



Comparative Study on the Electrical and Thermal Performance Efficiencies of Film Water-Cooled Solar Photovoltaic Modules

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Abstract

High operating temperature remains a major factor limiting the outdoor performance of solar photovoltaic (PV) modules, particularly in hot climatic regions. This study aimed to determine the solar input and output power and heat of PV modules under natural air-cooling and film water-cooling conditions, to evaluate the corresponding electrical and thermal performance efficiencies, and to compare the relative performance gains achieved by film water-cooling. The experiment was conducted in Sokoto, Nigeria, using two identical PV modules operated simultaneously under natural air-cooling and film water-cooling conditions. Outdoor measurements were taken from 8:30 am to 5:00 pm over five consecutive days. Solar irradiance, voltage, current, module temperature, water temperature, ambient temperature, and wind speed were measured, and the recorded data were used to calculate solar input and output power and heat, as well as electrical and thermal efficiencies. The results showed a clear diurnal variation in solar input, with peak irradiance, input power, and input heat of 605.2 W/m², 484.2 W, and 242.2 J, respectively, recorded at 12:30 pm. The film water-cooled module generally exhibited higher output power and output heat than the naturally air-cooled module during most observation intervals. Electrical efficiency ranged from 6.22% to 10.52% for the film water-cooled module and from 5.90% to 8.52% for the naturally air-cooled module. Thermal efficiency ranged from 18.82% to 70.64% for the film water-cooled module, compared with 19.26% to 41.16% for the naturally air-cooled module. Overall, film water-cooling improved the electrical and thermal response of the PV module under the tested hot-climate conditions, with the strongest benefit observed during periods of higher solar loading.

Keywords: Solar photovoltaic; Film water-cooling; Thermal management; Electrical efficiency; Hot climate performance

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INTRODUCTION

The increasing global demand for clean and sustainable energy has accelerated the deployment of solar photovoltaic (PV) systems as one of the most promising alternatives to conventional fossil-fuel-based energy sources. Owing to their environmental benefits, modularity, and broad applicability in both grid-connected and off-grid systems, PV technologies continue to play an increasingly important role in the transition toward low-carbon energy systems. In many developing countries, particularly those endowed with abundant solar resources, PV systems offer substantial potential for improving electricity access, strengthening energy security, and supporting sustainable development. However, despite the availability of solar resources in such regions, the actual outdoor performance of PV modules often differs from their rated performance under standard test conditions. One of the main reasons for this discrepancy is the rise in module operating temperature during solar exposure. As PV module temperature increases, the

electrical characteristics of the cells deteriorate, leading to a reduction in output voltage, a decline in power generation, and a decrease in conversion efficiency. Prolonged thermal stress may also accelerate material degradation and adversely affect module reliability and service life (Sengupta et al., 2018; Shahria et al., 2023; Lyubenova et al., 2024).

The thermal behavior of PV modules has therefore become an important issue in solar energy research and system optimization. Although incident solar radiation is necessary for electricity generation, only a fraction of the absorbed energy is converted into useful electrical output, while a considerable portion is dissipated as heat. This heat accumulation raises the module operating temperature above ambient conditions, especially in hot climates characterized by high solar irradiance, elevated air temperature, and limited natural convective cooling. Under such conditions, thermal management becomes essential not only for improving electrical output but also for promoting more stable and reliable PV operation. In response to this challenge, a wide range of cooling strategies has been investigated to reduce temperature-related performance losses and improve PV efficiency. These include passive and active approaches such as natural air cooling, forced air circulation, water-based cooling, heat sinks, phase change materials, and hybrid thermal management systems. The practical suitability of these methods depends on climatic conditions, cooling effectiveness, system complexity, maintenance requirements, and intended application (Njomo et al., 2020; Sharaf et al., 2022; Saliha et al., 2022; Pathak et al., 2023; Alexa et al., 2022).

Among the available cooling techniques, water-based cooling has attracted considerable attention because of the relatively high heat capacity of water and its ability to remove heat effectively from the PV surface. In particular, film water-cooling, in which a thin layer of water flows over the front surface of the module, has emerged as a relatively simple and practical approach for controlling operating temperature. This approach is attractive because it enables direct heat removal from the exposed module surface while relying on comparatively uncomplicated hardware and operating arrangements. Earlier studies have shown that surface water cooling can suppress temperature rise, mitigate thermal stress, and improve electrical performance, especially during periods of high irradiance and elevated ambient temperature (Agyekum et al., 2021; Silva et al., 2021a; Silva et al., 2021b). Additional experimental and modeling studies likewise indicate that water-film or water-spray cooling can reduce PV operating temperature and improve power output under hot-weather operating conditions, although the magnitude of improvement varies with system configuration and boundary conditions (Cuong et al., 2022; Mutasher et al., 2020; Alghamdi et al., 2023).

The interest in film water-cooling is further reinforced by studies highlighting the close coupling between thermal regulation and PV electrical response. Because PV cells exhibit a negative temperature coefficient, reducing cell temperature allows the module to operate under more favorable electrical conditions and thereby supports improved output performance. In some configurations, the cooling water may also serve as a medium for heat extraction, creating the possibility of simultaneous electrical generation and thermal utilization within photovoltaic/thermal (PV/T) systems (Silva et al., 2021a; Saliha et al., 2022; Cui et al., 2021). This broader perspective is supported by studies showing that water-

assisted cooling may improve both the electrical and thermal usefulness of solar systems, including building-integrated and hybrid PV/T applications (Al-Waeli et al., 2020; Maghrabie et al., 2021; Dubey & Subiantoro, 2018; Sudhakar et al., 2017). Although the present work is not intended as a full PV/T investigation, this broader body of literature remains relevant because it demonstrates that water-based cooling affects not only electrical output but also the thermal response of PV modules.

At the same time, the effectiveness of film water-cooling is influenced not only by the presence of flowing water itself, but also by several design and operating parameters. Film thickness, inlet water temperature, flow velocity, and the geometry of the water distribution arrangement all affect the rate and uniformity of heat transfer across the PV surface. Parametric and modeling studies have shown that suitable control of these variables can improve cooling effectiveness and enhance the electrical benefits of the system while maintaining a feasible energy balance for the cooling arrangement (Fouas et al., 2022; Silva et al., 2021a; Sharaf et al., 2022). Other studies similarly emphasize that film uniformity and the distribution network strongly influence local heat transfer and the spatial uniformity of cooling, which in turn affects the consistency of electrical response across the module surface (Kirpichnikova et al., 2019; Cuong et al., 2022). In addition, coupled thermal-electrical analyses indicate that the interaction among the PV module, the cooling film, and the surrounding environment can be represented with reasonable accuracy when local meteorological and operational conditions are adequately considered, underscoring the value of site-specific experimental studies (Li et al., 2021; Bonilla et al., 2025).

Despite the growing body of work on PV cooling, much of the literature has focused primarily on the electrical dimension of PV performance, especially changes in current, voltage, power output, and electrical efficiency. While these parameters are essential for assessing PV operation, they do not by themselves provide a complete picture of the thermal response of the module or the overall effectiveness of the cooling process. A broader assessment that considers both electrical and thermal performance can therefore provide a more comprehensive understanding of how cooling influences PV behavior under actual operating conditions. This is particularly relevant in hot climatic regions, where heat accumulation remains persistent and where cooling strategies should be assessed not only in terms of electrical benefit but also in relation to their thermal effect. Moreover, the gains reported for water-film cooling are not uniform across the literature. Differences in PV technology, climatic conditions, water temperature, flow arrangement, and test configuration can all influence the extent of temperature reduction and performance improvement. Some studies report more pronounced gains under high-radiance conditions, whereas others indicate more moderate improvements under less severe operating environments (Sharaf et al., 2022; Shahria et al., 2023; Silva et al., 2021b; Alexa et al., 2022). These differences do not diminish the relevance of water-film cooling; rather, they highlight the need for location-specific experimental assessment.

Climate context is especially important in evaluating cooling strategies for outdoor PV systems. In high-temperature environments with strong solar radiation, PV modules are more likely to operate substantially above standard test

temperatures, which increases the likelihood of thermal losses and reduced electrical efficiency. Field investigations conducted in desert, tropical, and other hot-climate environments have repeatedly emphasized that the effect of cooling becomes particularly relevant under such conditions, while also noting that the magnitude of the benefit may vary with irradiance level and time of day (Ali et al., 2024; Kiwan et al., 2020; Ngunzi et al., 2023; Pansiri et al., 2022). Sokoto State, Nigeria, provides a suitable setting for such an investigation because it is characterized by strong solar radiation and elevated ambient temperatures over much of the year. Experimental studies conducted under these conditions can therefore offer useful insight into the response of cooled and uncooled PV modules under realistic field exposure. In addition, comparative evaluation using two identical PV modules operated simultaneously under the same environmental conditions offers a more reliable basis for isolating performance differences attributable to the cooling method itself while minimizing the effect of changing weather conditions.

Against this background, the present study was designed to comparatively examine the behavior of two identical solar PV modules operated under two different cooling conditions, namely natural air-cooling and film water-cooling. By exposing both modules to the same outdoor climatic environment and monitoring their performance response, the study seeks to clarify the extent to which film water-cooling influences module behavior relative to natural cooling. In line with the variables considered in the present work, the analysis focuses on both electrical and thermal responses, including solar input and output power, solar input and output heat, and the corresponding performance efficiencies under each cooling condition. Such a comparative framework is useful because the effectiveness of a cooling technique is better understood when electrical and thermal indicators are evaluated together rather than separately, particularly under outdoor conditions where irradiance and thermal loading vary throughout the day (Pansiri et al., 2022; Lyubenova et al., 2024).

Accordingly, this study comparatively investigates the electrical and thermal performance efficiencies of a solar PV module operating under natural air-cooling and film water-cooling conditions in Sokoto, Nigeria. The specific objectives of the study are to:

- (1) determine the solar input and output power and heat of PV modules under natural air-cooling and film water-cooling conditions;
- (2) evaluate the electrical and thermal performance efficiencies of each module under the two cooling conditions; and
- (3) compare the performance efficiencies of the natural air-cooled and film water-cooled PV modules in order to identify the relative efficiency gains associated with film water-cooling.

The novelty of this study is reflected in its integrated and location-specific comparative evaluation of solar photovoltaic module performance under natural air-cooling and film water-cooling conditions in Sokoto, Nigeria. Unlike many previous studies that have focused primarily on the electrical aspect of PV cooling performance, especially changes in current, voltage, power output, and electrical efficiency (Sharaf et al., 2022; Shahria et al., 2023; Silva et al., 2021b; Alexa et al., 2022), the present study simultaneously examines both electrical and thermal

responses by comparing solar input and output power, solar input and output heat, as well as electrical and thermal efficiencies using two identical PV modules operated side by side under the same outdoor climatic exposure. This approach provides a more comprehensive assessment of the effectiveness of film water-cooling under hot-climate field conditions and offers experimental evidence on how the cooling method influences PV behavior across varying levels of daytime solar loading.

METHODS

The materials, experimental setup, measurement procedure, and analytical approach used to evaluate the electrical and thermal performance of solar PV modules under natural air-cooling and film water-cooling conditions are described in this study. Two identical PV modules were exposed simultaneously to the same outdoor environment, and the resulting measurements were used to determine solar input and output power, solar input and output heat, as well as the corresponding electrical and thermal performance efficiencies of the two cooling configurations.

Materials

This study employed two identical solar photovoltaic (PV) modules, a water container, a perforated PVC pipe, a solar power meter, digital multimeters, a digital infrared thermometer, and a digital anemometer. The two PV modules were obtained from the Sokoto Energy Research Center (SERC), Usmanu Danfodiyo University Sokoto (UDUS), whereas the remaining experimental materials and measuring instruments were procured from Ranganda marketplace, Sokoto. The use of identical PV modules was intended to minimize variability arising from differences in module characteristics and to ensure that the observed performance differences could be attributed primarily to the cooling condition.

The water-cooling arrangement consisted of a 15-L water container connected to a 50 cm PVC pipe perforated with 3 mm holes, which enabled the distribution of water across the front surface of one PV module. Electrical measurements were obtained using digital multimeters, solar irradiance was recorded using a solar power meter, module and water temperatures were monitored using a digital infrared thermometer, and ambient wind conditions were measured using a digital anemometer. The dimensions of the PV cells were measured with a meter rule in order to determine the effective module area used in the performance calculations. As reported in the manuscript, the module effective area was derived from 36 cells and a cell area of 0.022 m². The specifications of the principal materials and measuring instruments used in the experiment are presented in Table 1.

Table 1. Specifications of the materials used in the experiment

Material	Specification
1. Two identical PV modules	SOL-SH180, SUNSHINE SOLAR
2. Water container	15 L
3. PVC pipe	50 cm length with 3 mm holes
4. Solar power meter	SL102, Di-LOG
5. Digital multimeters	DT9205A, ANENG
6. Digital infrared thermometer	GM320 IR, BENETECH
7. Digital anemometer	TAB161, TASI

Experimental Setup

The experiment was conducted outdoors at the Sokoto Energy Research Center (SERC), UDUS, under unobstructed solar exposure. Two identical PV modules were mounted side by side and exposed simultaneously to the same outdoor climatic conditions throughout the experimental period. One module served as the reference module under natural air-cooling, in which heat was dissipated only through interaction with the surrounding ambient air. The second module served as the film water-cooled module, in which a thin layer of water was allowed to flow over the front surface of the module through the perforated PVC pipe connected to the water container. This side-by-side arrangement enabled a direct comparison between natural air-cooling and film water-cooling under identical environmental exposure.

Both modules were installed with the same orientation and were positioned at a tilt angle of 3° facing north. Maintaining the same tilt and orientation for both modules was necessary to ensure comparable irradiance exposure and to reduce the influence of installation geometry on the comparative analysis. Under this arrangement, any observed difference in performance could therefore be interpreted primarily in relation to the cooling condition applied to the module surface.

Measurement Procedure

The experimental measurements included solar irradiance, module voltage, module current, module temperature, cooling-water temperature, ambient temperature, and wind speed. Solar irradiance was measured using the solar power meter. Voltage and current were measured using digital multimeters. Module surface temperature and cooling-water temperature were recorded using the digital infrared thermometer, whereas ambient temperature and wind speed were monitored using the digital anemometer. The dimensions of the PV cells were measured using a meter rule and were used to determine the effective surface area of the module for the performance calculations.

Electrical measurements were obtained under two rheostat settings, namely $9\ \Omega$ and $18\ \Omega$, as indicated in the reported results. For each observation period, the measured electrical quantities were used to calculate the module output power, and the maximum measured voltage and current values were applied in the electrical power model. The same procedure was applied to both modules in order to preserve comparability between the natural air-cooled and film water-cooled conditions.

Measurements were recorded simultaneously from 8:00 am to 5:00 pm over five consecutive days in order to capture the diurnal variation in PV module performance under the climatic conditions of Sokoto. Instantaneous readings were taken at 30 s intervals. For data presentation and comparative analysis, the recorded values were subsequently averaged and reported at 30 min intervals from 8:30 am to 5:00 pm. These averaged values formed the basis for the analysis of solar input and output power, solar input and output heat, and the corresponding electrical and thermal performance efficiencies of the two modules.

Performance Calculations

The electrical and thermal performance of the modules was assessed from the incident solar energy, the measured electrical response, and the estimated thermal

output under each cooling condition. The effective area of each module, A_{eff} , was used in the calculations. In this study, A_{eff} was determined from the product of the number of cells and the area of an individual cell. Based on the module geometry reported in the manuscript, the effective area was expressed as:

$$A_{\text{eff}} = N_c \times A_c \quad (1)$$

where A_{eff} is the effective module area (m^2), N_c is the number of PV cells, and A_c is the area of one PV cell (m^2). For the present module, $N_c = 36$ and $A_c = 0.022 \text{ m}^2$.

The solar input power to each module was calculated as the product of the measured solar irradiance and the effective module area. Following the formulation adopted in the manuscript, the input solar power was determined as:

$$P_{\text{in}} = I_s A_{\text{eff}} \quad (2)$$

where P_{in} is the solar input power (W), I_s is the measured solar irradiance (W m^{-2}), and A_{eff} is the effective module area (m^2).

The input solar heat was estimated from the incident solar energy over the measurement interval. To avoid confusion with temperature notation, the time interval is expressed here as Δt . The input solar heat was therefore calculated as:

$$Q_{\text{in}} = I_s A_{\text{eff}} \Delta t \quad (3)$$

where Q_{in} is the input solar heat (J) and Δt is the time interval associated with each measurement. This expression was used to estimate the incident thermal energy received by the module surface during the observation interval.

The electrical output power of the module was determined from the measured voltage and current values. In accordance with the model used in the manuscript, the output power was calculated as:

$$P_{\text{out}} = V_{\text{max}} I_{\text{max}} \quad (4)$$

where P_{out} is the output electrical power (W), V_{max} is the measured maximum voltage (V), and I_{max} is the measured maximum current (A). This expression was applied to both the natural air-cooled and film water-cooled modules at each observation interval.

The thermal output was estimated separately for the two cooling conditions because the dominant heat-removal pathways differed between them. For the natural air-cooled module, the thermal output was estimated using a convective heat-transfer formulation:

$$Q_{\text{out,a}} = h A_{\text{eff}} \Delta T_a \quad (5)$$

where $Q_{\text{out,a}}$ is the thermal output associated with the natural air-cooled module (J), h is the heat-transfer coefficient for the air-cooling condition ($\text{W m}^{-2} \text{K}^{-1}$), A_{eff} is the effective module area (m^2), and ΔT_a is the temperature difference associated with heat transfer under natural air-cooling (K or $^{\circ}\text{C}$). This relation was used to represent the heat removed from the reference module by ambient air.

For the film water-cooled module, the thermal output was estimated from the thermal energy associated with the flowing water film. Following the formulation reported in the manuscript, the thermal output was calculated as:

$$Q_{\text{out,w}} = \dot{m}_w c_w \Delta T_w \quad (6)$$

where $Q_{\text{out},w}$ is the thermal output associated with the film water-cooled module (J), \dot{m}_w is the water mass flow rate (g s^{-1}), c_w is the specific heat capacity of water ($\text{J g}^{-1} \text{K}^{-1}$), and ΔT_w is the water temperature change during the cooling process (K or $^{\circ}\text{C}$). This expression was used to estimate the thermal energy removed from the module surface by the water film.

The electrical performance efficiency of each module was evaluated as the ratio of the output electrical power to the input solar power. The electrical efficiency was calculated as:

$$\eta_{\text{el}} = \frac{P_{\text{out}}}{P_{\text{in}}} \times 100 \quad (7)$$

where η_{el} is the electrical performance efficiency (%), P_{out} is the output electrical power (W), and P_{in} is the input solar power (W). This metric was used to compare the electrical conversion performance of the naturally air-cooled and film water-cooled modules under the same field conditions.

The thermal performance efficiency of each module was evaluated as the ratio of the useful thermal output to the input solar heat. To preserve notational consistency for the two cooling conditions, the thermal efficiency was written in general form as:

$$\eta_{\text{th}} = \frac{Q_{\text{out}}}{Q_{\text{in}}} \times 100 \quad (8)$$

where η_{th} is the thermal performance efficiency (%), Q_{out} is the output heat corresponding to the applicable cooling condition, and Q_{in} is the input solar heat (J). For the natural air-cooled module, $Q_{\text{out}} = Q_{\text{out},a}$, whereas for the film water-cooled module, $Q_{\text{out}} = Q_{\text{out},w}$. These expressions were used to compare the thermal response of the two cooling configurations under identical outdoor exposure.

Data Presentation

The calculated values of solar irradiance, input solar power, input solar heat, output power, output heat, electrical efficiency, and thermal efficiency were organized according to time of day and averaged over the five-day experimental period. These averaged values were then presented at 30 min intervals and used as the basis for the comparative analysis of the natural air-cooled and film water-cooled PV modules. This approach allowed the diurnal variation in module behavior to be evaluated in a consistent manner under the climatic conditions of Sokoto.

RESULTS AND DISCUSSION

Results

The results are discussed in terms of the experimental arrangement, solar input conditions, solar output response, and the corresponding electrical and thermal performance efficiencies of the naturally air-cooled and film water-cooled PV modules. The averaged values presented in Tables 2-4 provide the basis for evaluating the diurnal performance of the two modules under the climatic conditions of Sokoto. Because the two identical modules were operated simultaneously under the same outdoor exposure, the differences observed in their output response can be interpreted primarily in relation to the applied cooling condition.

Experimental arrangement and effective module area

The physical arrangement of the experiment is presented in Figure 1. As shown in the setup, the study was conducted at the Sokoto Energy Research Center (SERC) using two identical PV modules exposed side by side under the same outdoor conditions. One module operated under natural air-cooling, whereas the other was subjected to film water-cooling through a water container and perforated PVC pipe arrangement. The modules were positioned at a tilt angle of 3° facing north. In addition, the effective module area used in the calculations was obtained from the product of the number of cells and the area of each cell.

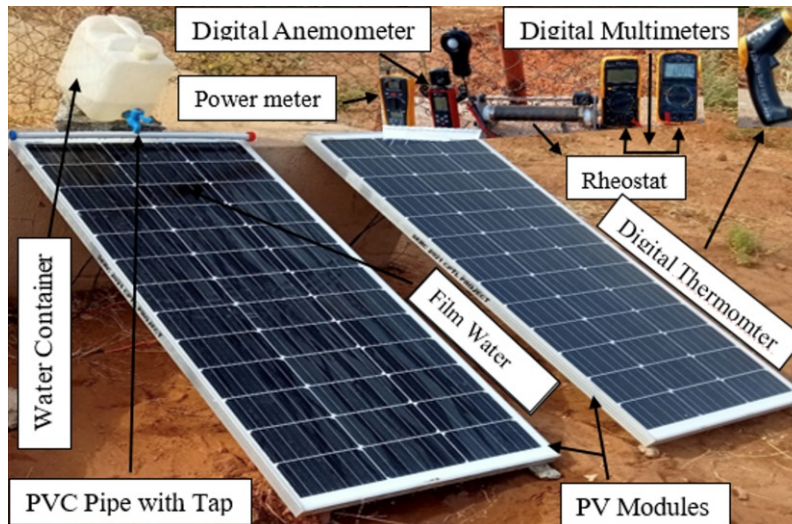


Figure 1. Experimental setup for natural air-cooling and film water-cooling modules

Figure 1 shows the essential components of the experimental system, including the PV modules, digital multimeters, digital anemometer, thermometer, rheostat, power meter, water container, and PVC pipe with tap. This arrangement provided a direct basis for comparing the performance of the two cooling configurations under identical solar exposure. Because the modules were of the same model and rating and were installed under the same geometric conditions, the setup minimized experimental bias arising from module specification and placement.

The configuration also highlights the fundamental difference between the two operating conditions. The natural air-cooled module relied only on ambient air for heat dissipation, while the film water-cooled module was subjected to surface cooling by a thin layer of water distributed over the front surface. This makes the setup appropriate for examining how surface water-film cooling alters the electrical and thermal response of the PV module under realistic outdoor conditions.

Solar input power and heat

The averaged solar irradiance, input power, input heat, and wind speed are summarized in Table 2, while their temporal behavior is illustrated in Figure 2. These variables represent the common solar and atmospheric conditions under which both modules operated. Since the two modules were exposed simultaneously to the same environment, the solar input conditions were identical for both cooling configurations. The highest averaged irradiance, input power, and input heat were

all recorded at 12:30 pm, with values of 605.2 W/m², 484.2 W, and 242.2 J, respectively.

Table 2. Solar irradiance and input power and heat with wind speeds

Time	Irradiance (W/m ²)	Input Power (W)	Input Heat (J)	Wind
8:30am	446.2	356.8	178.4	0.18
9:00am	480.2	384.2	192.4	0.30
9:30am	563.0	450.4	225.2	0.38
10:00am	558.0	446.2	223.4	0.56
10:30am	596.8	477.4	238.6	0.44
11:00am	567.2	453.8	226.8	0.52
11:30am	554.6	443.8	222.0	0.26
12:00pm	578.2	462.4	231.4	0.42
12:30pm	605.2	484.2	242.2	0.64
1:00pm	523.8	419.0	209.6	0.82
1:30pm	546.2	436.8	218.6	0.76
2:00pm	575.4	460.4	230.2	0.64
2:30pm	575.6	460.4	230.2	0.14
3:00pm	518.0	414.4	207.2	0.28
3:30pm	474.4	379.6	189.8	0.28
4:00pm	412.6	330.0	165.0	0.48
4:30pm	399.0	322.8	161.4	0.48
5:00pm	312.8	250.2	125.0	0.34

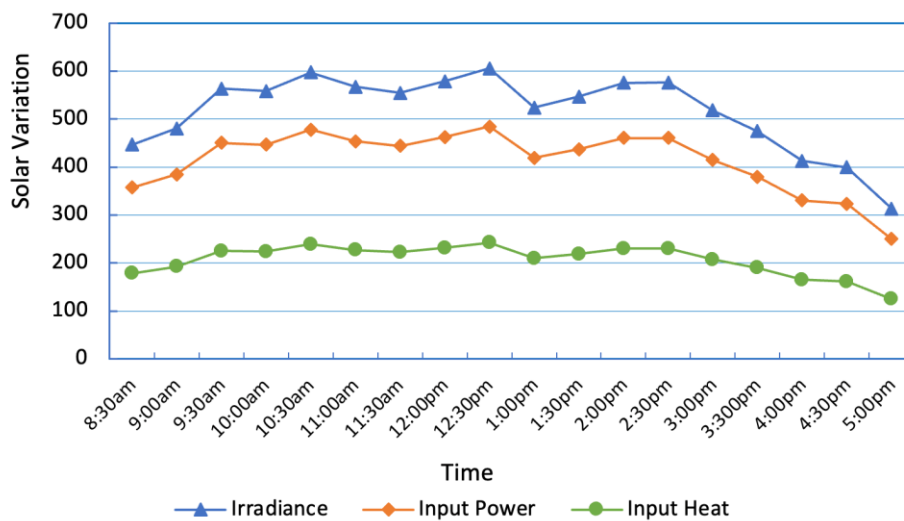


Figure 2. Variation of solar irradiance and input power over time

Figure 2 shows a clear diurnal trend in solar irradiance and the derived input variables. From 8:30 am to 12:30 pm, irradiance increased from 446.2 W/m² to 605.2 W/m², and this increase was accompanied by a corresponding rise in input power and input heat. After 12:30 pm, all three variables declined gradually toward the late afternoon, with the lowest values recorded at 5:00 pm. This pattern is consistent with the expected daily variation in solar energy availability and confirms that the modules experienced changing solar loading throughout the test period.

The importance of this pattern is that it defines the common input condition for both modules. Since the input solar energy was not constant during the day, the comparative output performance of the two modules must be interpreted in

relation to the prevailing irradiance level at each time interval. The strongest solar loading occurred from late morning to early afternoon, and this period is therefore the most relevant for evaluating the effectiveness of film water-cooling in mitigating temperature-related PV performance losses. The wind-speed values reported in Table 2 also varied during the day, but because both modules were exposed to the same ambient environment, the principal distinction between their responses remains the cooling mechanism applied at the module surface.

Solar output power and heat under the two cooling conditions

The averaged output power and output heat of the natural air-cooled and film water-cooled modules are presented in Table 3 and illustrated in Figure 3. These results provide the first direct comparison of module response under the two cooling configurations. In general, the film water-cooled module produced higher output power and higher output heat than the natural air-cooled module over much of the operating day.

Table 3. Solar output power and heat of natural air-cooling and film water-cooling modules

Time	Natural Air-Cooling Output Power (W)	Natural Air-Cooling Output Heat (J)	Film Water-Cooling Output Power (W)	Film Water-Cooling Output Heat (J)
8:30am	28.26	73.42	29.30	90.60
9:00am	28.20	66.90	31.16	112.20
9:30am	27.10	65.80	31.18	99.40
10:00am	32.88	70.30	35.64	94.20
10:30am	31.44	74.86	33.18	79.00
11:00am	30.78	64.20	32.36	92.00
11:30am	31.20	56.54	32.68	99.60
12:00pm	31.24	71.76	32.16	76.20
12:30pm	30.18	72.16	33.62	136.80
1:00pm	30.64	58.06	33.70	83.00
1:30pm	30.24	53.12	32.38	48.00
2:00pm	27.20	61.70	28.16	74.80
2:30pm	28.02	43.94	28.98	80.40
3:00pm	24.84	56.36	24.02	76.00
3:30pm	24.52	62.20	24.58	102.80
4:00pm	23.84	59.72	23.60	98.40
4:30pm	24.30	60.78	18.34	110.40
5:00pm	21.08	42.60	14.52	81.00

The results shows that the film water-cooled module generally maintained higher electrical output than the naturally air-cooled module over most of the day. For example, at 10:00 am the film water-cooled module produced 35.64 W compared with 32.88 W for the natural air-cooled module. At 12:30 pm, the values were 33.62 W and 30.18 W, respectively, while at 1:00 pm the corresponding values were 33.70 W and 30.64 W. These differences suggest that the film water-cooling arrangement helped the module operate under a more favorable thermal condition during periods of relatively high solar input.

The Figure 3 also shows that the output heat of the film water-cooled module was generally higher than that of the natural air-cooled module, indicating more effective heat removal from the module surface. The highest thermal output

recorded for the film water-cooled module was 136.8 J at 12:30 pm, whereas the highest value for the naturally air-cooled module was 74.86 J at 10:30 am. The larger output heat associated with the cooled module indicates that the water film enhanced heat extraction from the module and thereby altered the thermal response of the PV surface during operation.

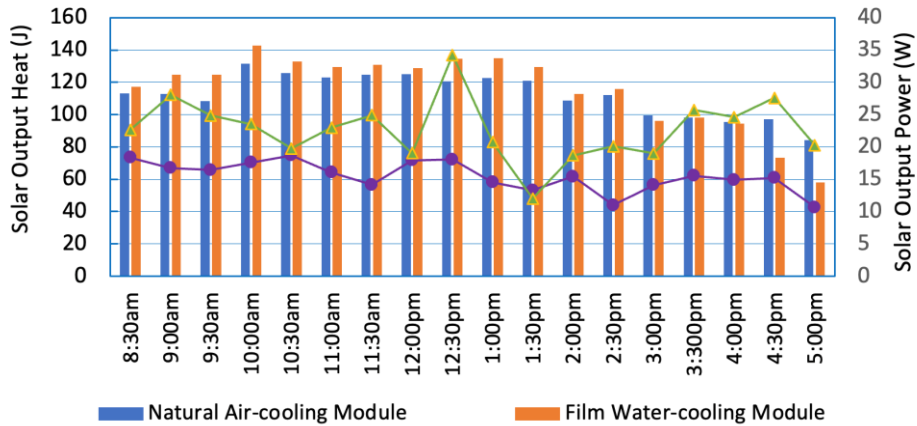


Figure 3. Solar output power and heat over time

However, the Figure 3 further indicates that the electrical advantage of film water-cooling was not uniform throughout the entire day. At 3:00 pm, the output power of the film water-cooled module was 24.02 W, which was slightly below the 24.84 W recorded for the natural air-cooled module. A similar pattern occurred at 4:00 pm, 4:30 pm, and 5:00 pm, when the film water-cooled module recorded 23.60 W, 18.34 W, and 14.52 W, respectively, compared with 23.84 W, 24.30 W, and 21.08 W for the naturally air-cooled module. This suggests that the benefit of film water-cooling was more evident under stronger solar loading and became less pronounced under lower late-afternoon irradiance. Accordingly, the effect of film water-cooling on output power should be interpreted as time-dependent rather than constant over the full operating day.

Electrical performance efficiency

The electrical and thermal performance efficiencies of the two modules are summarized in Table 4. The electrical efficiency trends are further illustrated in Figure 4, which allows a direct comparison of the electrical conversion performance of the natural air-cooled and film water-cooled modules. The results show that the film water-cooled module generally achieved higher electrical efficiency than the naturally air-cooled module for most of the observation period.

Table 4. Electrical and thermal performance efficiency of natural air-cooling and film water-cooling modules

Time	Natural Air-Cooling Electrical Efficiency (%)	Natural Air-Cooling Thermal Efficiency (%)	Film Water-Cooling Electrical Efficiency (%)	Film Water-Cooling Thermal Efficiency (%)
8:30am	8.06	41.16	10.52	61.10
9:00am	7.32	35.14	8.80	70.64
9:30am	6.04	29.40	7.78	56.80
10:00am	7.44	31.92	7.62	38.08
10:30am	6.62	31.76	7.34	24.72
11:00am	6.80	27.82	7.66	32.86

Time	Natural Air-Cooling Electrical Efficiency (%)	Natural Air-Cooling Thermal Efficiency (%)	Film Water-Cooling Electrical Efficiency (%)	Film Water-Cooling Thermal Efficiency (%)
11:30am	7.52	26.12	8.88	45.78
12:00pm	6.80	31.26	7.52	30.42
12:30pm	6.28	30.02	6.90	50.98
1:00pm	7.34	27.34	8.08	35.78
1:30pm	6.96	24.60	7.66	18.82
2:00pm	5.90	27.08	6.22	27.96
2:30pm	6.06	19.26	6.48	30.82
3:00pm	6.02	27.64	6.98	33.16
3:30pm	7.08	33.98	8.14	54.36
4:00pm	7.34	37.90	8.92	59.80
4:30pm	7.90	39.42	8.42	70.20
5:00pm	8.52	35.62	8.36	66.82

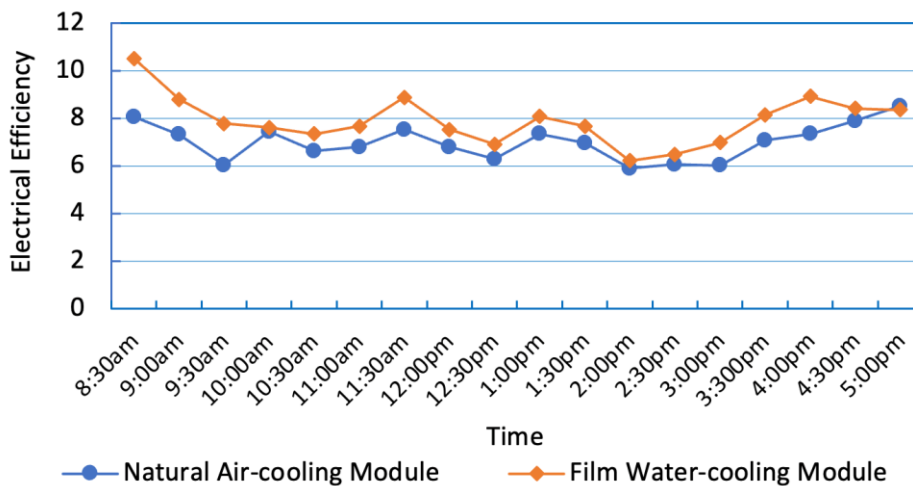


Figure 4. Comparisons between electrical performance efficiency of solar PV modules

Figure 4 indicates that the electrical efficiency of the naturally air-cooled module ranged from 5.90% to 8.52%, while the film water-cooled module ranged from 6.22% to 10.52%. The highest electrical efficiency of the film water-cooled module occurred at 8:30 am, where it reached 10.52%, whereas the highest efficiency of the natural air-cooled module was 8.52% at 5:00 pm. Across most of the observation intervals, the film water-cooled module maintained higher electrical efficiency than the reference module. For instance, at 11:30 am the electrical efficiencies were 8.88% for the film water-cooled module and 7.52% for the natural air-cooled module, while at 4:00 pm the corresponding values were 8.92% and 7.34%.

The diurnal trend of electrical efficiency shown in Figure 4 is also physically meaningful. Efficiency was relatively high in the early morning, declined toward midday, and then recovered again later in the afternoon. This behavior is consistent with the thermal sensitivity of PV modules, since the rise in module temperature during the late morning and midday period tends to reduce output voltage and suppress electrical conversion efficiency. The generally higher efficiency of the film water-cooled module therefore suggests that surface water cooling helped reduce part of the temperature-induced electrical loss.

Nevertheless, the figure shows that the difference between the two modules became smaller at certain times, especially toward the end of the day. At 5:00 pm, for example, the electrical efficiencies were 8.52% for the natural air-cooled module and 8.36% for the film water-cooled module. Thus, although film water-cooling generally improved electrical efficiency, its advantage was not identical at all times and was more evident when the module experienced stronger thermal loading.

Thermal performance efficiency

The thermal efficiency comparison is also derived from Table 4 and is presented graphically in Figure 5. These data show the relative thermal response of the natural air-cooled and film water-cooled modules under the same outdoor input conditions. Overall, the film water-cooled module exhibited higher thermal efficiency than the naturally air-cooled module for most of the monitoring period, although the fluctuations were more pronounced than in the electrical efficiency case.

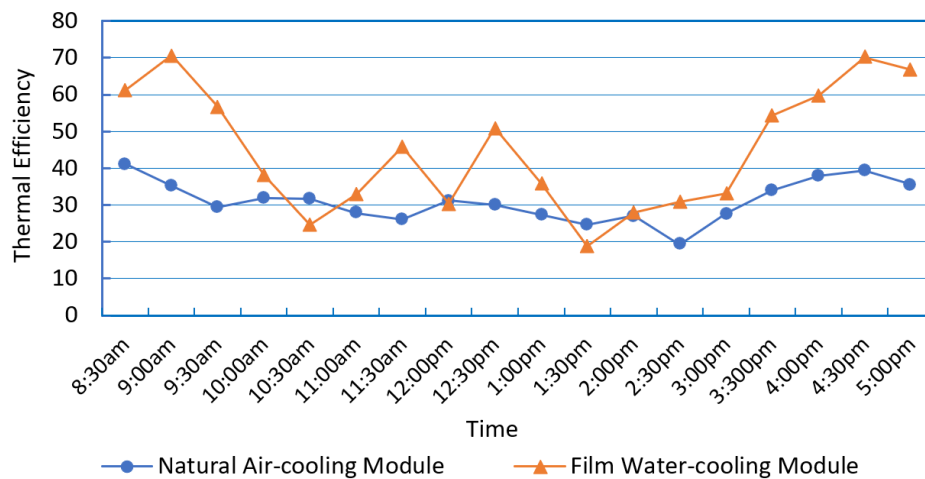


Figure 5. Comparisons between thermal performance efficiency of solar PV modules

Figure 5 shows that the thermal efficiency of the naturally air-cooled module ranged from 19.26% to 41.16%, while the film water-cooled module ranged from 18.82% to 70.64%. The highest thermal efficiency of the film water-cooled module was recorded at 9:00 am with a value of 70.64%, and another high value of 70.20% was recorded at 4:30 pm. By contrast, the naturally air-cooled module remained mostly below 40%, with its highest value of 41.16% observed at 8:30 am. These values indicate that film water-cooling generally enhanced heat removal from the module surface and improved the thermal response of the PV system.

At the same time, Figure 5 reveals that the thermal benefit of the water film was not constant over the entire day. The film water-cooled module dropped to 24.72% at 10:30 am and further to 18.82% at 1:30 pm. At 12:00 pm, the thermal efficiencies of the two modules were also very close, with 31.26% for the natural air-cooled module and 30.42% for the film water-cooled module. These fluctuations show that the thermal behavior of the cooling system changed over time and depended on the interaction between solar input, module heating, and the cooling mechanism itself.

From a thermal-management perspective, the higher thermal efficiencies observed for the film water-cooled module suggest that the flowing water layer

provided a more effective heat-removal pathway than ambient air alone. However, the presence of several low or near-equal values indicates that the thermal advantage was dynamic rather than uniform. Therefore, the thermal efficiency results support the overall usefulness of film water-cooling while also showing that its magnitude of benefit varied across the observation period.

Comparison of the two cooling configurations

The combined results reported in Tables 3 and 4 show that film water-cooling generally improved the daytime performance of the PV module relative to natural air-cooling. Across most observation intervals, the film water-cooled module displayed higher output power, higher output heat, higher electrical efficiency, and higher thermal efficiency. These trends indicate that, under the climatic conditions of Sokoto, the application of a thin water film on the PV surface enhanced module thermal regulation and generally supported better PV performance.

When Figures 3-5 are considered together, the most noticeable advantage of film water-cooling appears during periods of relatively high irradiance, especially from late morning to early afternoon, when the solar input and thermal burden on the module were greatest. Under these conditions, the difference between the two modules became more evident, suggesting that the water film was particularly beneficial in mitigating temperature-related performance losses. In contrast, during the late afternoon, when irradiance declined, the performance gap narrowed and in some cases the naturally air-cooled module produced comparable or slightly higher electrical output. This indicates that the benefit of film water-cooling was condition-dependent rather than perfectly uniform over the full day.

Overall, the results indicate that film water-cooling improved both the electrical and thermal behavior of the tested PV module under the observed outdoor conditions. A balanced interpretation of the findings is that the water-film arrangement provided a measurable performance advantage during most observation intervals, particularly under stronger solar loading, while its relative benefit became less distinct under lower irradiance conditions. This comparative outcome supports the practical relevance of film water-cooling as a simple thermal management approach for PV operation in hot climates under the tested conditions.

Discussion

The results of this study show that film water-cooling generally improved the performance of the tested PV module compared with natural air-cooling under the climatic conditions of Sokoto. Across most observation intervals, the film water-cooled module exhibited higher output power, higher output heat, and better electrical and thermal efficiencies than the naturally air-cooled module. This overall pattern suggests that the application of a thin water film over the PV surface enhanced heat removal and helped maintain a more favorable operating condition during outdoor exposure. A comparable trend has been reported in previous studies of water-film and water-based PV cooling, where reductions in operating temperature were associated with measurable improvements in PV performance, particularly under hot outdoor conditions (Silva et al., 2021a; Sharaf et al., 2022).

The higher electrical performance observed for the film water-cooled module can be interpreted in relation to the well-known temperature sensitivity of PV cells. As operating temperature increases, voltage and overall conversion efficiency tend

to decline; therefore, limiting the temperature rise helps the module maintain better electrical output. In the present study, the film water-cooled module generally sustained higher electrical efficiency than the naturally air-cooled module during most of the daytime period. This agrees with the established understanding that the benefit of cooling becomes more apparent when irradiance and thermal loading are high, since temperature-related electrical losses are then more pronounced (Shahria et al., 2023; Pansiri et al., 2022).

The output power trend further supports this interpretation. The advantage of the film water-cooled module was more evident during the late-morning and early-afternoon periods, which coincided with the highest irradiance and input power levels recorded in this study. This indicates that the cooling effect became most relevant when the thermal burden on the module was greatest. Earlier work on water-film cooling similarly showed that the clearest electrical gains tend to occur during peak daytime conditions, when the temperature coefficient of the PV cells exerts a stronger influence on the module operating point (Silva et al., 2021b; Pathak et al., 2023). Thus, the present findings suggest that film water-cooling did not merely alter the module surface condition, but improved the electrical response during the most thermally demanding hours of operation.

The thermal results also indicate that the water film enhanced heat extraction from the PV surface. Compared with the naturally air-cooled module, the film water-cooled module generally showed higher output heat and higher thermal efficiency, which suggests that the cooling layer provided a more effective heat-removal pathway than ambient air alone. This interpretation is consistent with the thermal-fluid explanation reported in the PV/T literature, where water-assisted cooling improves convective heat transfer and modifies the thermal balance of PV-based systems (Cui et al., 2021; Fouas et al., 2022). From this perspective, the present findings are relevant not only in terms of electrical improvement, but also in showing that the cooling mechanism had a clear influence on the thermal response of the module.

At the same time, the results show that the benefit of film water-cooling was not uniform throughout the day. During the late afternoon, the difference in output power between the two modules became smaller, and at some intervals the naturally air-cooled module produced comparable or slightly higher electrical output than the film water-cooled module. A similar fluctuation was also visible in the thermal efficiency profile. Rather than weakening the overall conclusion, this pattern indicates that the benefit of cooling was condition-dependent. Previous studies have shown that the relative advantage of water-based cooling may diminish under lower irradiance, when the system becomes more radiation-limited and the incremental effect of temperature reduction on electrical output becomes smaller (Li et al., 2021; Silva et al., 2021b).

This time-dependent behavior is important because it leads to a more balanced interpretation of the present findings. The data do not indicate that film water-cooling provides the same level of benefit at every hour of operation. Rather, they show that the method is most effective when the module is exposed to strong irradiance and elevated thermal stress, while its relative advantage becomes less pronounced as solar input declines. Such variation is realistic under outdoor operating conditions and reflects the fact that cooling effectiveness depends not

only on the cooling principle itself but also on the surrounding climatic and operating environment (Sharaf et al., 2022; Fouas et al., 2022).

The Sokoto climatic setting further strengthens the relevance of the present results. In high-temperature environments with strong solar radiation, PV modules are more likely to operate substantially above standard test temperatures, so temperature-related losses become more significant. Under such conditions, even a relatively simple cooling intervention can produce a meaningful improvement in module behavior. The generally better performance of the film water-cooled module observed in this study is therefore consistent with the expectation that water-based PV cooling may be particularly relevant in hot and semi-arid settings (Ali et al., 2024; Ngunzi et al., 2023).

Although this study was not designed as a full PV/T system investigation, the higher output heat and thermal efficiency observed for the cooled module remain relevant in the broader context of water-assisted PV systems. In the PV/T literature, extracted heat is often considered an additional energetic benefit that can enhance the overall usefulness of the system. While such downstream thermal utilization was not evaluated in the present work, the observed thermal advantage of the film water-cooled module is consistent with the broader concept that water-based cooling can improve both the electrical and thermal behavior of PV systems (Al-Waeli et al., 2020; Maghrabie et al., 2021).

The findings of this study support the conclusion that film water-cooling provided a measurable performance advantage over natural air-cooling during most of the observation period. The method enhanced heat removal from the PV surface and generally supported better electrical and thermal performance under the tested outdoor conditions. At the same time, the fluctuations observed across the day indicate that the magnitude of the benefit depended on the prevailing irradiance and operating conditions. A balanced interpretation is therefore that film water-cooling was effective under the tested hot-climate conditions, particularly during periods of stronger solar loading, while its relative advantage became less distinct under lower irradiance conditions. This conclusion is consistent with the broader understanding of water-based PV cooling reported in the recent literature (Silva et al., 2021a; Pathak et al., 2023).

CONCLUSION

This study comparatively evaluated the electrical and thermal performance of two identical solar PV modules operated under natural air-cooling and film water-cooling conditions in Sokoto, Nigeria. Based on the averaged outdoor measurements collected over five consecutive days, the study successfully determined the solar input and output power and heat of the two modules, evaluated their electrical and thermal performance efficiencies, and compared the relative performance of the two cooling configurations. The results showed a clear diurnal variation in solar input conditions, with the highest irradiance, input power, and input heat recorded at 12:30 pm. Under these common input conditions, the film water-cooled module generally produced higher output power and higher output heat than the naturally air-cooled module during most observation intervals.

The performance-efficiency analysis further showed that film water-cooling generally improved both the electrical and thermal behavior of the PV module. The film water-cooled module recorded electrical efficiencies ranging from 6.22% to

10.52%, compared with 5.90% to 8.52% for the naturally air-cooled module. Similarly, the thermal efficiency of the film water-cooled module ranged from 18.82% to 70.64%, whereas that of the naturally air-cooled module ranged from 19.26% to 41.16%. Overall, these results indicate that the application of a thin water film over the PV surface enhanced heat removal and generally supported better module performance under the tested hot-climate conditions.

Although the performance advantage of film water-cooling was not uniform at every time interval, the comparative results show that its benefit was more evident during periods of stronger solar loading, when temperature-related losses were expected to be more pronounced. Therefore, within the scope of the present experiment, film water-cooling can be regarded as an effective thermal management approach for improving the electrical and thermal response of PV modules in hot outdoor environments. The study thus provides experimental evidence that simple surface water-cooling has practical potential for enhancing PV module performance under the climatic conditions of Sokoto and in similar high-temperature regions.

RECOMMENDATION

Further research is recommended to evaluate the long-term performance of film water-cooling under extended outdoor operation and under different seasonal climatic conditions. Such studies would be useful for assessing the consistency of the cooling effect over time and for determining whether the observed electrical and thermal benefits can be maintained under broader environmental variability. In addition, future work may examine the influence of key operating parameters, such as water flow condition, film distribution uniformity, and water temperature, in order to better understand the factors governing the effectiveness of film water-cooling in practical PV applications. It is also recommended that future studies explore the application of film water-cooling at larger system scale and in combination with other thermal management strategies. Comparative investigations involving hybrid cooling approaches, such as combined water and air cooling, may provide further insight into whether additional performance improvements can be achieved under high-temperature operating conditions. Moreover, studies that examine the practical utilization of the extracted heat may help extend the present findings toward broader photovoltaic/thermal applications.

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