Experimental investigation of passively cooled photovoltaic modules on the power output performance

Emy Zairah Ahmad¹,², Kamaruzzaman Sopian¹, Adnan Ibrahim¹, Chin Kim Gan³, Mohd Suffian Ab Razak⁴
¹Solar Energy Research Institute, Universiti Kebangsaan Malaysia, Bangi Selangor, Malaysia
²Faculty of Electrical & Electronic Engineering Technology, Universiti Teknikal Malaysia Melaka, Malaysia
³CeRIA Faculty of Electrical Engineering, Universiti Teknikal Malaysia Melaka, Malaysia
⁴Faculty of Mechanical and Manufacturing Engineering Technology, Universiti Teknikal Malaysia Melaka, Malaysia

Article Info

ABSTRACT

The power output performance of a photovoltaic (PV) module decreases as the temperature increases. The increase in module temperature above the standard test conditions (25 °C) could reduce the average power output by at least 0.2% for each 1 °C rise. Hence, keeping the module temperature low is necessary for PV systems exposed to high solar irradiance throughout the year. Therefore, this study aims to experimentally analyse the electrical performance of passively cooled PV modules in the tropics. The developed cooling approach consists of rectangular plate fins made of aluminum 6061, attached to the rear surface of Tedlar layer. The results indicated that the average module temperature reduction of 3.25 °C was observed under outdoor exposures. As a result, the heat sink improved the overall power output up to 14.2%. As the PV performances are site-dependent, these findings are beneficial as it provides a thorough explanation of fin heat sink behavior under long-term field exposures of tropics.

Keywords:
Fins heat sink
Photovoltaic cooling
Power conversion efficiency
PV module temperature
PV performance

1. INTRODUCTION

Solar energy has the potential to reduce the profound long-term threat of global carbon dioxide (CO₂) emissions. Research on alternative energy resources started to emerge, and evaluating each technology is necessary to support climate change policies and mitigation. The International Energy Agency (IEA) has recently reported that 27% of global energy generation in 2050 will be supplied by solar photovoltaic (PV). However, an in-depth research is required to enable the competitiveness of solar PV in the future energy market. Nevertheless, a silicon (Si) PV module technology absorbs 80% of incident solar irradiance, but only 20% is converted into useful energy [1]. The percentage of power reduction per degree Celsius ranges typically from 0.2%/°C to 0.5%/°C and highly influences the decrease in voltage and power conversion efficiency (PCE) [2]. It has been a constant challenge for a PV system exposed to continuously high solar irradiance [3]. To overcome this limitation, keeping the module temperature low is necessary.

Various authors reported significant studies on different PV cooling methodologies, and it can be categories as passive and active cooling [4]. The primary concern of PV cooling is to eliminate excess heat in periods of high solar irradiance and over long field exposures. Despite various cooling techniques addressed in [5]–[11], passive cooling is more promising than active cooling. They require no auxiliary input power, and surrounding air naturally cools the PV modules. For instance, Johnston et al. [12] proposed a continuous
Experimental investigation of passively cooled photovoltaic modules on ... (Emy Zairah Ahmad)
reliable for improvement in temperature reduction using fin heat sinks. It allows stakeholders such as PV installers, PV plant owners, and other parties to favor an informed decision towards the heat sink cooling mechanism to enhance the PV system performance.

2. METHODOLOGY

The electrical output performance of a PV module is highly site-dependent, but the rated nominal power is based on the controlled environments known as standard test conditions. Various methods have been proposed to determine the module efficiency through simplified working equations [21–24]. However, the following equation is widely used to determine the PV module efficiency described as follows (1) [25].

$$\eta = \eta_{STC} \left[1 - \beta(T_{PV} - T_{STC})\right] + \gamma \log G$$  

(1)

$\eta_{STC}$ is the efficiency of a PV module at $\text{STC}(25^\circ\text{C})$, G is the irradiance level measured in W/m$^2$, and $T_{PV}$ is the PV module temperature, $\beta$ and $\gamma$ are the coefficients for the temperature and solar irradiance, respectively. The values for $\eta_{STC}$, $\beta$, and $\gamma$ are given in the module datasheet. However, under real operating conditions (ROCs), the power output of the PV modules installed at the test site differs from the power stated in the module datasheet. Several derating factors that need to be considered, known as power derating, $k_{\text{power derating}}$, and can be determined using (2) and (3) [26].

$$P_{\text{roc}} = P_{\text{STC}} \times k_{\text{power derating}}$$  

(2)

$$k_{\text{power derating}} = k_{\text{module mismatch}} \times k_{\text{temp}} \times k_{g} \times k_{\text{dust}} \times k_{\text{aging}}$$  

(3)

Where $P_{\text{roc}}$ is the power rated at STC as per manufacturer’s specification (Wp), $k_{\text{module mismatch}}$ is the module mismatch derating factor, $k_{\text{temp}}$ is the module temperature derating factor, $k_{g}$ is the peak sun factor obtained by dividing the instantaneous irradiance with 1000 W/m$^2$, $k_{\text{dust}}$ is the dust effect derating factor, and $k_{\text{aging}}$ is the derating factor due to PV module’s aging. In this study, $k_{\text{module mismatch}}$, $k_{\text{dust}}$, and $k_{\text{aging}}$ parameters are constant (=1.0) throughout the experiment and can be combined as $\alpha$. Therefore, the (2) becomes;

$$P_{\text{roc}} = P_{\text{STC}} \times k_{\text{temp}} \times k_{g} \times \alpha$$  

(4)

The values of $k_{\text{temp}}$ and $k_{g}$ can be estimated using [27]:

$$k_{\text{temp}} = 1 + \left(\frac{\gamma_{\text{mp}}}{100}\right) \times (T_{\text{module}} - T_{\text{STC}})$$  

(5)

$$k_{g} = \frac{\text{solar irradiance} \times \text{G}}{1000}$$  

(6)

where $\gamma_{\text{mp}}$ is the module’s temperature coefficient given in %/°C. The module temperature, $T_{\text{module}}$ is measured using K-type thermocouples positioned at the front and backside of PV modules. The IV curve defines the performance of PV modules, which shows how the current varies as a function of the voltage. Based on the IV curve, several parameters are used to characterize the electrical performance of the PV module, as presented in the fill factor (FF) in (7).

$$\text{FF} = \frac{I_{mp} \times V_{mp}}{I_{sc} \times V_{oc}}$$  

(7)

Where $I_{mp}$ is current recorded at the maximum point of the IV curve, $I_{sc}$ is short-circuit current, $V_{mp}$ is the voltage at maximum power, and $V_{oc}$ is open-circuit voltage [27]. The FF can be used to determine the efficiency of a PV module at specific irradiance and temperature. The expected yield can be defined as (8) [28].

$$Y_{\text{exp}} = P_{\text{STC}} \times PSH_{\text{poa}} \times k_{\text{total deration}} \times \eta_{\text{sub system}}$$  

(8)

PSHpoa is the peak sun hour (h), and $\eta_{\text{sub system}}$ is the product of inverter and cable efficiency.

The test-rig setup was developed to evaluate the PV module performances under the local climate conditions of Malaysia (2.1896° N, 102.2501° E). The main components for the experimental setup are the PV module, PV mounting structure, current-voltage tracer, and weather monitoring unit. The design consists of
two identical monocrystalline PV modules (120 Wp) and tilted at 18° from the horizontal facing South to receive the maximum solar radiation. The fin geometry is illustrated in Figure 2 (a). One module was attached with the heat sinks for cooling (Panel A), while the other was used as a reference module (Panel B), as demonstrated in Figure 2 (b). The measures of incident solar irradiance shall comply with IEC 60904-3 [29]. Therefore, this work uses PV reference cells of the same glazing and technology for solar irradiance measurement with ±0.2% sensitivity. All measurements were recorded every 2s interval from 09:00 a.m to 05:00 p.m. The K-type thermocouples were used to measure the ambient temperature and the surface temperature of PV modules. The thermocouples were placed at several points at the front and rear side of PV modules having a sensitivity of ±0.5% and the temperature range of -200 °C to +300 °C. All temperature sensors were connected to the advanced data acquisition modules (ADAM 4018+), interfaced with the single RS-485 network.

3. RESULTS AND DISCUSSION
3.1. The influence of fins heat sink on the PV module temperature

The two modules were installed to investigate comparatively the PV-Fin module with the conventional module. Although all the data was recorded for several days, the data is presented for the day with clear sky and stable solar irradiance on July 19, 2021. Solar irradiance, ambient temperature, and the surface temperature of PV modules were measured at the test site and presented in Figure 3 and Figure 4. Since Malaysia is located near the equator, the climate is hot and humid throughout the year. The recorded temperatures were high and stable between 26 to 37 °C throughout the day. It should be noted from the solar irradiance plot that cloudy conditions have occurred in the morning from 10:00 a.m. to 3:00 p.m., characterized by the dotted lines. The average highest and lowest solar irradiance values were recorded at 980 and 520 W/m², respectively.

As shown in Figure 4, the graph for the surface temperature of PV modules (with fins and without fins) is highly influenced by solar irradiance. The PV surface temperature plot is observed to have similar trends with the plot of solar irradiance. The surface temperature of the PV module with fins is lower than the surface temperature of the PV module without fins throughout the day. The maximum temperature difference between the two modules is 5.77 °C, and the average temperature difference is 3.25 °C. The surface temperature...
plot shows one peculiarity: The module with fin demonstrates a significant impact on the module temperature reduction at solar irradiance greater than 600 W/m². The surface temperature reduction was observed between 3.47 and 4.60 °C. Meanwhile, the temperature reduction between both modules was insignificance as the weather got too cloudy, as shown in areas X and Y. The temperature reduction drops between 1.29 to 1.5 °C. The temperature derating factor is an important parameter for assessing the PV module performance under long-term field exposure. Hence, the amount of $k_{temp}$ for both modules was determined based on (5). The lowest recorded $k_{temp}$ for PV with fins and PV without fins were 0.908 and 0.917, respectively. Based on Figure 5, it can be concluded that fin heat sinks positively influenced the $k_{temp}$ by at least 3.4 % throughout the day.

3.2. The influence of fins heat sink on the power output performance

Temperature variation within the PV module significantly impacts the electrical output performance. Hence, the PV module performance is characterized by a current-voltage ($I-V$) curve measured from the current-voltage tracer. The measurements were recorded every 1-hour intervals. The experimental results produce several important electrical parameters, including short-circuit current ($I_{sc}$), open-circuit voltage ($V_{oc}$),
current at maximum power \(I_{mp}\), and voltage at maximum power \(V_{mp}\). During these measurements, the minimum and maximum recorded solar irradiances were 520 and 980 W/m\(^2\), respectively. It can be observed that the \(V_{oc}\) for the PV module with fins is higher than the reference module by at least 3.14 % (see Figure 6). However, Figure 7 shows the power curves for both PV modules tested under outdoor operating conditions. Since solar cells are made up of semiconductor materials, the increase in temperature excites excess electrons and holes, causing the greater depletion region width known as the charge separation layer [30]. Hence, the \(V_{oc}\) is very much dependent on the temperature. Besides, the value of \(V_{mp}\) had increased from 17.2 V to 20.4 V when using fins. Consequently, the fill factor (FF) values had improved from 0.744 to 0.826.

The recorded \(I_{oc}\) for the PV module with fins and without fins was 6.08 A and 6.10 A, respectively. The change of \(I_{oc}\) with temperature highly depends on the light trapping properties of the designed solar cell. Hence, it can be observed that the change in \(I_{oc}\) is much smaller than the \(V_{oc}\). The overall electrical performances for tested PV modules are summarized in Table 1. It is worth noting that when the module temperature drops, the voltage rises, resulting in a substantial increase in available maximum electrical power despite a slight decrease in short-circuit current. The average power output is improved by 14.2 % when using fin heat sinks as the cooling approach, as shown in Figure 8.

![Figure 6. Current-Voltage curves](image1)

![Figure 7. Power curves](image2)

### Table 1. The overall electrical performances under outdoor testing conditions

| Electrical parameters | Measured data at an irradiance of 980W/m\(^2\) and ambient temperature of 34.11 °C |
|------------------------|---------------------------------------------------|
|                        | PV without fins | PV with fins |
| Short-circuit current, \(I_{sc}\) | 6.10 A | 6.08 A |
| Open-circuit voltage, \(V_{oc}\) | 21.2 V | 22.4 V |
| Current at the maximum point, \(I_{mp}\) | 5.6 A | 5.52 A |
| Voltage at the maximum point, \(V_{mp}\) | 17.1 V | 20.4 V |
| Maximum power output, \(P_{mp}\) | 98.56 W | 112.6 W |
| Fill factor, FF | 0.744 | 0.826 |

![Figure 8. The impact of power output under varying solar irradiances](image3)

### 4. CONCLUSION

This work reports the experimental findings on the passively cooled PV modules using rectangular fin heat sinks under outdoor testing conditions. It can be concluded that the proposed cooling approach results in a 3.25 °C average reduction in the PV module temperature. Thus, the maximum electrical power output increases up to 14.2 % by integrating the fin heat sink at the backside of the PV module. It was found that the heat sink effect on the PV module performance is significant at high solar irradiance than low solar irradiance. The finding suggests the feasibility of implementing the heat sink as a cooling approach in countries near the equator.
ACKNOWLEDGEMENTS

The authors would like to acknowledge the Universiti Kebangsaan Malaysia (UKM) for supporting this research through research funding FRGS/1/2019/TK07/UKM/02/4 (Fundamental Research Grant Scheme), the Ministry of Higher Education Malaysia, and Universiti Teknikal Malaysia Melaka (UTeM) for some of the equipment used in the experiment.

REFERENCES

[1] M. A. Green, “Photovoltaic technology and visions for the future,” Prog. Energy, 2019, doi: 10.1088/2516-1083/ab0f08.

[2] I. Marinic-Kragic, S. Nizetic, F. Gruhishi-Cabo, and D. Coko, “Analysis and optimization of passive cooling approach for free-standing photovoltaic slabs,” Energy Convers. Manag., 2019, doi: 10.1016/j.enconman.2019.112277.

[3] E. Z. Ahmad, A. Fazaizil, J. Harjini, K. Sopian, and A. Ibrahim, “Enhanced heat dissipation of truncated multi-level fin heat sink (MLFHS) in case of natural convection for photovoltaic cooling,” Case Stud. Therm. Eng., vol. 28, p. 101578, 2021, doi: 10.1016/j.csite.2021.101578.

[4] H. A. Kazem, M. T. Chaichan, A. H. A. Al-Waial, and K. Sopian, “A review of dust accumulation and cleaning methods for solar photovoltaic systems,” J. Clean. Prod., vol. 276, p. 123187, 2020, doi: 10.1016/j.jclepro.2020.123187.

[5] J. Siecker, K. Kusakana, and B. P. Numbi, “A review of solar photovoltaic systems cooling technologies,” Renewable and Sustainable Energy Reviews, pp. 192–203, vol. 79, 2017, doi: 10.1016/j.rser.2017.05.053.

[6] S. Nizetic, M. Jurcevic, D. Coko, and M. Arpag, “A novel and effective passive cooling strategy for photovoltaic panel,” Renew. Sustain. Energy Rev., vol. 145, no. March, 2021, doi: 10.1016/j.rser.2021.111164.

[7] S. Nizetic, E. Giama, and A. M. Papadopoulos, “Comprehensive analysis and general economic–environmental evaluation of cooling techniques for photovoltaic panels, Part II: Active cooling techniques,” Energy Convers. Manag., vol. 155, October 2017, p. 301–323, 2018, doi: 10.1016/j.enconman.2017.10.071.

[8] M. N. Kamarudin, S. Rozaiz, and M. S. Jamri, “Active cooling photovoltaic with IoT facility,” Int. J. Power Electron. Drive Syst., vol. 12, no. 3, pp. 1494–1504, 2021, doi: 10.11591/ijped.v12i3.

[9] A. Fudholi, M. Zohri, I. Taslim, M. A. Indrianti, and I. N. Manyoe, “Theoretical approach model of building integrated photovoltaic thermal air collector,” Int. J. Power Electron. Drive Syst., vol. 11, no. 2, pp. 1002–1010, 2020, doi: 10.11591/ijped.v11i2.pp1002-1010.

[10] I. M. Saadon, H. Windiarti, M. N. Othman, E. Z. Ahmad, and K. A. M. Ammar, “River Debris Management System using Off-Grid Photovoltaic Module,” in MATEC Web of Conferences, 2017, vol. 97, p. 10.1051/matecconf/20179701070.

[11] Y. H. Hamdan, N. H. Hussin, R. M. Said, K. Hanizah, and E. Z. Ahmad, “ARAR algorithm in forecasting electricity load demand in Malaysia,” Glob. J. Pure Appl. Math., vol. 12, no. 1, 2016.

[12] E. Johnston, P. S. B. Szabo, and N. S. Bennett, “Cooling silicon photovoltaic cells using finned heat sinks and the effect of inclination angle,” Therm. Sci. Eng. Prog., vol. 23, no. March, p. 100902, 2021, doi: 10.1016/j.tsep.2021.100902.

[13] L. Idoko, O. Anaya-Lara, and A. McDonald, “Enhancing PV modules efficiency and power output using multi-concept cooling technique,” Energy Reports, vol. 4, pp. 357–369, 2018, doi: 10.1177/2352544816649969.

[14] A. A. raheem Ama, A. M. Hassan, M. Abdel-Salam, and A. H. M. El-Sayed, “Enhancement of photovoltaic system performance via passive cooling: Theory versus experiment,” Renewable Energy, 2019, doi: 10.1016/j.renene.2019.03.048.

[15] A. M. Elbreki, K. Sopian, A. Fazaizil, and A. Ibrahim, “Case Studies in Thermal Engineering An innovative technique of passive cooling PV module using lapping fins and planner reflector,” Case Stud. Therm. Eng., vol. 19, no. January, p. 100607, 2020, doi: 10.1016/j.csite.2020.100607.

[16] F. Gruhsit-Cabo, S. Nizetic, D. Coko, I. Marinic-Kragic, and A. Papadopoulos, “Experimental investigation of the passive cooled free-standing photovoltaic panel with fixed aluminum fins on the backside surface,” J. Clean. Prod., vol. 176, pp. 119–129, 2018, doi: 10.1016/j.jclepro.2017.12.149.

[17] Z. Ariffin, D. D. D. P. Tjahjana, S. Hadi, R. A. Rachmananto, G. Setyoandoko, and B. Sutanto, “Numerical and experimental investigation of air cooling for photovoltaic panels using aluminum heat sinks,” Int. J. Photoenergy, vol. 2020, 2020, doi: 10.1155/2020/1574274.

[18] F. Bayrak, H. F. Oztop, and F. Selimefendigil, “Effects of different fin parameters on temperature and efficiency for cooling of photovoltaic panels under natural convection,” Sol. Energy, vol. 188, no. June, pp. 484–494, 2019, doi: 10.1016/j.solener.2019.06.036.

[19] J. G. Hernandez-Perez, J. G. Carrillo, A. Bassam, M. Flota-Banuelos, and L. D. Patino-Lopez, “Thermal performance of a discontinuous finned heatsink profile for PV passive cooling,” Appl. Therm. Eng., no. April, p. 116238, 2020, doi: 10.1016/j.applthermaleng.2020.116238.

[20] F. Selimefendigil, F. Bayrak, and H. F. Oztop, “Experimental analysis and dynamic modeling of a photovoltaic module with porous fins,” Renew. Energy, vol. 125, pp. 193–205, 2018, doi: 10.1016/j.renene.2018.02.002.

[21] M. Mittal, B. Bora, S. Saxena, and A. M. Gaur, “Performance prediction of PV module using electrical equivalent model and artificial neural network,” Sol. Energy, vol. 176, no. October, pp. 104–117, 2018, doi: 10.1016/j.solener.2018.10.018.

[22] A. M. Muzathik, “Photovoltaic Modules Operating Temperature Estimation Using a Simple Correlation,” International Journal of Energy Engineering, vol. 4, pp. 151–158, 2014.

[23] H. Zainuddin, S. Chaari, A. M. Omar, S. I. Sulaiman, Z. Mahmud, and F. Muhamad, “Prediction of module operating temperatures for free-standing (FS) photovoltaic (PV) system in Malaysia,” Int. Rev. Model. Simulations, 2011.

[24] A. A. Hamid, A. Ibrahim, J. Assadeg, E. Z. Ahmad, and K. Sopian, “Techno-economic Analysis of a Hybrid Solar Dryer with a Vacuum Tube Collector for Hibiscus Cannabis L. Fiber,” Int. J. Renew. Energy Res., vol. 10, no. 4, pp. 1669–1613, 2020.

[25] A. Pavgi, J. Oh, J. Kuitche, S. Tatapudi, and G. Tamizhmani, “Thermal Uniformity Mapping of PV Modules and Plants,” 2017 IEEE 44th Photovoltaic Specialist Conference (PVSC), 2017, pp. 1877–1882, doi: 10.1109/PVSC.2017.8366308.

[26] A. M. Omar and S. Chaari, “Sizing verification of photovoltaic array and grid-connected inverter ratio for the Malaysian building integrated photovoltaic project,” Int. J. Low-Carbon Technol., vol. 4, no. 4, pp. 254–257, 2009, doi: 10.1093/ijlct/cip033.

[27] S. N. Geoff Stapleton, Grid-connected Solar Electric Systems: The Earthscan Expert Handbook for Planning, Design and Installation, vol. 1. Routledge, 2012.

[28] E. Z. Ahmad et al., “Recent advances in passive photovoltaic methods for photovoltaic performance enhancement,” Int. J. Electr. Comput. Eng., vol. 11, no. 1, pp. 146–154, 2021, doi: 10.11591/ijece.v11i1.pp146-154.

[29] L. Dunn, M. Gostein, and K. Emery, “Comparison of pyranometers vs. PV reference cells for evaluation of PV array performance,” Int J Pow Elec & Dri Syst, Vol. 13, No. 1, March 2022: 520-527.
Experimental investigation of passively cooled photovoltaic modules on ... (Emy Zairah Ahmad)