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Sustainable Cooling Technique for Maximizing Performance of Photovoltaic Panel in The Hot Climate of Rajasthan

Lalit Jyani[a,*], Kailash Chaudhary[a], Kamlesh Purohit[a] and Shivangi Sharma[b]

[a]*Department of Mechanical Engineering, MBM University Jodhpur, India 342001*

[b]*Birmingham Energy Institute, University of Birmingham, Birmingham B155 2TT, United Kingdom*

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A B S T R A C T

This study evaluates the performance of an automated water cooling system to enhance the performance of a Photovoltaic (PV) panel in the climatic conditions of Rajasthan. A 105-watt photovoltaic system with integrated electrical, mechanical and control components was developed and tested. MATLAB was used to simulate panel performance under different sunlight and temperature conditions. Using two Identical panels, one cooled and the other noncooled, the system operated for 3 minutes every hour during daylight. Results showed a 3.6% increase in energy output and a 3.57°C reduction in panel temperature for the cooled system. With just 27 minutes of daily operation, the cooling method proved significantly more efficient than those in previous studies. The findings highlight the potential of automated water cooling in optimizing PV performance under high temperature conditions like Rajasthan, contributing to sustainable and efficient solar energy generation. This approach combines simplicity, low operating time, and measurable performance benefits.

1. Introduction

The performance of a photovoltaic (PV) panel is dependent on the immediate sunlight level and surrounding temperature. There is a direct relationship between sunlight intensity and power output, while output power is inversely related to ambient temperature [1–7].

The association between power generation and output voltage from the solar PV panel is nonlinear across different weather conditions [8,9]. Various research endeavors focus on improving PV system efficiency by developing effective algorithms for optimal operational settings, particularly the bias potential for achieving maximum power output. Various algorithms have been developed for optimizing systems, including the adjusted the

*Corresponding Author Email: Jyani.lalit809@gmail.com

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modified perturb and observe [10], fuzzy logic control [11], particle swarm optimization [12], artificial neural network combined with P&O algorithm [13,14], integrated fuzzy logic control and artificial neural network [15], as well as neural network with sliding mode control [16].

The efficiency of solar cells relies not only on the methods used in their production but also on factors like the amount of sunlight they receive, the temperature of the modules, wind conditions, humidity, and dust. A higher module temperature can notably decrease the effectiveness of solar panels. It is essential to cool the panels to maintain a high level of system performance, with the use of cooling recognized as one of the most efficient methods [17].

Many Researchers have focused on lowering the working temperature of the solar cells to boost panel performance through increased output power [18-21]. A study combined the benefits of utilizing an Artificial Neural Network algorithm with lowered temperature of Panel, resulting in a 12% decrease in the number of PV panels needed to provide the same electrical capacity with a 10°C-12°C temperature drop [22]. Experimental research has explored enhancing panel efficiency through water cooling [23–27]. Additionally, a study investigated how cell temperature affects PV performance in temperatures ranging from 20–55°C at a light intensity [25]. In a laboratory experiment, researchers varied the module temperature from 26°C to 56°C under a constant solar radiation level of 1000 W/m^2 [26]. Furthermore, the effect of cleaning the Solar panel surface with water on panel efficiency was examined [27].

A research study utilizing a simulation model introduced an advanced water based cooling system to enhance the efficiency of Photovoltaic panel [28]. Another study showcased the impact of cooling PV panels on module efficiency through the circulation of water across their surfaces [29]. Performance evaluation of a solar Panel power generation setup using water spray cooling indicated superiority over conventional water-cooling methods in the climate conditions of Iraq [30,31]. Findings exhibited a 24.4% enhancement in the power output of cooled CPV systems utilizing water and a 10.65% improvement in CPV systems.

Sornek and colleagues built and evaluated a specific water cooling system for photovoltaic (PV) panels in controlled laboratory settings and real world conditions. Their experiments demonstrated that the water cooled panel maintained a significantly lower maximum temperature, resulting in a 10% increase in power output [32]. In a separate study, a photovoltaic-thermal system with a heat sink based on water cooling was examined in the harsh climate. The research also examined that higher water flow rates improves the electrical efficiency of the Photovoltaic thermal system from 12.6% to 15% by reducing the average PV temperature [33].

This literature illustrates the vital importance of integrating water cooling to improve the performance of Photovoltaic systems, especially in dry and hot areas. While current research has primarily focused on boosting the performance of Solar panels with continuous cooling systems based on water cooling, there is a growing need to explore water cooling methods that are effective yet environmentally friendly in terms of water and energy usage.

The objective of this study is to find the effectiveness and feasibility of water cooling for Photovoltaic systems and their potential to improve their performance in the arid climate of Jodhpur, Rajasthan. Specifically, this study introduces an automated water-cooled Photovoltaic system to evaluate its performance under the local climatic conditions. By investigating the application of water cooling for PV systems, this research addresses a research gap in existing literature. The outcomes of this study could help advance the development of sustainable and efficient Photovoltaic systems.

1.1 PV panel specifications

The operation of a solar panel involves converting Solar radiation into direct current electricity. The electrical output, such as current, voltage, and power, changes according to the intensity of light received. This variation is inversely related to the surrounding temperature. Figure 1 illustrates the circuit representing a Photovoltaic solar cell. Equations (1–5)[7-12] describe how the output current, voltage, and cell parameters are interrelated. The total output voltage (V_{tot_out}) from solar cells in series (N_s) and the total output current (I_{tot_out}) from solar cells in parallel (N_p) can be evaluated using Equations 6 and 7 respectively [7–12].

$$I_{out} = I_{SC} - I_1 - I_2 \tag{1}$$

$$I_{sc} = \frac{G}{G_{ref}}(I_{sc_{ref}} + K_{SCT}(T_C - T_{C\_ref})) \tag{2}$$

$$I_1 = I_0[e^{\frac{V_d}{V_t}-1}] \quad (3)$$

$$I_2 = \frac{V_d}{R_2} \quad (4)$$

$$V_{out} = V_d - R_1 I_{out} \quad (5)$$

$$V_{tot} = N_S \times V_{out} \quad (6)$$

$$I_{tot} = N_p \times I_{out} \quad (7)$$

The working of a solar panel involves the conversion of sunlight into direct current electricity. The electrical characteristics, like current, voltage, and power, adjust based on the amount of light received. This relationship is linked to the ambient temperature. Diagram 1 depicts the electric structure depicting a solar photovoltaic cell. Formulas (1-4) outline the connection between the output current, voltage, and cell parameters. The total output voltage (V_{tot}) obtained from solar cells in series (N_s) and the total output current (I_{tot}) from solar cells in parallel (N_p) can be computed using Equations (6) and (7) respectively.

In this research, Simulink® was utilized for modeling the chosen solar PV module and plotting the current and power curves at different Solar Irradiance and ambient temperature

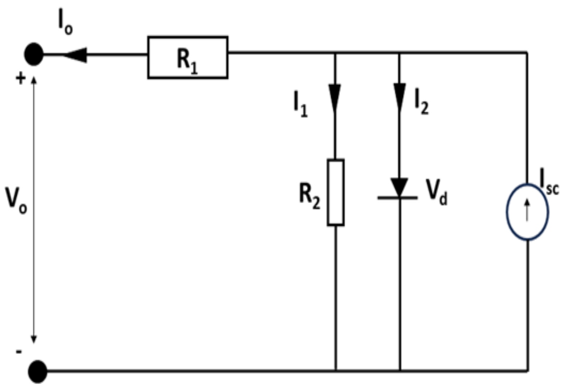

Figure 1. Photovoltaic cells Equivalent Circuit

Figure 2 illustrates the charts detailing current and power variations under different sunlight intensities of 100, 300, 500, 700, and 1000 W/m^2, alongside a consistent surrounding temperature of 25°C. In comparison, Figure 3 displays the current and power plots under varying ambient temperatures of 5°C, 25°C, 50°C, 75°C, and 100°C, with a stable Irradiance of 1000 W/m^2.

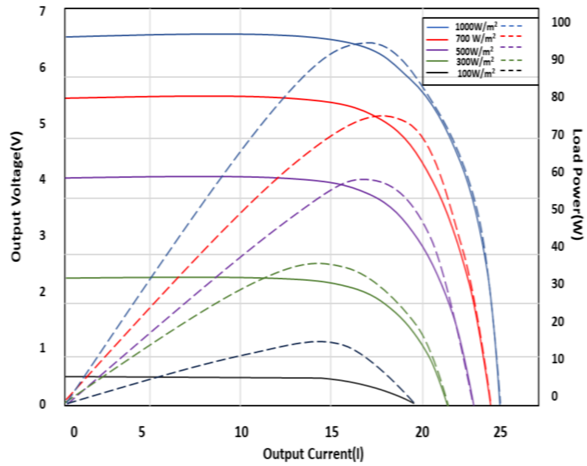

Figure 2. The I-V and P-V characteristic curves of the chosen photovoltaic (PV) module under various light intensities and a constant ambient temperature of 25°C

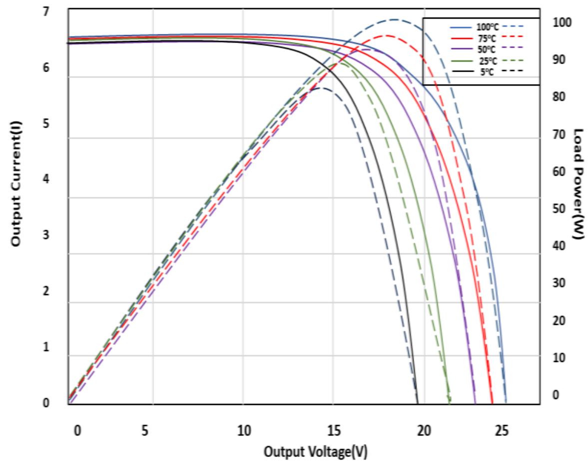

Figure 3. The I-V and P-V characteristics of the chosen solar panel at varying ambient temperatures and a constant light intensity of 1000 W/m^2

2. Circuit Diagram

The diagram in Figure 4 illustrates the assessment system for evaluating the performance of PV modules. The system commences with a recurrent timer as its initial component, serving to control the water cooling pump by activating and deactivating it. Inside this timer lies a relay output that dispatches the ON/OFF commands to the pump at scheduled intervals, allowing for the cooling cycle to be implemented on the specific PV panel at a set frequency. Following this, the subsequent section portrays a water tank boasting a capacity of 500 Liters. This segment additionally houses an electric water pump with a power rating of 0.7 H.P. The connections between the tank, pump, and the water spray manifold situated on top of the Panel surface are facilitated by water pipes.

Table 1. Solar module WS-5W/12V(Spec) [34]

Various Parameter	**Value**
Maximum power, P_{mp}	105 W
Tolerance	±3%
Open-circuit voltage, V	22.02
Short-circuit current, A	6.36
Voltage at peak power, V_{mp}	17.49
Current at peak power, I_{mp}	6.01
Efficiency, η	15.03 %
Operating temperature, °C	-40°C to +85°C
Coefficient of Current (I_{sc}), (%/ºC)	0.051
Coefficient of Voltage (V_{oc}), (%/ºC)	-0.2775
Coefficient of Power (P_m), (%/ºC)	-0.3859

The cooling system is designed to cover the entire surface area of the initial module effectively. Additionally, the setup includes two identical 105-Watt Photovoltaic panels labeled as Solar Panel WS-105/12V in the diagram presented in Figure 4. For individual monitoring of each PV panels performance, a connection to an I–V curve tracer module (Novic PV-900 Tracer Unit) in the final block is established. The tracer can connect a load of up to 3200 W and can track various parameters of each PV panel such as voltage, current, power, and temperature through separate channels. These readings are then transferred to a computer system for real time display and recording at one minute intervals

3. Experimental Setup

The schematic figure of the Experimental setup, as shown in Figure 5, includes the general design with the water cooling system. Figure 6 depicts two identical 105-Watt Photovoltaic panels installed on a metal frame with movable Photovoltaic bases. In Figure 8 the structure for adjusting the tilt angles for Solar panel is shown. Each PV panel can be adjusted from 0° to approximately 45° when the frame is placed on a even surface, as shown in Figure 8. While multiple tilt angles are possible for each PV panel, the current work utilizes a 30° tilt angle [35].

Figure 8(a) shows thermocouple (K type) used in this study [36] along with its connection arrangement to measure the Photovoltaic panel temperature of the two identical modules.

Figure 9 shows frontal perspective of the I–V curve tracer module Novtech PV-900 Multi Tracer IV Master device [37]. In this research, the tracer is utilized to monitor the functionality of cooled and noncooled photovoltaic Solar panels. Acting as an intermediary device, the tracer collects real time data on the panel. Here device collects real time data of panel surface temperature, voltage and current through different channels. This intermediary device assesses the effectiveness of Photovoltaic panels by introducing various resistive loads to the panels output terminals. The cooling mechanism implemented in this study involves an automated cooling setup using a water cooling technique.

The complete cooling system comprises a 110-gallon water tank (around 500 liters), a pump, interconnected valves, piping and a spray distribution system. In order to analyze the cooling efficiency, specifically cool the surface water is directed on the initial PV panel through a 0.7 HP i.e approximately 520 watts, while the other panel remains uncooled. A recurring timer arrangement was employed to control the pump for consistent cooling. The concept of employing an efficient water-cooling method with minimal water and energy consumption warrants further attention, especially in Rajasthan, a desert region where every drop of water is precious.

The objective of this study is to explore the practicality and efficiency of utilizing an automated intermittent water cooling system for Photovoltaic systems in hot climates. The design is based on optimizing the cooling process by automating it and providing a high level of flexibility in setting the operating time. By connecting two timers, the system allows for a 30-minute ON period followed by a 30-minute OFF period in each one-hour cycle. Additionally, the second timer can adjust the ON time with time duration of 5 seconds to 10 minutes within an hour. This setup enables a thorough examination of the required cooling duration to achieve an effective cooling strategy while conserving water and energy. The programmed timer activates the pump for 3 minutes every 60 minutes during daylight hours.

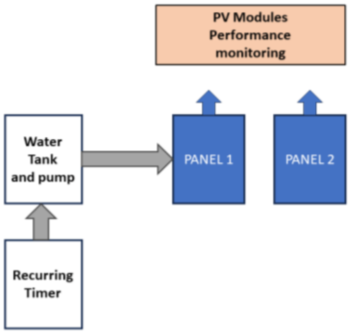

Figure 4. Block diagram of the present PV system.

Figure 10 illustrates the water circuit and cooling system utilized for cooling solar panels. Additionally, Figure 11 displays the selectable timing options for running the pump within a specific range. Furthermore, Figure 12 exhibits the electrical layout of the timer designed with indicator lights and main circuit breaker system. Lastly, Figure 13 presents the frontal perspective of the repeating timer along with its connections, including wiring.

4. Experimental methodology

The research involved setting up a photovoltaic system with two similar 105 Watt Photovoltaic solar panels under various cooling conditions to evaluate their performance. One panel was cooled with water by spraying it through a manifold positioned on the top surface, while the other panel remained uncooled. Both panels were inclined at 30 degrees. They were connected to a variable resistive load on the Current-Voltage tracer to gather data on current, voltage, and power through two separate channels. To monitor the PV modules temperature, Type K thermocouples were used to measure the temperature of Solar panels by placing them on back surface of Panel. A specially designed computer program was used as an interface between the measuring devices and the PC.

All Experimental tests were conducted at MBM University of Jodhpur with thorough testing and calibration of all system components at each stage. Data collection took place on a clear day, 1st September 2024(Sunday), over a continuous operation, from 7:30 a.m. to 4:30 p.m. In its current programmed mode, the pump runs for 3 minutes every hour from 7:30 AM to 4:30 PM, totalling about 27 minutes daily. This results in a daily water consumption of approximately 270 Liters and an electricity use of around 0.23 kWh. Although the system uses water for cooling, significant savings are achieved compared to continuous cooling, which would consume about 5400 Liters of water and 4.68 kWh of electricity per day. Thus, the intermittent cooling strategy saves approximately 5130 Liters of water and 4.45 kWh of electricity daily. These savings are substantial in water-scarce regions like Rajasthan, emphasizing the importance of optimizing cooling durations for both performance and resource conservation. The systems economic viability is favourable compared to previous studies, as shown in Table 3, with the costs of 270 Liters of water and 0.23 kWh of electricity being justified by the net energy gains. Future research should integrate water recycling and further optimize cooling schedules to maximize efficiency and minimize resource use.

Throughout the testing period, data on current, voltage, power, and temperature were gathered and logged every Minute

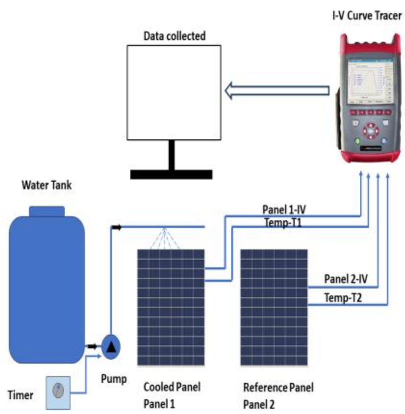

Figure 5. A diagram illustrating the photovoltaic system with the water-cooling component

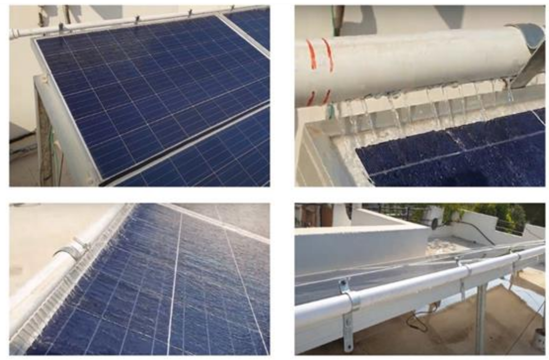

Figure 6. The configuration of the PV system includes movable 105-Watt Solar panels and a spray system for cooling the PV panels from various perspectives

The meteorological weather data for the area was acquired from the NREL website [37] and from the Indian Meteorological Department Jodhpur.

5. Results and Discussions

An experimental investigation was performed on two identical PV panels, with one panel receiving water cooling and the second panel left without water cooling. The water flow rate during cooling was approximately 10 liters per minute. During the day of Experimentation as shown in Figure 14, which displays the fluctuations in Global solar irradiance measured by the meteorological station, with a peak of 850 W/m^2 midday. Relative humidity and ambient temperature changes throughout the day are exhibited in Figure 15.

Experiments were conducted on the panels, with water cooling applied solely to Panel-1 for investigation purposes and the reference panel was kept without cooling. The temperature variances for both photovoltaic modules were illustrated in Figure 16. The impact of cooling on temperature reduction is evident when comparing the cooled panel, which fluctuated around 12°C between 10:00 a.m. and 2:00 p.m. In contrast, the noncooled panel reached over 50°C during the same period due to higher ambient temperatures, as shown in Figure 15. Despite being active for only 3 minutes each hour, the cooling process successfully lowered the panel temperature by more than 8°C during certain time intervals.

The average temperature of the panels can be determined by applying Equations 8 and 9 to cooled and Non cooled Panel [8-10]. To find the decrease in the average temperature of the solar panel resulting from cooling, Equation 10 was used to calculate the difference between the average temperatures of the cooled panel (TAv1) and the non-cooled panel (TAv2), taking into account the total number of recorded data points (N) [8]:

$$T_{Av1} = \frac{[\sum_{i=1}^{N} T1_i]}{N} \quad (8)$$

$$T_{Av2} = \frac{[\sum_{i=1}^{N} T2_i]}{N} \quad (9)$$

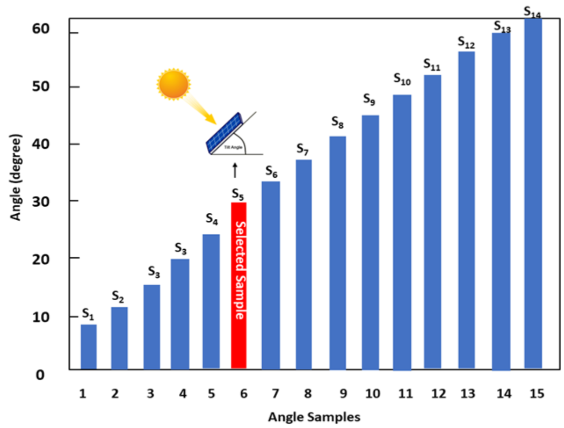

Figure 7. The range of possible inclinations and the confirmed selection of a 30-degree angle

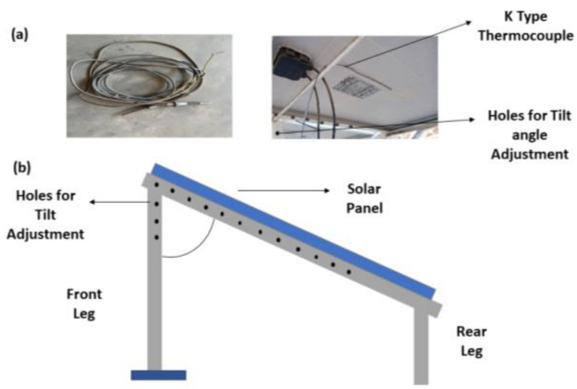

Figure 8. Comparison of the Type K thermocouple placement (a) located at the top left and its corresponding connection arrangement on the solar panel (b) Situated at the top right. Furthermore, a structured depiction of the process for adjusting the tilt of the solar panel

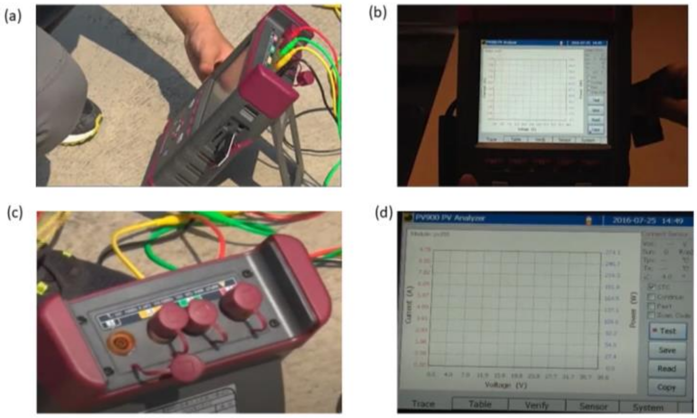

Figure 9. A different view of the I–V curve tracer (Novic PV-900 Tracer) [37]

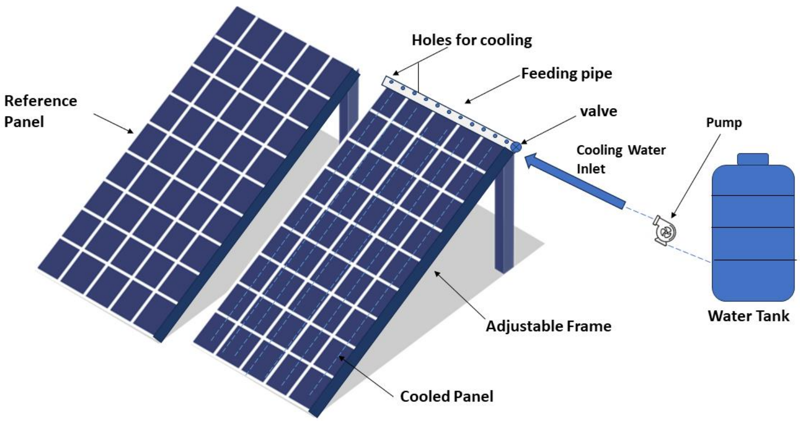

Figure 10. The setup of the Cooling mechanism with the water circuit

$$\Delta T_{Av} = T_{Av2} - T_{Av2} \qquad (10)$$

Where temperatures measured in the experiment for the first and second panels are denoted as T1i and T2i, respectively. The average temperatures of the two photovoltaic panels are detailed in figure 16, with readings of 40.56^{o}C for the cooled panel and 44.56^{o}C for the noncooled panel. By implementing the cooling process, an average temperature reduction of 7% was seen throughout the entire operational period.

Figure 17 displays the difference in panel temperature compared to the surrounding ambient temperature of two Photovoltaic Panels. Initially, there is minimal temperature variance between the panels and the environment during the first 30-40 minutes due to thermal inertia. The temperature of the noncooled panel remains around 12-15 °C higher than the ambient temperature from 10:00 a.m. to 2:00 p.m. Conversely, the temperature of the cooled PV panel reaches the ambient temperature with the application of cooling.

The readings for Output voltage, current and power were recorded using a Current-voltage tracer and a PC. Data for cooled and noncooled panels for Load power were recorded and plotted as shown in Figure 18. The impact of the cooling using water on output power is clearly visible in Figure 18. The variation in the immediate power output of the cooled photovoltaic (PV) panel corresponds to the type of cooling method implemented. As illustrated in the data, the real time output values for the cooled PV panel consistently surpass those of the uncooled panel. The cooled panel shows a maximum output power exceeding 80 W, while the uncooled panel only reaches around 72 W. To calculate the average power (PAV1 and PAV2) produced by both

Photovoltaic panels, Equations (11) and (12) are employed based on the instant load power measured, i.e. P1i and P2i, respectively. The difference in average power, ΔPAV, resulting from cooling can be determined using Equation (13). In Figure 17, the average load power produced by the two PV panels is illustrated. Upon the application of cooling using water to Photovoltaic Solar panels, the output power increased from 48.95 to 50.82 Watt. The increase in mean power of about 3.6 % due to water cooling was observed. Additionally, an added 6.5 Wh of harvested energy was obtained through the adoption of water cooling, which can be estimated using Equations (13) and (15) [8-12]:

$$P_{Av1} = \frac{[\sum_{i=1}^{N} P1_i]}{N} \quad (11)$$

$$P_{Av2} = \frac{[\sum_{i=1}^{N} P2_i]}{N} \quad (12)$$

$$\Delta P_{Av} = P_{Av1} - P_{Av2} \quad (13)$$

$$P_{+}\% = \frac{Pav1 - Pav2}{Pav2} \mathrm{X}100 \quad (14)$$

$$E_{+} = \Delta P_{Av} \mathrm{X} h \quad (15)$$

The improvement in the performance of the PV system through the proposed water-cooling method is illustrated in Table 3, which compares the current study with various previous research studies in the field. Earlier studies listed in the table used continuous water cooling systems, whereas this study used an intermittent cooling strategy. The new cooling method resulted in a total operating time of only 27 minutes per day, which is much less compared to the long operating hours reported in other studies. This approach reduces water usage and energy consumption while providing a reasonable increase in the efficiency of the cooled PV system.

6. Uncertainty analysis

Uncertainty analysis plays a crucial role in experimental measurements and data analysis, offering a numerical evaluation of the uncertainties or errors linked to a calculation and measurement. This evaluation is essential for assessing the precision and reliability of the outcomes. Specifically, within photovoltaic (PV) systems, conducting an uncertainty analysis is of great significance due to the impact of factors like solar radiation, temperature, environmental variables, and measurement uncertainties on the system's performance. By accurately estimating and addressing uncertainties in the initial experimental measurements, one can make informed choices regarding alternative methods for measuring a specific variable. Furthermore, it steers towards improving the overall precision of measurement by tackling crucial factors within the measurement procedure. The methodology is based on uncertainty principles [31]. A precise method for assessing the variability in experimental results involves defining uncertainties in multiple independent primary experimental measurements and adjusting them based on the partial derivatives of the output outcomes in relation to the independent variables. This process can be represented mathematically as adjusting the input variables by the partial derivatives of the output variable [37]:

$$w_R = [(\frac{\partial R}{\partial x_1} w_1)^2 + (\frac{\partial R}{\partial x_2} w_2)^2 + ... + (\frac{\partial R}{\partial x_n} w_n)^2]^{\frac{1}{2}} \quad (16)$$

The value of w_R represents the uncertainty in the outcome, while w_1, w_2,..., w_n represent the uncertainties associated with the independent factors. A detailed breakdown of the uncertainties related to the variables within the PV system is provided in Table 2 and Table 4. Similarly, the Ranges of Experimental Error versus observed performance are depicted in Table 5. The formula mentioned above is commonly applied to calculate the uncertainty in output by considering the uncertainties in measured voltage and current, without directly incorporating uncertainties from other factors like PV panel temperature and solar radiation. Through the application of the law of propagation of uncertainties, an approximate overall uncertainty of ±0.16% is estimated for the power output of the PV panel.

The method assumes the independent and uncorrelated nature of uncertainties in input variables i.e voltage and current and the linearity of the power output equation. If these assumptions prove false, the accuracy of estimating power output uncertainty using this method could be compromised. In such cases, the law of propagation of uncertainties must be applied to combine uncertainties from all input variables, even those not directly considered in the power output equation. Consequently, the overall uncertainty in the power output of the PV panel is estimated to be approximately ±1.98%.

Table 2. Uncertainty in the observed parameters of the photovoltaic system

Equipment	**Variables**	**Uncertainty**
Ammeter	Current	±0.10%
Voltmeter	Voltage	±0.10%
Pyranometer	Irradiance	±0.25%
Thermocouple (K type)	Temperature	±1ºC or 1.5%

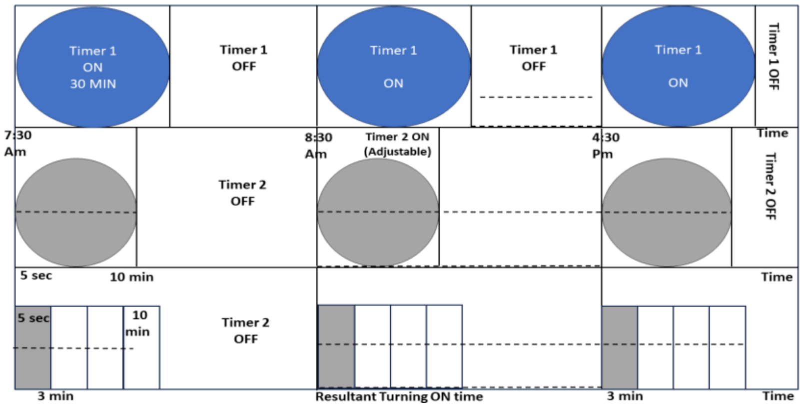

Figure 11. A systematic layout for a Timer set with a timing range

7. Conclusion and future recommendations

The experimental study effectively demonstrates the advantages of an intermittent water cooling method applied to photovoltaic (PV) panels under real-world conditions.

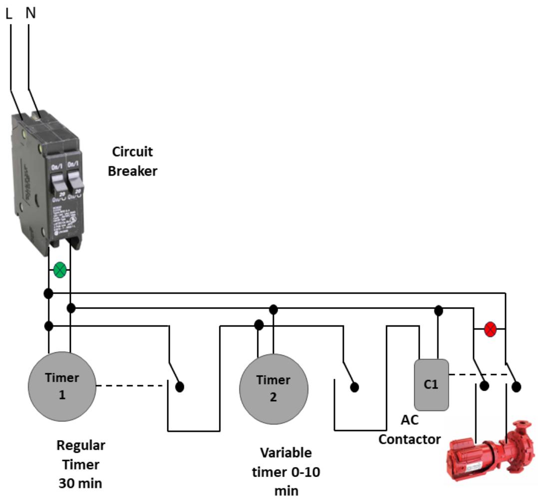

Figure 12. Electric circuit of a timer with a circuit breaker

Water cooling led to a 7% average reduction in panel temperature, lowering the cooled panel temperature to 40.56°C compared to 44.56°C for the uncooled one. During peak hours, temperature differences reached over 8°C, despite the cooling system operating for only 3 minutes per hour. The cooled panel consistently outperformed the noncooled panel in terms of power generation. A maximum output power exceeding 80 W was recorded for the cooled panel, while the uncooled one reached only about 72 W. The average power output increased from 48.95 W to 50.82 W, resulting in a 3.6% improvement in mean power. An additional 6.5 Wh of energy was harvested daily due to the cooling, emphasizing the method's potential for boosting energy yield. Compared to previous studies employing continuous water cooling, this intermittent strategy significantly reduces water usage (only 27 minutes of operation per day) while still achieving a notable performance enhancement. However, the primary limitation observed was the relatively high cost and bulkiness of the experimental setup. This limitation can be addressed in future studies through the integration of optimization techniques based on Artificial Intelligence (AI) and the Internet of Things (IoT), which have the potential to minimize system size, complexity, and operational costs effectively.

Future work will also explore the best cooling frequency and duration to optimize energy and water usage efficiently. The energy and water saving achieved in this study are crucial in water-scarce regions like Rajasthan, highlighting the importance of optimizing cooling durations for both performance and resource conservation. Additionally, the system shows strong scalability potential for large PV installations by employing programmable timers and low power pumps, and its design can be adapted for different climatic zones by adjusting cooling intervals based on ambient temperature, humidity, and solar irradiance levels. Incorporating water saving strategies such as water recirculation, greywater usage, or integrating condensate collection systems can further enhance sustainability and feasibility. The system's economic viability is favourable compared to previous studies, as shown in Table 3, with operational costs justified by net energy gains. Future research should focus on region specific cooling optimization, water reuse integration, and techno-economic analysis to enable broader deployment across diverse climatic zones.

Figure 13. The connection actual layout for cooling the Photovoltaic Panel on the timer

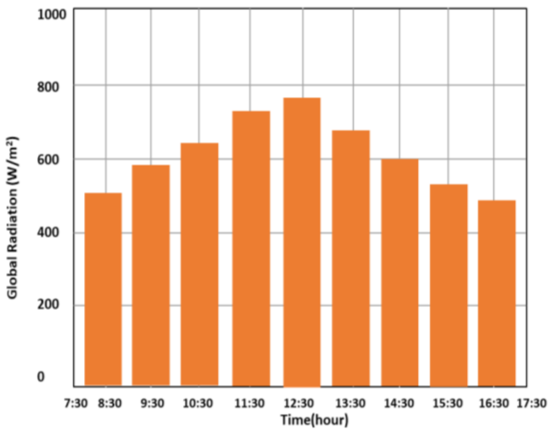

Figure 14. Global solar radiation variation on 1 September 2024

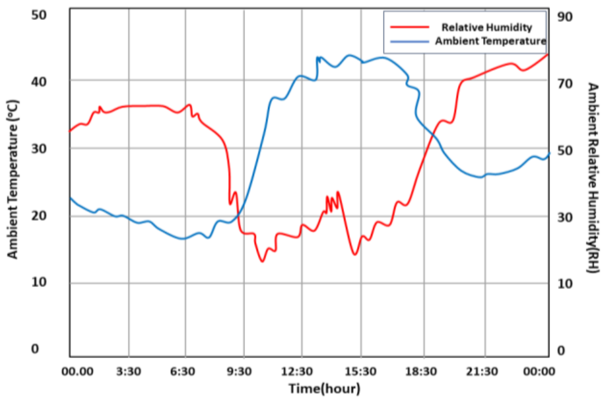

Figure 15. Fluctuations in the surrounding temperature and the level of humidity [32]

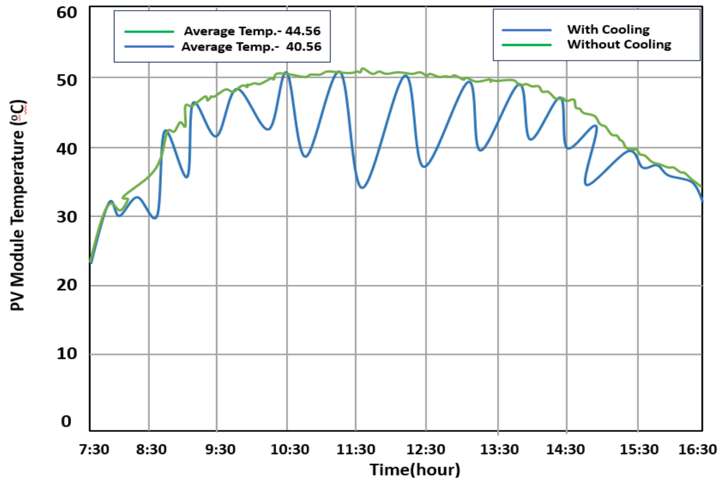

Figure 16. Temperature versus time duration for PV Panel-1 (equipped with a cooling system) and Panel-2 (noncooled)

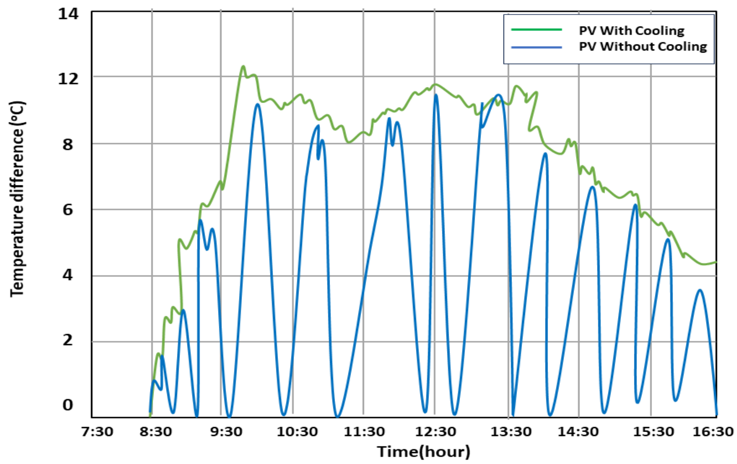

Figure 17. Temperature difference versus time duration for cooled and noncooled panel

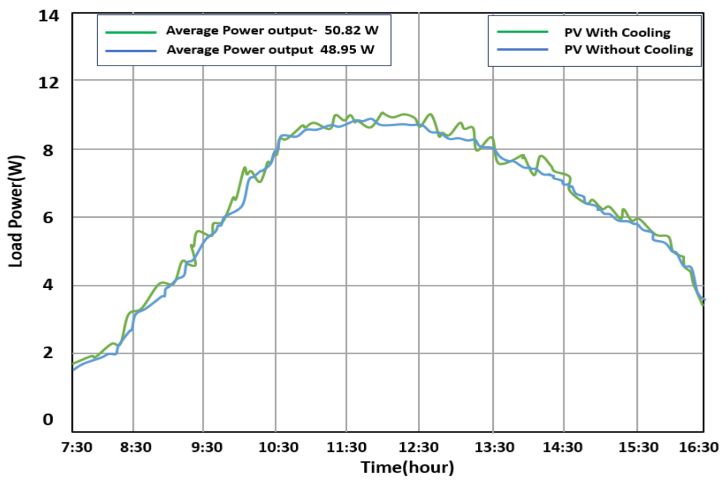

Figure 18. Load power versus time duration for cooled and noncooled panel

Table 3. Comparison between the current study and previous research

Reference, year	**Ref [17], 2009**	**Ref [23], 2014**	**Ref [18], 2016**	**Ref [24], 2022**	**Ref [25], 2022**	**Present work**
PV module type	Multicrystalline	Monocrystalline	Polycrystalline	Monocrystalline	Polycrystalline	Monocrystalline
Rated power output	60 Watt	175 Watt	12 Watt	230 Watt	320 Watt	105 Watt
Cooling type	Continuous	Continuous	Continuous	Continuous water	Continuous	Intermittent
Process	water cooling	water cooling	sponge water cooling	spray cooling	water cooling	water cooling
Panel cooling	Front side	Front side	Back side	Back side	Front side	Front side
Water pump	12 VDC, 7 W	5 VDC, 7 W	N/A	0.5 hp, 370 W, AC pump	AC pump	0.7 hp, 520 W, AC pump
Flow rate	4 L/min	7 L/min	1–2 L/min	37.5 L/min	3 L/min	10 L/min
Tilt	Variable	Fixed 30°	Fixed 45°	Not mentioned	Fixed 34.5°	Fixed 30°
Duration of testing	6:00 a.m. to 7:00 p.m.	11:40 a.m. to 5:30 p.m.	8:00 a.m.to 6:00 p.m.	9:00 a.m. to 3:00 p.m.	10:30 a.m. to 2:30 p.m.	7:30 a.m. to 4:30 p.m.
Reduction in Temperature	From 58°C to 32°C	From 55°C to 40°C	Average reduction = 1.7°C	From 419.6 K to 310 K	From 57.5°C to 34.3°C	Average reduction = 3.57°C
Load type	Variable resistor	Home electric appliances	Constant (8 W)	Constant 3 × 70 W	Variable resistor	Variable resistor
Efficiency	Average	Improvement	Average	Improvement 9%	Improvement	Improvement
Improvement in efficiency	improvement 7%	8.3%	improvement 11.5%		2.8%	3.6 %
Working hours of water pump	13 hours	5 hours + 50 minutes	N/A	6 hours	4 hours	27 minutes

Table 4. Uncertainty in the observed parameters of the photovoltaic system

Equipment	**Variables**	**Uncertainty**
Ammeter	Current	±0.10%
Voltmeter	Voltage	±0.10%
Pyranometer	Irradiance	±0.25%
Thermocouple (K type)	Temperature	±1ºC or 1.5%

Table 5. Experimental Error Ranges versus Observed Performance

Measured Parameter	Observed Improvement	Experimental Uncertainty	Significance
Output Power	3.6% (from 48.95 W to 50.82 W)	±1.98% (overall power uncertainty)	Improvement exceeds uncertainty margin
Panel Temperature	3.57°C average reduction	±1°C (thermocouple uncertainty)	Temperature reduction is larger than the uncertainty

Nomenclature

E^+	Extra energy obtained due to the cooling process (Wh)
G	Global Irradiation (W/m^2)
G_{ref}	Reference solar radiation (W/m^2)
I_{out}	Output current produced by the solar cell (A)
I_d	Current flowing through the diode (A)
I_o	Solar cell saturation current (A)
I_p	Current flowing in parallel (A)
I_{sc}	Current generated (dependent on temperature) (A)
I_{sc_ref}	Short circuit current of solar panel (A)
I_{tot}	Total output current of solar panel (A)
I_{MPP}	Current at maximum power point (A)
K_{SCT}	Temperature coefficient (A/°K)
N	Number of experiments
N_s	Number of Solar cells in series
N_P	Number of Solar cells in parallel
P_{1n}	Output Power of Panel-1 (W)
P_{2n}	Output Power of Panel-2 (W)
P_{AV1}	Average power for cooled panel (W)
P_{AV2}	Average power for noncooled panel (W)
ΔP_{AV}	Improvement in delivered power (W)
$P_+\%$	Power improvement (%)
P_{MPP}	Maximum power point (W)
R_s	Resistor connected in series in a solar cell (Ω)
R_p	Resistor connected in parallel in a solar cell (Ω)
T_{1i}	Surface temperature of cooled panel (°C)
T_{2i}	Surface temperature of noncooled panel (°C)

T_{AV1}	Average temperature of cooled panel (ºC)
T_{AV2}	Average temperature of noncooled panel (ºC)
T_c	Temperature of cell junction (ºC)
T_{c_ref}	Reference temperature of the cell (ºC)
ΔT_{AV}	Reduction in average temperature of panel (ºC)
V_d	Solar cell diode voltage (V)
V_{out}	solar cell output voltage (V)
V_t	Output voltage of Panel (V)
V_{tot}	Total output voltage of the Solar Panel (V)
V_{MPP}	Maximum power point (V)
η_{PV}	Panel efficiency (%)

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