

Research paper

Comprehensive assessment of the thermal performance, economic viability, and technical aspects of a novel photovoltaic-based heat sink system

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ARTICLE INFO

Keywords:

Heat sink fin

Electrical efficiency

Passive cooling

PV cell temperature

PV power conversion efficiency

ABSTRACT

Even though photovoltaic systems are viable sources of energy production, efficiency is highly affected by surface temperature heat accumulation. Therefore, literature has suggested many strategies to tackle the problem. Attaching fins as a heat sink is among the most common ways by which photovoltaic systems are cooled. Nevertheless, most of the heat sink designs available in the literature encounter problems such as low thermal performance and high weight which causes them to drop over time. Thus, this study tries to design a new heat sink featuring a multi-stage interdigitated crimped truncated fin. The study conducts numerical analysis, outdoor experiment, economic, and technical feasibility assessments to prove that the new design outperforms PV alone and conventional heat sink featuring rectangular fins. The results show that the new design manages heat accumulation better than bare PV and PV with a conventional heat sink. Specifically, it outperforms them in surface temperature reduction (9.6%, 6.8%), electrical efficiency (7.2%, 14%), and power production (7.3%, 14.1%), respectively. Additionally, it records enhancements in the cost of energy by (7.2%, 4.2%) and energy payback period by (7.6%, 2.5%) compared to bare PV and PV with a conventional heat sink. Finally, it has less weight compared to other available designs in the current literature.

1. Introduction

The growing industrial activities and global population growth have led to an escalating energy demand [1]. In recent decades, renewable energy has become a viable substitute for conventional energy sources [2]. With its vast potential for generating electricity, solar energy stands out as a leading renewable resource, playing a vital role in meeting global power demands and addressing key environmental challenges [3]. Photovoltaic modules (PV) are generally less efficient at energy conversion compared to other standard electricity generation methods. Additionally, PV module efficiency is always measured under standard test conditions (STC), which are defined as solar irradiance of 1000 W/m², temperature 25 °C and air velocity of 1 m/s [4]. Silicon photovoltaic modules' efficiency is strongly influenced by temperature, as a 1 °C rise in temperature can result in an efficiency drop from 4 % to 6.5 % [5]. To ensure optimal efficiency and service period of PV modules, maintaining operating temperature of PV modules should be close to the

standard test condition. Elevated temperatures not only lower the electrical output of PV modules but also hasten the material deterioration [6]. As a result, the scientific community is exploring viable methods, cost-effective and maintenance-free cooling techniques to prevent excessive heat stress in photovoltaic modules [7]. To improve the efficiency of PV modules, two primary categories of cooling are employed: Active cooling method, where external energy sources, mechanical components or fluids are used to dissipate heat from the PV module. This type of cooling is more effective and suited for systems where robust thermal management is required [8]. However, a passive cooling method that employs geometry design elements or materials to dissipate heat from the PV modules is more favourable [9]. Passive cooling method can be identified as transferring heat from the PV module to the surrounding air without energy consumption, such as through creating more turbulence in the flow, expanding the contact area, engineering the microstructure of the material, and generating more vortex in the flow [10]. In this paper, the focus is on the passive air cooling natural convection, which is presented as a heat sink. Natural

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<https://doi.org/10.1016/j.rineng.2026.110573>

Received 7 January 2026; Received in revised form 11 March 2026; Accepted 15 April 2026

Available online 16 April 2026

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Nomenclature			
Abbreviations			
A_{pv}	Area of the photovoltaic module (m^2)	G_t	Annual Solar Irradiance ($kWh/m^2/day$)
AC	Annual Cost (\$)	i	Interest Rate (%)
AMC	Annual Maintenance cost (\$)	I_{sc}	Short Circuit Current (A)
ASV	Annual Salvage Value (\$)	MSICTF	Multi-stage Interdigitated Crimped Truncated Fins
C_e	Cost of Electricity (DC)	n	Number of Years
CED	Cumulative Energy Demand (MJ)	P	Initial Cost
CRF	Capital Recovery Factor	S	Salvage Value
dg_{pv}	Annual Model Degradation (%)	SFF	Sink Fund Factor
En_{ele}	Annual Electrical Production (kWh)	V_{oc}	Open Circuit Voltage (V)
EPBP	Energy Payback Period (years)	Greek Symbols	
FAC	First Annual Cost	α_{cell}	Absorptivity of PV Cell
		τ_{gl}	Glass Transmissivity
		η_{ele}	Electrical Efficiency (%)

convection can be defined as the cooling of the PV module by the flow of cooling air due to a temperature or pressure difference [11]. The heat sink, which employs natural convection or forced convection as a cooling method, is essentially a metal component designed to increase the contact surface area between the PV module and its surrounding environment, thereby supporting efficient heat dissipation through natural or forced convection [12,13]. The heat sink is favorable due to its merits as a maintenance-free, cost-effective, simple, and affordable solution for cooling the PV module [14].

Many researchers have studied the effect of the heatsink on the thermal management of PV modules and the output electrical power of PV modules. M.A. Bashir and H.M. Ali [15] conducted a simulation study of different fin shapes: rectangular pin, circular, and long rectangular attached to a 50 W solar module. The study considered different tube dimensions (diameter, length), number of fins, and the spaces between the fins. The results showed that rectangular pin fins outperform the circular and long rectangular fins in heat loss by 33.77 % and 41.4 %, respectively. A.A. Jasim et al. [16] carried out a parametric study to analyze the performance of heat sink attached to 40 W PV panel, nine fins configuration with different height, length, number, thickness, and slope degree were studied. The results show the best design reduced the surface temperature by 36.8 % and enhanced electrical efficiency by 16.75 %, confirming improved heat dissipation and PV performance. A. Djebara et al. [17] have designed and evaluated an indoor experiment of a novel U-shaped mini-channel fin heat sink to increase the contact heat transfer area and to obstruct the velocity of airflow, the results showed a cell temperature reduction of 57.44 % which led to 26.6 % increase in electrical efficiency and an increase of 37.55 % in output power. K. Mankani et al. [18] conducted a simulation study using CFD to find the effects of varying fin height, fin spacing, fin thickness, base thickness, and material of heat sink on the temperature reduction. The results of the optimal design reduced the temperature by 3.5 %, 4 %, and 9 %, respectively. Ahmed Saad Soliman [19] presented a new heat sink with phase change material (PCM), the proposed system include two mono facial PV cells, PCM (Paraffin wax) and two aluminum plates with eight ribs, the results offered a higher power per unit area as compared to a system without cooling with 1.6 % increased electrical efficiency reaching an optimal power of 27.21 W. Kumar B. et al. [20] conducted an experiment to prove the thermal performance regulation using three configuration namely, bare heat sink, three heat sink with heat pipe and heat pipe finned heat sink with PCM, with different level of power input, orientation and temperature. The results prove that the third configuration has the best thermal regulation, with 69.55 % heat transported by the heat pipe during charging. An integration of PCM and fins was studied by F. Wang et al. [21] using simulation to prove the effects of fin height, fin spacing, the effect of environmental temperature, and solar irradiance on the thermal management of PV modules. The optimum design of 6 mm fin spacing and 70 mm fin height showed a reduction of

31.9 °C as compared to a system without cooling. Q. Li et al. [22] developed a passive solid-liquid PCM integrated with bifurcated fractal heatsink fins attached to a PV module to optimize the heat dissipation by changing the inclination angle, fin length, and bifurcation fractal fin angle. The results showed a reduction in temperature of 19.2 K and uniformity in temperature of 2.8 K compared to a system without cooling.

S.-V. Hudisteanu et al. [23] have conducted an experiment in real-world conditions for four different types of perforated fins attached to PV modules. The results showed a significant improvement in efficiency for all types of fins. The PV module with perforated fins model advances the bare PV module by 0.54 % and 0.23 %, respectively. M. Krstic et al. [24] have studied a PV module performance enhancement using different fin geometries attached to the rear of the PV module, the study includes a comparison between computational fluid dynamics (CFD) simulation and experimental results. The results show a temperature decrease of 7.5 °C and an open circuit voltage increase of 0.27 V. In a separate outdoor study, S.N. Razali et al. [25] evaluated a 405 W PV module equipped with multidirectional, multi-level tapered fins against a bare module. The findings showed a 12 °C reduction in surface temperature and a 1.53 % improvement in module efficiency with the finned design. A.S. Soliman and P. Cheng [26] have simulated a PV module with a proposed fin design and PCM, the numerical study included different number of fins, PCM thickness and 3 various PV module tilt angle are applied in this study. The results revealed that PV module with configuration of 6 fins with PCM of (RT-35:10 mm and RT-27:30 mm) is the optimum design as compared to bare PV module and recorded a reduction in the temperature of 27.9 %, 29.54 % and 31.11 % and enhancement in electrical efficiency of 17.22 %, 17.39 % and 17.41 % for PV module tilt angles of 90°, 60° and 30°, respectively. E.Z. Ahmad et al. [27] have conducted an outdoor experiment in a tropical region to compare two PV modules of 120 W, the first one is bare PV module considered as a reference module and the other one is a PV module equipped with novel multi-level truncated fins. At a solar irradiance of 941 W/m^2 and an ambient temperature of 36.17 °C, the findings indicated an 8.45 °C drop in surface temperature accompanied by a 9.56 % increase in electrical output.

Previous studies show that numerous researchers have explored different fin geometries and carried out experiments aimed at lowering PV surface temperatures to improve electrical efficiency. However, there remains a research gap concerning enclosed environments with poor air circulation, where heat buildup significantly raises surface temperatures. This study addresses that gap by assessing a novel cooling approach, i.e., the multi-stage interdigitated crimped truncated fins (MSICTF) mounted on a 40 W PV module to optimise natural convection. The MSICTF consists of two fin rows: the first row features long fins measuring 250 mm in length, 200 mm in height, and inclined at 40°, with 16 fins in total and a 15 mm truncation at the tip; the second row

comprises shorter fins of the same length, height, and inclination, but with 15 fins. Field experiments were conducted outdoors under tropical Malaysian conditions, using a tilt angle of 14°. Three configurations were tested: a bare PV module, a PV module with rectangular fins, and a PV module with the MSICTF design. The investigation focuses on evaluating the thermal performance, electrical gains, cost-effectiveness, and practical applicability of the proposed heat sink, offering a potential solution for regions where PV heat management is challenging.

2. Methodology

As elucidated in the previous section, this study strives to compare the performance of a PV module cooled by a novel heat sink featuring multi-stage interdigitated crimped truncated fin (MSICTF) to an uncooled PV and a conventional heat sink featuring rectangular fins. The study will incorporate four main stages namely a numerical, aiming at showing the new design better manages surface temperature accumulation, a meticulous outdoor experimentation under the weather condition of Malaysia, focusing on surface temperature, electrical efficiency, and power production, an in-depth economic evaluation to verify the cost-effectiveness of the proposed design, and technical feasibility with the aim of showing that the new design has less weight compared to other designs. Fig. 1 presents a schematic illustrating the methodology employed in this research. The study will only do experiments on one day in time interval of 15 min from 9 am to 4 pm. Since the study rigorously collects data from 9 am to 4 pm, which includes solar irradiances from 189 W/m² to 868 W/m², the study did not have to collect additional data on other days. Moreover, studying the effect of wind speed, which is the most essential element, was tackled by another study conducted indoors with full control of wind speed.

2.1. The numerical investigation

As outlined earlier, the primary focus of this work is to assess the performance of three PV module configurations under Malaysian climatic conditions. In addition to the experimental work, a numerical simulation was performed to demonstrate the improved heat dissipation capability of the new design compared to both a bare PV module and one equipped with a conventional rectangular-fin heat sink. Computational Fluid Dynamics (CFD) simulations were carried out in ANSYS, where the model was solved under steady-state, incompressible flow conditions using second-order upwind discretization for all governing equations. The residuals of the energy, continuity, and momentum equations were monitored and set to converge at 10⁻⁶ to ensure the accuracy of the

solution. A grid independence test was also conducted to determine the optimal mesh size, and an element count of 3.5 million was selected as the point where temperature variations became negligible. Fig. 2 presents the mesh of the proposed model and the grid-independent study result.

2.1.1. Governing equations

Incompressible Navier-Stokes equations [16], coupled with the energy equations, are used as the governing equations for simulation with steady state fluid flow (Eqs. (1) to (3)) as follows:

Continuity equation

$$\frac{\partial \rho \bar{u}_i}{\partial x_i} = 0 \quad (1)$$

Momentum equation

$$\rho \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = -\frac{\partial \bar{P}}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\mu_t \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) \right] \quad (2)$$

Energy equation

$$\rho \bar{u}_j \frac{\partial \bar{T}}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\left(\frac{\mu_1}{\sigma_1} + \frac{\mu_t}{\sigma_t} \right) \frac{\partial \bar{T}}{\partial x_j} \right] \quad (3)$$

where u is the velocity, T is the temperature, μ is the dynamic viscosity, P is the pressure, ρ is the density of air.

2.2. The experimental analysis

2.2.1. The physical modules

The study will conduct simultaneous experiments on the following modules at the same time on 30 August 2024 from 9 am to 4 pm.

- Bare PV
- PV cooled by rectangular fin
- PV cooled by multi-stage interdigitated crimped truncated fin (MSICTF)

The first module tested was an uncooled monocrystalline PV module with a length, width, and thickness of 500 mm, 500 mm, and 2 mm, respectively. The adopted module had a power production capacity of 40 W with maximum voltage, maximum current, open circuit voltage, and short circuit current of 16.5 V, 2.42 A, 19.8 V, and 2.59 A, respectively. The second module employed the same module with an attached heat sink at its rear. The heat sink utilized 16 rectangular fins with a length and thickness of (500 mm) and (2 mm), respectively. Fig. 3(A) shows a picture of the PV module cooled by a heat sink featuring rectangular fins.

The final module, which is the novel design of this study, integrated the same PV module as the two previous modules with a novel heat sink featuring a multi-stage interdigitated crimped truncated fin (MSICTF). Fig. 3(B) is a demonstration of the novel heat sink attached to the rear surface of the adopted module. As depicted in the figure, the novel design incorporates two rows of fins, namely long and short fins. The long fins are 16 and have a length, height, slope degree, and truncation of 250 mm, 200 mm, 40°, and 15 mm, respectively, as shown in Fig. 3 (C). In contrast, the short-fin set, illustrated in Fig. 3(D), comprises 15 fins of the same length and slope angle, but with a reduced height of 150 mm and an identical 15 mm truncation. The weight of long fins and short fins is shown in Fig. 4. The presented novel design is expected to provide better airflow circulation compared to the conventional heat sink featuring rectangular fins, resulting in more reduction in surface temperature. Additionally, it should be pointed out that the geometrical parameters of the novel design have been optimized using Computational Fluid Dynamics (CFD) in ANSYS. However, its details are considered to be beyond the scope of the current study.

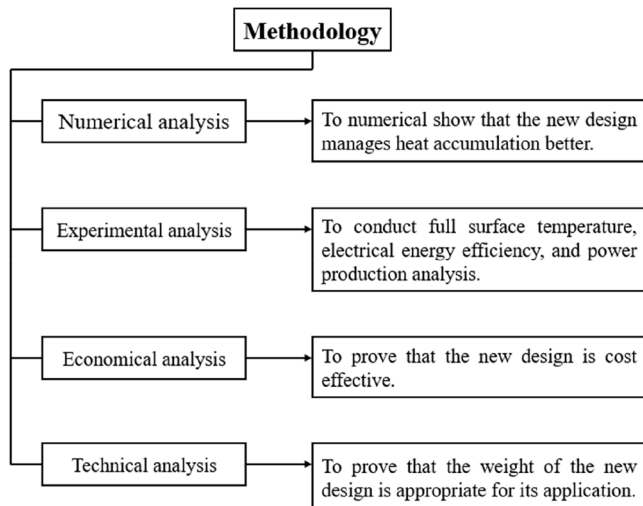


Fig. 1. An illustration of the methodology employed in study.

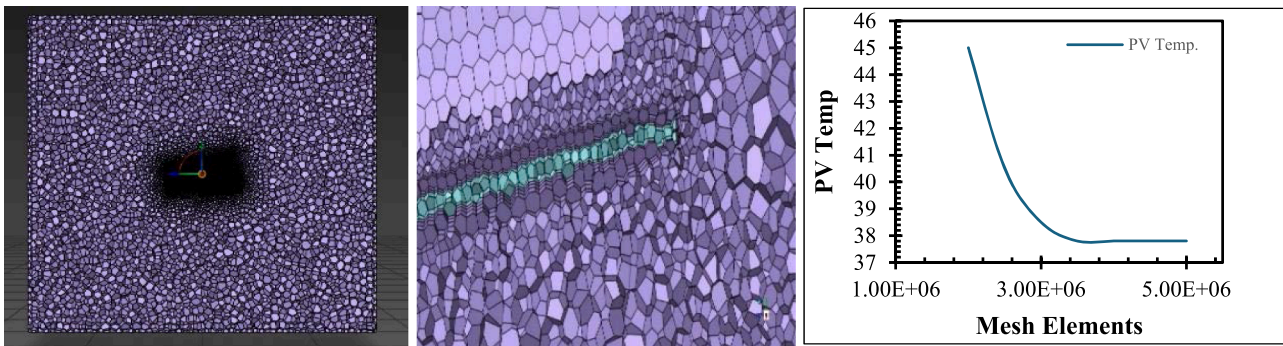


Fig. 2. The meshing demonstration and grid-independent test result.

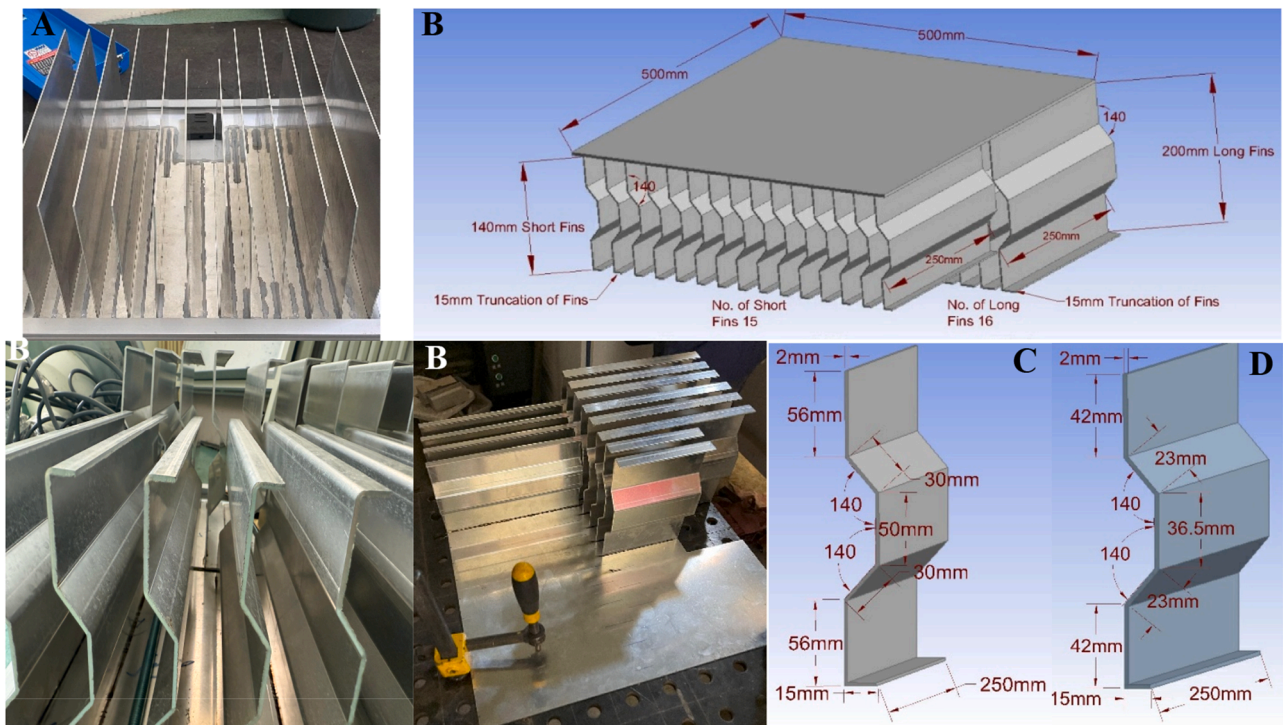


Fig. 3. A 3D and physical demonstration of the tested heat sinks in a way that (A) is a picture of the rectangular fins, (B) is a 3D and physical picture of the novel design, (C) is the geometrical details of the long fins, and (D) is the geometrical details of the short fins.

2.2.2. The experimental rig

As the previous sections elucidated, the study conducted experiments on three modules simultaneously. The experiment was conducted on 30 August 2024 at the rooftop of the Research Complex at the National University of Malaysia. The average solar irradiance, wind speed, and humidity were recorded at 464 W/m^2 , 1.2 m/s , and 60% , respectively. Fig. 5 is a demonstration of the experimental setup used in this study. A Davis Vantage Pro2 weather station was utilised to accurately measure environmental parameters, including solar irradiance, wind speed, and humidity. This device is capable of capturing data at one-second intervals with high precision. In parallel, an MP-11 I-V analyser was used to log the electrical performance of all three modules at the same time. It is also capable of capturing the electrical output of multiple modules at second-level intervals. Finally, the experiment also monitored the surface temperature of the three modules, using K-type thermocouples and DT80 data logger. It should be mentioned that all the equipment used were connected to a computer, and they were recorded simultaneously to avoid any systematic errors that may be introduced due to inconsistencies in the usage of the devices. The authors made sure that the experiment did not encounter any random or systematic errors that

should be mentioned, except for the errors coming from the percentages of error each device is subjected to, which will be discussed in the coming section. Fig. 5 shows the experimental setup illustration.

2.2.3. The data reduction models used in the experimental phase

Conducting experiments on three PV modules and collecting data about surface temperature, environmental-related data, and electrical outputs enabled authors to perform detailed energy analysis, which reveals the electrical efficiency of the modules, economic feasibility, which proved the cost effectiveness of the new module, and environmental analysis, which showed that the new design plays a significant role in reducing CO_2 emission.

2.2.3.1. The energy analysis. First, the study conducted an energy analysis to reveal the electrical performance of the three modules. In Eqs. (4) to 9 [28], A_{pv} represents the photovoltaic (PV) surface area, τ_{gl} denotes the transmissivity of the top cover, α_{cell} is the absorptivity of the PV cell, I and V stand for current and voltage, respectively, FF denotes the fill factor, I_{sc} represents the short-circuit current, V_{oc} refers to the open-circuit voltage, and η_{el} is the electrical efficiency.



Fig. 4. The weight of the long and the short fins.



Fig. 5. A demonstration of the experimental rig in a way that 1) is Davis Vantage Pro2 weather station, 2) is the three modules, 3) is data collection house, 4) is the new heat sink, 5) is the heat sink with rectangular fin, 6) is PV alone, 7) is MP-11 I-V analyser, 8) is a computer, 9) is DT80 data logger, and 10) is K-type thermocouples.

$$\sum \dot{E}_{in} = \sum \dot{E}_{out} + \sum \dot{E}_{loss} \quad (4)$$

$$\dot{E}_{sun} + \dot{E}_{mass\ in} = \dot{E}_{el} + \dot{E}_{mass\ out} + \dot{E}_{loss} \quad (5)$$

$$\dot{E}_{sun} = I * A_{pv} * \tau_{gl} * \alpha_{cell} \quad (6)$$

$$\dot{E}_{el} = I_{sc} * V_{oc} * FF \quad (7)$$

$$FF = \frac{I_{max} V_{max}}{I_{sc} * V_{oc}} \quad (8)$$

$$\eta_{el} = \frac{\dot{E}_{el}}{\dot{E}_{sun}} = \frac{I_{sc} * V_{oc} * FF}{I * A_{pv} * \tau_{gl} * \alpha_{cell}} \quad (9)$$

2.2.4. The uncertainty analysis

It is worth noting that the only source of uncertainty in this experiment originated from the measuring devices used. For instance, the Davis Vantage Pro2 weather station is subject to an error allowance of ± 0.1 , the MP-11 I-V analyser ± 1.0 , the DT80 data logger ± 0.01 , and the K-type thermocouple ± 0.1 . Using Eq. (10) [29], the overall experimental error was determined to be 1.01 %.

$$W_R = \left[\left(\frac{\partial R}{\partial X_1} W_1 \right)^2 + \left(\frac{\partial R}{\partial X_2} W_2 \right)^2 + \dots + \left(\frac{\partial R}{\partial X_n} W_n \right)^2 \right]^{0.5} \quad (10)$$

$$W_R = [(0.1)^2 + (1)^2 + (0.01)^2 + (0.1)^2]^{0.5},$$

$$W_R = 1.01\%$$

2.3. The economic analysis

The study first sought to calculate the total life-cycle energy output of the three modules using Eq. (11) [28,30], where G_t is average irradiance and dg_e denotes the electrical degradation rate of the PV module.

$$E_{ele} = (365 \times G_t \times \eta_{ele} \times A_{pv})(1 - dg_e)^{t-1} \quad (11)$$

Once the total output energy of the three modules was calculated, the study used literature to obtain information about the total input energy of the three tested modules. Having calculated the output and input energy of the three modules, Eqs. (9) to 16 were employed to calculate the annual cost (AC), cost of energy (C_e), and energy payback period (EPBP) of all three modules [31]. In Eqs. (12) to 19, where P is the initial value of the modules, I is the interest rate, N is the lifespan, FAC is the first annual cost, AMC is the annual maintenance cost, ASV is the annual salvage value, CRF is the capital recovery factor, and SFF is the sink fund factor. Table 1 presents the assumptions made to calculate the annual cost of the tested model.

$$AC = FAC + AMC - ASV \quad (12)$$

$$FAC = CRF \times P \quad (13)$$

Table 1

Assumptions used to calculate the annual cost of the three tested models.

Parameter	PV	PV+Rect.	PV+MSICTF
P initial cost \$	20	22	23
Interest rate I	0.08	0.08	0.08
N Year	25	25	25
S salvage value \$	2	3	4
CRF capital recovery factor	0.094	0.094	0.094
FAC	1.874	2.061	2.155
AMC	0.281	0.309	0.323
SFF	0.014	0.014	0.014
ASV	0.027	0.041	0.055

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (14)$$

$$AMC = 0.15 \times FAC \quad (15)$$

$$ASV = S \times SFF \quad (16)$$

$$SFF = \frac{i}{(1+i)^n - 1} \quad (17)$$

$$C_e = \frac{AC}{AEP} \quad (18)$$

$$EPBP = \frac{CED}{AEP} \quad (19)$$

2.4. The technical feasibility analysis

Literature has pointed out that one of the main problems of the applications of heatsinks in PV systems is that the heat sinks tend to drop off over time due to the weight. However, this study has made an attempt to show that the new design has less weight compared to other designs published in the literature.

3. Results and discussion

3.1. The numerical results

As noted in the methodology section, this work does not aim to provide an in-depth numerical representation of the three tested PV systems, as such an analysis lies beyond the scope of the present study. However, it should be mentioned that the geometrical parameters of the new design are chosen using optimization techniques and CFD analysis, as proved by reference number [16].

However, this study conducted a numerical analysis to reveal the capacity of a conventional heat sink featuring a rectangular fin and the novel fin design of this study. Fig. 6 presents the temperature counter of the two designs. It is clearly demonstrated in the figure that the new design is significantly cooler compared to the conventional heat sink. This is primarily due to the improved airflow management of the new design, allowing air to pass smoothly over its features and enabling the module to cool more quickly.

3.2. The experimental phase

3.2.1. Environmental operation analysis

The experiment was conducted on 30 August 2024 at the level 7 rooftop of the Research Complex at the National University of Malaysia. The minute-by-minute data collected by the weather station is presented as an average of 15 min, as shown in Fig. 7. Ambient temperature started from 28 °C at 9 am and peaked at 3:30 pm with a value of 32 °C. Nevertheless, solar irradiance recorded a fluctuating trend (a typical trend for Malaysian weather [32]). Generally, it began at 287 W/m² and reached its maximum of 868 W/m² at 1:30 pm.

3.2.2. Surface temperature analysis of the examined models

As is shown in Fig. 8(A), the study recorded the surface temperature of the three modules throughout the day. However, the figure only shows data for selective times of the day, as this will help readers follow the patterns more easily. Generally, the PV, the PV cooled by a conventional rectangular fin, and PV cooled by the novel heat sink recorded average daily surface temperatures of 44.48 °C, 43.12 °C, and 40.19 °C. The recorded values show that the new design records an enhancement of 9.6 % and 6.8 % in daily average surface temperature. The observed improvement is attributed to the new design's ability to channel wind flow more efficiently, resulting in greater surface temperature

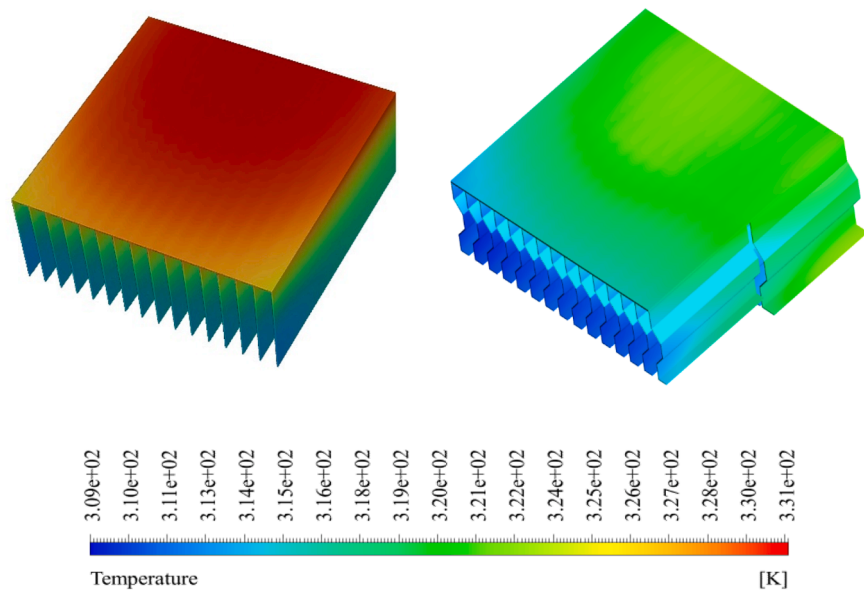


Fig. 6. The numerical results of the two tested PV systems.

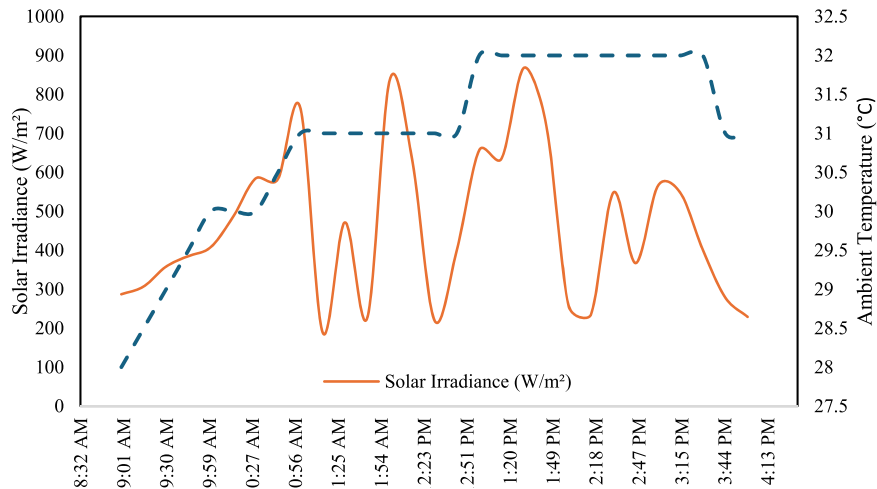


Fig. 7. The recorded solar irradiance and ambient temperature.

reduction. The results obtained are rational since studies conducted by the references [33–35] have recorded similar percentages of enhancement.

To get more details on the performance of each module individually, the study revealed that the three modules, namely PV, PV cooled by rectangular fin, and PV cooled by the novel design, recorded the lowest surface temperature of 35.1 °C, 32.9 °C, and 32.8 °C, respectively, at around 9 am. As can be seen, the differences are not significant since the surface temperature for all the modules is low. However, as the surface temperature of all the modules goes up, the differences in better temperature reduction from one module to another module also become prominent. For instance, at 1:50 pm, the PV, PV cooled by rectangular fin, and PV cooled by the novel design recorded surface temperatures of 54.6 °C, 53.5 °C, and 48.7 °C. Since the surface temperature is higher, the differences in temperature reduction also become more significant, demonstrating that the new design has better performance at higher surface temperatures. This result is expected since it agrees with the fundamental principles, and it is also confirmed in studies such as those in reference numbers [14,17]. Finally, around 4:00 pm, the PV, PV cooled by rectangular fin, and PV cooled by the novel design recorded surface temperature values of 39.8 °C, 37.4 °C, and 36.4 °C, respectively,

reconfirming all the above-drawn conclusions.

Finally, the study also assesses a thermal camera to take thermal pictures of the two modules, namely PV cooled with a rectangular fin, and PV cooled with the novel design. As presented in Fig. 8(B), the colour of the surface of the module cooled by the rectangular fin is red with a yellow and green circumference. Nevertheless, the colour for the module cooled by the new design is a mixture of blue and purple, proving that the new design on average, has a lower surface temperature. However, it should be said that the temperature distribution of the module cooled with a rectangular fin is better. This is due to the rectangular fin having a more equal distribution with poor flow management, whereas the new design has better flow management, which still requires more design optimizations to tackle the problem of surface temperature distribution management. However, the conclusion can be drawn that the new design overall reduces surface temperature more effectively compared to the other two designs examined in this study, which will lead to higher electrical efficiency and more power production, as it will be demonstrated in the coming sections of this study.

3.2.3. Electrical efficiency and power production analysis

As demonstrated above, the new design recorded superior

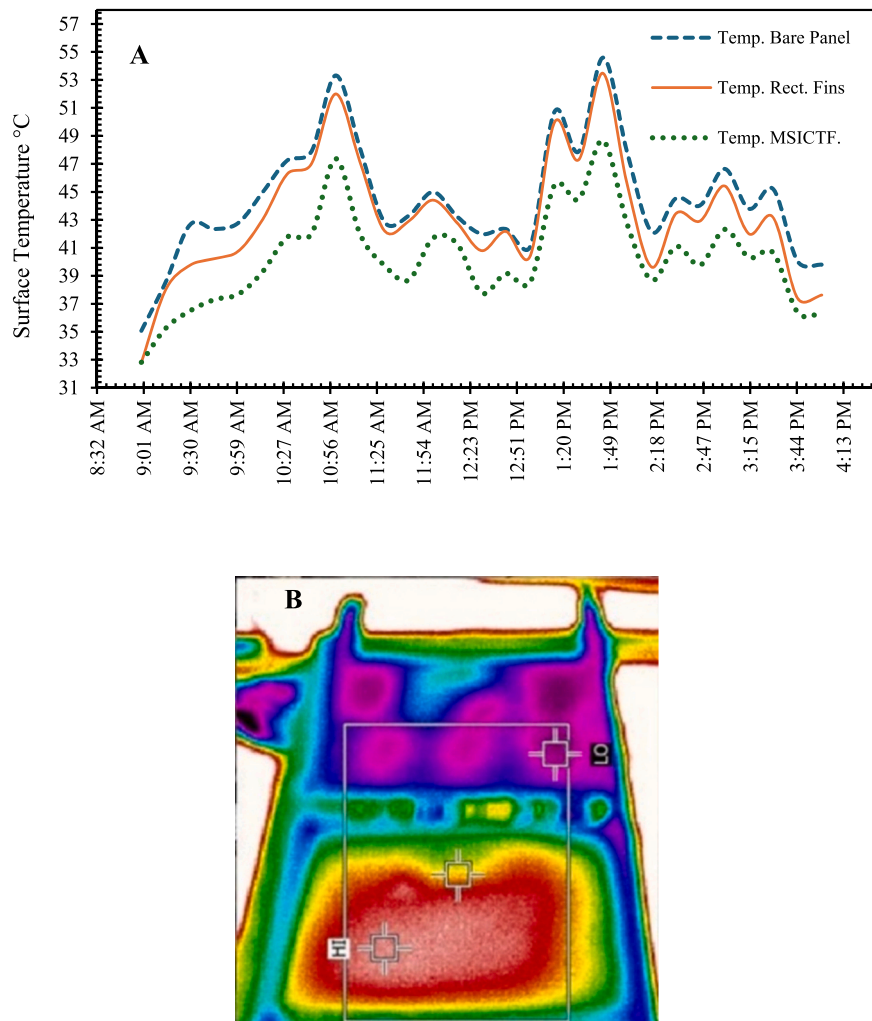


Fig. 8. (A) The surface temperatures of the three modules. (B) The thermal picture of the two modules equipped with heatsinks.

performance in reducing surface temperature compared to the conventional design and the bare PV. Therefore, it is anticipated that the novel design will have better electrical power production and electrical efficiency. Fig. 9 (A and B) captures detailed data about the electrical efficiency and power production of the three adopted modules. The results show that the new design achieved improvements of 7.2 % and 14 % in daily average electrical efficiency over the conventional design and bare PV, respectively, which correspond to increases of 7.3 % and 14.1 % in daily average power output. As discussed earlier, these gains are primarily due to the design's superior airflow management, which results in greater surface temperature reduction. It should be mentioned that the results obtained regarding daily average electrical efficiency and power production can be validated by comparison with studies conducted by reference [36], which have obtained similar results to the results presented in this study.

A deeper analysis shows that there is a reverse proportional relationship between solar irradiance and electrical efficiency, as is the case with studies conducted by reference number [37]. For instance, from 1 to 2 pm, solar irradiances escalate to the highest value of 868 W/m², which produces an average electrical efficiency of 11.6 %, whereas the value increases to 16.87 % when solar irradiances decline to 279 W/m² between 3 and 4 pm. This is a good indication that the new design performs better at lower solar irradiances. This is mainly because the new design is less effective at handling high solar irradiance levels, leading to heat accumulation. It should be mentioned that electrical efficiency dropped significantly around 10:20 am to 11:50 am,

recording the lowest value of 3.8 % to 4 % for all three modules. This is largely due to the cloudy weather during the study period, which significantly reduced the modules' performance. Even though solar irradiances and electrical efficiency are inversely proportional, the dramatic drop in electrical efficiency between 10:20 am to 11:50 am is due to the fact that solar irradiances during the cloudy period drop to a level as low as it does not maintain the reverse relationship, but rather the relationship becomes directly proportional, meaning electrical efficiency also decreases due to low power production.

Power production also shows a fluctuating trend throughout the day. It records values between 8.8 to 9 W around 9 am, then goes up to values like 25 to 26 W around 10:30 to 11:30 am before it lowers to values such as 4.4 to 5 W around 11:20 am to 11:50 am. The second half of the day showed the same fluctuating trend, starting from 6.5 to 7 W around 12:20 pm to 12:50 pm and increases to values such as 29 to 30 W around 1:20 to 1:40 before it goes back to as low values as 7.5 to 8.5 W around 2:15 to 2:30 pm. It should be mentioned that power production is proportional to solar irradiance, considering the effects of heat accumulation. The obtained results of electrical efficiency and power production attained in this study are validated by comparison with values obtained in other studies of literature, such as those provided in the reference [38].

3.3. Economic analysis

Even though the main emphasis of this study was devoted to

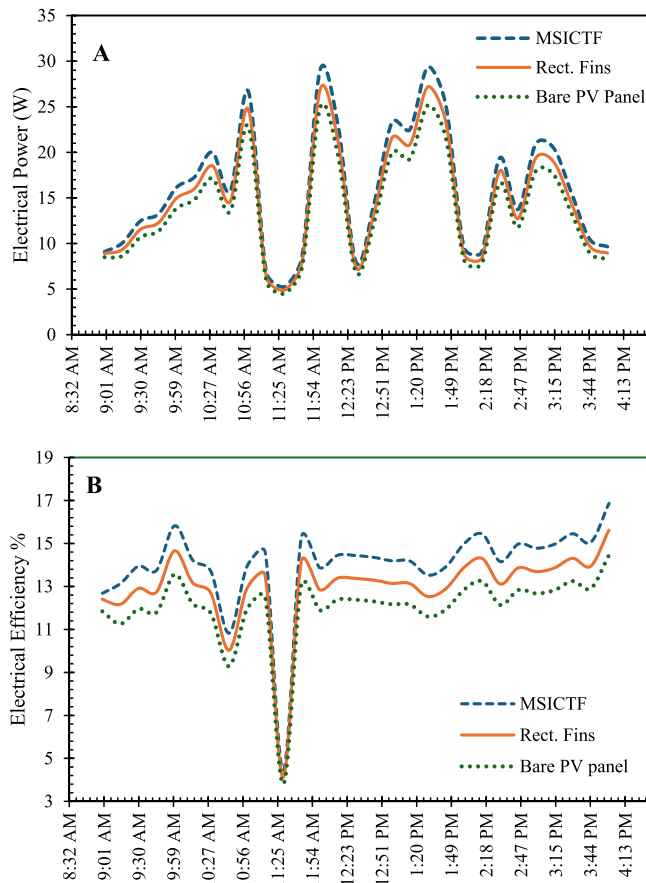


Fig. 9. (A) The electrical power (W) of the three modules. (B) The electrical efficiency (%) of the three modules.

increasing the efficiency of the tested modules in converting irradiances to electricity, it is always very important to make sure that the attained enhancement is not costly. Therefore, the study will comprehensively analyze the economic feasibility of the new design compared to stand-alone PV and conventional heat sink featuring a rectangular fin. The study will first calculate the annual energy output of the tested modules using Eq. (8). Then, the Cumulative Energy Demand (CED) for the modules will be taken from the literature. Once those two values are calculated, Cost of Energy (Ce) and Energy Payback Period (EPBP), which are the two most common economic indicators, will be calculated.

The results show that there are enhancements of 11.4 % in annual energy production when comparing the rectangular heat sink to bare PV. Replacing the rectangular heat sink with the novel design boosts the improvement to 18.3 %. The enhancements mentioned are good indicators that the novel design will be economical. However, there is also a need to conduct other calculations. For instance, the cost of energy, which is a common way to test whether a system is economically feasible, demonstrates that there is an increase of 3.1 % when shifting from bare PV to PV with the conventional heat sink. The enhancement further increases to 7.1 % when the novel heat sink is employed. This is a good indication that the new design is economical, even though the novel heat sink costs 8.6 % and 11.9 % more compared to the conventional heat sink and the bare PV, respectively. Finally, the study also conducted an Energy Payback Period analysis to determine which of the tested modules will recoup its initial investment cost factor. The results show that the novel heat sink pays back its initial investment cost faster than the bare PV and the PV cooled by the conventional heat sink by 7.6 % and 2.5 %, respectively.

It is important to highlight that all economic indicators used in this

study support the viability of transitioning from a bare PV system to one cooled with either a conventional rectangular-fin heat sink or the novel heat sink proposed here. Therefore, it can be claimed that the new design of this study can be considered in industrial applications as it achieves higher efficiency while remaining economically attractive. All the results reported regarding the economic feasibility of novel design are valid since they are close in value to results reported in other studies of the literature, such as those reported in the reference number [39]. Fig. 10(A, B, and C) numerically shows all the calculations elucidated in this section.

3.4. Technical feasibility

One of the most common problems of heat sink designs in PV systems is that the weight of the fins is as much as they tend to drop from the back of the PV over time. This issue poses a considerable challenge, as observed in the designs reported in reference [40]. However, the present study ensures that the new design not only provides effective airflow management but also incorporates a heat sink optimized for minimal weight, thereby enabling its sustained placement at the rear surface of the PV module over extended periods. As depicted in Fig. 4, the weight of a single long fin is only 0.31 kg, while the weight of a single short fin is only 0.24 kg, making the total weight of the heat sink 8.56 kg, which is a lot lower than previous studies, such as those shown in reference number [35]. Notably, the present design delivers dual accomplishment, i.e., it lowers the overall system weight while improving the fins' thermal performance. This optimization not only contributes to improved heat dissipation efficiency but also facilitates easier integration and structural stability of the cooling system, particularly in applications intended for a long period of time. In the final stage, Table 2 demonstrates a comparison of the previous fins design findings with the findings of this study.

4. Conclusions

As was meticulously demonstrated in the above sections, the novel design of this study, which is a heat sink featuring MSICTF, outperforms a conventional heat sink cooling a photovoltaic and a bare photovoltaic. Additionally, this study shows that the new design is also more cost-effective and technically feasible. The main conclusions that can be drawn from this study can be summarized as follows.

Additionally, it records enhancements in cost of energy and energy payback period by 7.2 %, 4.2 % and 7.6 %, 2.5 %. Finally, it has less weight compared to other available designs in the current literature.

- The new heat sink records enhancements of 6.8 % and 9.6 % in surface temperature reduction compared to conventional heat sink and bare PV, resulting in electrical efficiency enhancements of 7.2 % and 14 %, respectively.
- The new design proves to be more cost-effective compared to the conventional heat sink and bare PV by recording enhancements of 4.2 % and 7.2 % in cost of energy and 2.5 %, 7.6 % in energy payback period.
- The new design is considered technically feasible since it has a total weight of 9.1 kg, which is lower than other designs of literature.
- The numerical study also demonstrates that the newly designed heat sink has a lower surface temperature compared to the heat sink featuring a rectangular fin.

Even though this study has tackled the new design from many aspects, there are still some areas that remain untouched and limitations. Therefore, it is suggested that future studies should give more emphasis to the following points.

- Environmental feasibility analysis of the design should be conducted to guarantee that the new design meets the sustainability principles.

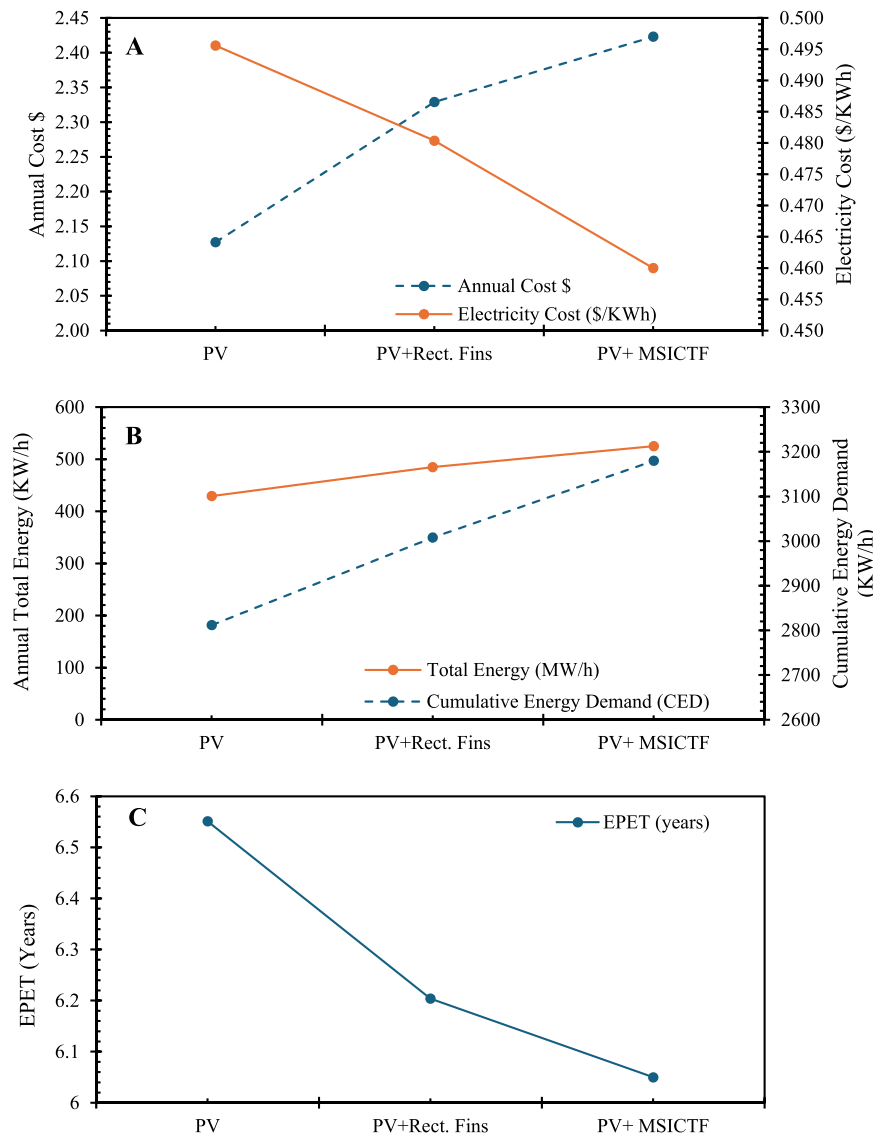


Fig. 10. (A) Annual cost and the electricity cost of the modules, (B) Annual total energy and cumulative energy demand, and (C) the energy payback period for all the modules.

Table 2
Lately developed PV modules using fins findings.

[Ref.] Year	Type of study	Major findings
[41] 2024	Simulation & Experiment	An electrical power enhancement of 4 % and a temperature reduction of 8 °C.
[25] 2023	Experiment	An electrical efficiency enhancement of 1.53 % and temperature reduction of 12 °C.
[42] 2021	Simulation & Experiment	An electrical efficiency enhancement of 2.96 % and a temperature reduction of 5 °C.
[43] 2024	Experiment	Temperature reduction of 9.8 °C.
[24] 2024	Simulation & Experiment	The PV temperature dropped by 7.5 °C.
[44] 2021	Experiment	An electrical efficiency enhancement of 8.5 %.
[33] 2024	Experiment	An electrical energy enhancement of 8.61 %.
Present study	Simulation & experiment	Compared to a bare PV module, the system lowered PV temperature by 25.22 °C and increased electrical efficiency by 1.65 %.

- Attempts should be made to incorporate an energy storage component into the new design through the integration of a nanophase-changing material.

- More advanced passive cooling techniques, such as dimples, ribs, and grooves, can be added to the surface of the fins employed in the new design so that more turbulence and equal distribution are added to the airflow.
- A detailed examination of mass flow rates, solar irradiances, and pressure drops should be conducted numerically, while its validation should be done in an indoor experiment.

CRediT authorship contribution statement

Ali Abdulrazzak Jasim: Writing – original draft, Visualization, Validation, Methodology, Data curation, Conceptualization. **Ahmad Fazlizan:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Hariam Luqman Azeez:** Visualization, Validation, Methodology, Conceptualization. **Rasha Almaawi:** Visualization, Validation, Methodology, Data curation. **Banw Omer Ahmed:** Visualization, Validation, Methodology, Data curation. **Mahmoud Jaber:** Visualization, Validation, Methodology, Data curation. **Sharul Sham Dol:** Writing – review & editing, Visualization, Validation, Methodology. **Adnan Ibrahim:** Writing – review & editing, Validation, Supervision, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to express appreciation to Universiti Kebangsaan Malaysia (UKM) and Abu Dhabi University for funding this research.

Data availability

Data will be made available on request.

References

- [1] H.L. Azeez, A. Ibrahim, B.O. Ahmed, J. Kasprzak, A.H.A. Al-Waeli, M. Jaber, 5E assessments of a novel solar collector under high cooling demand scenarios: experimental and sustainability studies, *Energy* 326 (2025) 136297, <https://doi.org/10.1016/j.energy.2025.136297>.
- [2] H.A. Kazem, A.A. Al-Waeli, M.T. Chaichan, K. Sopian, A.-A. Ahmed, W.I. Wan Nor Roslam, Enhancement of photovoltaic module performance using passive cooling (Fins): a comprehensive review, *Case Stud. Therm. Eng.* 49 (2023) 103316, <https://doi.org/10.1016/j.csite.2023.103316>.
- [3] R.A. Jasim, et al., Experimental evaluation of a newly designed photovoltaic thermal collector featuring a ring inserter as a flow enhancement mechanism, *Case Stud. Therm. Eng.* 75 (2025) 107193, <https://doi.org/10.1016/j.csite.2025.107193>.
- [4] H. Luqman Azeez, A. Ibrahim, B. Omer Ahmed, A.H.A. Al-Waeli, M. Jaber, M. Aqil Afham Rahmat, Energy and exergy analysis of a novel collector design in a photovoltaic thermal system: an experimental study, *Appl. Therm. Eng.* 256 (2024) 124125, <https://doi.org/10.1016/j.applthermaleng.2024.124125> no. May.
- [5] I.O. Harmailil, S.M. Sultan, C.P. Tso, A. Fudholi, M. Mohammad, A. Ibrahim, A review on recent photovoltaic module cooling techniques: types and assessment methods, *Results Eng* 22 (2024) 102225, <https://doi.org/10.1016/j.rineng.2024.102225>.
- [6] R. Gupta, K. Sahay, Efficiency enhancement using thermal management of PV cells in solar panels, in: 2024 IEEE Third International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES), IEEE, 2024, pp. 1151–1154, <https://doi.org/10.1109/ICPEICES62430.2024.10719124>.
- [7] A. Sohail, M.S. Rusdi, M. Waseem, M.Z. Abdullah, F. Pallonetto, S.M. Sultan, Cutting-edge developments in active and passive photovoltaic cooling for reduced temperature operation, *Results Eng* 23 (2024) 102662, <https://doi.org/10.1016/j.rineng.2024.102662>.
- [8] M.A. Akrouch, K. Chahine, J. Faraj, F. Hachem, C. Castelain, M. Khaled, Advancements in cooling techniques for enhanced efficiency of solar photovoltaic panels: a detailed comprehensive review and innovative classification, *Energy Built. Environ.* 6 (2) (2025) 248–276, <https://doi.org/10.1016/j.enbenv.2023.11.002>.
- [9] Y. Liu, Z. Liu, Z. Wang, W. Sun, F. Kong, Photovoltaic passive cooling via water vapor sorption-evaporation by hydrogel, *Appl. Therm. Eng.* 240 (2024) 122185, <https://doi.org/10.1016/j.applthermaleng.2023.122185>.
- [10] D. Van Binh, et al., Passive cooling for photovoltaic using heat sinks: a recent research review, in: 2023 Asia Meeting on Environment and Electrical Engineering (EEE-AM), IEEE, 2023, pp. 01–06, <https://doi.org/10.1109/EEE-AM58328.2023.10395427>.
- [11] E. Mariam, et al., Emerging trends in cooling technologies for photovoltaic systems, *Renew. Sustain. Energy Rev.* 192 (2024) 114203, <https://doi.org/10.1016/j.rser.2023.114203>.
- [12] A.M. Elbreki, M.A. Alghoul, K. Sopian, T. Hussein, Towards adopting passive heat dissipation approaches for temperature regulation of PV module as a sustainable solution, *Renew. Sustain. Energy Rev.* 69 (2017) 961–1017, <https://doi.org/10.1016/j.rser.2016.09.054>.
- [13] B. Kumar, Y. Naresh, J. Banerjee, A PCM based finned heat sink coupled with a finned heat pipe is an efficient thermal management option for portable electronic gadgets, *Energy Convers. Manag.* 352 (2026) 121118, <https://doi.org/10.1016/j.enconman.2026.121118>.
- [14] A.M. Elbreki, A.F. Muftah, K. Sopian, H. Jarimi, A. Fazlizan, A. Ibrahim, Experimental and economic analysis of passive cooling PV module using fins and planar reflector, *Case Stud. Therm. Eng.* 23 (2021) 100801, <https://doi.org/10.1016/j.csite.2020.100801>.
- [15] M.A. Bashir, H.M. Ali, Numerical investigation of passive cooling of the PV module using extended fin heat sinks: a parametric analysis, *Process Saf. Environ. Prot.* 195 (2025) 106749, <https://doi.org/10.1016/j.psep.2025.01.003>.
- [16] A.A. Jasim, A. Fazlizan, H.L. Azeez, A. Ibrahim, R. Almaawi, K. Sopian, Enhancing PV module performance through a novel fin heat sink design: a numerical and experimental study, *Case Stud. Therm. Eng.* 74 (2025) 106842, <https://doi.org/10.1016/j.csite.2025.106842>.
- [17] A. Djebara, et al., Performance evaluation of a folded mini-channel heat sink for solar cell cooling: experimental study, *Sol. Energy* 289 (2025) 113326, <https://doi.org/10.1016/j.solener.2025.113326>.
- [18] K. Mankani, H. Nasarullah Chaudhry, J. Kaiser Calautit, Optimization of an air-cooled heat sink for cooling of a solar photovoltaic panel: a computational study, *Energy Build* 270 (2022) 112274, <https://doi.org/10.1016/j.enbuild.2022.112274>.
- [19] A.S. Soliman, 4E analysis of a new design heat sink for cooling a bifacial photovoltaic system using PCM and ribs, *J. Energy Storage* 73 (2023) 108907, <https://doi.org/10.1016/j.est.2023.108907>.
- [20] B. Kumar, Y. Naresh, J. Banerjee, S. Saini, Thermal performance of PCM-based heat sink integrated with heat pipe: influence of ambient temperature and orientation, *Int. J. Therm. Sci.* 223 (2026) 110575, <https://doi.org/10.1016/j.ijthermalsci.2025.110575>.
- [21] F. Wang, et al., Heat-dissipation performance of photovoltaic panels with a phase-change-material fin structure, *J. Clean. Prod.* 423 (2023) 138756, <https://doi.org/10.1016/j.jclepro.2023.138756>.
- [22] Q. Li, J. Jiang, Y. Hong, J. Du, Numerical investigation of thermal management performances in a solar photovoltaic system by using the phase change material coupled with bifurcated fractal fins, *J. Energy Storage* 56 (2022) 106156, <https://doi.org/10.1016/j.jest.2022.106156>.
- [23] S.-V. Hudisteanu, N.-C. Chereches, F.-E. Turcanu, I. Hudisteanu, M. Verdes, A.-D. Ancaş, Experimental analysis of innovative perforated heat sinks for enhanced photovoltaic efficiency, *Energy Convers. Manag.* X 25 (2025) 100842, <https://doi.org/10.1016/j.ecmx.2024.100842>.
- [24] M. Krstic, et al., Passive cooling of photovoltaic panel by aluminum heat sinks and numerical simulation, *Ain Shams Eng. J.* 15 (1) (2024) 102330, <https://doi.org/10.1016/j.asej.2023.102330>.
- [25] S.N. Razali, et al., Performance enhancement of photovoltaic modules with passive cooling multidirectional tapered fin heat sinks (MTFHS), *Case Stud. Therm. Eng.* 50 (2023) 103400, <https://doi.org/10.1016/j.csite.2023.103400> no. February.
- [26] A.S. Soliman, P. Cheng, A new heat sink for cooling photovoltaic systems using fins filled with multiple PCMs, *J. Energy Storage* 131 (2025) 115875, <https://doi.org/10.1016/j.est.2025.115875>.
- [27] E.Z. Ahmad, K. Sopian, A. Fazlizan, H. Jarimi, A. Ibrahim, Outdoor performance evaluation of a novel photovoltaic heat sinks to enhance power conversion efficiency and temperature uniformity, *Case Stud. Therm. Eng.* 31 (2022) 101811, <https://doi.org/10.1016/j.csite.2022.101811> no. January.
- [28] H.L. Azeez, A. Ibrahim, J. Kasprzak, B.O. Ahmed, A.H.A. Al-Waeli, M. Jaber, Economic and environmental feasibility analysis of a photovoltaic thermal system with passive cooling techniques, nanofluid, and phase changing materials, *Appl. Therm. Eng.* 274 (2025) 126782, <https://doi.org/10.1016/j.applthermaleng.2025.126782>.
- [29] B.O. Ahmed, A. Ibrahim, H.L. Azeez, S.S. Dol, A.H.A. Al-Waeli, M. Jaber, Energy and exergy analysis of a newly designed photovoltaic thermal system featuring ribs, petal array, and coiled twisted tapes: experimental analysis, *Case Stud. Therm. Eng.* 63 (2024) 105388, <https://doi.org/10.1016/j.csite.2024.105388>.
- [30] A.K. Abdulrazzaq, G. Bognár, B. Plesz, Combined electro-thermal model for PV panels, *Pollack Period* 16 (1) (2021) 7–13, <https://doi.org/10.1556/606.2020.00145>.
- [31] S. Praveenkumar, E.B. Agyekum, A. Kumar, V.I. Velkin, Thermo-enviro-economic analysis of solar photovoltaic/thermal system incorporated with u-shaped grid copper pipe, thermal electric generators and nanofluids: an experimental investigation, *J. Energy Storage* 60 (2023) 106611, <https://doi.org/10.1016/j.est.2023.106611>.
- [32] E.Z. Ahmad, A. Fazlizan, H. Jarimi, K. Sopian, A. Ibrahim, Enhanced heat dissipation of finned multi-level fin heat sink (MLFHS) in case of natural convection for photovoltaic cooling, *Case Stud. Therm. Eng.* 28 (2021) 101578, <https://doi.org/10.1016/j.csite.2021.101578> no. October.
- [33] A. Khelifa, M. El Hadi Attia, K. Harby, A. Elnaby Kabeel, M.M. Abdel-Aziz, M. Abdelgaied, Experimental and economic evaluation on the performance improvement of a solar photovoltaic thermal system with skeleton-shaped fins, *Appl. Therm. Eng.* 248 (2024) 123180, <https://doi.org/10.1016/j.applthermaleng.2024.123180> PA.
- [34] Y. Wang, et al., A review: the development of crucial solar systems and corresponding cooling technologies, *Renew. Sustain. Energy Rev.* 185 (2023) 113590, <https://doi.org/10.1016/j.rser.2023.113590>.
- [35] A.M. Elbreki, K. Sopian, A. Fazlizan, A. Ibrahim, An innovative technique of passive cooling PV module using lapping fins and planar reflector, *Case Stud. Therm. Eng.* 19 (2020) 100607, <https://doi.org/10.1016/j.csite.2020.100607> no. February.
- [36] P. Singh, et al., Solar photovoltaic panels with finned phase change material heat sinks, *Energies* 13 (10) (2020) 2558, <https://doi.org/10.3390/en13102558>.
- [37] A.B. Taha, S.F. Babiker, Irradiance variation effect on the electrical performance of a grid connected PV system, in: 2019 International Conference on Computer, Control, Electrical, and Electronics Engineering (ICCEEE), IEEE, 2019, pp. 1–4, <https://doi.org/10.1109/ICCEEE46830.2019.9071427>.
- [38] D.R. Ahmed, et al., The correlation of device parameters with illumination energy to explore the performance of a monocrystalline silicon solar module, *Silicon* 14 (4) (2022) 1439–1445, <https://doi.org/10.1007/s12633-021-00966-z>.
- [39] A. Shohdy, M. Emam, H. Sekiguchi, M. Ahmed, Enhancing the performance of low-concentrator photovoltaic systems using novel configurations of radially microchannel heat sinks, *Sol. Energy* 273 (2024) 112513, <https://doi.org/10.1016/j.solener.2024.112513>.

- [40] S. Khan, A. Waqas, N. Ahmad, M. Mahmood, N. Shahzad, M.B. Sajid, Thermal management of solar PV module by using hollow rectangular aluminum fins, *J. Renew. Sustain. Energy* 12 (6) (2020), <https://doi.org/10.1063/5.0020129>.
- [41] E. Chan-Dzib, A. Bassam, J.G. Carrillo, Novel curled cooler to enhance the efficiency of a photovoltaic panel system, *Appl. Therm. Eng.* 249 (2024) 123317, <https://doi.org/10.1016/j.applthermaleng.2024.123317>.
- [42] J.G. Hernandez-Perez, J.G. Carrillo, A. Bassam, M. Flota-Banuelos, L.D. Patino-Lopez, Thermal performance of a discontinuous finned heatsink profile for PV passive cooling, *Appl. Therm. Eng.* 184 (2021) 116238, <https://doi.org/10.1016/j.applthermaleng.2020.116238>.
- [43] M.H. Hamed, H. Hassan, S. Ookawara, S.A. Nada, Performance comparative study on passively cooled concentrated photovoltaic (PV) using adsorption/desorption and heat sink cooling methods: experimental investigations, *Energy* 307 (2024) 132700, <https://doi.org/10.1016/j.energy.2024.132700> no. January.
- [44] A.A. Farhan, D.J. Hasan, An experimental investigation to augment the efficiency of photovoltaic panels by using longitudinal fins, *Heat Transf.* 50 (2) (2021) 1748–1757, <https://doi.org/10.1002/htj.21951>.