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Experimental Investigation on Use of U-Grooved Fins to Enhance the Performance of Photovoltaic Modules

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ABSTRACT

Solar cell efficiency is significantly impacted by operating temperature. As temperature rises, efficiency declines. Fins accelerate heat transfer in PV cooling systems by triggering a change in airflow pattern within the finned area. The aim of this study is to compare the performance of U-grooved fins-mounted module performance with bare module performance. In this study, the performance of the modules mentioned above was measured from 11:00 am to 04:00 pm to compare the electrical efficiencies of both modules. The novelty of this study is that U-grooved fins can reduce the module temperature by dispersing heat through natural convection and, in turn, boost their efficiency. Outdoor testing of two modules was performed to investigate the effects of varying solar irradiance (600-1000W/m^2) and ambient temperature (28-38°C) on system performance. The temperature of the bare PV module and the U-grooved fins attached to the backplate of the PV module were measured and compared at 600, 800, and 1000W/m^2. Results indicate that U-grooved fins effectively reduced module temperature by up to 7°C compared to the bare module. This temperature reduction led to a notable 1.5% increase in efficiency and a 45-watt power output enhancement. These findings demonstrate that U-grooved fins are a promising technology for improving the performance and energy yield of PV systems.

Keywords: Passive cooling; PV Performance; U-grooved fins; electrical efficiency; temperature reduction

INTRODUCTION

As people notice the hazards of climate change, the transition of energy systems toward environment-friendly energy resources has become attractive, and the use of renewable energies, especially solar, has gained traction (Ahmada et al. 2024; Ismail et al. 2024; Nawab et al. 2022). In recent years thanks to extensive research, the cost of solar energy systems, especially photovoltaic (PV) systems, has been comparable to traditional energy systems (Hasan, 2018; Rahmat et al. 2023). The PV systems require less maintenance and can be installed easily (Ahmad et al. 2022). However, the PV system's performance degrades with increased cell temperature (Ishak et al. 2023). Normally the efficiency of solar cells decreases by 0.4% to 0.5% with a 1°C rise in cell temperature (Altegoer et al. 2022; Liia et al. 2024). Therefore, arrangements for lowering the PV cell temperature are necessary. There are two types of PV cooling strategies: passive and active. As it does not necessitate any extra energy and requires less maintenance to run, the passive cooling solution for PV modules is favoured by many scientists (Hasanuzzaman et al. 2016). The primary objective of passive cooling systems is to regulate and lower the temperature of solar modules without using any extra energy. This method has many edges in overactive cooling, including increased energy output and efficiency, a longer lifespan, and lower maintenance needs. The efficiency of a passive cooling system depends on the strategies utilized, the weather conditions, and the layout of the solar system. Figure 1 classifies the passive cooling technologies; the red boxes mark the ones used in this study.

Recent studies have reported the negative effects of high module temperature (Alktranee et al. 2023; Eldehn et al. 2016; Hindee et al. 2016; Sato et al. 2019). Fatih Bayrak et al. compared the cooling performance of Pulse change materials (PCM), thermoelectric (TE), and aluminium fins for PV modules. The results confirmed the superiority of aluminium fins over the other two methods (Selimefendigil et al. 2018). Ammar A. Farhan et al. (Amr et al. 2019) checked the performance of longitudinal aluminium fins and found that using fins has increased the module's efficiency from 14% to 15.3% (Farhan et al. 2021). Table 1 illustrates a comprehensive review of prior studies on PV cooling systems. Hernandez-Perez et al. used the segmented aluminium fins for PV cooling and found that fins reduced the module temperature by 5°C (Hernandez-Perez et al. 2021). E.Z. Ahmad et al. noticed that multi-level fin heat sinks (MLFHS) mounted PV module has 8.1°C less temperature than the bare module, and the MLFHS has increased the electrical efficiency by 9.56% (Ahmad et al. 2022). Jiaqi Li et al. checked the performance of different height-embedded and non-embedded fins. They found that the 60 mm fins had the best performance, reduced the temperature by 13.6K, and improved the electric efficiency by 4.4% (J. Li et al. 2022). Fahad Al-Amri et al. proposed a new racking structure for PV modules that will support modules and work as a heat sink for modules. The racking structure acts like rectangular fins for PV modules. The result confirmed that the proposed racking structure had reduced the module temperature by 6.3°C and levelized the cost of Energy by 5% (Al-Amri, Saeed, et al. 2022). Gautam Raina et al. conducted experiments for 3 months to evaluate the performance of rectangular fins cooling systems for PV. The experimental results showed a 40% decrease in temperature coefficient and 5.47% increase in efficiency (Raina et al. 2022). The above studies confirm the efficacy of different types of Aluminium fins for passive cooling of PV modules. Currently, there has been a lack of comprehensive research examining the impacts of utilizing different fin designs on the performance of photovoltaic modules. Due to that, in this study we are evaluating a novel U-grooved fins, which has been tested yet. This study employs a novel U-grooved design to optimize heat management in photovoltaic (PV) modules by facilitating enhanced air circulation in the central region. The experimental setup differentiates itself from previous work by utilizing cutting-edge 405 Wp PERC half cut PV modules. This decision enables us to establish a connection between investigations conducted in laboratory settings and their practical implementations in real-world scenarios, thereby addressing the current discrepancy. Some of the recent works have been summarized in Table 1.

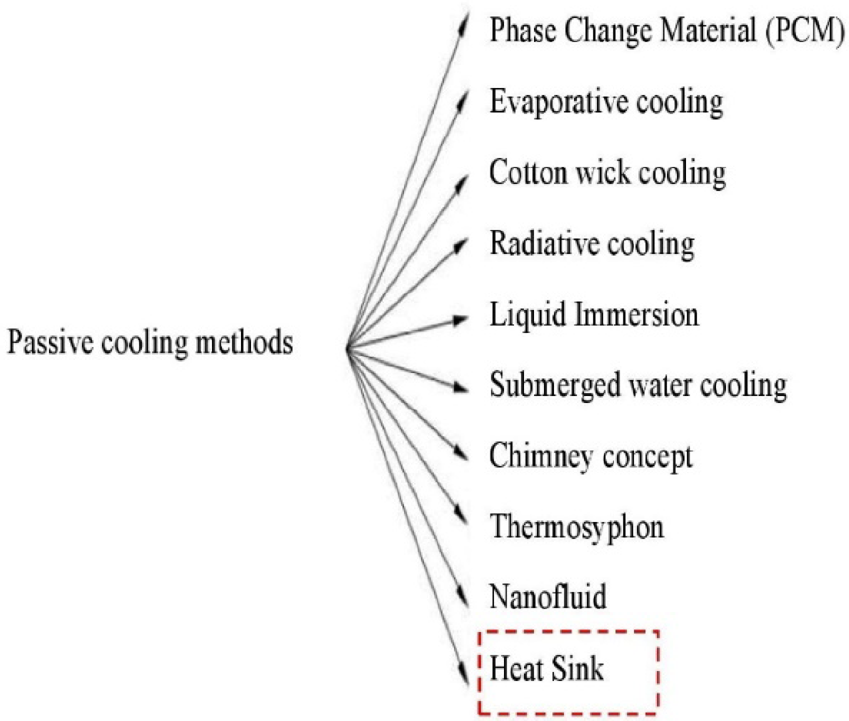


FIGURE 1. Passive cooling methods for PV modules

TABLE 1. Selected works utilizing passive cooling techniques for cooling PV modules.

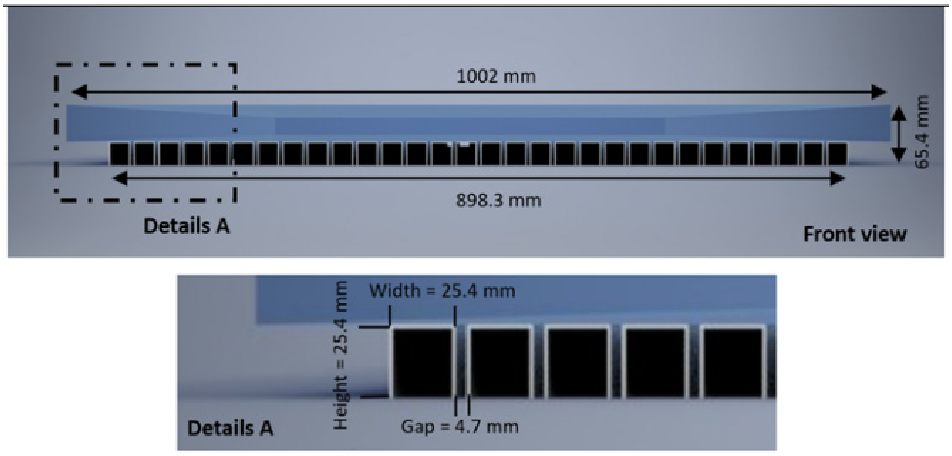
Ref.	Year	Fins design	Type of PV module	Temperature reduction (°C)	Efficiency improvement (%)
(Grubišić Čabo et al. 2020)	2017	Perforated aluminium fins	Polycrystalline 50Wp	-	2
(H. Li et al. 2019)	2018	Porous metal	Polycrystalline 75Wp	-	1
(Selimefendigil et al. 2018)	2018	Perforated-L	Polycrystalline 50Wp	-	2
(Idoko et al. 2018)	2018	Aluminium rectangular fins	Suntech 250Wp	-	5
(Amr et al. 2019)	2019	Rectangular fins	Monocrystalline 250Wp	4.0	-
(Karathanassis et al. 2015)	2019	Longitudinal fin	Polycrystalline 250Wp	-	5
(Bayrak et al. 2020)	2020	Rectangular fins	Polycrystalline 75Wp	2.4	-
(Elbreki et al. 2020)	2020	Lapping and longitudinal fins	Monocrystalline 40Wp	-	1.39
(Farhan et al. 2021)	2021	Longitudinal fins	Polycrystalline 50Wp	5.5	-
(Hernandez-Perez et al. 2021)	2021	Discontinuous fins	Polycrystalline 50Wp	5.0	-
(Ahmad et al. 2021)	2022	Multi-level height fins	Monocrystalline 120Wp	8.45	-
(H. Li et al. 2019)	2022	Rectangular fins (Embedded and non-embedded)	Bifacial (n/a)	11.9	-
(Al-Amri, Maatallah, et al. 2022)	2022	Rectangular fins	Monocrystalline 290Wp	6.3	-
(Raina et al. 2022)	2022	Rectangular fins	Thin film (n/a)	-	5.47
(Alktranee et al. 2023)	2023	Rectangular fins	Polycrystalline 50Wp	-	5.48
Present work	2024	U-Grooved fins	Monocrystalline Half-cut (405Wp)	7	1.5

METHODOLOGY

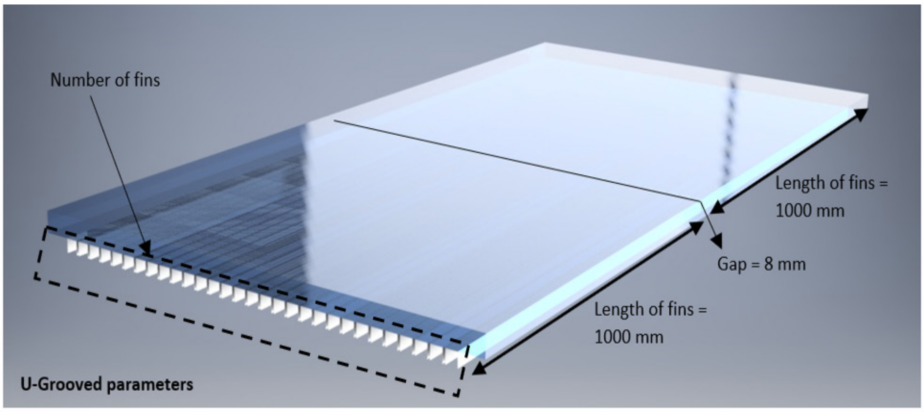
EXPERIMENTAL SETUP

This experiment employed a half-cut mono perc PV module with 20.13%. The innovative design of the U-grooved fins made of aluminium alloy was affixed to the rear side of the module, as depicted in Figure 2. The experimental setup was conducted at the National University of Malaysia (UKM) Solar Energy Research Institute (SERI) in Bangi, Selangor. The temperature of the PV modules was tracked by sticking adhesive thermocouples to the bottom of each module. One PV module remained without additional components, while another had u-grooved fins on the backplate to assess its outdoor electrical performance. This experiment was conducted in a naturalistic environment over a six-month period, from 11 am to 4 pm daily with 15 degrees (Wong et al. 2023) of inclination according to the Malaysian standard. The materials and methods used in this study are discussed below:

1. Half-cut monocrystalline cells (405 Wp) (Details are given in Table 2).
2. Commercially available aluminum 6063 fins and a sheet connected to the back of PV modules.
3. U-grooved fin designs are examined to minimize the stagnation zone inside the heat sinks by increasing air turbulence, as shown in Figures 2 (a) and (b).



a)



b)

FIGURE 2. (a) Dimension details for U-grooved fins design (b) Geometry drawing drawn by modeler design

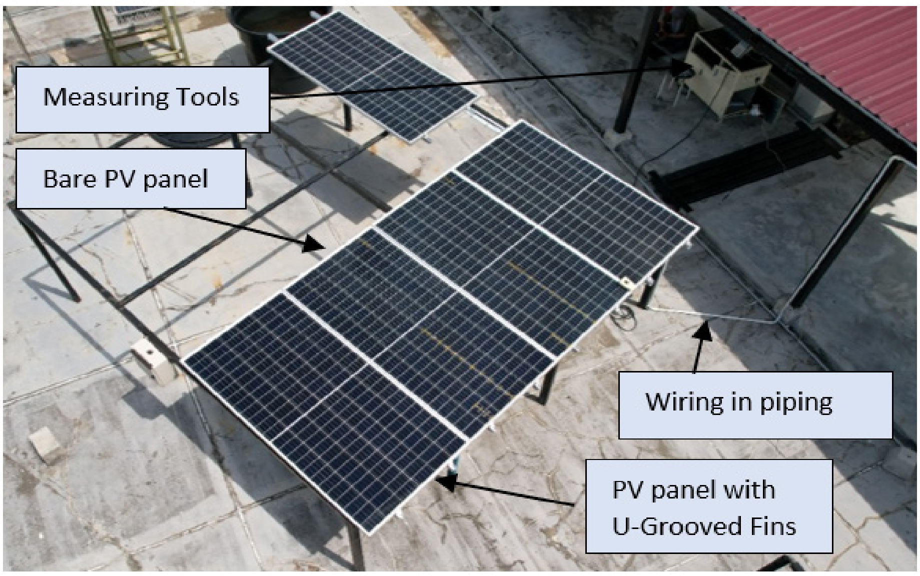


FIGURE 3. The experimental setup overview

TABLE 2. Electrical parameters of the selected monocrystalline half-cut cell PV module

Parameters	Value
Maximum Power (P_{max})	405W
Open-Circuit Voltage (V_{oc})	50.1V
Optimum Operating Voltage (V_m)	42.0V
Short-Circuit Current (I_{sc})	10.48A
Operating Current (I_m)	9.65A
Operating Temperature (°C)	-40°C~ +85°C
Tolerance of the rating power	0~+3%
Temp. coefficient of I_{sc}	0.048%°C
Temp. coefficient of V_{oc}	-0.29%°C
Temp. coefficient of P_m	-0.35%°C
Dimensions	2008 x 1002 x 40 mm

CALCULATION PARAMETERS

Analytical estimates of the electrical output power of PV modules under real operating conditions (*ROC*) can be derived as follows:

The electric output of a PV module under a naturalistic environment can be estimated by considering the derating factors due to module mismatch (k_{mm}) (positive or negative power tolerance), temperature (k_{tem}), the peak sun factor (k_g), dust accumulation (k_{dirt}), and aging (k_{age}). Module mismatch derating (k_{mm}) is derived from the manufacturer's specified power tolerance (Mojumder et al. 2016). On the other hand, the dust (k_{dust}) and aging (k_{age}) factors are estimations based on the installation and production years. The voltage and current values are significantly impacted by derating factors, namely the temperature derating factor ($ktem$) and the solar irradiation derating factor (kg). The derating factors are calculated by applying the following formulas:

$$k_{tem}=1+[(\frac{\delta}{100\%})\times(T_m-T_{stc})] \quad (1)$$

Where Tm (Module efficiency at ROC in °C), T_{stc} (Module temperature at standard Test Conditions (STC) in °C), and K_{temp} (derating factor due to temperature in °C). Consider that δ represents α

(power), β (voltage), and γ (current). The module temperature can be determined analytically using the Ross-thermal model, which is as follows:

$$T_m=T_{amb}+[(\frac{NOCT-20\ ℃}{800Wm^{-2}})\times G] \quad (2)$$

T_{amb} (ambient temperature in °C), and G is the solar irradiance (W/m^2). The formula for calculating the irradiance derating factor is:

$$K_g=\frac{G}{1000} \quad (3)$$

The predicted electrical outputs of a PV module at ROC (P_{ROC}) can be determined by adding together all the derating factors, as shown below in Equations 4 and 5.

$$P_{ROC}=P_{STC}\times k_{power\ derating} \quad (4)$$

$$K_{powerderating}=k_{mm}\times k_{tem}\times k_g\times k_{dirt}\times k_{age} \quad (5)$$

Where P_{STC} is the power rating at STC.

Electrical efficiencies can be calculated by using equation (6) to examine the impact of a temperature increase on a module:

$$\eta_{eff}\ =\eta_{eff}[1-\beta_{eff}\,(T_{cell}\,-\,T_{reff})] \quad (6)$$

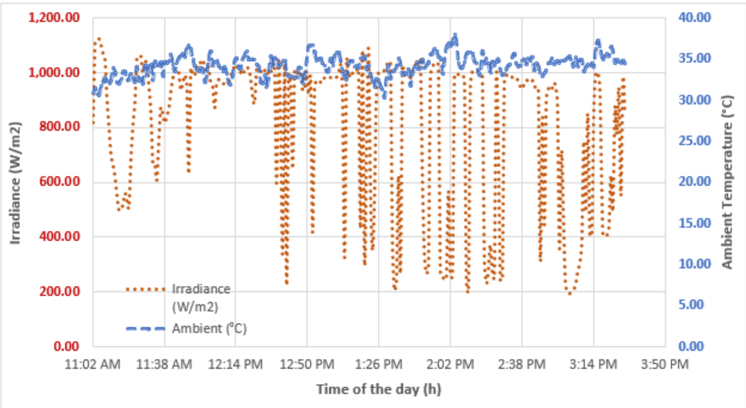
η_{eff} is the PV module efficiency (25 °C and 1000W/m^2, β_{eff} is the cell relative temperature coefficient, is an experimentally PV module temperature, and T_{reff} is the module temperature at STC (25 °C).

RESULTS AND DISCUSSIONS

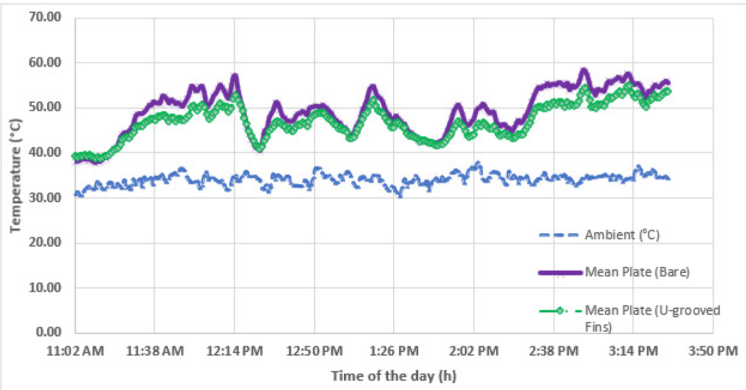
PV MODULE AND TEMPERATURE

Previous studies demonstrate that the fins on the heat sink have a major effect on the temperature uniformity of the PV modules (Ahmad et al. 2022). As a result, the average plate temperature was used to assess the effectiveness of the fins heat sink mounted PV modules and then compared with modules without fins (T_{cell}). Figure 4(a) displays irradiance and ambient temperature from 11:00 am to 4:00 pm. Figure 4(b) indicates the photovoltaic module temperature.

In contrast to bare modules, the photovoltaic (PV) modules featuring U-grooved fins exhibit significantly superior performance from 11:00 am to 4:00 pm. These assessments were conducted within temperature ranges of 28°C to 38°C, with average irradiances from 600 to 1000W/m^2. In March 2022, at 3:00 pm, the outside temperature was expected to be around 38°C. The solar module temperature distribution, as illustrated in Figure 4(b), plays a critical role in determining the reliability of the solar module. Using finned surfaces on the opposite side of the module improves heat exchange efficiency. As shown in Figure 4(b), the difference between a bare module and with u-grooved fins can be seen; there is an improvement of 3.5%. The U-grooved fins on the PV module attained a maximum temperature of 51 °C and normally cooled down to around 38 °C. The highest temperature on the unfinned PV module was 58 °C.



a)



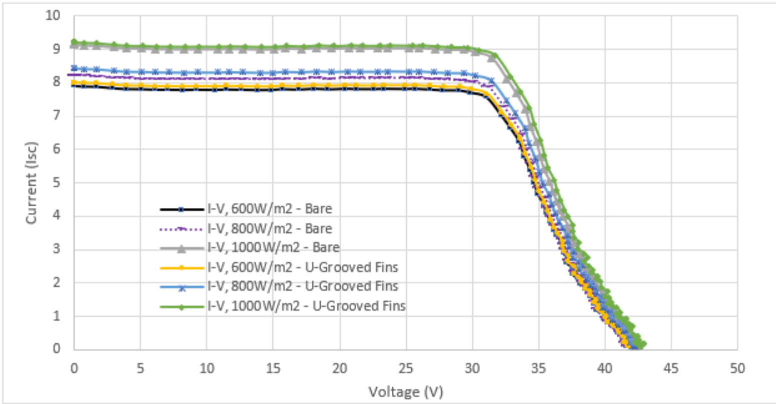
b)

FIGURE 4. Outdoor experimental results: a) Irradiance and ambient temperature b) Changes in temperature between the finned module, the bare module, and the ambient temperature

MODULES PERFORMANCE

Figure 5 demonstrates IV characteristics and power outputs of the PV module without fins, and with U-Grooved fins, fins mounted module has high efficiency (attained due to lower Module temperature). Figure 5(a) depicts the output current (I) and voltage (V) of a bare PV in contrast to PV modules equipped with a heatsink at irradiances between 600 to 1000 W/m^2. So, comparing these two PV modules revealed that as module temperature drops (due to natural convection), the output current for PV modules with the heatsink increases marginally while the voltage increases dramatically. Because of heat dispersion by the wind velocity, the modules with heat sink maintained a constant average output current of about 9.21A. After cooling, the typical output current increases by 0.07%, from 9.05A to 9.21A at 23.62V to 23.84V. The findings show that improvement in output power due to the heat sink is evident in the early stages of operation. The increase in ambient temperature slows the heat transfer process, and the impact of the heat sink on output decreases. Figure 5(b) depicts the PV curves of bare PV modules and U-grooved fins-mounted PV modules. The PV datasheet shows that the power coefficient of the PV module would drop by -0.35%/°C when operating at the nominal operating cell temperature (NOCT). A cooling system added to a PV module reduces the module's temperature, increasing the Energy harvested. When used with a heat sink, a solar module's highest possible output power is 280W. Figure 5(c) provides a clear and concise representation of experimental research into the effects of varying irradiances on the electrical efficiency and output performance of

U-grooved heat sink fins. The relative efficiency was achieved at 22.82%, indicating a 1.5% gain. Each module has a different voltage coefficient and power output. High-irradiance locations affect these coefficients. As the PV module has a connection to the heatsink, these parameters can be altered to enhance efficiency. Wind velocity (natural convection) aided this process in PV modules equipped with a heat sink, as illustrated in Table 3.



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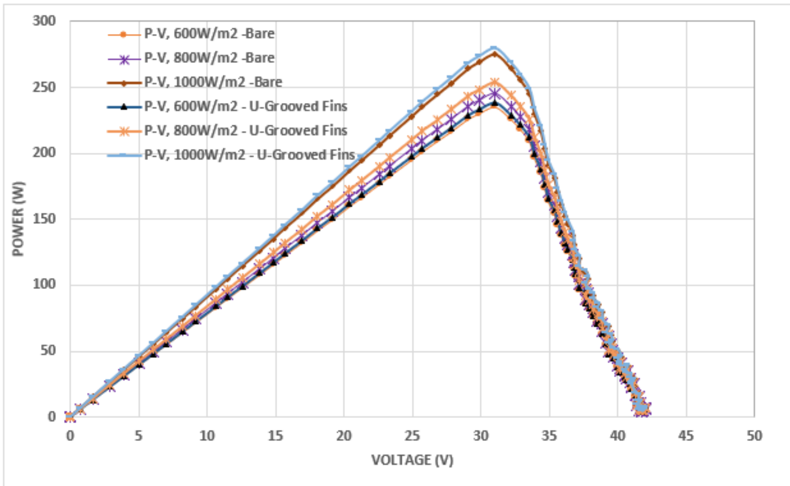

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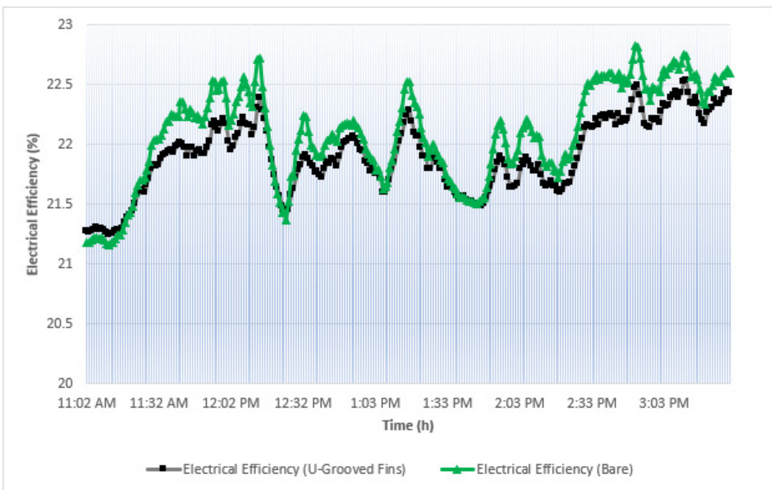

c)

FIGURE 5. Outdoor experimental results: a) IV curve b) PV curve c) Efficiency

TABLE 3. Comparison of voltage and current under different irradiances and wind speed.

Time	Wind Velocity (m/s)	Irradiances (W/m^2)	PV module without Fins		PV module with U-Grooved Fins	
			Voltage (V)	Current (A)	Voltage (V)	Current (A)
9:00	1.1	560.00	8.28	9.01	8.36	9.08
10:00	0.9	819.00	15.02	9.01	15.15	9.08
11:00	1.8	903.00	23.62	9.05	23.84	9.21
12:00	1.0	1,022.00	33.29	7.68	33.59	7.74
13:00	1.3	1,049.00	36.82	3.98	37.15	4.01
14:00	2.1	1,007.00	39.81	1.73	40.17	1.74
15:00	0.5	1,003.00	41.59	0.66	41.97	0.66
16:00	1.7	943.00	42.13	0.14	42.51	0.14

CONCLUSION

Under real-world outdoor conditions, especially in regions with intense sunlight, it is impractical to maintain the module temperature at the ideal 25°C. Consequently, the actual power output often falls short of the maximum achievable under standard test conditions (STC), which is stated as 405 watts. As outlined in the PV datasheet, the power coefficient of the module is expected to decrease by -0.35% for every degree Celsius increase in temperature. This highlights the crucial role of heat sinks in mitigating the adverse effects of high temperatures on the electrical performance of solar modules.

U-grooved heat sink fins were tested outdoors to observe how they affect the temperature and the final output of solar modules. A bare PV and a U-grooved module's efficiency were evaluated under the same tropical conditions. These are the main findings:

1. The experiment confirms the efficacy of the passive cooling system in reducing the temperature and increasing the electrical efficiency of the module.
2. The PV module's maximum temperature was 51°C as compared to 58°C on the PV module without a cooling system,
3. U-grooved fins increase PV module electrical efficiency at 1000W/m^2 by 22.82% indicating 1.5% gain under real operating conditions, which increases the power output by 45 watts as opposed to the bare PV module.
4. The shape and arrangement of fins on a solar module can significantly impact how well it absorbs sunlight and how hot it gets.
5. To further decrease temperatures and avoid hotspots at the junction box of PV modules, future research could focus on combining the proposed method with forced convection cooling.

This in-depth analysis of U-grooved fin heat sinks on solar module performance has generated significant discoveries. The outcomes of this study provide a solid platform for advancing the efficiency and robustness of solar systems and analogous technologies.

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DECLARATION OF COMPETING INTEREST

None.

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