International Journal of Electrical and Computer Engineering (IJECE)
Vol. 15, No. 5, October 2025, pp. 4387~4394
ISSN: 2088-8708, DOI: 10.11591/ijece.v15i5.pp4387-4394

Development and testing of a dedicated cooling system for photovoltaic panels

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Article Info

Article history:

Received Nov 6, 2024
Revised Jul 4, 2025
Accepted Jul 12, 2025

Keywords:

Aluminum heat sinks
Panel cooling systems
Passive cooling
Photovoltaic performance
Solar energy

ABSTRACT

Solar energy is a viable alternative to fossil fuels, but its efficiency is limited by photovoltaic panel overheating, which causes a decrease in efficiency. This paper suggests a passive cooling method that incorporates aluminum heat sinks beneath the solar cells. This simple, low-cost device maximizes heat dissipation using natural convection. It requires no external energy. The goal is to provide a solution to the challenge of selecting an effective, sustainable, and flexible cooling system while considering technological, economic, and environmental constraints. Experimental results demonstrate that modules fitted with heatsinks experience an average 8.13 °C drop in temperature, as well as a 0.51 V rise in open-circuit voltage when compared to the reference panel. This increase demonstrates how well-designed passive solutions can dramatically improve the energy performance of solar panels. The study emphasizes the relevance of thermal design in photovoltaic system optimization and provides specific opportunities for the development of more efficient solar technologies, particularly in high-temperature situations.

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1. INTRODUCTION

Renewable energy is becoming increasingly important for lowering carbon emissions and pollution, which helps to combat global warming. Photovoltaic (PV) solar energy is one of the most extensively utilized methods for generating electricity, and it is also one of the simplest to install, whether as an off-grid system or connected to the power grid. Photovoltaic systems rely on the features of semiconductor materials, which emit electrons when exposed to solar radiation. The conversion efficiency is the percentage of solar energy that a photovoltaic cell converts into electricity. Solar modules confront both obstacles and opportunities [1], [2], with ambient temperature, solar radiation intensity, panel surface temperature, dust, and shading all influencing their performance. These problems can be avoided by installing efficient cooling and cleaning systems. Cooling systems for solar panels [3], [4] use a variety of physical processes and fluids to reduce the panels' surface temperature. These technologies are classified as passive (needing no external energy) or active (requiring additional energy to circulate the cooling fluid). Passive cooling approaches [5], [6] include employing fins or expanded surfaces to improve heat dissipation, phase change materials to absorb heat from the panel, heat pipe systems, and natural convection through water or air. Active methods [7], [8] move air or water across panel surfaces, often with the help of fins. When comparing active and passive solar panel cooling systems, various considerations must be considered. The ease of use is determined by the specific cooling system, as well as aspects such as system size and placement, maintenance requirements, performance efficiency in hot and humid conditions, and overall cost when comparing various solutions.

Currently, new technologies are being developed to improve the efficiency of photovoltaic solar panels via effective cooling strategies and improved thermal management systems. For example, Hassabou and Isaifan [9] designed and simulated phase change material matrix absorbers (PCM-MA) composed of a fibrous aluminum cellular structure packed with phase change material (PCM) for photovoltaic panel passive temperature control. Arifin *et al.* [10] tested three types of PCM: soy wax, paraffin, and beeswax, and found that beeswax PCM is the most effective at lowering the operating temperature of solar systems. Zhao *et al.* [11] proposed installing a water-cooled wall in the air channel of building-integrated photovoltaic thermal (BIPVT) to cool the air, hence increasing the cooling impact on photovoltaic panels.

Abdullah and Majel [12] created a mathematical model using computational fluid dynamics (CFD) to simulate the thermal performance of a photovoltaic thermal solar panel with square and elliptical fin cooling modules. They discovered that square pin fins had higher fluid velocities between the pins than other varieties, which leads to better water circulation and cooling. Meanwhile, Alayi *et al.* [13] developed a photovoltaic thermal system with air conditioning to improve efficiency using energy analysis. Their studies revealed that injecting water improves the photovoltaic/thermal collector's efficiency over bigger areas, which is expected to be rather amazing. Khairunnisa *et al.* [14] conducted research on heat exchangers, identifying rectangular and spiral rectangular tube topologies for convection cooling using fluid water in photovoltaic solar panels. They discovered that the spiral rectangular tube layout generated the greatest power boost when compared to the rectangular tube. Meanwhile, Praveenkumar *et al.* [15] used a thermoelectric cooling system to cool a photovoltaic panel during real-world weather conditions. Their experimental results showed a substantial drop in temperature in the redesigned PV module. Zhou *et al.* [16] created two types of flat planar PC films with efficient radiative cooling capabilities. These films have a highly reflective coating formed of metal and metal oxide connected to the back of the PC, consisting of only three layers. It has been demonstrated that using a PC or R-PC layer can reduce device temperature and increase efficiency. Sornek *et al.* [17] developed and tested a water cooling system optimized for photovoltaic panels. This decrease in cell temperature resulted in a higher power output compared to uncooled panels. Meanwhile, Yildirim *et al.* [18] demonstrated a novel thermal collector for photovoltaic-thermal (PV/T) systems. Their findings show that with a mass flow rate of 0.014 kg/s and an inlet temperature of 15 °C, the PV module has an electrical conversion efficiency of 17.79% and a thermal efficiency of 76.13%. Arifin *et al.* [19] discovered that utilizing soy wax to cool photovoltaic panels resulted in the smallest drop in PV temperature compared to panels without a cooling mechanism. Salman *et al.* [20] investigated the effect of cooling strategies employing porous media on the average surface temperature of PV modules. They employed three different types of porosity for the porous medium and discovered that raising the mass flow rate increased heat transmission, reducing the surface temperature of the PV panels.

Al Miaari and Ali [21] proposed an innovative solution that involves employing six small containers packed with phase transition material that can be readily constructed and disassembled, rather than a single container. Rehman [22] evaluated solar panel cooling options using the multicriteria visual PROMETHEE technique, which included nine potential alternative cooling methods. When operating efficiency was highlighted, fin cooling was shown to be the most effective way to cool solar panels. Almeshaiei *et al.* [2] proposed a method called rapid evaluation of solar panel cooling (RESC). Their findings show that this method efficiently compares various cooling solutions, allowing for an assessment of their performance and payback periods over a short time frame. Meanwhile, Krstic *et al.* [23] investigated how to increase output characteristics by passively cooling solar panels using aluminum heat sinks of various geometries. Masalha *et al.* [24] studied porous supports (gravel) with different porosities (0.35, 0.40, and 0.45), as well as flow rates of 1 L/min, 2 L/min, and 3 L/min. They discovered that a porosity of 0.35 was the most effective of all evaluated alternatives, and that raising the flow velocity resulted in lower surface temperatures of the PV panels. In a second investigation, Rahman *et al.* [25] used aluminum heat sinks and pulsed air cooling methods. To help lower the temperature of the solar cell, they configured a cooling circuit that connected a 6-inch plenum with five T-shaped pipes beneath it. Urdiroz *et al.* [26] investigated the impact of combining light captation and radiative cooling on biaxial solar panels and concluded that silica texturation significantly improves light captation, whereas encapsulating glass texturation increases the radiative cooling of the panel independent of the silica surface. Yang *et al.* [27] proposed a new cooling configuration with two humid channels: one in the conventional chiller (DPEC) to produce pre-cooled air and the other behind the photovoltaic panel. The proposed system promotes evaporation cooling by adding a humid channel to the back of the photovoltaic panel. The explanation above shows that the temperature of photovoltaic panels has a substantial impact on their efficiency, and cooling solar panels can assist maintain or improve that efficiency. Passive cooling and fan cooling are among the most basic, dependable, and cost-effective technologies available.

This study presents a novel technique to increasing the energy efficiency of solar panels using a modular and scalable cooling system created exclusively for these devices. In response to the major effect of temperature on solar panel performance, the study investigates the application of passive cooling technologies, which are known for their dependability, simplicity, and low cost. This study is unique in that it incorporates finned heat sinks that have been meticulously developed to enhance heat transmission while minimizing structural and economic restrictions. The technical analysis focuses on six essential parameters that influence heat dissipation: the contact surface with the back of the panel, the size of the base, the length of the fins, the non-finned surface, and the resistance to heat spreading. To obtain a balanced, high-performance arrangement, these elements were geometrically optimized with special care. This approach is part of a rigorous experimental framework intended to validate the proposed system's relevance under real-world operating situations.

This article is organized into five sections. Section 1 is an introduction; section 2 covers the many criteria that influence module efficiency; and section 3 covers materials and methodology. Section 4 contains the findings and discussion, and section 5 closes the paper with conclusions and recommendations for further research.

2. MATERIALS AND METHODOLOGY

The prototype shown is a passive cooling system for solar panels composed of aluminum U-shaped profiles with fins. These 50×50 U-profiles are designed to be installed on the surface of solar panels. The fins enhance the contact area with the surrounding air, which improves heat dissipation. The fins help to keep the temperature lower by absorbing the heat created by the solar panels, which improves efficiency and extends the panels' lifespan. As a passive cooling system, it does not rely on external power or active components like fans. Instead, it leverages natural convection to dissipate heat, making it energy-efficient and more dependable over time.

In this experimental work, an SX 55 U photovoltaic module was used, and its important technical features are listed in Table 1. The solar panel's performance was analyzed at 25 °C ambient conditions, 1000 W/m² irradiance, and 47 ± 2 °C NOCT. Under standard test conditions (STC), photovoltaic cells have an electrical efficiency of 18%, with a short-circuit current (Isc) of 3.69 A and an open-circuit voltage (Voc) of 20.6 V. To improve heat dissipation, aluminum fins were added on the module's back side to act as heat absorbers. Figure 1 depicts a cooling circuit constructed specifically for this study.

Table 1. Electrical characteristic

Characteristic	BP SX 55	BP SX 60	BP SX 65
Maximum power (Pmax)	55 W	60 W	65 W
Voltage at Pmax (Vmp)	16.5 V	16.8 V	17.2 V
Current at Pmax (Imp)	3.33 A	3.56 A	3.77 A
Guaranteed minimum Pmax	50 W	55 W	60 W
Short-circuit current (Isc)	3.69 A	3.87 A	4.06 A
Open-circuit voltage (Voc)	20.6 V	21.0 V	21.5 V
Temp. Coefficient of Isc	(0.065±0.015)%/°C	(0.065±0.015)%/°C	(0.065±0.015)%/°C
Temp. Coefficient of Voc	-(80±10) mV/°C	-(80±10) mV/°C	-(80±10) mV/°C
Temp. Coefficient of power	-(0.5±0.05)%/°C	-(0.5±0.05)%/°C	-(0.5±0.05)%/°C
NOCT		47±2 °C	

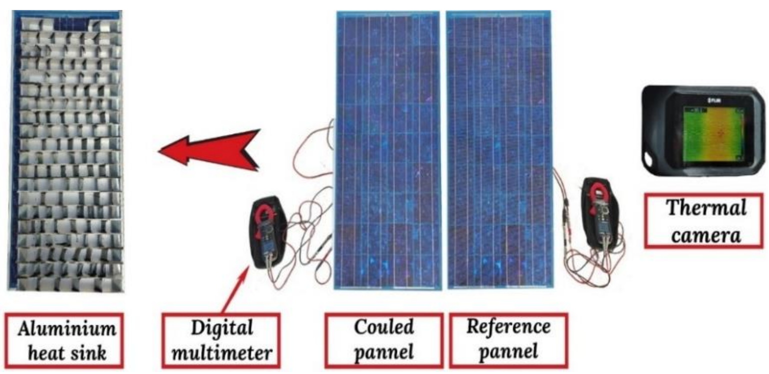

Figure 1. Depicts an overview of the experimental setup, including two panels (cooled and reference) with measurement instruments

2.1. Description

The experiment involved two identical PV panels installed side by side in similar climatic conditions. One of the panels was fitted with a passive thermal cooling system (hereinafter referred to as the cooled panel), whereas the other was left in its original state with no cooling mechanism. This design enables a direct and thorough comparison of the thermal and electrical performance of both systems.

2.2. Experimental setup

The cooling solution for the cooled panel is an aluminum finned heat sink constructed using optimization criteria specified within the scope of this study. This heat sink is mounted to the back of the panel to minimize temperature rise. It is predicted to improve the module's overall energy efficiency.

2.3. Instrumentation and measurement protocols

Thermal measurements: An infrared thermal camera was used to capture the temperature of both panels, allowing for a quick and accurate measurement of the temperature distribution across the entire module surface. This method gives a detailed representation of the system's thermal behavior both with and without cooling.

Electrical measurements: A high-precision digital multimeter was used to measure key electrical characteristics such as open-circuit voltage (Voc) and short-circuit current (ISc). These measurements were obtained every 30 minutes from 9:30 a.m. to 3:00 p.m., which corresponds to the peak daily sun irradiance period.

2.4. Objective of the experimentation

This methodology seeks to give trustworthy comparative data for determining the effectiveness of the proposed passive cooling system. The thermal and electrical influence of the cooling system on the performance of solar panels may be reliably quantified due to measurement repeatability and consistency of exposure circumstances.

3. RESULTS AND DISCUTION

Figure 2 depicts the average temperatures obtained by taking ten readings per hour. At 13:00, the cooled panel attained a maximum temperature of 60.4 °C, while the reference panel reached a peak of 77.2 °C. Notably, these maximum temperatures corresponded to the highest ambient temperature observed throughout the experiment. During testing, the cooled module maintained an average temperature of 46.15 °C, compared to 54.28 °C for the reference module. The thermally improved PV module reduced temperatures by 8.13 °C compared to the uncooled panel. Figure 3 demonstrates that the temperature reduction can reach as much as -36% at 11 a.m., demonstrating the system's efficiency.

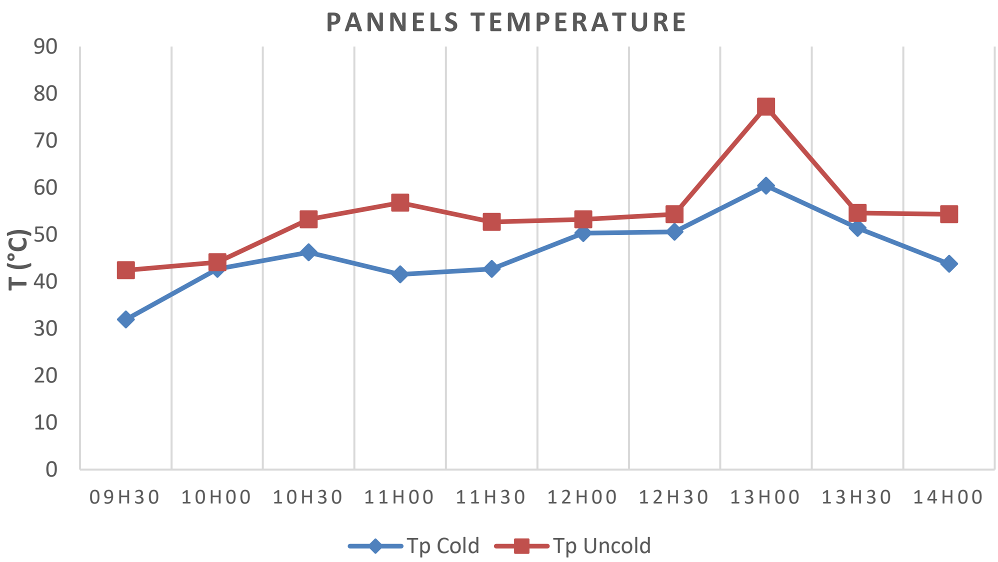

Figure 2. Temperature comparison of cooled and uncooled panels

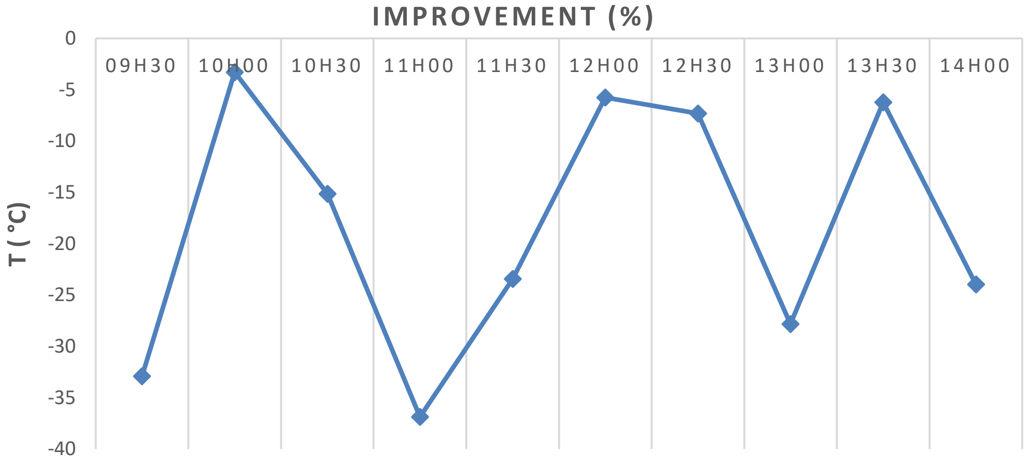

Figure 3. Improvement in temperature between both modules

According to the measurements, the highest open-circuit voltage for the referenced module was 18.87 V, while the cooled module had 19.35 V. The referenced module's lowest open-circuit voltage is 18.03 V, while the cooled panel's is 18.47 V. The referenced and cooled modules have an average open-circuit voltage of 18.32 and 18.83 V, respectively. This translates to a 0.51 V difference, indicating that the cooling operation was successful in improving the module's open-circuit voltage by approximately 0.51 V. The open-circuit voltages of the two PV modules are depicted in Figure 4, and Figure 5 depicts the system efficiency between 09:30 and 14:00; the maximum recorded value is 4.32%, while the lowest is 0.26% at 10 a.m.

Comparing results obtained from the current study to other works as presented in Table 2, Cooling treatments using phase change materials reduced temperatures by 8.1 °C [10], while polycarbonate sheets decreased temperatures by 6.02 °C [16]. Using soybean wax as a phase change material resulted in a temperature reduction of 6 °C [19]. Aluminum heat sinks reduced temperatures by 7.5 °C [23], whereas forced convection by fans decreased temperatures by 6.24 °C [28]. A DC brushless fan reduced temperature by 6.1 °C [29], whereas general fan cooling resulted in a 7 °C decrease [30]. A DC brushless air cooling mechanism caused a 2.56 °C decline [31]. Yellow petroleum jelly reduced temperature by 4.3 °C [32], while fin cooling achieved a 5.9 °C reduction [33]. Microencapsulated phase change materials reduced temperature by 1.8 °C [34], whereas heat sink fins resulted in a 7.4 °C decrease [35]. Evaporative cooling resulted in an 8 °C reduction [36], while CPU heat sinks reduced by 2.98 °C [37]. The current investigation found that employing aluminum heat sinks resulted in an 8.13 °C temperature reduction, it is clear that the temperature reduction achieved in this study outperforms that reported in most earlier studies by other researchers.

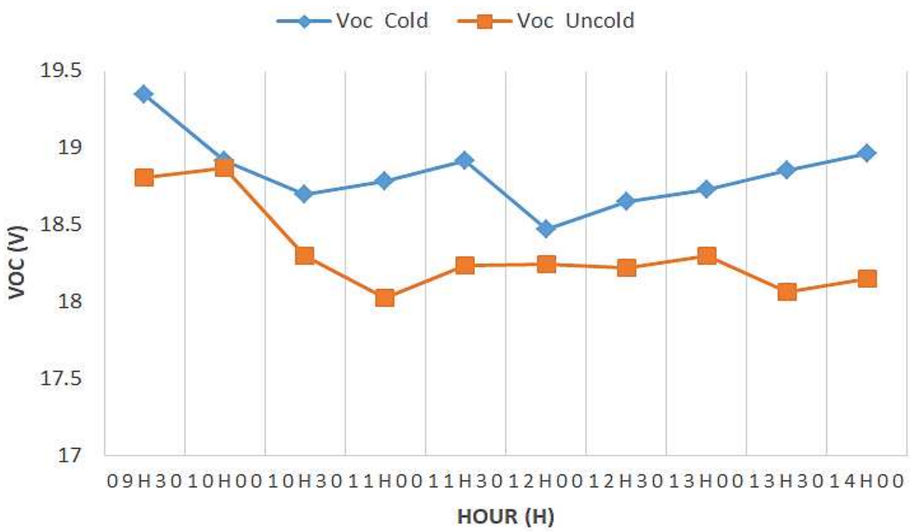

Figure 4. Open-circuit voltage comparison of cooled and uncooled panels

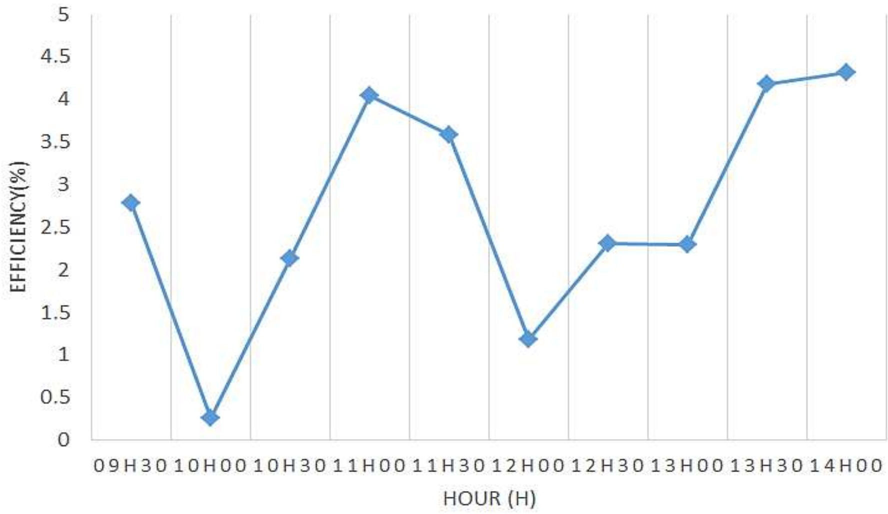

Figure 5. Panel open circuit voltage efficiency

Table 2. Results of prior studies for comparison

References	Cooling mechanism	Temperature reduction (°C)
[10]	Phase change material cooling treatment	8.1
[16]	polycarbonate films	6.02
[19]	Soybean wax as a phase change material	6
[23]	aluminum heat sinks	7.5
[28]	Forced convection induced fans	6.24
[29]	DC brushless fan	6.1
[30]	Fan cooling	7
[31]	DC brushless air-cooling mechanism	2.56
[32]	Yellow petroleum jelly	4.3
[33]	Fin cooling	5.9
[34]	Microencapsulated phase change material	1.8
[35]	Heat sink fins	7.4
[36]	Evaporative cooling principle	8
[37]	CPU heat sinks	2.98
Current study	aluminum heat sinks	8.13

4. CONCLUSION

The paper describes an innovative and practical way to passive cooling of solar panels using aluminum heat sinks. This method is especially useful in low-resource environments because it is simple to install, affordable, and versatile. The remarkable improvement in performance seen, notably the 8.13 °C drop in temperature and the 0.51 V gain in open-circuit voltage, testifies to the genuine promise of this technology for boosting the energy efficiency of solar installations.

Aside from the experimental results, the work presented opens up exciting possibilities for the development of more efficient and sustainable photovoltaic systems. The examination of heatsink design provides real avenues for thermal optimization, whilst integration with phase-change materials opens the door to intelligent hybrid solutions. This work aligns with current energy transition challenges by enhancing installation performance and longevity, offering a solid foundation for practical research at various scales of solar operation.

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