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Water-Cooling-Based Approach for PV System Performance Enhancement towards UAE Future Energy Efficiency Policies

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ABSTRACT

United Arab Emirates (UAE) has implemented the UAE Energy Strategy 2050, targeting a 50% increase in renewable energy's contribution by 2050. Steps to achieve this strategy include accelerating efficient consumption of energy and focusing on research and development for sustainable energy solutions. This research aims to investigate the potential improvement in the performance of PV systems as a result of panel's water-cooling under the UAE climatic conditions. In this work, a PV system consists of two identical 100-W PV panels and an automated water cooling arrangement was built. To assess the effectiveness of the cooling method used, one PV panel was subjected to water cooling, while the other remained uncooled in order to be taken as a benchmark. The experiments took place over a typical summer day during the period between 8:00 am and 5:00 pm. The proposed cooling strategy was repeatedly applied every half an hour to investigate the temperature reduction behavior at different times of the day. The experimental results demonstrated that the adopted water approach was able to achieve a temperature drop of up to 14.6 K. The corresponding power output was improved by up to 12% as a result of the PV panel cooling.

Keywords: Photovoltaic, Water-cooling, Sustainability, Power Generation, Energy Efficiency
JEL Classifications: C93, O33, Q20, Q28

1. INTRODUCTION

In the recent years, the global energy demand has remarkably increased due to the rapid industrial development, continuous world population growth, and the life style and wellbeing. Currently, fossil fuels still dominate most of the global energy needs. As per 2019 statistics, more than 84% of the global primary energy consumption comes from fossil fuels with almost 16% (15.7% to be precise) comes from low-carbon sources. Out of the low-carbon sources, only about 11.4% is based on renewable energy resources while 4.3% comes from nuclear (Ritchie and Roser, 2022). This current strong dependence on fossil fuels has resulted in increasing the annual fossil fuel consumption from 122,857 to 168,469 TWh between 2000 and 2020 (Ritchie and Roser, 2022). Consequently, about 36.3 billion tons of carbon dioxide emissions are emitted annually into the atmosphere in 2020 (IEA, 2021a). Based on a report released by the UAE government in 2015, the country's daily electricity demand is approximately 20-30 kw-h. Given the continuous expanding economy, the overall energy demand is projected to grow by up to 9% annually (Alshami and Sabahm, 2020).

Among the prospective means to tackle the problem of energy shortage and to alleviate the negative environmental impacts caused by the extravagant consumption of fossil fuels are to utilize alternative clean energy sources (i.e. solar, wind, geothermal, etc.) and develop efficient energy conversion systems (Ozlu and Dincer, 2015).

The world now experiences strong signals to develop a clean energy future with a continuous increase in the global investments in clean energy generation. For example, the world wind-energy industry has grown over the last three decades at an average rate of approximately 30%/year to reach a total installed capacity of 239 GW by the end of 2011. On the other hand, the solar photovoltaic (PV) technology has grown with a faster pace over a shorter period of time from its low base to reach a worldwide installed capacity of about 69 GW in 2011 - EPIA, 2012 (Lovegrove and Stein, 2012). Between 2010 and 2021, the share of wind energy source in world electricity generation increased from 1.6% to 6.7% with about 4 times an increase. During the same period, the share of solar PV increased by 34 times, from only 0.1% to 3.4% (IEA, 2021b).

The solar PV panel performance characterizes by its efficiency and the quantity of the output power. The PV panel performance strongly depends on the operating conditions. The output power of the PV panels is proportional with the level of light intensity and inversely proportional with the ambient temperature. Another vital parameter which has a significant impact is the level of dust over the panel surface. Wind speed should not be ignored due to its impact on the PV performance.

Many studies have been conducted to enhance the PV panel performance by considering the effect of the above parameter. Different techniques were suggested in the literature for improving the PV performance. Many algorithms have been proposed to guarantee the condition of Maximum Power Point Tracking (MPPT) for maximum power harvesting regardless the change in the weather conditions over the months of the year (Dhaouadi, 2019, Narwat, 2020, Wei and Li, 2022, Nagaraja Rao, 2022, Attia and Hossin, 2022; Mrad et al., 2023). The effect of dust on the PV module performance has been experimentally investigated in (Al-Maghalseh, 2018).

On the other hand, numerous researchers have explored the relationship between the panel's temperature and its overall performance by proposing different cooling techniques. Although several cooling approaches have been recently examined, only studies investigating the effect of PV panel cooling via water are presented in this section. Such a cooling methodology is viewed as one of the most efficient among the many techniques available today (Moharram et al., 2018).

Odeh and Behnia (2009) proposed cooling of the PV panel by introducing water trickling configuration on the upper surface of the panel. The experimental results revealed that the system's output increased by approximately 15% under peak radiation scenarios. Yearly performance simulations of the system indicated a 5% rise in energy output from the PV module during dry and hot periods. In a similar study, experiments were conducted to study the impact of cooling on the performance of PV solar cells. A direct correlation was observed between temperature and the PV module's efficiency. The data revealed that water cooling reduces the temperature of the PV panel by 4-5°C, leading to a notable boost in efficiency, ranging from 7% to 12% (Iqbal et al., 2016). Cooling the PV panel by flowing water over its surface was highlighted in (Smith et al., 2014). This method managed to decrease the panel's temperature by about 15°C. Under regular operating conditions, the augmented energy yield from the panels easily offsets the energy needed to pump the water. An artificial intelligence-driven water cooling system were introduced in (Ehtishaan and Saifee, 2016) for PV systems to optimize energy production. In (Zhao et al., 2022), a performance evaluation of a solar PV power generation system using water spray cooling was carried out. The findings indicated that spray cooling was more effective compared to conventional water cooling, and there was an optimal spray flow rate that maximizes the net output power. Numerical and experimental investigations on standard PV panels, concentrated PV (CPV) systems, and water-cooled CPV systems were carried out under the climatic conditions of Iraq (Zubeer and Ali, 2022). The findings revealed that the output power of the water-cooled CPV systems increased by 24.4%, while the CPV systems showed a boost of 10.65%.

A water-cooling system for PV panels was designed and tested under both laboratory and on-site conditions by Sornek et al. (2022). The results revealed that the peak temperature of the water-cooled panel was reduced by about 24°C, resulting in a 10% increase in power output. Hasan et al. (2022) experimentally investigated a PVT system with a water-cooled heat sink during the summer season in Iraq. The results demonstrated that higher water mass flow rates increases the PVT system's efficiency from 11.7% to 14% when the mean PV temperature is reduced from 73°C to 45°C. The design and implementation of an automated water-cooled 100-W PV system for performance evaluation under the UAE climatic conditions were presented in (Attia et al., 2023). With only 2 min of cooling operation every 30 min during day hours, the average output power increased by about 1.6%, corresponding to a decrease in the average temperature of the PV panel of approximately 6%.

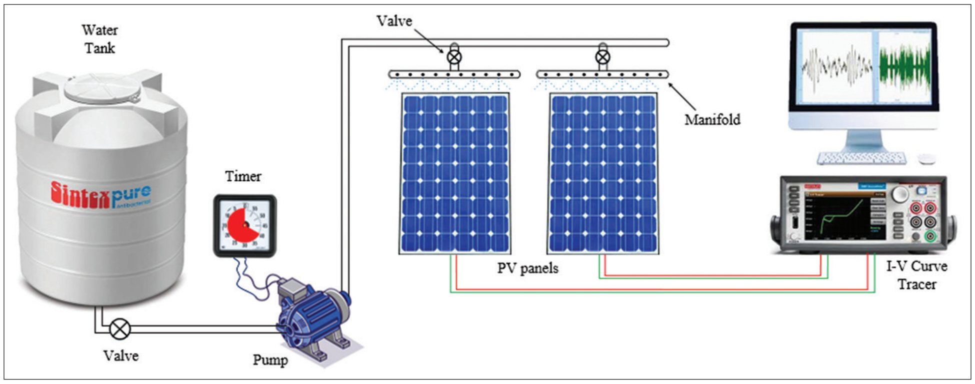
Although numerous studies have explored the relationship between PV panel temperature and its behavioral performance in various global locations, there remains a noticeable gap in the literature concerning experimental research under UAE climatic conditions. This study attempts to fill this gap in the literature, given the rapid growth and significance of the PV technology in the region. The UAE has undertaken serious strategic initiatives to boost economic growth via various energy efficiency measures. In 2017, the UAE launched 'Energy Strategy 2050' that aims to increase the share of clean energy in the total energy mix from 25% to 50% by 2050 (Ministry of Energy and Industry, 2017). It is anticipated that this type of research will attract the attention of academics and decision-makers locally and globally.

2. EXPERIMENTAL APPARATUS

2.1. The Proposed Water-Cooling Approach

In this work, the PV system was designed in such a way that the temperature of the PV modules can be controlled via a cost-effective cooling approach. The adopted cooling process comprises an automated water-cooling system that is developed based on a water spraying mechanism via water manifolds mounted on the top of each panel in the PV array, as schematically shown in Figure 1. The concept of employing a water-cooling technique that minimizes both water and energy consumption merits further exploration. In its basic components, the cooling system consists of a water tank, water pump, connection pipes, valves and a spray manifold. The pump is connected to a special timer to regulate the time and period of the cooling process. Valves are

Figure 1: A schematic of the PV system with the proposed water-cooling arrangement



also integrated in the piping system in a way to direct the water to a certain piping path. In other words, the cooling process can be applied to the desired PV panel with a certain frequency. With such an arrangement, the cooling effectiveness can be investigated on a comparison basis. To achieve the cooling process, water is sprayed on the top edge of the PV panel and then flows over the panel surface downwards the bottom edge. The idea of using an effective water-cooling approach with minimal use of both water and energy deserves more attention.

2.2. Specifications of the PV Module

The PV system of the present work is constructed from three PV panels of the same module type (Solar-module-100W-Mono-CL-100-WM). Figure 2 shows a physical front view of the PV module used in this study. The module includes 36 serially connected PV cells. The function of the cell and the module is to convert the energy of the incident light on the surface of the cell to proportional electricity. The produced electric power is positively proportional with the amount of incident light intensity, whereas it is negatively proportional with the ambient temperature.

Figure 3 shows the representation of solar cell as an equivalent electric circuit. Equation (1)-(5) demonstrate the expressions of the produced load current (I_L) and voltage (V_L). In addition, they explain how other variables in the circuit affect the produced electricity by the cell (Al-Najideen and Alrwashdeh, 2017, Wang et al., 2018, Gupta et al., 2022, Sutanto et al., 2022). Two resistors are included in the equivalent circuit; the current source shunt resistor R_{sh}, and the output terminal series resistor R_s. V_D is the diode voltage, I_D is diode current, V_{th} is the cell thermal voltage, I_{sc} is the generated current, I_{sh} is the shunt current. I_{sat}, I_{sat_ref}, G, G_{ref} are the diode saturation current, the reference saturation current, the insolation, and the reference insolation respectively.

$$I_L = I_{sc} - I_D - I_{sh} \tag{1}$$

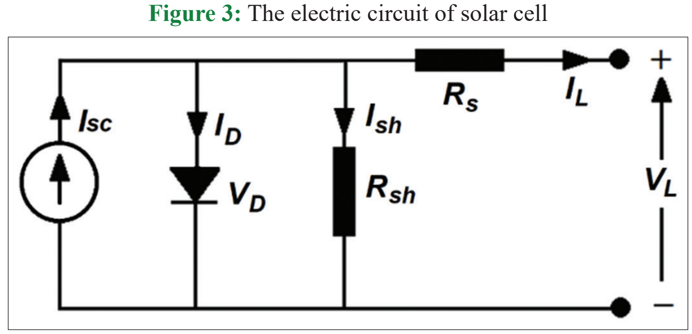
$$I_{sc} = \frac{G}{G_{ref}}\left(I_{sc\_ref} + K_{SCT}\left(T_c - T_{c\_ref}\right)\right) \tag{2}$$

$$I_D = I_{sat}\left[e^{\frac{V_D}{V_{th}}} - 1\right] \tag{3}$$

$$I_{sh} = \frac{V_D}{R_{sh}} \tag{4}$$

Figure 2: Physical front view of the PV module

Figure 3: The electric circuit of solar cell



$$V_L = V_D - R_s I_L \tag{5}$$

To obtain the desired DC link voltage, V_{o_panel}, from the PV system, solar cells should be connected in series. If the number of serially connected cells is N_{serial}, then we can write:

$$V_{o\_panel} = N_{serial} \times V_L \tag{6}$$

The required current from the PV system is obtained when the panels are connected in parallel with $N_{parallel}$ as shown in Eq. (7).

$$I_{o\_panel} = N_{parallel} \times I_L \quad (7)$$

The specifications of the PV panels under investigations of the present study are listed in Table 1 below:

The selected PV panels were firstly simulated using MATLAB/Simulink® software. Current and power curves at different levels of insolation and fixed ambient temperature of 25°C are presented in Figures 4 and 5, respectively. Current and power curves at different ambient temperatures and fixed insolation of 1000 W/m^2 are plotted in Figures 6 and 7, respectively.

2.3. Test Rig Construction

In this work, a PV system consists of three identical 100-W PV modules (Solar-module-100W-Mono-CL-100-WM) was constructed. As demonstrated in Figure 8, these three PV modules are mounted on a metal frame featuring three individually movable bases to allow adjusting each PV panel to different tilt angles independently. Therefore, the tilt angle of each PV panel can be set to any inclination between 0° and 45° relative to the horizontal plan. The PV system arrangement is integrated with the water cooling system described in the previous section. A water tank with a volumetric capacity of 1000 L is used to store water. Water is sprayed on the desired PV modules via water distribution manifolds placed on top of the panels. A half-horsepower pump is used to deliver water from the tank towards the PV panels through connection pipes. The piping network is equipped with multiple valves to facilitate the cooling process for specific PV modules when required. The pump operation is controlled by a cyclic timer ensuring consistent cooling intervals. The timer can be adjusted to initiate a turn-on sequence ranging from 5 s up to 10 min within each recurring a half-hour operation cycle. This allows for an exploration into the optimal cooling duration, aiming for an efficient cooling strategy that reduces both the water and energy required to keep the PV panel at its optimal operating temperature. Figure 9 depicts the water tank, pump and timer

Table 1: PV panel specifications for Solar-module-100W-Mono-CL-100-WM (Westech-Solar Energy, n.d.)

Parameter	Value
Open circuit voltage	21.6 V
Short circuit current	6 A
Power at MPP point	100 W
Voltage at maximum power, V_{MPP}	18 V
Current at maximum power, I_{MPP}	5.56 A
Number of serially connected cells	36
Efficiency, η	18.56%

Figure 4: Current curves at different levels of insolation levels and ambient temperature 25°C

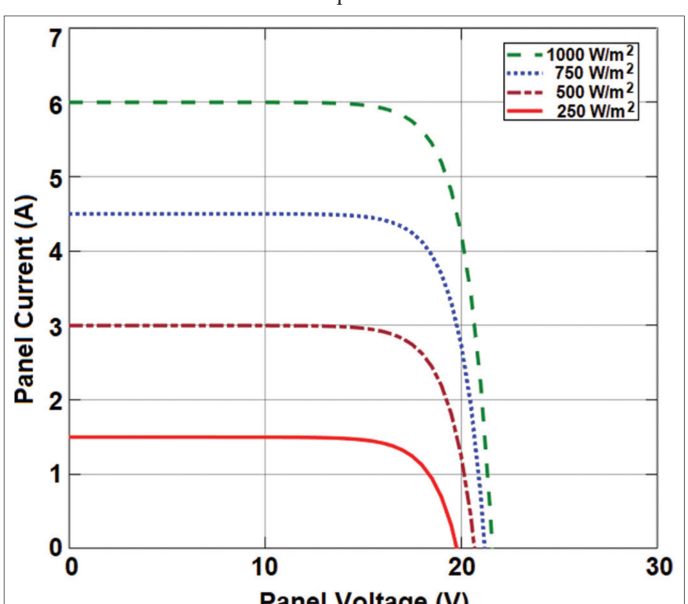


Figure 5: Power curves at different levels of insolation levels and ambient temperature 25°C

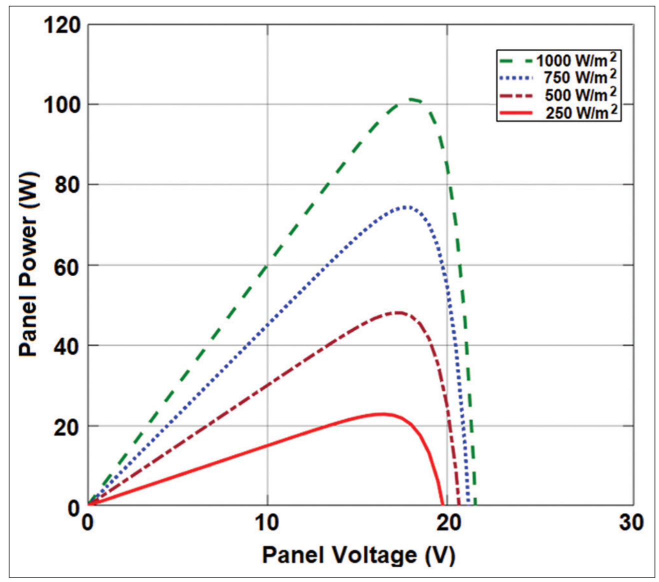
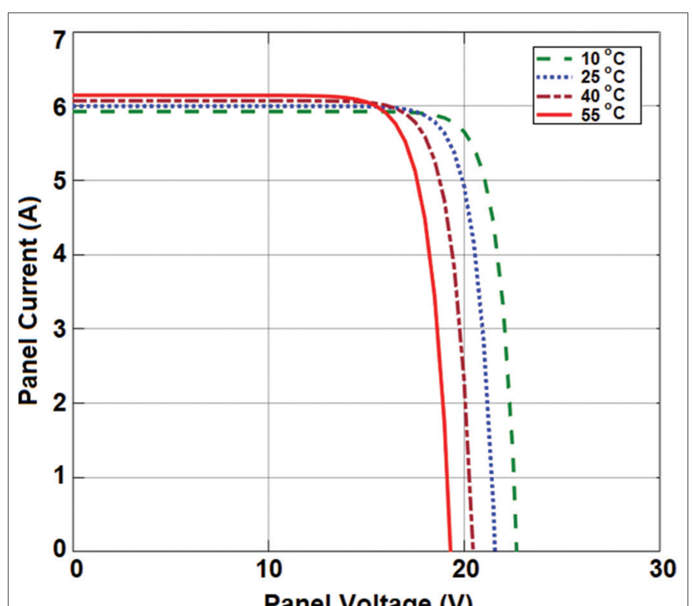


Figure 6: Current curves at different levels of ambient temperature and insolation of 1000 W/m^2



arrangement. The water distribution manifolds used for spraying water are shown in Figure 10.

In this work, a tracer is employed to track the performance of two PV panels, one with water cooling and one without. Figure 11 displays the front view of the I–V curve tracer module (Raydec RD-3200 Multi-Tracer IV Master Unit) (Raydec, Inc., n.d.). This tracer acts as an intermediate unit that collects real-time data including the PV panel temperature, output voltage, current, and power across 10 separate channels. It evaluates the performance of the PV panels by connecting different resistive loads to the panels' output terminals. The maximum load capacity that can be connected to the tracer is 3200 W. The tracer is connected to a dedicated computer system where data is recorded.

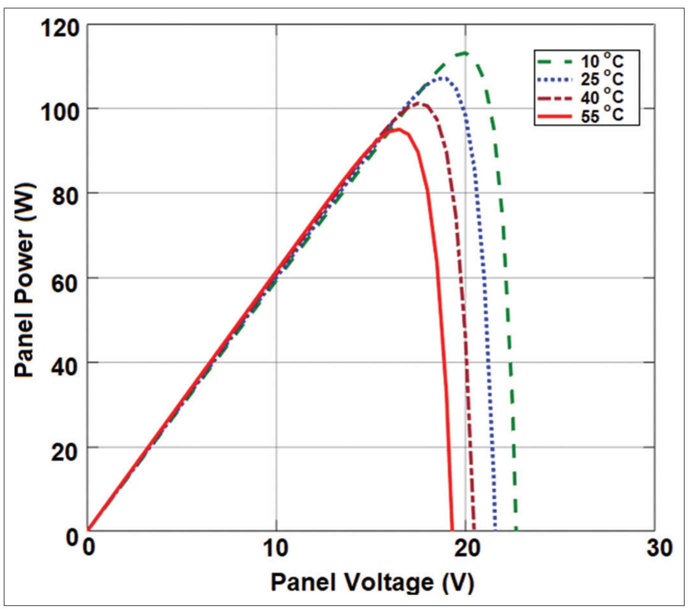
3. EXPERIMENTAL PROCEDURE

The tests were conducted during a typical summer day under the climatic conditions of Ras Al Khaimah (25°46′N 55°57′E), UAE at Ras Al Khaimah Research and Innovation Center (RAKRIC). Only two adjacent PV panels were utilized to conduct the current work. In order to investigate the effectiveness of the adopted cooling approach, water cooling was applied to one PV panel with a frequency of 2 min every half-hour whereas the other panel was kept without cooling. During the experiments, both PV panels were set to a tilt angle of 22°. The tests were conducted during a typical summer day on September 24, 2023. Experiments were carried out on a day long basis of system operation during the period between 8:00 a.m. and 5:00 pm. This allows assessing the cooling process leverage at different operating and environmental conditions in order to have more comprehensive results.

Both PV panels were connected to variable resistive load of the I–V tracer where current, voltage and power records were collected through two channels. The temperature measurements of the two PV modules were conducted using Type K thermocouples (±1.1°C or 2.15%), placed on the back surface of the PV panel. In order to verify the accuracy of the readings, temperature of the PV modules was also measured using Fluke IRR1-SOL (±1.0°C) at both top and bottom sides. Assuming that the temperature gradient across the PV panel is linear, the average value between the top and bottom surfaces was considered to represent the panel temperature.

Data including current, voltage, power and temperatures were collected and recorded simultaneously for the two PV panels during the testing period. A dedicated developed computer program was used as an interface between the measuring instruments and the PC unit. The meteorological weather conditions for the test location were obtained from the weather station already built at RAKRIC.

Figure 7: Current curves at different levels of ambient temperature and insolation of 1000 W/m²



4. RESULTS AND DISCUSSION

The performance of the two solar PV panels were studied over a day-long period on September 24, 2023 under the climatic conditions of Ras Al Khaimah, UAE. The variation of the solar radiation and ambient temperature during daylight hours for the day of experiments are shown in Figure 12. As shown in the figure, the hourly solar radiation and ambient air temperature have the same thermal pattern. Starting from the morning, the temperature steadily increases with the increase in the solar radiation, reaching maximum values between 12.00 and 14.00. The highest recorded air temperature and solar radiation are 42.2°C and 990 W/m², respectively. After this peak period, the ambient temperature starts to decline gradually by evening as solar radiation decreases.

Figure 8: The PV system arrangement with three movable 100W PV panels

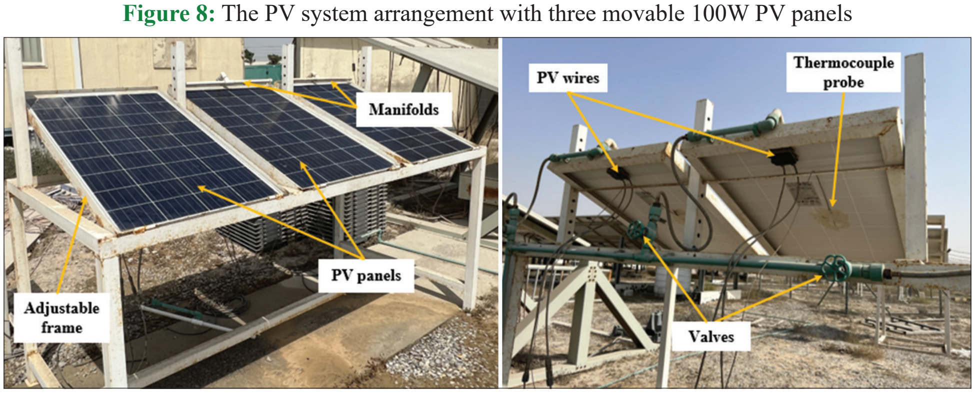


Figure 9: The water tank, pump and timer arrangement

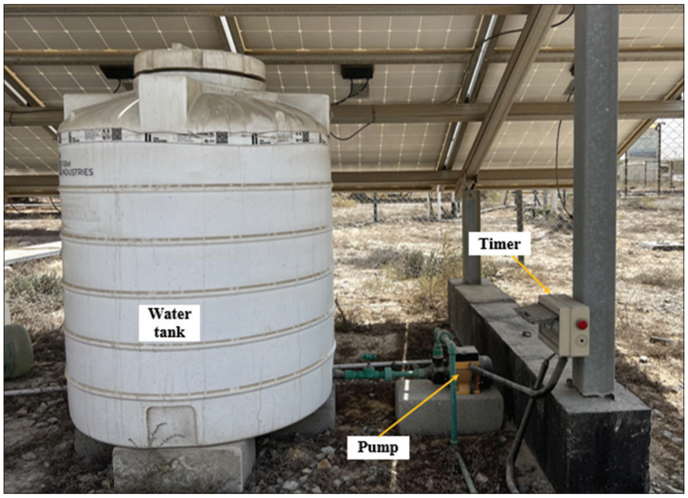


Figure 10: The water distribution manifold

To examine the impact of cooling on the PV performance, tests were carried out on two identical PV panels repeatedly every 30 min during the day. At each of these intervals, measurements were made for both water-cooled and uncooled PV panels, along with the corresponding weather data. During the water-cooling operation, the volume flow rate of water was estimated as 13.0 L/min. Figure 13 presents the measured PV panel temperatures for the two tested PV modules at various intervals throughout the day. Comparing the two PV panels, the water-cooled panel evidently maintains a lower temperature. As it can be noticed, the cooling becomes more effective when the PV panel temperature is relatively higher. In other words, the water cooling significantly reduces the panel temperature during the period between 9:30 and 15:30, where the PV temperature already exceeds 45°C. During this period, a decrease in the temperate of more than 10 K was achieved. The maximum temperature reduction was 14.6 K when the PV panel temperature reached 57.5°C at 12:30. However, the difference in temperature between the two PV panels is relatively smaller at early morning and late evening. Despite water cooling is applied only for a period of 2 min each half-hour, its impact of the temperature reduction was reasonably noticed.

Real-time measurements of the voltage, current, and output power were captured using the I–V tracer and recorded in a developed computer system. Experimental data of the output power for both

Figure 11: A front view of the I–V curve tracer module

Figure 12: Variations of solar irradiance and ambient temperature for September 24th, 2023

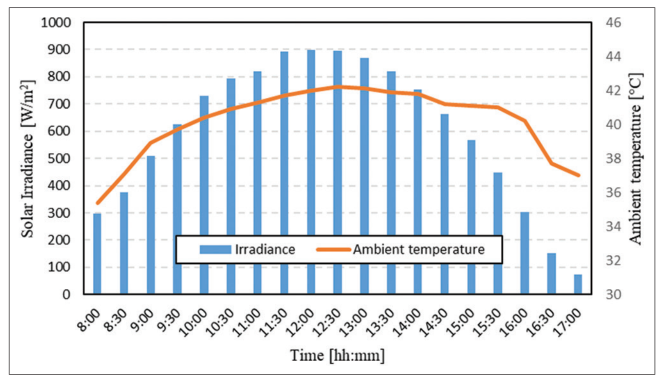
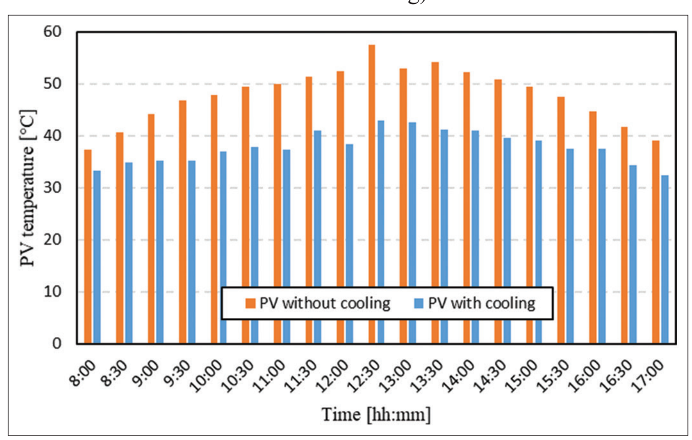


Figure 13: The measured temperature for both PV panels (with and without cooling)



PV panels were demonstrated in Figure 14. The enhancement in the output power due to the water-cooling process is clearly evident at all conducted tests. As indicated in the figure, the output power values for the water-cooled PV panel are typically greater than those of the uncooled one. It is also noticed that there is a higher increase in the power output whenever a more reduction in the PV panel temperature is achieved. In contrast to the uncooled panel, the cooled PV panel produced an output power exceeded 85.5W

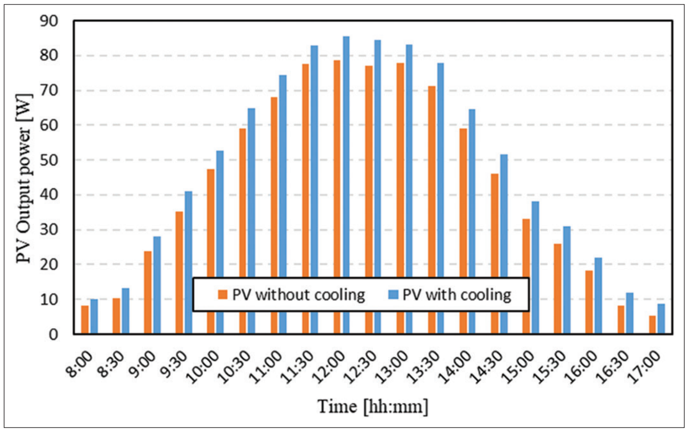


Figure 14: The measured output power for both PV panels (with and without cooling)

at the middle of the day. The maximum corresponding power generated by the uncooled panel was only 78.5 W. The percentage increase in the output power due to cooling was in the range of 7-12%, depending on the amount of temperature drop.

5. CONCLUSION

In this research, the potential enhancements in PV system performance via water-cooling of panels was investigated. A test rig with two identical 100-W PV panels was constructed. The PV system was integrated with an automated water-cooling mechanism in which water cooling was applied to one of the PV panels whereas the other one maintained uncooled. The experiments were conducted over a typical summer day of Ras Al Khaimah's climatic conditions. Experimental tests were carried out during the period between 8:00 am. and 5:00 pm. The cooling technique was applied for a continuous 2 min-periods at half-hourly intervals. The results showed that the temperature of the PV panel can be dropped by around 14 K although the water cooling was applied for only 2 min. The corresponding enhancement in the output power due to panel cooling was approximately 12%. This elucidates the promising potential of water-cooling strategies in elevating the performance of PV panels in hot and arid climates like those in the UAE.

6. ACKNOWLEDGEMENTS

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