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Experimental Study on the Cooling of PV Solar Panels Using Cross-fin Configuration

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This experimental research underscores two fin configurations that were assessed under actual outdoor settings to evaluate the effect of fin positions on heat dissipation and energy output. In the first setup, standard perforated and vertical fins were mounted on the back surface of the PV panel. The panel without cooling fins reached a maximum power of approximately 52 W, and this configuration produced a temperature reduction ranging from 7 °C to 9.5 °C and a power increase of up to 2.14 W, reaching a pinnacle output of 53 W, showing a gain of 1 W compared to a panel without fins. The efficiency boost reached up to 43.9 %, confirming the benefit of passive cooling in lessening temperature-induced losses. The second configuration utilized a more advanced design with perforated and cross fins. Compared to the panel without fins, this setup reduced panel temperature by 9 °C to 14 °C and increased power output by up to 4 W, achieving a maximum of 59 W, showing a gain of 7 W. The efficiency gain reached 53 %, which is roughly 10 % higher than that of the vertical fin configuration. The results show that passive cooling, especially with perforate and cross fin is a straightforward, economical, and highly efficient technique for enhancing PV system performance in relation to the perforate and vertical fins. These improvements are especially valuable in high-radiation environments, where higher panel temperatures can adversely affect energy yield and durability. Furthermore, the economic and reliability assessment demonstrated that the proposed PV system with cross-fins offers a net economic gain of 10.578 DA and a return on investment of about 34 % over 25 years, confirming both its financial feasibility and long-term operational reliability under Algerian climatic conditions. Although these are low-power experimental panels, commercial PV modules typically exceed 300 W, and future studies may consider higher-power modules to evaluate the scalability and practical applicability of passive cooling fins. The research emphasizes the potential of innovative thermal management designs and promotes additional research into both passive and hybrid cooling solutions to advance solar energy efficiency.
Keywords: renewable energy, photovoltaic system, passive cooling, solar radiation, fin, configurations temperature reduction.

1. INTRODUCTION

Photovoltaic (PV) solar energy is among the most promising renewable technologies to meet the increasing global demand for clean and sustainable electricity [1]. However, the escalating challenge of sustaining high photovoltaic efficiency in hot climates represents a major obstacle to large-scale solar deployment worldwide. Improving thermal management in PV systems is therefore essential not only to maximize power generation but also to support the global transition toward sustainable and reliable energy systems. Nonetheless, the performance of PV panels is very sensitive to operating temperature. As the temperature of PV cells rises, their electrical efficiency and power output decline due to the negative temperature coefficient of the semiconductor materials utilized [2]. This impact is especially important in areas with high solar irradiance and raised ambient temperatures, where panels frequently function well above their standard temperature, resulting in energy losses that can surpass 20 % [3]. To address this issue, several cooling techniques have been suggested and investigated. These approaches can be roughly categorized into active and passive cooling systems [4]. Active cooling techniques, like forced air cooling or liquid circulation systems, can offer substantial temperature decreases but add intricacy, necessitate extra energy input, and involve increased installation and maintenance expenses [5].

Conversely, passive cooling solutions like fins, heat sinks, and phase change materials provide simplicity, low cost, and energy independence, rendering them particularly appealing for sizable PV installations [6]. Among passive approaches, affixing fins to the rear surface of PV panels has shown notable potential for improving heat dissipation via natural convection [7]. By increasing the heat exchange surface, fins help lower PV cell temperature and enhance electrical output. But, the geometry and arrangement of the fins play a crucial role in determining the system's cooling performance. Traditional longitudinal fin configurations

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may not fully exploit natural airflow, especially under low-wind conditions or in confined environments [8].

The cross-fin configuration, as cited by Hussein A. Kazem et al. [9], improves heat dissipation in PVT systems by increasing the heat exchange surface area, enhancing airflow distribution, and optimizing space utilization. This leads to more uniform cooling and improved photovoltaic cell efficiency.

In this context, the present study focuses on the experimental assessment of a cross-fin configuration designed to enhance natural air circulation and better convective heat transfer. An approach that, to our knowledge, hasn't been previously investigated under real outdoor conditions. The objective is to compare the thermal and electrical performance of three distinct PV panel configurations: 1) a panel equipped with conventional longitudinal cooling fins, 2) a panel operating without any cooling device (ambient conditions), and 3) a panel fitted with cross fins intended to optimize passive cooling performance.

The experimental campaign was conducted under real outdoor conditions, with measurements taken from 8:00 am to 5:00 pm to capture the full range of daily variations in solar irradiance and ambient temperature. The parameters recorded include panel temperature, output current, output voltage, generated power, and overall energy efficiency [10, 11]. These data provide valuable insights into the effectiveness of the cross-fin configuration and its potential benefits over conventional fin systems.

The originality of this work lies in the experimental implementation and assessment of a cross-fin cooling system applied to PV panels, a configuration that has received limited attention in the existing literature [9]. Additional insights on fault conditions and environmental impacts on PV performance are also considered [12, 13]. The study also considers recent advances in thermal management and modeling of PV modules under varied climatic conditions [14 – 16]. This comprehensive approach contributes to the development of cost-effective passive cooling solutions that can improve the reliability, longevity, and performance of PV systems in harsh environmental conditions.

2. METHODOLOGY

2.1. Geographic location

The comparative tests performed in this study concentrated on two sorts of photovoltaic panels: one module fitted with a passive cooling system utilizing fins, and a standard module without any cooling apparatus. These tests were performed under genuine outdoor conditions at the i2E center of Abou Bekr Belkaïd University in Tlemcen situated at an average altitude of 843 meters above sea level (see Fig. 1). Tlemcen encounters a semi-arid Mediterranean climate, characterized by hot, dry summers and mild, wet winters [17, 18]. Such climatic conditions have a direct impact on PV performance.

Summer temperatures in Tlemcen regularly exceed 35 °C, with heatwaves driving them past 40 °C. These elevated temperatures significantly decrease PV module performance: every degree Celsius above the standard testing temperature (25 °C) can reduce efficiency by roughly 0.4 – 0.5 % due to the negative temperature coefficient of silicon cells [19, 20]. Consequently, summer performance losses in Tlemcen can surpass 10 – 15 % if no cooling system is implemented.

Proper module orientation and tilt angle are vital to offset some of these losses. For fixed installations, a tilt between 30° and 32° facing south has been demonstrated optimal in Tlemcen's latitude [21]. Implementing this optimal tilt improves solar irradiance capture and ensures consistent conditions for comparing panel configurations.

These geographical and climatic characteristics make the location perfect for assessing passive cooling approaches and refining PV system designs for hot, arid areas.

a b

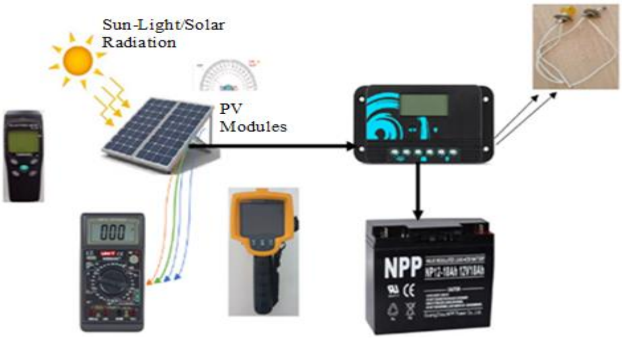
Fig. 1. a – geographic location of center I2E; b – the I2E center building

2.1. Experimental apparatus

The experimental setup for this research, depicted in Fig. 2 a, involved two identical monocrystalline photovoltaic (PV) panels. One of which included aluminum cooling fins of different sizes and configurations, featuring cross-fin arrangements, and the second was kept standard for comparison. Different sizes of aluminum fins shown in Fig. 2 b, were chosen because of their high thermal conductivity and lightweight characteristics, as suggested in PV cooling literature [22]. A solar charge controller was used to control energy flow and protect the connected 12 V deep-cycle battery from overcharging and deep discharging, ensuring consistent storage and system lifespan [23, 24]. Solar irradiance was measured constantly using a calibrated solarimeter to correlate input radiation with electrical performance [25]. Output voltage, current, and power were monitored employing precision digital multimeters, in accordance with standard practices in PV system analysis [26]. Surface temperature distribution across the panels and cooling fins was assessed utilizing a high-resolution thermal imaging camera, while type K thermocouples were installed at key locations to provide precise point temperature data [27]. This configuration allowed thorough monitoring of both thermal and electrical behaviors, providing reliable data for the evaluation of cooling strategies.

2.2. Experimental process

In this study, two identical monocrystalline photovoltaic (PV) modules were used to assess the impact of different passive cooling configurations. The first module, equipped with no fins, was used as a reference to establish baseline performance under natural ambient conditions.



a

Fins	Sizing
	Width = 10 cm Lenght =10 cm
	Width = 10 cm Lenght =12 cm
	Width = 10 cm Lenght =14 cm
	Width = 10 cm Lenght =29 cm

b

Fig. 2. a – experimental apparatus; b – various sizes of fins

The second module (Fig. 3 a) was initially fitted with perforated aluminum fins (Fig. 3 c) in vertical position, mounted on the rear side of the panel.

a

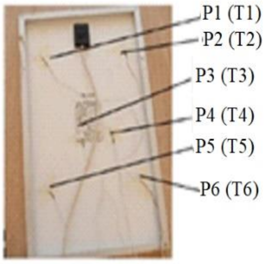
b

c

Fig. 3. a – perforate and vertical fins; b – perforate and cross fins; c – perforate fins

These fins were designed to increase the surface area for heat dissipation while maintaining similar environmental and structural conditions. The perforations in the fins were specifically made to promote airflow, consequently boosting passive cooling efficiency [28]. The fins were securely attached using a small amount of silicone adhesive.

Afterwards, the same module was re-arranged with a cross-fin's arrangement (Fig. 3 b), layout, still using perforated fins (Fig. 3 c). This configuration involved moving the fins to create a cross pattern, aiming to further enhance heat dissipation via optimized airflow dynamics. Sensors were positioned at particular (x, y) coordinates on the surface of the PV panels, as shown in Fig. 4 and described in Table 1, and thermal images of these spots were taken using a thermal camera to analyze temperature distributions.



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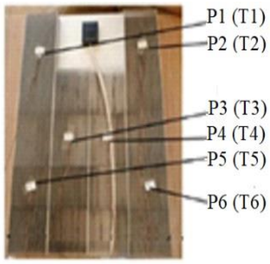

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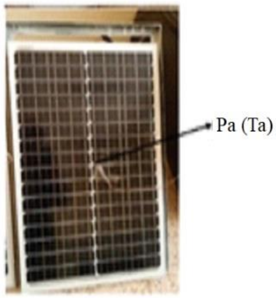


c

Fig. 4. Sensors positions: a – on back side of the panel without fin; b – on back side of the panel with fin; c – on front side of the panel

A digital multimeter recorded output current, voltage, and power, whereas a solar irradiance meter constantly measured the incoming solar energy. The entire system was tested outside to ensure exposure to actual environmental conditions, permitting an accurate evaluation of the cooling systems' impact on both thermal behavior and electrical performance of the PV modules.

Table 1. Sensor positions on the surface of the PV panels

Point	x, cm	y, cm
Pa (Ta)	20	30
P1 (T1)	5	51
P2 (T2)	35	51
P3 (T3)	15	25
P4 (T4)	25	27
P5 (T5)	5	15
P6 (T6)	35	15

The PV modules were both installed at a tilt angle of 37°, best for solar exposure at the study site, and linked to a solar charge controller to regulate power delivery to a 12 V battery. The electrical connections were made as shown in Fig. 5, and a suitable resistive load was applied using a rheostat to control and steady the electrical load during testing.

a b

Fig. 5. Field implementation of the experiment: a – front side of the panels; b – back side of the panels

3. THEORETICAL BACKGROUND

3.1. Heat transfer by convection

The transfer of heat from a solid surface at temperature Ts to the ambient environment at temperature occurs mainly through convection and is characterized by Newton's law of cooling [29]:

$$\dot{Q}_{\text{conv}} = h \times A_s \times (T_s - T_\infty), \quad (1)$$

where h is the convective heat transfer coefficient, W/m²·K; As is the surface area accessible for heat exchange, m²; T_s and T_∞ are the surface and ambient temperatures, respectively, K.

Two main ways can improve the rate of convective heat transfer; the initial one is growing the convective coefficient h through forced convection, e.g., via fans or pumps. This needs external energy input and might not always be practical in passive or low-energy systems. The second is increasing the effective surface area As by using fins, or extended surfaces, usually made of thermally conductive materials like aluminum. These fins are extruded, welded, or bonded to the surface, allowing enhanced heat dissipation via both natural convection and radiation [30].

3.2. Fin efficiency

The efficiency of a fin, denoted by η, quantifies its capacity to transfer heat compared to an ideal fin consistently maintained at the base temperature. In actuality, the temperature along a fin diminishes with distance from the base, which lessens its ability to transfer heat. Consequently, the fin efficiency is always less than unity. An experimental formula for fin efficiency based on surface temperature readings is provided by [31]:

$$\eta = \frac{\dot{Q}_{\text{actual}}}{\dot{Q}_{\text{ideal}}} = \frac{T_{without\ fins} - T_{with\ fins}}{T_{without\ fins} - T_{ambiant}}, \quad (2)$$

where $\dot{Q}_{\text{actual}}$ is the actual heat released by the fin at the n iteration, W; $T_{without\ fins}$ is the panel surface temperature without fins; $T_{with\ fins}$ is the panel surface temperature with fins, $T_{ambient}$ is the ambient air temperature.

This expression serves as a practical indicator for evaluating the effectiveness of passive cooling techniques such as fin configurations under real-world conditions.

3.3. Photovoltaic efficiency

The efficiency of a photovoltaic (PV) panel is defined as the ratio of its electrical power output to the incident solar power on its surface [32]:

$$\eta = \frac{P_{electrical}}{G \times A}, \quad (3)$$

where η is the panel efficiency (unitless or expressed as a %); $P_{electrical}$ is the electrical power output, W; G is the global solar irradiance, W/m²; A is the area of the PV panel, m².

The performance of PV modules is very sensitive to temperature, with efficiency declining as cell temperature rises because of a decrease in open-circuit voltage. Passive cooling tactics, like finned heat sinks, have consequently become a topic of interest to alleviate thermal losses and enhance the overall energy conversion efficiency.

3.4. Temperature impact on the voltage of a solar cell

The relationship between the open-circuit voltage (V_{oc}) of a solar cell and temperature (T) can be described by the Shockley diode equation [33]:

$$V_{oc} = n \, \frac{\mathrm{kT}}{\mathrm{q}} \ln\left(\frac{\mathrm{I_{ph}}}{\mathrm{I_0}} + 1\right), \quad (4)$$

where n is the diode ideality factor; k is the Boltzmann's constant (1.38×10^{-23}j/k); T is the cell temperature in Kelvin; q is the electron charge (1.602×10^{-19}C); I_{ph} is the photocurrent, which is relatively constant with temperature; I_0 is the reverse saturation current, which is highly dependent on temperature.

As the temperature increases, the reverse saturation current I_0 rises exponentially, which results in a reduction of V_{oc}. Consequently, the open-circuit voltage decreases approximately linearly with temperature.

For practical modeling purposes, this behavior is often expressed using a linear approximation provided in photovoltaic module datasheets [34]:

$$V_{oc}(T) = V_{oc,ref} + \frac{dV_{oc}}{dT}\,(T - T_{STC}), \quad (5)$$

where $V_{oc}(T)$ is the open-circuit voltage at temperature T; $V_{oc,ref}$ is the open-circuit voltage at the reference temperatre T_{ref}; $\frac{dV_{oc}}{dT}$ is the temperature coefficient of voltage, which is typically negative for silicon photovoltaic cells.

This simplified form provides a convenient means of estimating voltage variations under different thermal conditions. Thus, the linear expression can be viewed as a first-order approximation of the Shockley diode equation around a given reference temperature. It ought to be specified that photovoltaic modules are examined at 25 °C under Standard Test Conditions (STC), as described by the International Electrotechnical Commission (IEC) standards (IEC 61215 and IEC 60904). These standards relate to a solar irradiance of 1000 W/m², an air mass of 1.5, and a cell temperature of 25 °C, offering a reference framework for comparing the electrical performance of PV modules.

To illustrate the influence of temperature on performance, consider an elevation in cell temperature from

25 °C (STC) to 75 °C, i.e., a temperature rise of 50 °C. Assuming a typical temperature coefficient for voltage of $\frac{dV_{oc}}{dT} = -2.2$ mV/°C per cell, the open-circuit voltage variation can be evaluated as:

$$\Delta V_{oc} = \frac{dV_{oc}}{dT} \times (T - T_{STC}) = -110 \text{ mV } per\ cell. \qquad (6)$$

For a 60-cell module, this results in a total voltage drop of:

$$\Delta V_{oc} = -0.11 \times 60 = 6.6 \text{ V}. \qquad (7)$$

Hence, a module with $V_{oc,STC} = 37.2$ V would exhibit $V_{oc} \approx 30.6$ Vat 75 °C. Since the power output of a PV module is proportional to the product of voltage and current, this voltage reduction corresponds to an approximate power loss of 18 – 20 % under real operating conditions compared to STC.

This example highlights the significant influence of temperature on photovoltaic performance and emphasizes the necessity of implementing effective thermal management systems such as finned heat sinks or passive cooling techniques to maintain high conversion efficiency in real-world environments.

3.5. Instantaneous and daily electrical energy produced by the PV module

To evaluate the performance of the photovoltaic (PV) system, it is essential to determine the amount of electrical energy generated over time. The instantaneous power output of the PV module varies according to solar irradiance and temperature conditions. Therefore, the total energy produced can be obtained by integrating the power over the considered time period.

The instantaneous electrical energy produced by the photovoltaic (PV) module can be expressed as [35]:

$$\mathrm{E} = \int_{t_1}^{t_2} \mathrm{P(t)dt}, \qquad (8)$$

where E is the energy generated over the considered period, watt-hours; P(t) is the instantaneous electrical power, watts.

Using the measured values at different times of the day, the average total daily energy was estimated as [35]:

$$\mathrm{E_{day}} = \sum_{i=1}^{n} \mathrm{P_i} \times \Delta t, \qquad (9)$$

where P_i is the power at time interval i; Δt is the time step, h.

4. RESULTS

Two experimental sets were carried out in real-world outdoor conditions to examine the effectiveness of fin-based passive cooling techniques. The initial design entailed comparing a typical photovoltaic (PV) panel without cooling versus a similar panel equipped with perforated aluminum fins arranged vertically. The latter setup contrasted the same reference panel to a modified panel with cross-shaped perforated fins designed to improve heat dissipation by increasing airflow dynamics. Both experimental arrangements were carried out in June 2025 on separate days with alike weather to ensure the comparison's validity. Real-time data was gathered, including solar irradiance, surrounding temperature, panel surface temperature, and electrical output (current, voltage, power, and efficiency).

4.1. Solar irradiation

The irradiance profiles of both experimental setups, measured across the time interval from 8:30 a.m. to 3:30 p.m., are presented in Fig. 6. As shown, both curves following a typical bell-shaped trend, which is characteristic of clear and sunny days. The irradiance gradually increases during the morning hours, peaks around midday, and then declines toward the afternoon. Maximum irradiance values were recorded at approximately 1004 W/m² and 1060 W/m², respectively, for each experimental day.

The period between 11:30 a.m. and 1:00 p.m. corresponds to the highest solar exposure, coinciding with the sun being near its zenith. This time window is widely recognized as the most favorable for photovoltaic (PV) energy production, as the elevated irradiance levels substantially boost the electrical output of PV modules. The relatively smooth and consistent shape of the irradiance curves also indicates stable weather conditions, ensuring that the performance differences observed between the tested configurations are primarily attributable to the cooling systems and not to environmental fluctuations. This stable irradiance background provides a reliable basis for analyzing the thermal and electrical behavior of the PV panels under different cooling strategies.

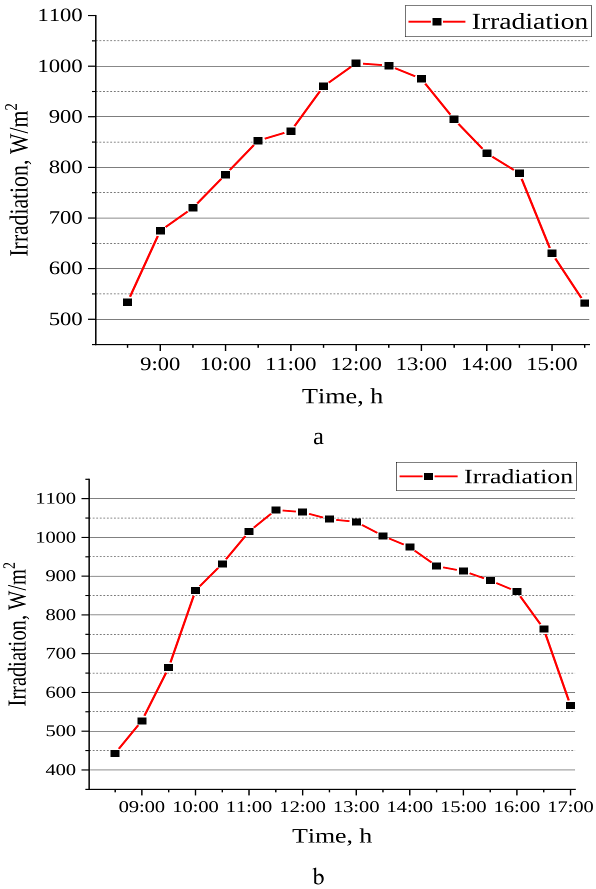
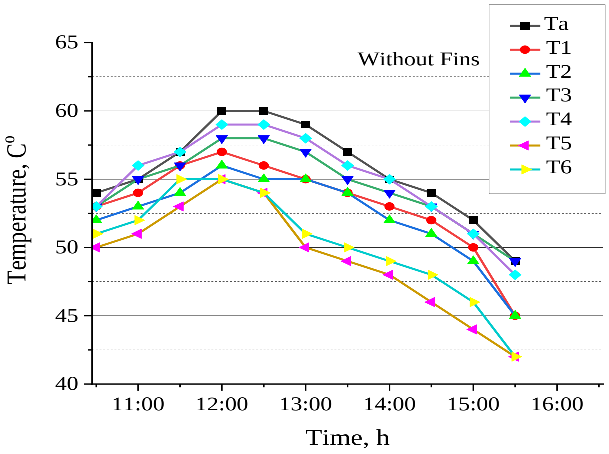


Fig. 6. The variation of the irradiation as a function of time for: a – first configuration; b – second configuration

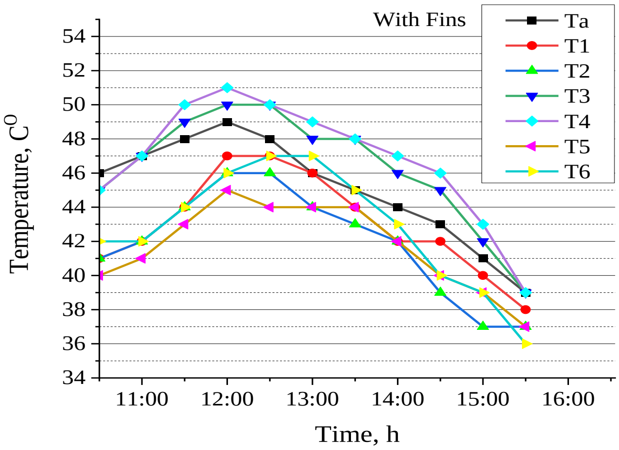
4.2. Temperature evolution analysis of PV panels

Fig. 7 and Fig. 8 present the thermal behavior of photovoltaic panels under different cooling configurations, focusing on both the front surface (Ta) and various rear measurement points (T1 to T6).

In the finless configuration (Fig. 7 a and Fig. 8 a), the temperature evolution is recorded between 10:30 a.m. and 3:30 p.m. The front surface temperature (Ta), directly exposed to solar radiation, is consistently higher than the rear surface temperatures. On average, Ta reaches a peak of 60 °C and 66 °C for vertical and cross fins respectively, clearly indicating significant heat accumulation on the exposed face. Meanwhile, the rear temperatures (T1–T6) range between (42 °C and 58 °C Fig. 7 a and 44 °C and 62 °C Fig. 8 a), with relatively small variations, reflecting a uniform thermal distribution at the back of the panel. The steady decrease in all temperature readings over time correlates with the natural reduction in solar irradiance during the afternoon.



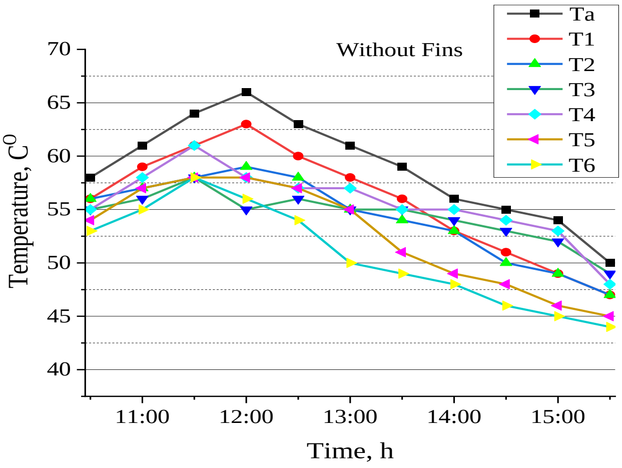
a



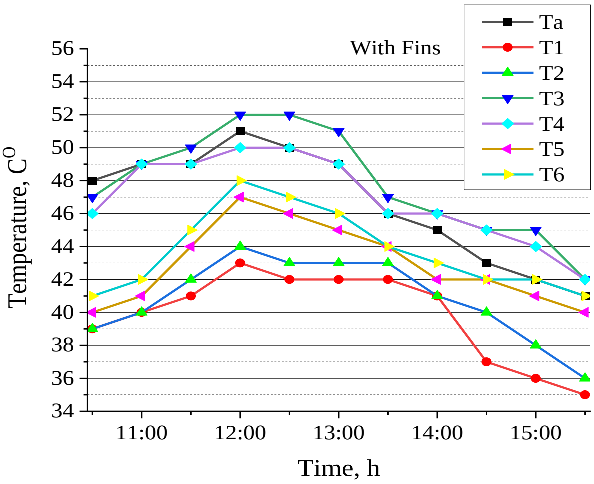
b

Fig. 7. The variation of the temperature as a function of the time for: a – panel without fins; b – panel with vertical fins

In the passively cooled configuration using vertical and cross fins shown in Fig. 7 b and Fig. 8 b respectively, the overall temperature profile shows a noticeable enhancement. The measurements show that the front surface temperature (Ta) stabilizes at 49 °C and 51 °C for vertical and cross fins respectively, whereas the remaining rear points (T1–T6) register slightly lower but closely aligned temperatures around 36 – 51 °C and 35 – 52 °C for vertical and cross fins, respectively. This demonstrates that the fins promote a more homogeneous thermal distribution, reducing hotspots and improving the cooling effect.



a



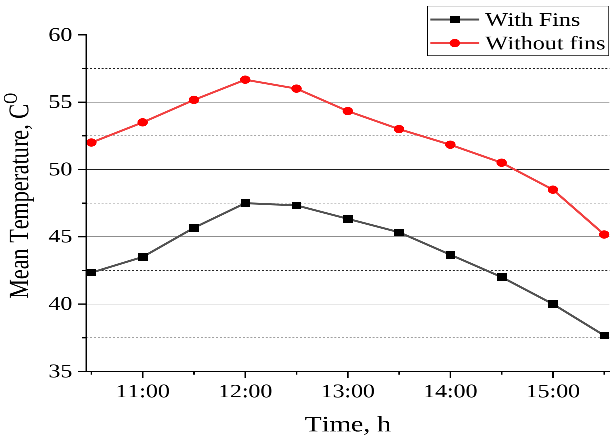
b

Fig. 8. The variation of the temperature as a function of the time for: a – panel without fins; b – panel with cross fins

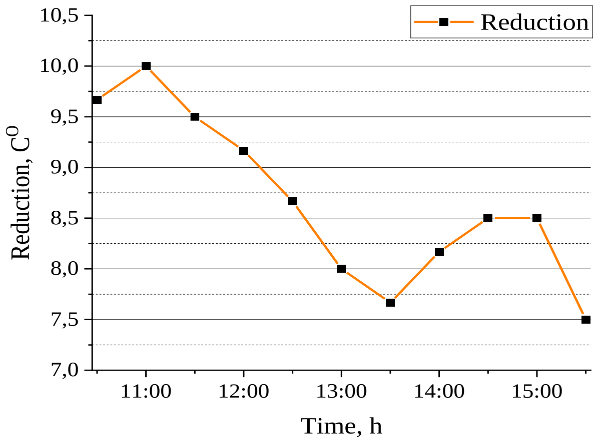
The comparison between the two configurations with and without fins highlighted in Fig. 7 and Fig. 8, clearly demonstrates the effectiveness of passive cooling. The temperatures recorded at all measurement points on panels equipped with fins are consistently lower than those observed on the panel without any cooling enhancement. Moreover, the cross-fin configuration showing even better thermal performance, attributed to improved airflow distribution and enhanced heat dissipation. This significant reduction in surface temperature confirms that passive cooling by this method effectively mitigates heat accumulation, which in turn is expected to enhance the electrical performance and extend the operational lifespan of the photovoltaic system.

4.3. Thermal performance comparison

Fig. 9 a and Fig. 10 a show the progression of surface temperatures for vertical and cross fins, and the other functioning without fins.



a



b

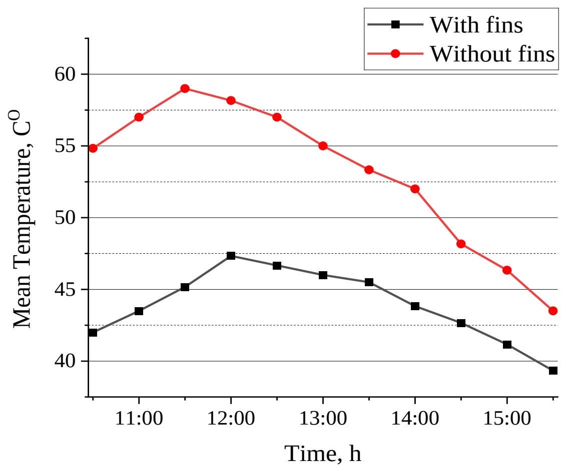
Fig. 9. a – the variation of mean temperature as a function of the time with vertical and without fins; b – the variation of mean reduction as a function of the time with vertical and without fins

During the day, from 10:30 a.m. to 4:00 p.m. In both instances, the temperature of the panel without fins is always higher than that of the finned panel throughout the observation period. The panel without fins reaches temperatures of 56 °C and 58 °C for Fig. 9 a and Fig. 10 a, while finned panels keep significantly lower temperatures of 47 °C for the vertical and cross fins. This temperature difference continues even in the afternoon. These trends clearly exhibit the effectiveness of fins in lessening thermal accumulation on the PV module surface and especially the cross fins panel.

Fig. 9 b and Fig. 10 b further demonstrate the temperature difference over time for vertical and cross fins, respectively, and the other operating without fins, showing a maximum reduction of 10 °C and 14 °C at 11:30 a.m. – 12:00 p.m. for the vertical and cross fins, correspondingly.

4.4. Thermal imaging analysis of PV panels

The thermal image in Fig. 11 shows two photovoltaic (PV) panels under the same sunlight on June 2025, at 12:00 p.m. Panel (a) has no cooling fins and reaches a high of about 59.9 °C. This suggests poor heat dissipation. On the other hand, panel (b) with passive cooling fins has a more even temperature. Its peak is around 48.8 °C. This shows how passive cooling helps spread out heat. It also reduces thermal buildup.



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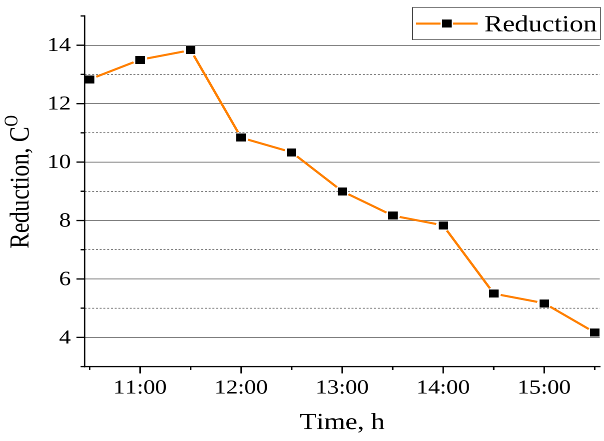


b

Fig. 10. a – the variation of mean temperature as a function of time with cross and without fins; b – the variation of mean reduction as a function of time with cross and without fins

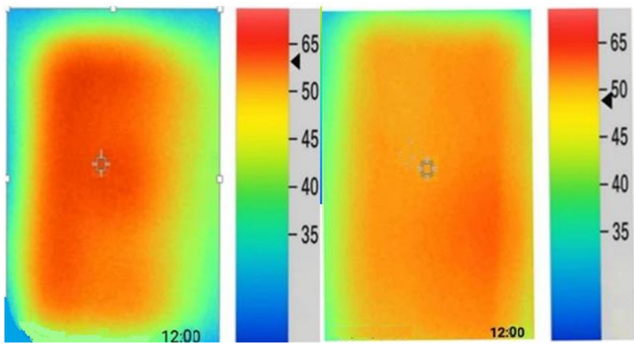


Fig. 11. Thermal camera image of PV panel: a – without fins; b – with vertical fins

Fig. 12 shows thermal images of two PV panels. They are under the same conditions on June 2025, at 12:00 p.m. Panel (a), without fins, shows a uniform temperature (red coloration) around 65.7 °C. This suggests a consistent heat level. Panel (b), with cross fins, has a varied temperature distribution. It has cooler areas (green and yellow) near the edges, with a maximum of about 51 °C. This shows better heat dissipation thanks to the fins. It leads to a cooler average surface temperature.

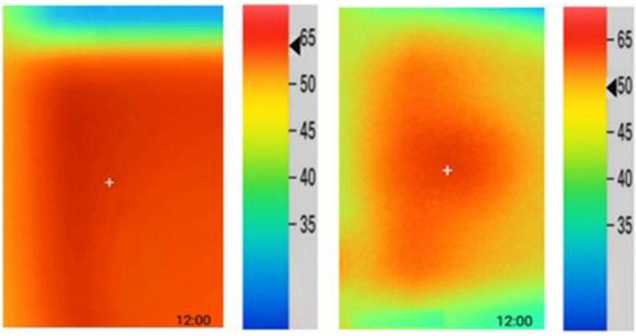
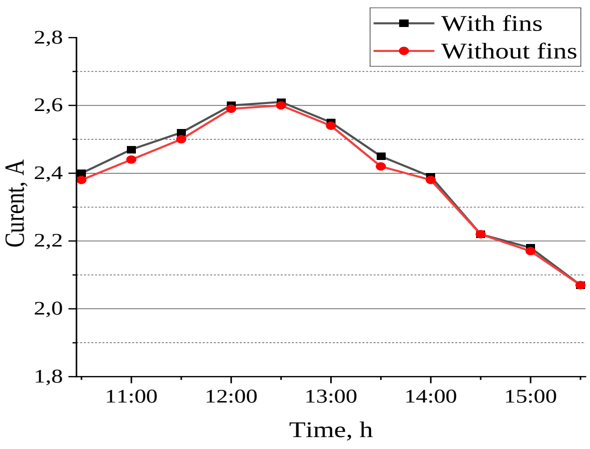


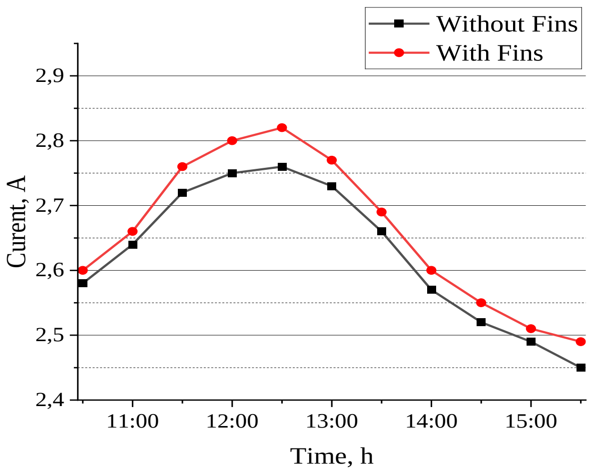
Fig. 12. Thermal camera image of PV panel: a – without fins; b – with cross-fins

4.5. Electrical current, output voltage and the power response of PV panels

Fig. 13 illustrates the time-dependent change of electrical current generated by two photovoltaic panels operating under actual outdoor situations: one absent any cooling setup and the other furnished with passive cooling fins, namely (a) vertical fins and (b) cross fins.



a

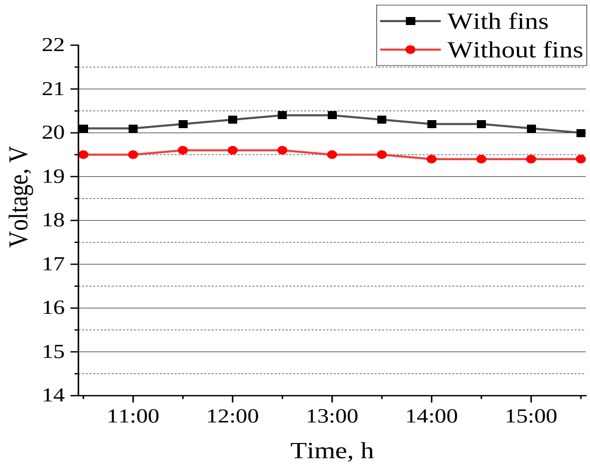


b

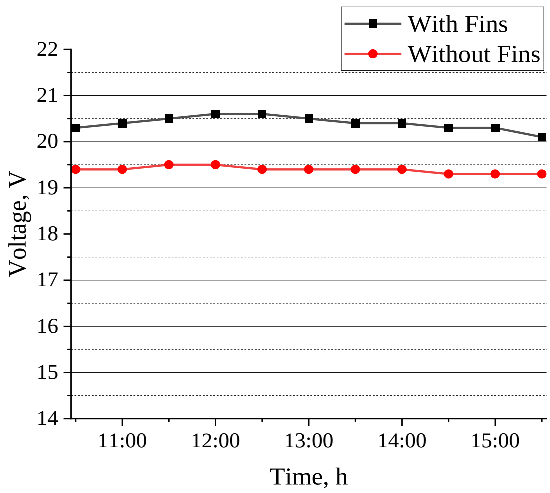
Fig. 13. The variation of curent as a function of time: a – without and with vertical fins panels; b – without and with cross-fin panels

In both arrangements, the electrical current climbs steadily from 11:30 a.m., hitting its maximum around 12:30 p.m., a time corresponding to peak solar irradiance. The panel with vertical fins attains a maximum current of 2.61 A, whereas the same panel absent fins peaks at 2.60 A. Regarding cross fins, the performance boost is more evident: the finned panel reaches 2.82 A, compared to 2.77 A for its unfinned equivalent. Subsequent to this peak, both configurations show a gradual decline in current output, corresponding with the afternoon drop in solar irradiance. A clear trend surfaces from the comparison: panels equipped with fins regularly generate higher current than those without, particularly between 11:00 a.m. and 1:00 p.m. Moreover, the panel with cross-fins displays a more substantial performance advantage than the one with vertical fins. This improvement is directly associated to improved thermal regulation: fins increase the effective surface area for heat exchange, encouraging better passive cooling and retaining lower cell temperatures.

Fig. 14 shows the temporal progress of the output voltage for two photovoltaic panels: one working without any cooling system, and the other equipped with passive cooling fins specifically (a) vertical fins and (b) cross fins.



a

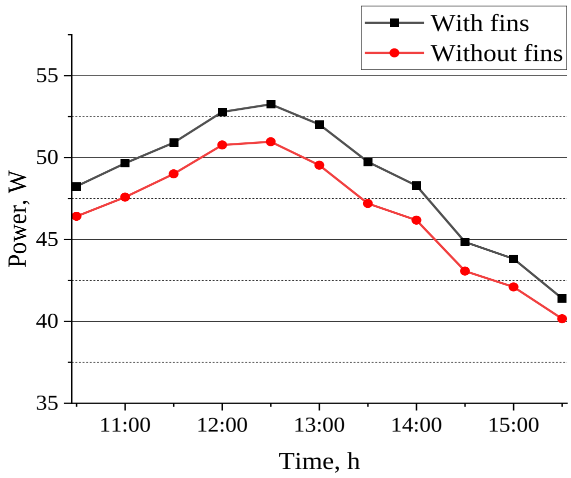


b

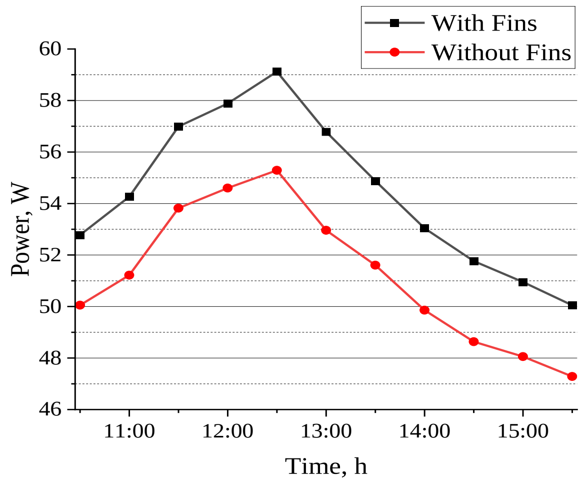
Fig. 14. The variation of voltage as a function of the time: a – without and with vertical fins panels; b – without and with cross-fins panels

The measurements were recorded between 10:30 a.m. and 4:00 p.m. under equivalent outdoor conditions. In both subfigures, the black curves represent the finned panels, while the red curves correspond to the panels sans fins. Across the measurement period, the panels equipped with fins constantly showed a higher and more stable voltage output. For the vertical fin configuration (Fig. 14 a), the average output voltage achieved about 20.4 V, contrasted to 19.5 V for the panel without fins. In the instance of the cross-fin configuration (Fig. 14 b), the voltage climbed slightly higher, averaging 20.6 V, further stressing the superior thermal performance of the cross-fin design.

Fig. 15 shows the temporal evolution of the electrical power output from two photovoltaic (PV) panels: one operating without any cooling improvement and the other equipped with passive cooling fins, specifically (a) vertical fins and (b) cross fins (a).



a



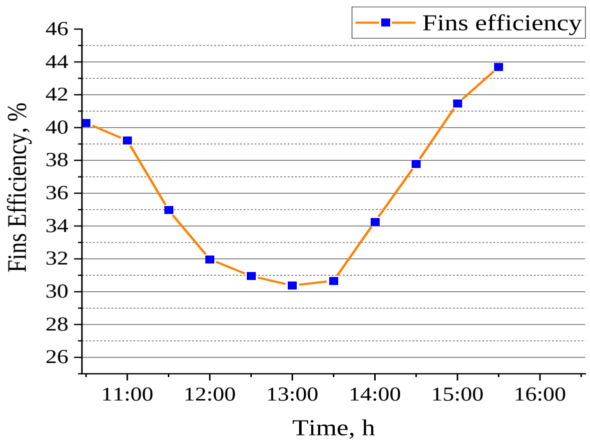
b

Fig. 15. The variation of power as a function of time: a – without and with vertical fins panels; b – without and with cross-fins panels

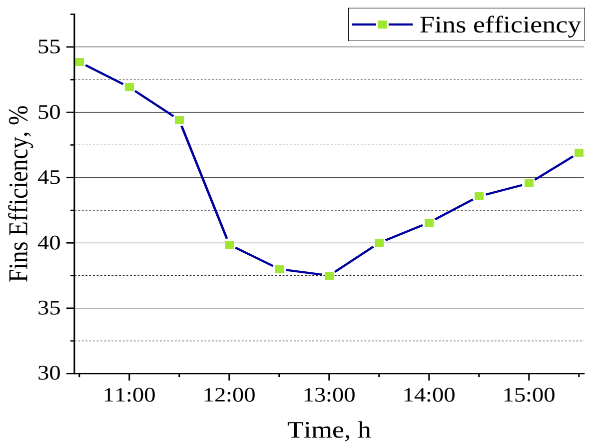
Measurements were documented from 10:30 a.m. to 4:00 p.m. under similar environmental circumstances. Black curves represent the finned panels, while the red curves correspond to the panels without fins. In both arrangements, the power output gradually increases in the morning, achieves its peak around 12:30 p.m, and then steadily declines in the afternoon. This trend is consistent with the natural variation in solar irradiance and the rise in panel temperature throughout the day, which adversely affects PV efficiency. Notably, the power curve of the finned panel consistently stays higher than that of the non-finned panel, particularly between 11:30 a.m. and 1:30 p.m. when thermal effects become more pronounced. For instance, at 12:00 p.m., the panel with vertical fins (a) delivers approximately 53 W, compared to 52 W for the panel without fins. However, in the cross fins (b) case, the performance difference is more apparent. At peak irradiance, the finned panel produces roughly 59 W, while the non-finned panel delivers only 55 W. This 4 W increase clearly shows the superior cooling performance of the cross-fin configuration. By improving natural convection and heat dissipation, the cross fins effectively reduce the panel's operating temperature, mitigating the impact of thermal stress and preserving the panel's energy conversion efficiency.

4.6. Fin efficiency and photovoltaic efficiency response of PV panels

Fig. 16 depicts the temporal variance in fin effectiveness for two photovoltaic (PV) panel setups operating under actual outdoor circumstances: one featuring vertical fins (Fig. 16 a) and the other with cross fins (Fig. 16 b).



a



b

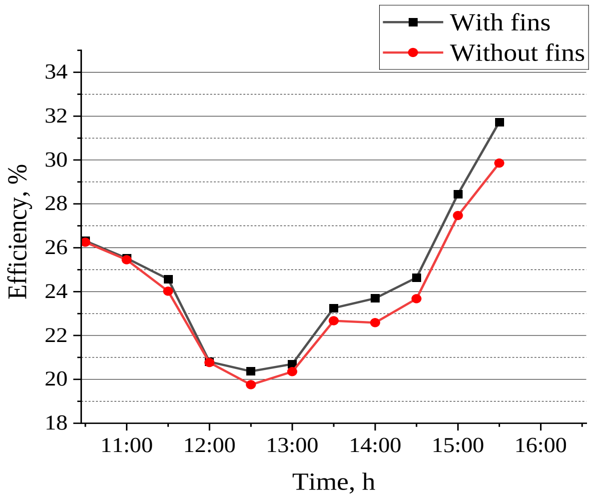
Fig. 16. The variation of fins efficiency as a function of time: a – without and with vertical fin panels; b – without and with cross-fin panels

Within Fig. 16 a, the panel with vertical fins shows an initial peak in effectiveness of approximately 40 % at 10:30 a.m., which gently declines as the day progresses, reaching a low of about 30.5 – 31 % between 12:00 p.m. and 13:30 p.m. This noon decrease can be attributed to the reduced efficiency of passive cooling when the temperature difference between the panel surface and adjacent air lessens, limiting convective heat dissipation. When the surrounding temperature drops in the afternoon, fin effectiveness improves once more, attaining as much as 43.9 % by 3:30 p.m., reflecting better cooling performance attributed to more favorable thermal conditions.

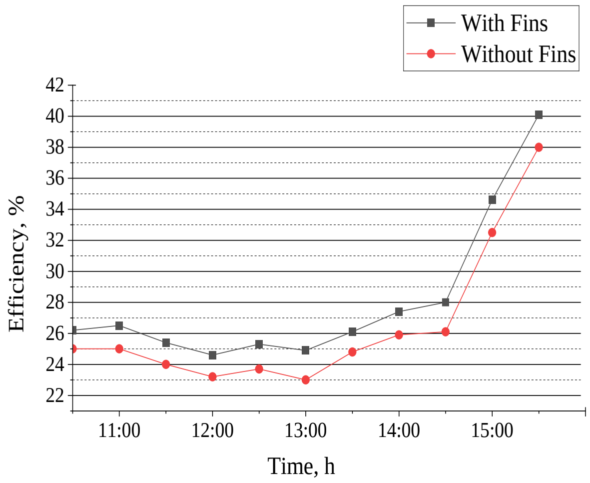
In Fig. 16 b, depicting the cross-fin configuration, a similar U-shaped pattern is observed; nevertheless, the total efficiency figures are consistently higher. The system achieves a peak efficiency of 54 % at 10:30 a.m., followed by a midday dip to roughly 37 %, and a later recovery to roughly 47% by 15:30 p.m. These findings imply that cross fins provide better thermal performance compared to vertical fins, especially during periods of decreasing solar irradiance and lower panel temperature. To summarize, both setups exhibit a U-shaped efficiency curve, typical of passive cooling systems exposed to fluctuating environmental conditions. The improved thermal regulation observed with cross fins illustrates their effectiveness in reducing thermal stress and boosting the overall electrical performance and stability of PV panels all day.

Fig. 17 presents the temporal progression of photovoltaic (PV) energy efficiency for two system arrangements: one sans any cooling improvement and the other fitted with passive cooling fins specifically (Fig. 17 a) vertical fins and (Fig. 17 b) cross fins. At the start of the observation period, both arrangements display a gradual reduction in efficiency. As shown in Fig. 17 a (vertical fins), at 10:30, the efficiency is around 26.1 % for both systems – with and without fins. It then lowers to a minimum of about 19.9 % (without fins) and 20.5 % (with fins) at 12:30, which coincides with the peak of solar irradiance and panel temperature. This decrease is mainly due to thermal stress, which negatively affects photovoltaic conversion efficiency. After 13:00, the efficiency starts to rebound as solar radiation declines and panel temperatures lessen. By 16:00, efficiency climbs to roughly 32 % for the fin-equipped system, in contrast to 30 % for the system without fins. These results demonstrate the helpful impact of passive cooling on stabilizing and improving PV performance under changing thermal conditions.

Fig. 17 b presents a different arrangement. At 10:30, the efficiency is recorded at 25 % without fins and 26.5 % with fins, trailed by a decrease as solar irradiance and temperature increase. Throughout midday (12:00 – 13:00), efficiency drops to roughly 23 % (without fins) and 25 % (with fins). In the afternoon (after 13:30), performance improves once more, attaining 38 % and 41 % at 15:30 for the systems without and with fins, respectively. This enhancement corresponds with lowered ambient temperatures and demonstrates the fins' capability to improve heat dissipation. Overall, the curve in this figure presents a typical U-shape, indicative of photovoltaic systems under fluctuating thermal loads. Significantly, this arrangement exceeds the vertical fin setup, further confirming the benefit of this passive cooling system.



a



b

Fig. 17. The variation of panels efficiency as a function of time: a – without and with vertical fin panels; b – without and with cross-fin panels

4.7. Economic and reliability assessment

The economic and reliability assessment of the proposed photovoltaic (PV) system, equipped with cooling cross-fins, was conducted to evaluate its long-term performance and feasibility under Algerian climatic conditions. Based on experimental measurements (Fig. 15 b), the average daily energy production of the PV module was found to be 303.55 Wh/day, which corresponds to a total electrical energy generation of approximately 2,771.88 kWh over its 25-year panel lifetime. Considering the current unsubsidized electricity price in Algeria (15 DA/kWh), the total economic value of this energy amounts to 41,578 DA.

The total installation cost, including the PV module and the integrated fins, was estimated at 31,000 DA. Consequently, the system yields a net economic gain of 10,578 DA and achieves a return on investment (ROI) of about 34 % over its operational lifespan of 25 years.

From a reliability perspective, the addition of fins enhances the thermal management of the PV module, reducing its operating temperature and mitigating performance degradation over time. This improvement contributes to maintaining the module’s electrical efficiency throughout its service life. Overall, the proposed PV system demonstrates both economic feasibility and operational reliability, making it a promising and sustainable solution for long-term deployment in Algerian environmental conditions.

5. CONCLUSIONS

The comparative study between the two experiments highlights the performance of two passive cooling setups applied to photovoltaic (PV) modules: 1) perforate and vertical fins, 2) perforate and cross fins. The analysis of all assessed technical aspects clearly demonstrates the better performance of the cross and perforate fin design, both thermally and electrically. Regarding temperature reduction, perforated and cross fins attain a notable decrease in module temperature, fluctuating between 9 °C and 14 °C, contrasted with merely 7 °C to 9.5 °C for perforated and vertical fins. This improved cooling outcome is vital, as it lessens the damaging effect of heat on PV cells, hence boosting their energy conversion efficacy.

This thermal improvement directly translates into better electrical performance. Indeed, the power gains associated perforate and cross fins are significantly higher, ranging from 2.7 W to 4 W, whereas perforate and vertical fins only yield 0.45 W to 2.14 W. Similarly, the peak output power reaches approximately 59 W with perforate and cross fins, showing a clear advantage over the 53 W recorded with perforate and vertical fins, which is roughly 10 % higher than that of the vertical fin configuration. Concerning crucial electrical specifications, the perforate and cross fins setup yields a marginally higher voltage (20.6 V vs. 20.4 V) and a significantly greater current (2.82 A vs. 2.6 A), indicating an enhanced ability for solar power conversion. Ultimately, the entire system's efficiency profits from the perforate and cross design, displaying a steady increase of 2 %, whereas the perforate and vertical fin arrangement reveals a smaller and more inconsistent improvement, varying from + 0.2 % to + 1.8 %.

The economic and reliability assessment further supports the feasibility of the proposed system. Under Algerian climatic conditions, the cooled PV module equipped with cross fins produced an average of 303.55 Wh/day, corresponding to approximately 2,771.88 kWh over a 25-year operational lifetime. Considering the current electricity cost (15 DA/kWh), this represents an accumulated energy value of 41,578 DA. With a total installation cost of 31,000 DA, the system generates a net economic gain of 10,578 DA and achieves a return on investment (ROI) of about 34 % over its lifetime.

From a reliability standpoint, the incorporation of cross fins enhances the module’s thermal management, effectively reducing temperature-induced degradation and maintaining consistent electrical performance over time. These results confirm that the proposed passive cooling approach provides a cost-effective, durable, and environmentally sustainable solution for improving PV performance under hot climatic conditions such as those in Algeria.

Nevertheless, further experimental investigations under diverse climatic conditions and extended exposure durations are recommended to validate the system’s stability and ensure its long-term efficiency and durability.

Acknowledgments

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