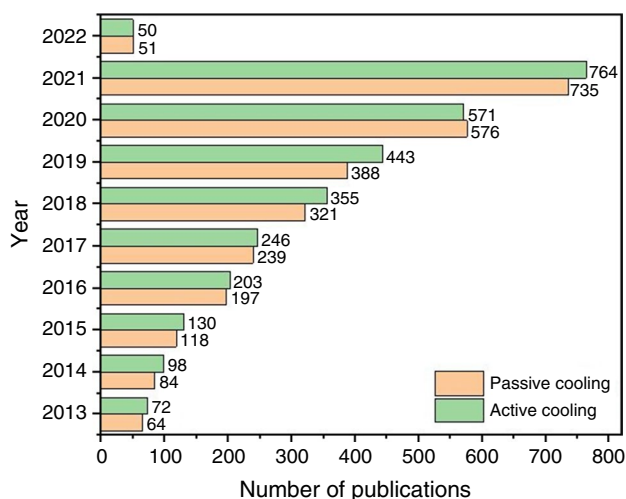


Fig. 1 Statistics of publications used active and passive cooling of PV modules (Scopus database)

The technique used led to the enhancement of efficiency to 21.19, 26.88 and 29.24% at solar radiation intensities of 410, 530 and 690 W m^{-2} , respectively. Mixed PCM with Boehmite nanopowder has better efficiency than the oils used. In a proposed model consisting of cylindrical pin fins with a heat sink, pin fins were arranged uniformly to transmit heat from the PV module to air and enhance the exchange of heat of the PV module. A moist wool wood pad was placed on the backside to ensure the touch with the backside surface of the heat sink, and water naturally dropped was used to provide a moist condition for the pad. The average PV module temperature decreased from 61 to 45 °C because of the prevailing moist condition at the backside of the PV module, thereby improving output power by 32.7% and PV efficiency by 31.7%. This cooling technique is characterised by easy maintenance and cost to reduce the PV module degradation [10]. Another method used thin rectangular fins placed longitudinally and integrated on the thin flat metallic sheet placed to the backside of the PV module. Fins helped to release heat from the rear of the PV to air effectively. Thus, the PV module increased the electrical and thermal efficiencies by 56.19 and 13.75%, respectively, using four fins under 700 W m^{-2} of solar radiation [11]. Alami [12] adopted the evaporative cooling technique involving a synthetic clay layer covering a copper sheet with a vaporiser and a measuring beaker filled with water used to spray the water onto the clay that integrates by the backside of the PV module. The results indicate that this technology improved the performance of the PV module by increasing the output voltage by 19.4% and output power to 19.1%.

Chandrasekar and Senthilkumar [13] propose fins in conjunction with cotton wicks attached at the backside of PV to control its temperature during operation. Cotton wick was supplied with fluid from the bottom to the top of the PV module. The study shows that using fins integrated with cotton wicks increased the electrical yield of PV modules to 14% because of a 12% decrease in the PV module temperature. The use of clay was markedly effective, affordable and environment friendly. A new design has been tested experimentally to cool the PV cell and increase the thermal efficiency by recycling the incident solar radiation on the PV module. The cooling design consisted of different cylindrical aluminium fins and geometries subjected to forced convection in a channel. The PV module efficiency was evaluated considering the effects of fins made in different array arrangements through the designed control volume. Different fin geometries have been used (helically shaped and axial channel), and the array positions were staggered and inline. The results designated a reduction in the PV cells' temperature and enhancement in the electrical efficiency. Used fins having different surface areas were absorbed the excess heat from the PV cells and prevented their electrical efficiency reduction by less than 7%. The thermal energy

loss prevented by control volume and the air speed was between 630–304 W [14]. Another technique represents by integrating the desiccants material on the backside of the PV module; at night, when the temperature decreases, desiccants work to adsorb water from the air when the relative humidity is high. During the day, when the temperature increases, water evaporates and takes excess heat from the PV module. The results referred to dropping the PV modules temperature lower than ambient air temperatures that may reduce to 30 °C with evaporative cooling. The yield of PV modules increases by over 10% in sunny conditions [15].

Praveenkumar et al. [16] experimentally investigated the effect of a passive cooling approach consisting of a CPU heat pipe sink without a fan to dissipate the rising temperature at the backside of the PV module and compared the PV module performance with another PV module without cooling. The cooling approach had decreased the PV module temperature by 6.72 °C, which increased the electrical power to 11.39 W compared with the uncooled PV module, which recorded 9.73 W. Therefore, the electrical efficiency of the PV module was improved by 2.98%. A numerical investigation was conducted to show the effect of active cooling on the PV cell efficiency under different mass flow rates, ambient temperatures (25, 35, and 45 °C), and various solar radiation ranges (between 600–1000 W m⁻²). Computational fluid dynamics (CFD) has been applied to evaluate the influence of temperature, mass flow rate and solar radiation on the efficiency of the PV cells at different water velocities at cooling channels. The results recorded highest enhancement of the PV cell efficiency at an inlet water velocity of 0.9 m/s, maximum solar irradiance of 1000 W m⁻², and an ambient temperature of 45 °C. A slight effect was found in the mass flow rate at high flow rates, and the current cooling approach is effective at high solar radiation values and ambient temperatures [17]. On the other hand, several configurations of active cooling technology were used, significantly improving the PV modules performance. For instance, aluminium pipes were designed serpentine as a flow channel of water without being placed on the absorber plate and attached to the backside of the PV module. The performance of the PV module improved to 9.2%, and the electrical and thermal energies of PVTC increased by 17.48 and 113.14 W, respectively, at 1% concentrated water/MWCNT nanofluid [18]. Gelis et al. [19] experimentally studied the effect of cooling nanofluids based SiO₂, Al₂O₃ and CuO on the PVT performance under laboratory conditions. A new partitioned cooler block, as a rectangular prism, has been designed to increase the contact between the backside surface of the PVT and the cooler block. Different independent variables were adopted, such the nanofluid type, volume concentrations, volumetric flow rate, and solar radiation level to investigate their effects on the PVT system performance. The study found that Al₂O₃ nanofluid has achieved higher electrical efficiency by

21.18% than SiO₂ and CuO nanofluids due to the temperature drop of the PV cells. In contrast, using CuO nanofluid resulted in higher thermal efficiency by 66.49% compared with the other nanofluids applied due to the higher thermal conductivity of CuO nanofluid.

Another configuration representing a stainless-steel tube designed as a serpentine exchanger bonded on a stainless-steel sheet has been placed at the PV module's backside. A two-phase flow of CO₂ passes inside the exchanger by a heat pump system. Decreased solar absorber plate temperature led to an increase in the yield of electrical power of the PV module. The proposed design helped to increase the electrical efficiency from 14.1 to 16% with 1.028 kW of thermal energy, and overall efficiency reached 72.3% [20]. AL-Musawi et al. [21] propose active cooling by a rectangular insulation duct integrated at the backside of the PV module. This duct was made of polystyrene sandwiched amongst galvanised steel sheets with a fan to circulate the air. The duct was designed to allow the distribution of air flow equally in each channel. The results demonstrated improved electrical and thermal efficiencies with an increased air mass flow rate. Thermal efficiency increased by up to 28–55%, whilst the electrical PV efficiency was between 10.6 and 12.2%.

Furthermore, a spiral flow absorber was used, which consisted of rectangular hollow tubes made of stainless steel. The tubes were connected by welding and attached to the backside of the PV module. Photovoltaic thermal (PVT) performances were tested under different solar radiation levels and mass flow rates. The results indicated that spiral flow absorbers provide superior performance at solar radiation of 800 W m⁻² and a mass flow rate of 0.041 kg s⁻¹. Electrical efficiency was 13.8%, with thermal efficiency reaching 54.6% and the overall efficiency of PVT was 68.4% [22]. Chidambaram et al. [23] adopted of water-to-air heat exchanger coupled with a PVT air collector; the heat exchanger consists of pipes with fins linked by the well that contains water at a constant temperature at 5 m depth and works as a geothermal energy source. Thus, the heat exchanger helps transfer energy from and to the water. The proposed system achieved the required heating and cooling and improved the PV module efficiency to 2% in the winter and 5.1% in the summer. The saved electrical and thermal energies for cooling were 3.14 kWh day⁻¹ and 24.79 kWh day⁻¹. PVT–fluid and PCM were used for three PV modules. The first module was conventional, while the second was equipped with a heat exchanger consisting of copper sheets and serpentine tubes placed at the back of the PV module. The third module was similar to the second but surrounded by PCM (paraffin wax) on the copper sheet to cool the nanofluids. The results indicated a decrease in PV cells temperature by 16 °C when using PVT/PCM-based pure water compared with the conventional PVT, thereby increasing thermal and electrical efficiencies by 25 and 8%, respectively. PVT/PCM with used nanofluid (SiO₂/water) increased thermal efficiency up

to 10.40%. By contrast, temperature and electrical efficiency were similar to pure water with PCM [24].

A new trend to restore waste recycling materials in solar systems, aluminium beverage cans filled with paraffin wax have been used to improve the efficiency of PV modules and compared their performance with conventional PV modules simultaneously. Experimental results showed an increment in electrical efficiency from 10.69 to 12.60%, while output power efficiency was from 61.72 and 71.56%, respectively, for PV modules integrated with aluminium beverage cans filled with paraffin wax and conventional [25]. An experimental analysis of three different PVT systems was designed, which used paraffin and nano-paraffin-based thermal energy storage units as a cooling media to improve the PV module performance compared with conventional PVT at different flow rates of 0.007 and 0.014 kg s⁻¹. The results show that the overall exergy efficiencies improved from 12.52–15.44%, 11.08–14.36%, and 10.52–13.59% for PVT nano-paraffin, PVT paraffin and conventional PVT, respectively. Thereby using a nano-thermal energy storage unit with an increased flow rate to improve the electrical and thermal efficiency of the PVT system [26]. A PVT collector integrated with a drying chamber as a hybrid PVT drying system has been experimentally tested under different air flow rates to enhance the PVT collector performance and utilisation of thermal energy for drying purposes. The experimental results illustrated an increment in the thermal efficiency of the PV collector from 61.32 to 77.49.

In contrast, the average overall exergy efficiency of the PVT collector and drying chamber was from 10.65 to 11.17% and 59.16–68.31%, respectively [27].

The present study investigates the effects of passive and active cooling on the PV module performance using different configurations [namely cotton wicks integrated with rectangular aluminium fins (CWIRAFs)] and photovoltaic thermal PVT collectors under hot conditions. Few studies on this method have been conducted with different techniques and operating conditions than the present research. Integrated aluminium fins by cotton wicks immersed in water from the top to the bottom help to increase the heat transfer area and the effective evaporative cooling at the back surface of the PV module, leading to temperature dissipation of the PV module into the surrounding air, then, improve its performance. The experimental results of each cooling technique applied are compared with other studies according to thermal behaviour, efficiency, and power yield to identify the appropriate cooling technique.

Experimental setup

Instruments

Temperature and solar radiation are the operation parameters of the PV module work. In the present study, solar

radiation was measured manually for 30 min using a power meter (Type SM206) with a 0.1 W m⁻² resolution. The temperature was measured through thermocouples installed at different PV module surfaces and backsides. Temperature, voltage and current were measured using an AT mega 2560 data logger multi-channel Arduino, which was programmed to record the data. The data logger consisted of 17 thermocouples with 0.25 °C resolution for measuring temperature, two sensors to measure the voltage with a resolution of 0.02445 V and two current sensors. Table 1 shows the data logger specification. The data logger recorded data with 10 min time step throughout the experiment days and saved the data in portable storage memory of 8 GB. Two 18-V lamps were used to complete the electrical circuit between the PV module voltage and current sensors.

Configurations of the cooling techniques

Passive cooling

Cotton wicks (CWs) were attached with rectangular aluminium fins (RAFs) by thermal silicon and attached at the rear of the PV module by thermal silicon adhesive. Fins are used as a partial rectangle (i.e. 52 cm long, 3 cm wide, and 1.5 mm thick) and uniform distance between RAFs. CWs were arranged in serpentine on the backside of the PV module, and fins formed contiguously without space between them. Table 2 shows the specifications of the CWIRAF components [22–24]. The CWs are characterised by suitable heat transfer coefficient, lower thermal conductivity, and high absorbent capacity, which helps to the distribution of water to all CWs attached at the behind of the PV module without using extra power. In addition, it's locally available, cost-effective and does not require maintenance. A total of 11 CW ends were submerged at the bottom of three plastic bottles full of water to supply water to CWIRAFs during the experiment, as shown in Fig. 2a. The CW ends placed in the water tank have continuously provided water from the top to the bottom of the PV module. Therefore, four thermocouples were placed on each of the surfaces of the PV modules at different places, three were placed on the backside, and one was used to measure ambient temperature.

Table 1 Specifications of devices/instruments used in the study

Item	Type/model	Range	Accuracy	Units
Thermocouples	K (2 m length)	– 200 to 1350	0.25	°C
Current sensor	ACS712	Up to 30	0.04	A
Voltage sensor	Module 25 V	Up to 25	0.02445	V
Solar power meter	SM206	1–3999	±0.1	W m ⁻²
Flow rate sensor	YF-S201	1–30	–	L m ⁻¹

Table 2 Material specifications used for passive cooling

Rectangular fins		Cotton wick	
Material	Aluminium	Cotton wick diameter	8 mm
Number of fins	20	Cotton wick length	50 m
Thermal conductivity	$237 \text{ W m}^{-1}\text{K}^{-1}$	Thermal conductivity	$0.048 \text{ W m}^{-1}\text{K}^{-1}$
Specific heat	$903 \text{ J kg}^{-1}\text{K}^{-1}$	Heat transfer coefficient	$36 \text{ W m}^{-1} \text{ }^\circ\text{C}^{-1}$
Density	2702 kg m^{-3}	–	–

Active cooling

PVT solar collector consists of a PV module with a 9.5-mm diameter copper pipe arranged in serpentine and

attached to an absorbent copper plate with 1.5-mm thickness placed on the rear side of the PV module. Copper pipes are covered by a layer of thermal wool insulation and aluminium cover, as shown in Fig. 2a. PVT collector

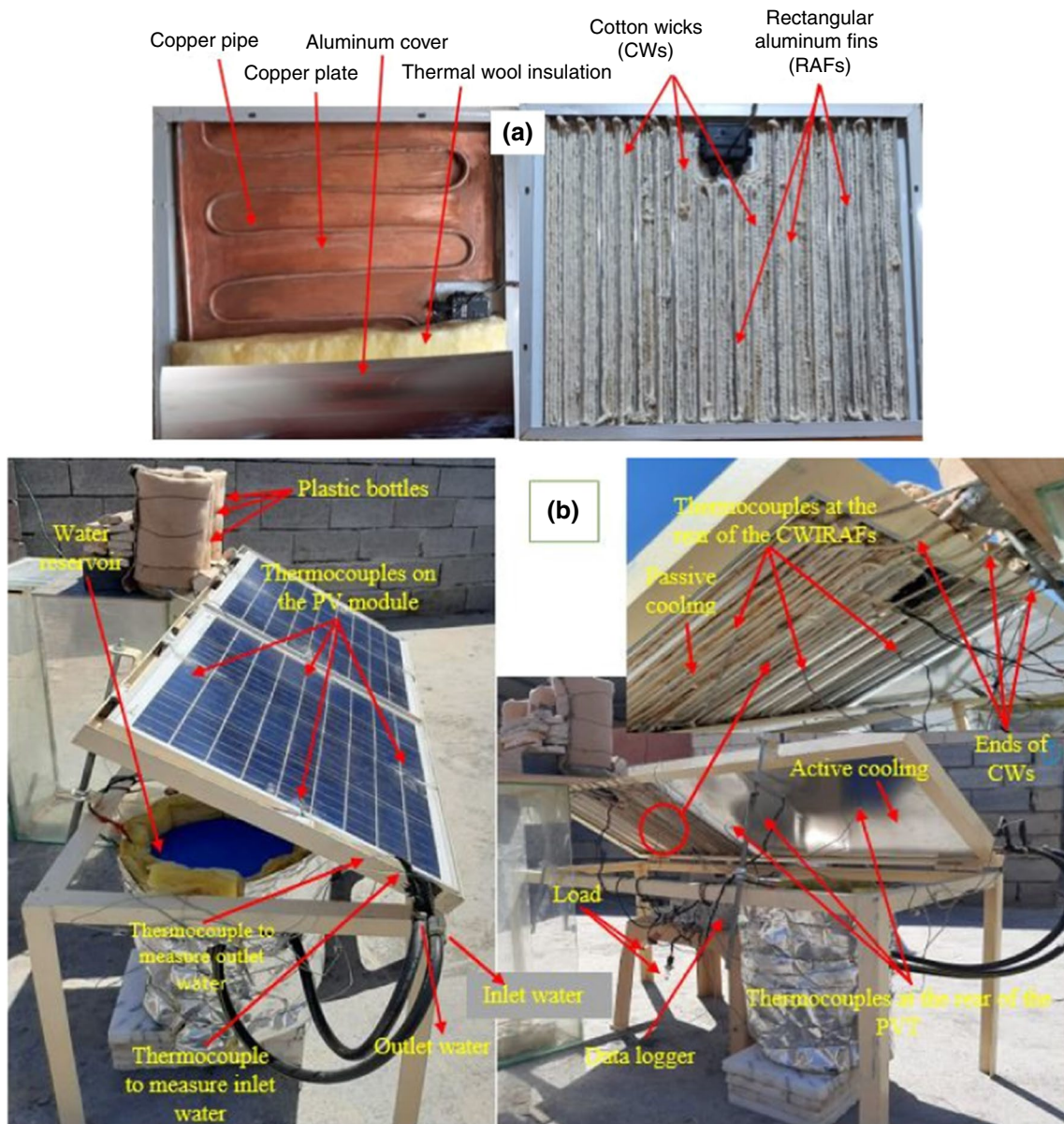


Fig. 2 Configurations of PV with CWIRAFs and PVT collector (a) and b using passive and active cooling with PV modules

uses water as a medium that enters and exits from an inlet and outlet of the collector. The outlet water passes via two copper pipes with small holes to re-cool the water before being collected in an insulated storage tank with 0.75 kg of ice added in the storage tank every 30 min. The storage tank cover is partially opened to enable air to circulate. The flow rate was 14.4 L min⁻¹ pumped by a tiny pump placed inside the storage tank. After that, two thermocouples were placed at the inlet and outlet of the PVT collector to measure water temperature. Figure 2b shows additional details of the system. The CWIRAF module and PVT collector performance is compared with conventional PV modules without cooling installed individually under the same operating conditions.

Experiment procedure

Experiments were conducted from 25 June to 15 July 2021 in Basra, Iraq (latitude: 30.5°; longitude: 48.14°). The weather during the experiments was sunny with a clear sky, and there was no substantial variation in temperature during the experiment days. According to the Iraqi Agricultural Meteorological Center, the average wind speed was 1.9–6.6 m s⁻¹ [28]. Solar radiation values increased gradually from the start of the experiment and decreased in the afternoon. Three 50-W polycrystalline PV modules were used with 0.65 m × 0.55 m × 0.03 m dimensions. Table 3 shows the electrical properties of the PV modules oriented in the south. The modules have a tilt angle of 29.19°. The distance between PV modules and the ground allows air to pass on the backside of PV modules, which boosts the rate of evaporative cooling because of a convection mass transfer. The output power (P_{out}) of the PV modules with CWIRAFs and PVTC is calculated by using Eq. (1) [13], depending on the output voltage (V_{out}) and current (C_{out}) of the modules obtained every 10 min.

$$P_{out} = V_{out} \cdot I_{out} \tag{1}$$

Depending on the solar radiation values (S) on the surface area of the PV modules (A_c), the electric efficiency of both modules can be calculated using Eq. (2) [29].

Table 3 Electrical characteristics under standard test condition (STC)

Characteristics	Values
Nominal power (P _{max})	50 W
Open circuit voltage (V _{OC})	22.28 V
Short circuit current (I _{SC})	2.88 A
Maximum power voltage (V _{max})	18.43 V
Maximum power current (I _{max})	2.71 A

$$\eta_{el} = \frac{P_{out}}{S \cdot A_c} \tag{2}$$

The overall efficiency of the PVT collector depends on thermal and electric efficiencies. The thermal efficiency of the PVT collector was calculated as the ratio of helpful energy Q_u calculated using Eq. (3) [30] over the solar radiation, according to Eq. (4) [31].

$$Q_u = \dot{m} \cdot C_p \cdot (T_o - T_i), \tag{3}$$

$$\eta_{th} = \frac{Q_u}{S \cdot A_c}, \tag{4}$$

where *m* is the mass flow rate (kg s⁻¹), C_p represents the specific heat of water (J g⁻¹K⁻¹), and T_o and T_i are the inlet and outlet temperatures (°C). Overall efficiency is the collection of thermal and electrical efficiencies as presented in Eq. (5) [32]:

$$\eta_{ov} = \eta_{el} + \eta_{th} \tag{5}$$

Uncertainty analysis

During experimental measurements, errors are possible to occur due to human or calibration concerns. Confirming the precision and reliability of the data recorded during the experiment is an important for analysis credibility of the results. For more accuracy in the electrical power and efficiency, the measurement errors such as voltage, current, and solar radiation have been considered for uncertainty measurements related to experimental data estimating the PV module's output power and efficiency. Uncertainty analysis in this work was conducted using the Coleman and Steele method [33] for the measurement reliability due to the measurement uncertainties that occur whilst estimating the PV modules' output power and efficiency. Equations (4) and (5) were applied to measure such quantities as current (I), voltage (V), solar (S) radiation and area (A_c). Uncertainties of measurements involved in the estimations are ±0.048% for output power and ±0.27% for efficiency.

$$\frac{\Delta P}{P} = \sqrt{\left(\frac{\Delta V}{V}\right)^2 + \left(\frac{\Delta I}{I}\right)^2} \tag{6}$$

$$\frac{\Delta \eta}{\eta} = \sqrt{\left(\frac{\Delta P}{P}\right)^2 + \left(\frac{\Delta A}{A}\right)^2 + \left(\frac{\Delta S}{S}\right)^2} \tag{7}$$

Results and discussion

PV module with CWIRAFs was supplied with water for two hours to ensure that all CWs were wet before the experiment began. The start of the experiment was simultaneous with the beginning of sunrise when the value of solar radiation is low but increases with an increase in sunlight intensity. Figure 3a presents the average solar radiation during the experiment period, which gradually increases with operation hours until 12:30 PM. The maximum solar radiation recorded was 1157 W m^{-1} but reduced progressively. Increasing the ambient temperature is associated with increased solar radiation intensity, in which the average ambient temperatures are variable along the experiment period. At the beginning of the experiment, the ambient temperature increased gradually, and the maximum ambient temperature reached $48.4 \text{ }^\circ\text{C}$ at 12:20 PM. After that, it decreased to $40.8 \text{ }^\circ\text{C}$ when the experiment was over. In July, most days are sunny months with rising temperatures and dropping humidity with moderate winds, as shown in Fig. 3b.

Effect of passive cooling on the PV module

Thermal behaviour of PV module with CWIRAFs

Thermocouples were distributed on the PV module glass surface and backside to measure the temperatures. Figure 4a, b shows the temperature distribution on the surface and backside of the PV module with used CWIRAFs and without cooling, respectively, throughout the experiment period. Temperature distribution on the sides of the PV module gives significant convergence, and this reason is logical to depend on the average temperature of the PV module in

calculations. The temperature of the PV module increased during the day because of the gradually increasing solar radiation and ambient temperature. The maximum temperature was recorded from 12:00 PM to 12:50 PM before decreasing until the end of the day. Figure 4c shows the average temperature of the surface, backside and PV module that used CWIRAFs. The evaporative cooling and increased heat dissipation area represented by integrating the rectangular aluminium fins with CWs have increased the heat transfer area of the PV modules backside and reduced PV module temperature. Maximum temperatures for both sides of the PV module with CWIRAFs recorded at 12:30 PM were 54.2 and $49.8 \text{ }^\circ\text{C}$, the maximum ambient temperature was $48.4 \text{ }^\circ\text{C}$, and the average temperature of the PV module was $52 \text{ }^\circ\text{C}$. The evaporative cooling in CW provides an appropriate cooling environment that lowers approximately 31.4% of the surface PV module temperatures compared with the PV module without cooling.

Thus, evaporative cooling in CW has provided an appropriate cooling environment, leading to lowers of approximately 32.4%, 30% of the backside and average PV module temperatures compared with the PV module without cooling. By contrast, the PV module temperature without cooling was recorded at $80.2 \text{ }^\circ\text{C}$ and $72 \text{ }^\circ\text{C}$ for both sides, and $75.8 \text{ }^\circ\text{C}$ was the average temperature of the PV module. Figure 4d presents the temperature variation of the PV module without cooling that increases to a critical scale, causing degradation of the PV module. The effectiveness of active cooling causes the backside of the PV module temperature to decrease below the ambient temperature at 2:50 PM, as shown in Fig. 4c, owing to reduced ambient temperature and increased wind speed. The decrease in the backside temperature was attributed to using CWIRAFs because of the effects of using evaporative cooling.

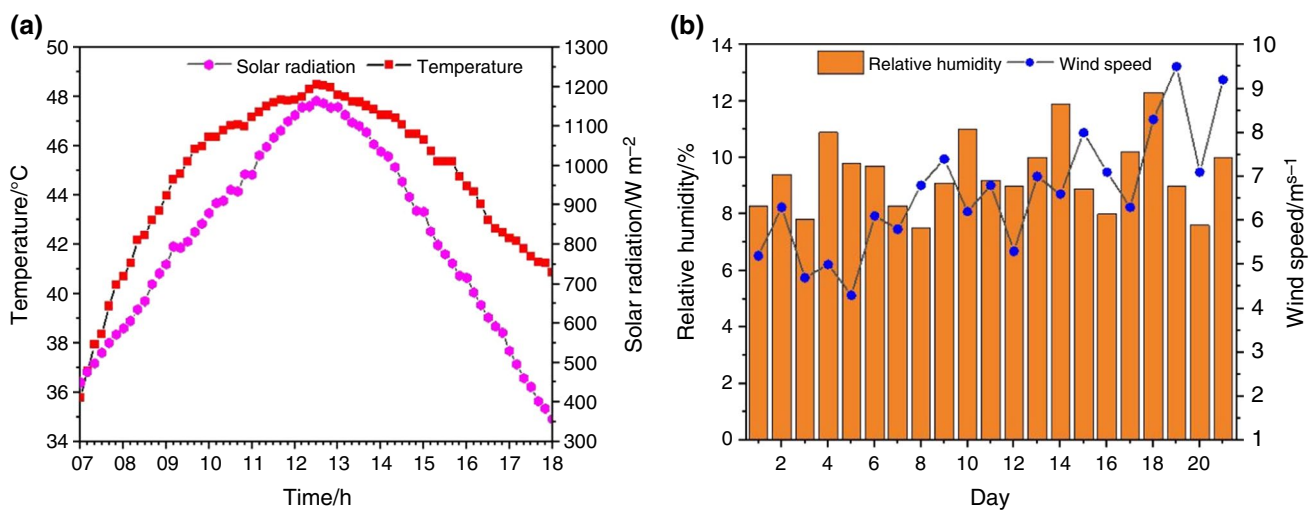


Fig. 3 The operational parameters a ambient temperature and solar radiation, b wind speed and humidity throughout the experiments

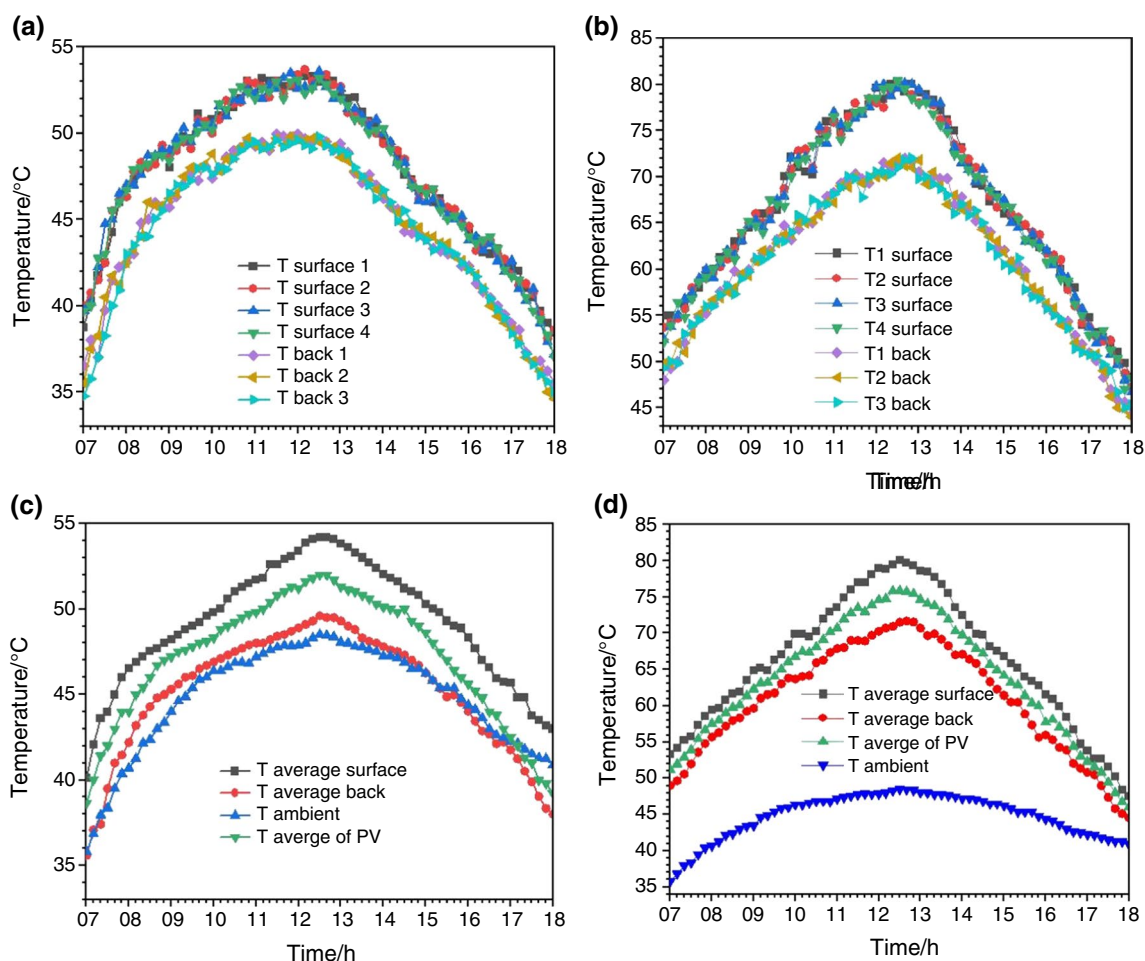


Fig. 4 Temperature distribution on PV modules **a** with cooling, **b** without cooling, Average temperature of PV module **c** with cooling and **d** without cooling

Performance of PV modules with CWIRAFs

PV module's power and efficiency values vary due to solar radiation and ambient temperature variables, and PV module temperature significantly affects its production, output voltage variation and current PV module. The CWIRAFs have enhanced the PV module's performance by reducing the temperature, which can be noticed in the increased output power shown in Fig. 5a. Compared with the PV module without cooling, the output voltage and current with CWIRAFs increased approximately 55.4 and 25%, respectively. Therefore, the used passive cooling represented by CWIRAFs has achieved an impressive performance that increased the PV module's output power. Maximum output power was recorded at 34.75 W at 12:10 PM, an increase of 66.6% compared with the PV module without cooling, and efficiency up to 8.6%. Figure 5b shows the degradation of the PV module without cooling that affects its performance, which is evident by significantly dropping both its voltage and current. Increasing the PV module temperature

to 80 °C without cooling caused a significantly low output power to 11.59 W, representing maximum output power. The maximum efficiency of the PV module without cooling was recorded at 3.12%, attributed to the significant deterioration of the PV module performance. Note the fluctuation and decrease in the PV module productivity and efficiency between 12:10 and 1:00 PM. After that, it slightly increased but declined again until the experiment ended owing to increasing temperature and direct solar radiation on the PV modules.

Effect of active cooling on PVT collector

Thermal characteristics of PVT collector

An increase in the intensity of solar radiation causes the ambient temperature to increase, thereby incrementing the surface and rear of the PV module temperature. The PV module surface recorded the highest temperature due to direct solar intensity exposure. Heat flows from the hot

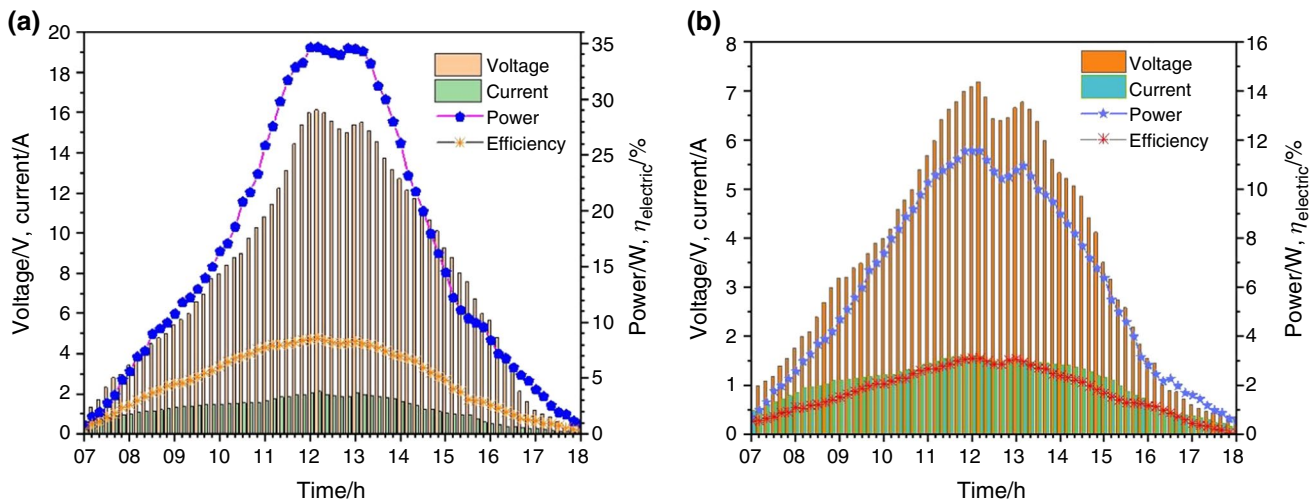


Fig. 5 Performance of PV module with CWIRAFs (a) and b without cooling

surface that is directly exposed to the intensity of solar radiation to the cold surface resulting in a higher backside temperature of the PV module than ambient temperature. At the beginning of the experiment, the PVT collector surface temperature was 41.4 °C, and the back side (absorb plate) of the PVT collector was 38.2 °C, but it gradually increased. The maximum temperature of the PVT surface was 66.2 °C at 12:20 PM. The backside was 55 °C, as shown in Fig. 6a. The used absorbing plate with water circulates into copper pipes attached to the backside of the PV module as active cooling has reduced the module temperature. Based on the average temperature, the surface and backside temperatures of the PVT collector were lower by approximately 17.4 and 23.6%, respectively, compared with the PV module without cooling. Decreased PV module temperature is attributed to conduction heat transfer from the copper plate directly attached on

the backside of the PV module to copper pipes. After that, heat convection is transferred to water circulation into the pipes to reduce the PVT collector temperature. Figure 6b shows the water temperature difference between the inlet and outlet water, in which the PVT collector recorded an average temperature reached 60 °C. Inlet water temperature slightly approached ambient temperature until 12:40 PM but decreased after that, affecting the thermal energy gained. Adding ice pieces in the storage tank with an air circulation could maintain water circulation temperature close to the ambient temperature or less. It can be noticed in the difference between inlet and outlet water temperatures. Using aluminium fins helps to increase the heat transfer area at the back surface of the PV module; integrating aluminium fins with cotton wicks immersed in water and exposed to the wind provides evaporative cooling that helps to reduce the

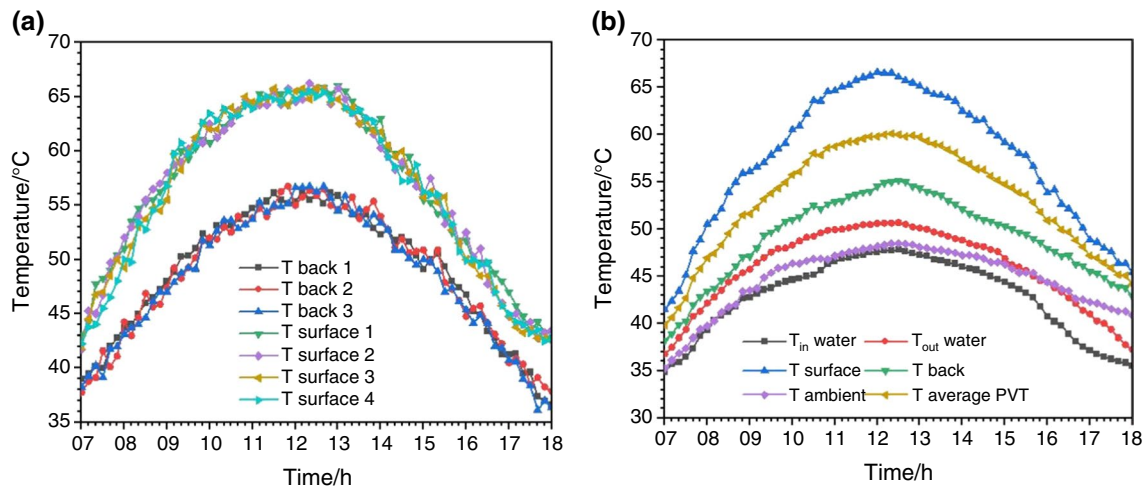


Fig. 6 The temperature profile of the PVT collector a surface, backside temperature b average temperature of the PVT collector

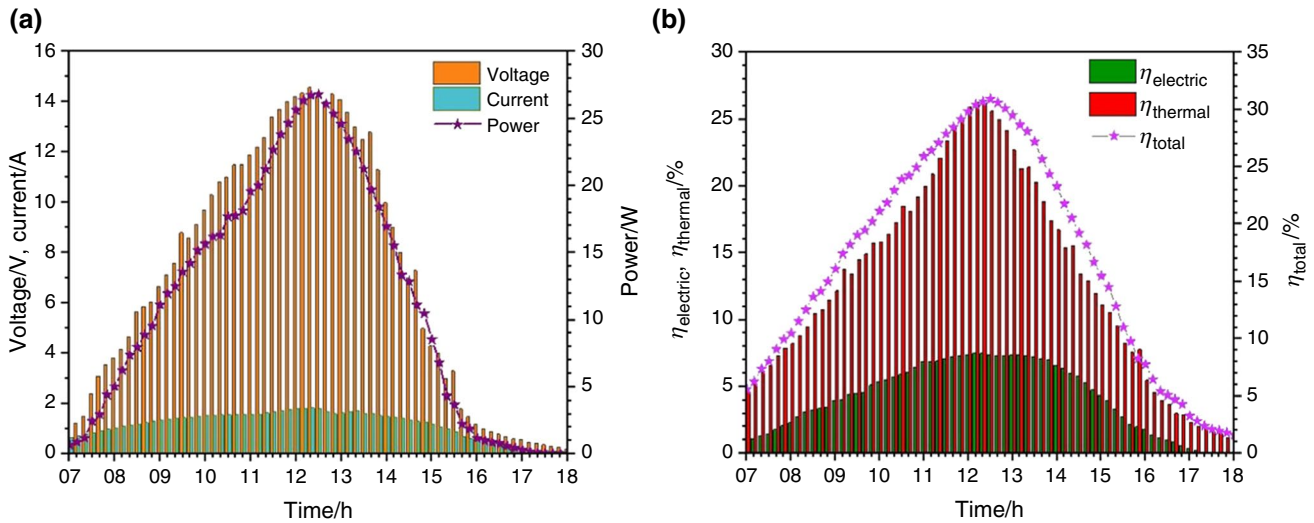


Fig. 7 Performance of PVT collector **a** energy yield and **b** efficiencies

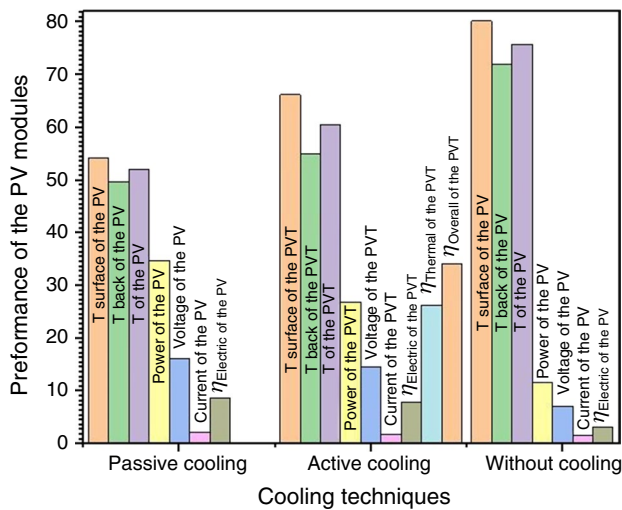


Fig. 8 Comparison of PV modules performance under different cooling techniques

temperature of the PV module. Thus, absorbing the temperature of the PV module and dissipating it into the surrounding air.

Performance of PVT collector

Circulating the water into copper pipes attached to the absorbing plate removes the PV modules' excess heat. Thus, the temperature of PV cells was reduced because of increased heat transfer by conduction between the absorbing plate and the PV module backside. The yield energy of the PVT collector improved compared with another PV module without cooling owing to the thermal conductivity of water that circulated, thereby facilitating the removal of a portion

of excess heat from the PV module backside. A reduction in the temperature of PV cells achieved increased productivity output voltage, current and power yield of the PVT collector, where the maximum output voltage and current were 14.5 V and 1.85 A, respectively, at 12:20 PM, with an output power of 26.8 W, as shown in Fig. 7a. However, reducing the PVT collector temperature has positively increased the electric efficiency by approximately 7.9%. The absorbing plate with pipes and water helps transfer the heat and achieve thermal efficiency reaching 26.3% see Fig. 7b, thereby enhancing the PVT collector performance by increasing the overall efficiency to 34.2%.

Comparison of performance under different cooling techniques

Increasing the PV cell temperature throughout the experiment affected the performance, particularly without cooling. The PV module output power and efficiency recorded lower values than active and passive cooling. The immersion of CWIRAFs by water with variable wind speed created a cooling environment during the experiment. It contributed to lowering the average temperature of the PV module by 13.4 and 31.4% compared with active and without cooling, respectively, at maximum temperature. The CWIRAFs as passive cooling achieved better performance than active cooling due to the evaporative cooling with increased heat dissipation area by aluminium fins. Therefore, output power increased by 22.8 and 66.6%, and electric efficiency was enhanced by 63.7 and 8.1%, compared with active cooling and without cooling, respectively, at maximum temperature. Active cooling, represented by water circulation into copper pipes attached to the absorbing plate, facilitates heat removal from the PV module backside. PVT collector achieved low PV cells temperature of approximately 20.8% compared with

Table 4 Comparing the PV modules performance with previous studies

References	Cooling techniques	Power increment %	Temperature reduction %	Electrical efficiency increment %
[34]	Passive cooling	5	10	6.7
[13]	Passive cooling	14	12	–
[10]	Passive cooling	32.7	16	31.7
[16]	Passive cooling	17.06	19.75	2.98
[25]	Passive cooling	61.72	–	12.06
[35]	Passive cooling	14.1	25.27	19.8
[36]	Passive cooling	14	27.2	14.5
Current study	Passive cooling	66.6	31.4	63.7

References	Cooling techniques	Thermal efficiency %	Electrical efficiency %	Temperature reduction %
[24]	Active cooling	25	8	16
[37]	Active cooling	52	13	9.8
[38]	Active cooling by water	17.23	1	1.83
	Active cooling by SiO ₂ nanofluid	35.56	4.98	14.27
	Active cooling by Ag nanofluid	43.8	6.73	19.55
[39]	Active cooling by WO ₃ nanofluid	30.1	9.82	21.4
Current study	Active cooling	26.3	8.1	20.8

that without cooling at maximum temperature, apart from the heat energy gained. Thus, the output power of the PV module with active cooling was enhanced by 56.7% compared with that without cooling, reflecting positively on electrical efficiency. The maximum thermal energy recorded by the PVT collector was 26.3%, which caused an increase in the overall efficiency of the PVT collector to 34.2%. Figure 8 shows the performance of the PV module under different cooling techniques. The PV module without cooling deteriorated its performance due to the increasing PV cell temperature. The results obtained in the current study are compared with other previous studies, considering some factors, such as the size of the PV/PVT system, type of cooling media applied, cooling configurations used, and measurement conditions, as shown in Table 4. In the current study, passive cooling by CWIRAF shows better performance than active cooling concerning the reduced PV module temperature and enhanced performance, which confirmed the effectiveness of passive cooling applied.

Conclusions

The current study compares passive (CWIRAF) and active cooling (circulated water) techniques to enhance the PV modules performance. Increasing the heat dissipation area of the back surface of the PV module by aluminium fins integrated with wet cotton bristles and that exposed to air contributed to creating a cooling environment during the experiment period. Thereby contributing to lowering the

PV module's average temperature more than the active cooling technique. The cooling techniques applied showed sustained performance of the PV modules under hot conditions. The following conclusions are derived from the present work, as follows:

- The CWIRAFs passive cooling technique shows improved behaviour and significantly enhanced the PV module performance by lowering its temperature under hot conditions using minimal equipment.
- Increasing the heat dissipation area of the back surface of the PV module by aluminium fins integrated with wet cotton bristles and exposed to air contributed to creating a cooling environment during the experiment period. Thereby contributing to lowering the PV module's average temperature more than the active cooling technique.
- A reduction in PV module temperature using the CWIRAF technique increased the power yield and efficiency by 22.8 and 11.2%, respectively, compared with the PVT collector.
- The passive cooling applied in this work effectively reduces the PV module temperature and improves its performance better than in other studies, which makes it more reliable.
- The active cooling technique showed lower performance than passive cooling under similar conditions. This result is attributed to heat transfer across different PVT collector layers, not directly, such as CWIRAFs cooling.
- The PVT collector contributes to enhancing thermal energy by removing excess heat of the PV module back-

side by circulation water inside pipes, improving the overall efficiency of the PVT collector.

- PV modules used without cooling in hot climate conditions significantly deteriorated their performance.

The cooling technique applied may be feasible for small installations of PV modules, such as a family house system. In the future work, the research domain will consider more extended experimental periods with the help of numerical tools and suggesting improvements for reducing water consumption.

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Data availability The data of this manuscript are available on request from the corresponding author.

Declarations

Conflict of interest The authors declare that there is no conflict of interest regarding the publication of this paper.

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