IKR Publishers

IKR Journal of Engineering and Technology (IKRJET)
Journal homepage: https://ikrpublishers.com/ikrjet/
Volume-2, Issue-4 (July-August) 2026

OPEN ACCESS
ISSN: 3107-7331 (Online)

Performance Evaluation of Thermal Regulation Methods for Photovoltaic Systems: A Case Study of PV Installation at Kwara State Polytechnic Diagnostic Centre

Saadu G. [1*], Lawal O. A.[2] & Bello B. A.[3]

[1,2,3]Department of Electrical and Electronic Engineering, Institute of Technology, Kwara State Polytechnic, Ilorin

DOI:*10.5281/zenodo.21443577*

ARTICLE INFO

Article history:
Received : 02-07-2026
Accepted : 11-07-2026
Available online : 19-07-2026

Citation: Saadu G., Lawal O. A. & Bello B. A. (2026). Performance Evaluation of Thermal Regulation Methods for Photovoltaic Systems: A Case Study of PV Installation at Kwara State Polytechnic Diagnostic Centre. *IKR Journal of Engineering and Technology (IKRJET), 2*(4), 62-72.

ABSTRACT **Original Research Article**

The performance of photovoltaic (PV) systems is significantly affected by operating temperature, particularly in tropical climates, where elevated module temperatures reduce conversion efficiency and power output. This study evaluates the effectiveness of passive thermal regulation using heat sinks on the performance of an 8 kWp photovoltaic system installed at the Diagnostic Centre of Kwara State Polytechnic, Ilorin, Nigeria. Experimental measurements were carried out under representative operating conditions between 08:00 and 16:00 h for two distinct scenarios, viz before and after heat sink implementation. Solar irradiance, ambient temperature, module temperature, output voltage, and current were monitored. Results showed that the maximum module temperature decreased from 70°C to 56°C after the introduction of heat sinks, representing a 14°C reduction. Peak output power increased from 6.32kW to 6.96kW, corresponding to a power enhancement of 10.02 %. The module efficiency improved from 15.82% to 17.40%, while the performance ratio increased from 79.05% to 86.98%. Daily energy yield increased from 37.94kWh/day to 41.75kWh/day and capacity factor improved from 19.8% to 21.7%. The results demonstrate that passive heat sink cooling offers a simple and cost-effective approach for mitigating temperature-induced losses in photovoltaic systems operating under tropical environments. The findings further establish the suitability of thermal regulation techniques for enhancing energy reliability and operational efficiency of standalone solar installations used for critical healthcare applications.

Keywords: Photovoltaic Systems, Thermal Regulation, Heat Sink Cooling, Module Efficiency, Performance Ratio, Energy Yield.

**Corresponding author: Saadu G.*
Department of Electrical and Electronic Engineering, Institute of Technology, Kwara State Polytechnic, Ilorin

Introduction

The growing global demand for sustainable, environmentally friendly energy sources has significantly increased interest in renewable energy technologies. Solar energy remains one of the most promising sources due to its abundance, environmental friendliness, and suitability for both grid-connected and standalone applications (IRENA, 2023; REN21, 2024). PV systems convert solar radiation directly into electrical energy without emitting greenhouse gases, making them highly attractive for residential, commercial, and industrial applications (IEA, 2023). In developing countries such as Nigeria, where unreliable grid electricity and frequent power outages persist, photovoltaic systems offer a practical and economic alternative for powering essential facilities (Oladipo & Adeyemi, 2023).

Healthcare facilities require uninterrupted electricity supply to ensure sustainable operation of critical medical equipment and maintain the quality of patient care. Diagnostic centers, laboratories, and clinics rely heavily on stable power for medical imaging, testing, and emergency procedures. In response to frequent grid interruptions, solar photovoltaic systems connected with battery storage and inverters have become increasingly adopted in healthcare infrastructure to improve energy reliability and reduce dependence on diesel generators (Sharaf et al., 2022).

Kwara State Polytechnic, Ilorin, conducted an energy audit at assess energy consumption patterns and identify opportunities for efficiency improvements in institutional buildings. Energy auditing has been widely recognized as an essential tool for optimizing energy use and integrating renewable energy solutions in public facilities (Ojo et al., 2023). The Diagnostic Center within the institution plays a critical role in healthcare service delivery by providing patient diagnosis, laboratory testing, and medical examinations. The facility comprises consulting rooms, waiting areas, offices, and sanitation units, all of which require continuous electricity supply for effective operation. The audit identified the Diagnostic Centre as one of the major energy-consuming units due to its extensive use of electrical and medical equipment (Ojo et al., 2023).

The Diagnostic Center operates a standalone photovoltaic system comprising a 10 kVA inverter and battery storage. This system has significantly reduced reliance on the national grid and diesel generators, thereby improving energy reliability and environmental sustainability (IEA, 2023). However, despite these advantages, the performance of photovoltaic systems is strongly affected by environmental conditions, particularly temperature (Kumar & Singh, 2022).

Photovoltaic modules are typically rated under standard test conditions of 1000 W/m² irradiance and a cell temperature of 25°C. In tropical regions, such as Nigeria, module temperatures often rise significantly above this standard due to high ambient temperatures and high solar radiation intensity. These elevated temperatures negatively affect PV performance by reducing open-circuit voltage and total conversion efficiency (Kumar & Singh, 2022). A significant portion of incident solar energy is also lost as heat, which further reduces system efficiency (Wang et al., 2021).

Nigeria receives high levels of solar irradiation, ranging from 4 to 7 kWh/m²/day, indicating strong potential for solar energy utilization (REN21, 2024). However, high ambient temperatures in tropical climates lead to higher PV module operating temperatures, reducing system output performance and negatively affecting efficiency (IRENA, 2023). This challenge makes thermal management strategies highly necessary for improving photovoltaic system performance.

Thermal regulation techniques for photovoltaic systems are generally classified into passive and active cooling methods. Active cooling methods include water circulation, forced-air cooling, and water-spraying systems. Although these methods are effective at reducing temperature, they often require additional energy input, increased maintenance, and higher operational costs (Sharaf et al., 2022). On the other hand, passive cooling methods rely on natural convection and enhanced heat-dissipation structures, without requiring external energy (Wang et al., 2021). Examples include heat sinks, fins, phase change materials, and heat spreaders, which are simple, cost-effective, and reliable.

Heat sinks enhance heat dissipation by increasing the surface area available for convective heat transfer between the PV module and the surrounding air. This reduces module temperature, thereby improving electrical performance and efficiency (Kumar & Singh, 2022). Heat sink cooling is particularly useful in tropical regions where high ambient temperatures make thermal management critical for system efficiency.

Although several studies have explored PV cooling techniques, most have focused on laboratory-scale systems or climates different from those in sub-Saharan Africa (Sharaf et al., 2022; Wang et al., 2021). Furthermore, limited research has examined passive heat-sink cooling in standalone PV systems used in healthcare facilities at Nigerian tertiary institutions. This creates a need for localized studies that reflect real operating conditions in tropical environments.

The energy audit conducted at Kwara State Polytechnic emphasizes the importance of improving energy efficiency and optimizing renewable energy systems within institutional facilities (Ojo et al., 2023). The Diagnostic Centre, due to its critical healthcare functions and energy demand, requires a highly reliable power supply. Therefore, maximizing the performance of its photovoltaic system is essential for ensuring uninterrupted healthcare services and minimizing energy losses.

This study investigates the effectiveness of passive heatsink cooling in improving the performance of a standalone photovoltaic system at the Diagnostic Center of Kwara State Polytechnic. Experimental measurements obtained under tropical conditions are used to evaluate the effect of thermal regulation on module temperature, output power, efficiency, performance ratio, energy yield, and capacity factor. Comparing pre-cooling and post-cooling conditions provides insight into the practical benefits of passive thermal management.

Specifically, the study aims to determine PV module temperature behavior under normal conditions, evaluate the effect of heat sink cooling on temperature reduction, analyze the impact on voltage, current, and power output, assess improvements in efficiency and performance ratio, and determine changes in energy yield and capacity factor.

Materials and Methods

Description of the Existing Photovoltaic System

The Diagnostic Centre is powered by a standalone photovoltaic system comprising a 10 kVA inverter and a lithium-ion battery storage system. The photovoltaic array consists of 40 Canadian Solar monocrystalline modules rated at 200 W each, for a total installed capacity of 8 kWp

(IRENA, 2023). Each module possesses an open-circuit voltage of 21.6 V, a short-circuit current of 10.5 A, a maximum voltage of 19 V, and a maximum current of 9.7 A. The dimensions of each module are 1500 mm × 680 mm × 35 mm.

Power conversion is achieved with a 10 kVA MPP Solar inverter, delivering an effective output power of 8 kW. The inverter operates at 50 Hz and delivers an AC output voltage of 220-230 V. Energy storage is provided by a 15 kWh lithium-ion battery operating at 48 V, which ensures continuous supply during periods of low irradiance and nighttime operation (IEA, 2023).

The installed system provides electrical power for critical medical equipment and essential loads within the Diagnostic Centre, thereby ensuring operational reliability and improved energy sustainability.

Heat Sink Cooling Arrangement

Thermal regulation of the photovoltaic modules was achieved using passive heat sink cooling. Heat sinks are metallic structures attached to the rear surface of photovoltaic modules to enhance heat dissipation through natural convection (Kumar & Singh, 2022). The increased surface area of the heat sink facilitates the effective transfer of heat from the photovoltaic cells to the surrounding environment.

Unlike active cooling methods, which require auxiliary components such as pumps and fans, passive heat sink cooling consumes no additional energy and requires minimal maintenance (Sharaf et al., 2022). Consequently, it provides a cost-effective, reliable solution suitable for tropical climates.

The heat sink arrangement was selected for its simplicity, durability, and ability to improve heat transfer without increasing energy consumption in the photovoltaic system.

Experimental Procedure

The experimental investigation was carried out under representative tropical operating conditions between 08:00 h and 16:00 h. Measurements were obtained at one-hour intervals under two operating conditions (Wang et al., 2021).

The first stage involved operating the photovoltaic system under normal conditions, without thermal regulation. During this stage, measurements of solar irradiance, ambient temperature, module temperature, output voltage, and output current were recorded.

Subsequently, passive heat sinks were attached to the rear surface of the photovoltaic modules, and the same measurements were repeated under comparable weather conditions. This enabled the evaluation of the influence of heat sink cooling on the thermal and electrical performance of the photovoltaic system (Kumar & Singh, 2022).

The output power of the system under both conditions was determined from the measured voltage and current. The performance of the system was subsequently evaluated based on module temperature reduction, output power enhancement, conversion efficiency, performance ratio, daily energy yield, and capacity factor (Ojo et al., 2023).

Performance Evaluation Parameters

The effectiveness of heat sink cooling was evaluated using several performance indices commonly employed in photovoltaic studies (Sharaf et al., 2022).

The electrical output power of the system was determined from the product of the output voltage and current. The conversion efficiency was evaluated by comparing the electrical power generated by the photovoltaic array with the incident solar power on the modules.

The temperature reduction achieved after the introduction of heat sinks was determined by comparing the module temperatures before and after cooling. Similarly, the percentage improvement in power output was calculated by comparing the power outputs under both operating conditions.

Other performance indices considered include the performance ratio, daily energy yield, and capacity factor. These parameters provide useful information regarding the total performance and energy production capability of the photovoltaic system.

Mathematical Formulation

These mathematical relationships were employed to evaluate the effect of heat sink cooling on the thermal and electrical performance of the photovoltaic system installed at the Diagnostic Centre of Kwara State Polytechnic.

The output power generated by the photovoltaic system is expressed as

$$P=VI \tag{1}$$

where P is the output power (W), V is the output voltage (V), and I is the output current (A).

The module efficiency is given by

$$\eta = \frac{P_{out}}{G \times A} \times 100 \tag{2}$$

where P_{out} is the electrical output power, G is the solar irradiance (W/m²), and A is the total area of the photovoltaic array (m²) (Kumar & Singh, 2022).

The temperature reduction due to heat sink cooling is evaluated using:

$$\Delta T = T_a - T_b \tag{3}$$

where Tb and Ta represent the module temperatures before and after cooling, respectively.

The percentage improvement in power output is determined from

$$\Delta P = \frac{P_a - P_b}{P_b} \times 100 \tag{4}$$

where P_a and P_b are the output powers after and before cooling, respectively.

The performance ratio is expressed as

$$PR = \frac{P_{actual}}{P_{rated}} \times 100 \tag{5}$$

The daily energy yield is determined using

$$E = P_{avg} \times t \quad 6$$

Where P_{avg} represents the average power output and (t) denotes the effective sunshine duration.

The capacity factor is obtained from

$$CF = \frac{E_{daily}}{P_{rated} \times 24} \times 100 \quad 7$$

Where CF = Capacity Factor, E_{daily}= Daily energy generated or produced kWh/day

Prated = Rated power of the system (kW), 24= Number of hours in a day and 100 = Conversion of the result to percentage.

The capacity factor indicates how effectively a power system is utilized compared to its maximum possible output.

Results and Discussion

Experimental Data Before Cooling

Table 1 presents the measured values of solar irradiance, ambient temperature, module temperature, output voltage, and output current obtained before heat sink cooling was applied. Irradiance increased steadily throughout the morning, reaching its maximum around noon. This behavior is typical of photovoltaic systems operating in tropical climates. Several studies have reported that increasing irradiance generally increases current generation, while excessive temperature rise reduces voltage output and the conversion efficiency (Wang et al., 2021; Sharaf et al., 2022).

The module temperature increased continuously from 36°C at 08:00 h to a maximum value of 70°C at 13:00 h. The corresponding voltage reduced from 730V to 690V, indicating the adverse effect of temperature on photovoltaic performance. Elevated temperatures are known to increase internal resistance and reduce the open-circuit voltage of photovoltaic modules, thereby decreasing the available electrical power (Sharaf et al., 2022). Similar observations were reported by Ibrahim et al. (2023), who showed that temperature rise remains one of the major causes of efficiency degradation in photovoltaic systems (Ibrahim et al., 2023).

Table 1: Experimental data before Heat Sink Cooling

S/N	Time (h)	Irradiance (W/m²)	Ambient Temperature (°C)	Module Temperature (°C)	Voltage (V)	Current (A)
1.	08:00	520	27	36	730	7.1
2.	09:00	670	29	44	720	7.8
3.	10:00	810	31	53	710	8.4
4.	11:00	910	33	61	700	8.9
5.	12:00	980	34	68	695	9.1
6.	13:00	950	35	70	690	9.0
7.	14:00	900	34	67	695	8.8
8.	15:00	820	33	62	705	8.5
9.	16:00	700	31	56	715	8.0

The experimental results obtained before the implementation of passive heat sink cooling are further presented graphically to provide a clearer understanding of the thermal and electrical behavior of the photovoltaic system under normal operating conditions. The graphical analysis illustrates the relationships among solar irradiance, module temperature, ambient temperature, voltage, current, and output power, thereby enabling a comprehensive assessment of the influence of temperature on photovoltaic performance under tropical climatic conditions.

Fig. 1: Voltage versus Current

The voltage-to-current characteristics of the photovoltaic system before heat sink cooling indicate that as solar irradiance increased during the daytime, the output current increased from 7.1A to 9.1A. In contrast, the output voltage gradually decreased from 730V to 690V. This reduction in voltage can be attributed to an increase in module operating temperature, which reached 70°C. The graph shows the negative effect of elevated temperatures on photovoltaic voltage performance under tropical operating conditions, leading to reduced power conversion efficiency.

Fig. 2: Irradiance versus Time

The irradianceversustime graph shows the typical solar radiation profile experienced under tropical climatic conditions. Solar irradiance increased progressively from 520 W/m² at 08:00 h to a peak of 980 W/m² at 12:00 h, then gradually decreased towards the evening. The increase in irradiance contributed to higher current generation; however, the associated rise in module temperature negatively affected the photovoltaic performance.

Fig. 3: Ambient and Module Temperature versus Time

The graph of ambient and module temperatures reveals that the photovoltaic module temperature increased substantially above the ambient temperature throughout the experimental period. While the ambient temperature ranged from 27°C to 35°C, the module temperature increased from 36°C to 70°C. This significant temperature rise confirms the accumulation of thermal energy within the photovoltaic cells, leading to increased thermal losses and reduced electrical performance.

Fig. 4: Module Temperature versus Voltage

The relationship between module temperature and output voltage demonstrates an inverse correlation. As the module temperature increased from 36°C to 70°C, the output voltage decreased from 730V to 690V. This behavior confirms the well-established effect of temperature on photovoltaic cells, where elevated operating temperatures reduce the semiconductor band-gap voltage and consequently decrease electrical output performance.

Fig. 5: Module Temperature versus Output Power

The graph illustrates the influence of module temperature on output power generation before cooling. Although power output initially increased with rising irradiance, excessive module temperatures above 65°C limited further improvement in electrical output. The peak power generated before cooling was 6.324 kW, indicating that thermal losses significantly affected the photovoltaic system's overall performance.

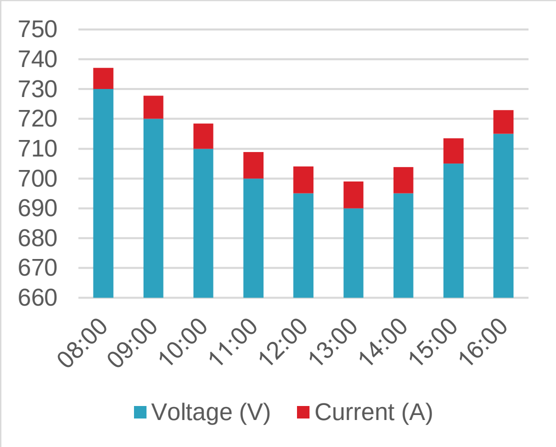

Fig. 1: Voltage Vs Current

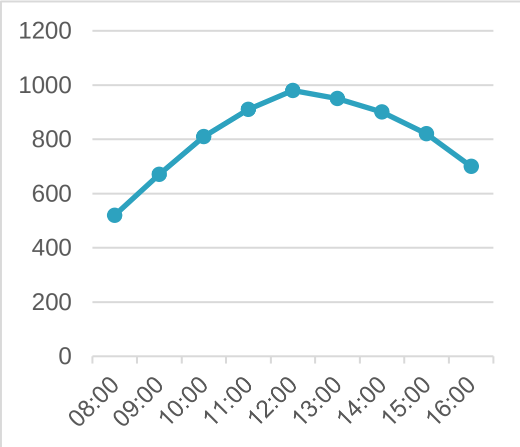

Fig. 2: Irradiance vs Time

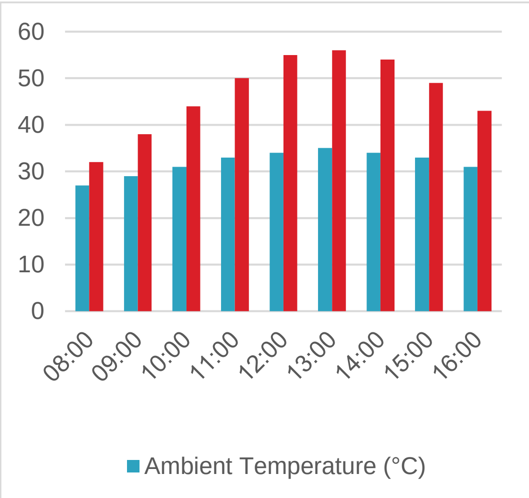

Fig. 3: Ambient and Module Temp. Vs Time

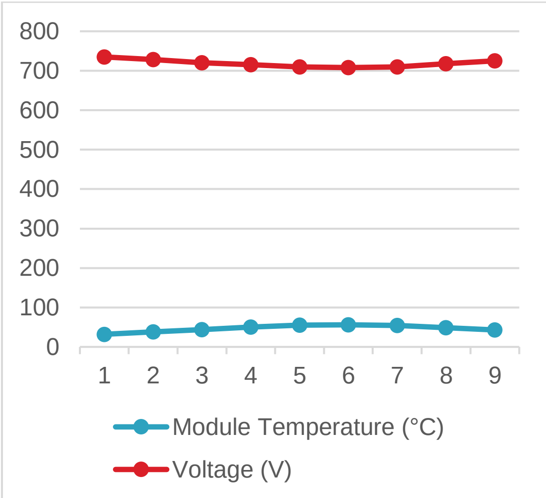

Fig.4: Modulated Temp. Vs Voltage

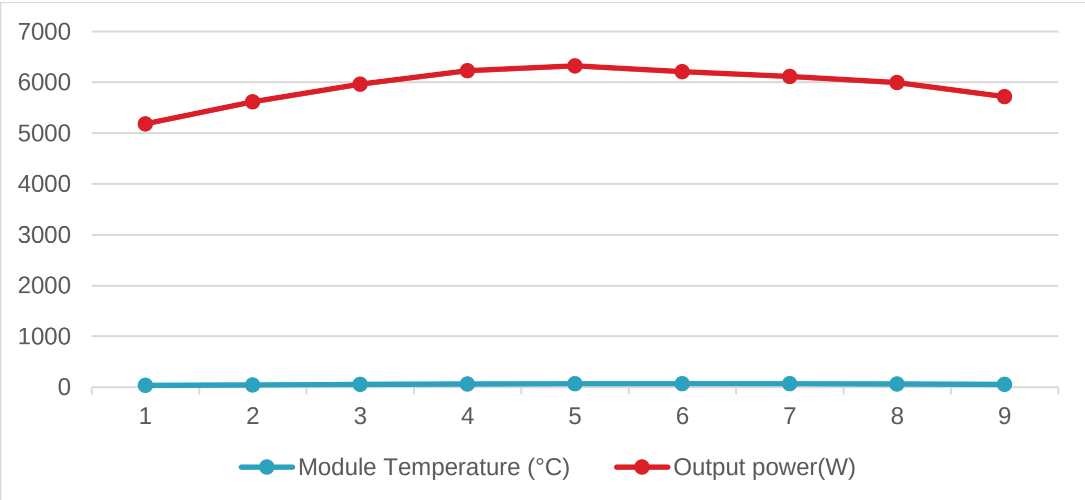

Fig. 5: Modulated Temp. Vs Output power

Experimental Data after Heat Sink Cooling

Table 2 presents the measured parameters after the implementation of passive heat sink cooling. A noticeable reduction in module temperature was observed throughout the day. The maximum temperature recorded after cooling was 56 °C compared to 70 °C before cooling. The reduction in operating temperature increased voltage and current, resulting in improved output power.

Passive cooling techniques have attracted considerable attention because they require no external energy input and require minimal maintenance (Jiao & Li, 2023). Comparative studies on photovoltaic cooling technologies have shown that passive methods such as fins, heat sinks, and phase change materials are particularly suitable for standalone systems operating in high-temperature regions (Journal of Cleaner Production, 2023). Moreover, recent reviews have emphasized that passive cooling enhances reliability and reduces operational complexity when compared with active cooling systems (Renewable and Sustainable Energy Reviews, 2024).

Table 2: Experimental data after Heat Sink Cooling

S/n	Time (h)	Irradiance (W/m²)	Ambient Temperature (°C)	Module Temperature (°C)	Voltage (V)	Current (A)
1.	08:00	520	27	32	735	7.2
2.	09:00	670	29	38	728	8.0
3.	10:00	810	31	44	720	8.8
4.	11:00	910	33	50	715	9.4
5.	12:00	980	34	55	710	9.8
6.	13:00	950	35	56	708	9.7
7.	14:00	900	34	54	710	9.5
8.	15:00	820	33	49	718	9.0
9.	16:00	700	31	43	725	8.4

To evaluate the effectiveness of passive heat sink cooling, the experimental results obtained after installing the heat sink arrangement are also presented graphically. The graphical representations facilitate direct observation of the improvements in thermal regulation, voltage stability, current generation, and power output achieved through passive cooling. The analysis provides a comparative assessment of the photovoltaic system performance under cooled operating conditions.

Fig.6: Voltage versus Current (After Heat Sink Cooling)

Following the implementation of passive heat-sink cooling, both voltage and current improved noticeably. The output voltage remained relatively stable between 735 V and 708V, while the current increased to a maximum value of 9.8A. The improved electrical characteristics demonstrate the effectiveness of heat sink cooling in reducing temperature-induced voltage losses and enhancing photovoltaic performance.

Fig. 7: Irradiance versus Time (After Heat Sink Cooling)

The irradiance profile after heat sink installation remained similar to that obtained before cooling, confirming that the observed performance improvement resulted primarily from thermal regulation rather than changes in solar radiation intensity. The peak irradiance remained approximately 980 W/m², providing a reliable basis for comparing the photovoltaic system's performance under both operating conditions.

Fig. 8: Ambient and Module Temperature versus Time (After Heat Sink Cooling)

The temperature profile after heat sink installation demonstrates a significant reduction in module operating temperature. While the ambient temperature remained within the same range of 27°C to 35°C, the maximum module temperature decreased from 70°C to 56°C. This reduction confirms the effectiveness of passive heat sink cooling in enhancing heat dissipation through natural convection under tropical environmental conditions.

Fig. 9: Module Temperature versus Voltage (After Heat Sink Cooling)

The temperature-voltage graph of the module after cooling shows that lower operating temperatures led to improved voltage performance. Despite increases in irradiance throughout the day, the output voltage remained relatively stable because the heat sink effectively mitigated thermal degradation. This improvement demonstrates the importance of thermal regulation in maintaining photovoltaic efficiency.

Fig.10 Module Temperature versus Output Power (After Heat Sink Cooling)

The module temperature-output power graph confirms that passive heat sink cooling significantly improved the electrical performance of the photovoltaic system. Despite maintaining module temperatures below 56°C, the system achieved a peak output power of 6.958 kW, representing approximately a 10.02% improvement over the normal operating condition. The results demonstrate that effective thermal management can substantially improve energy harvesting capability in photovoltaic systems operating under tropical climatic conditions.

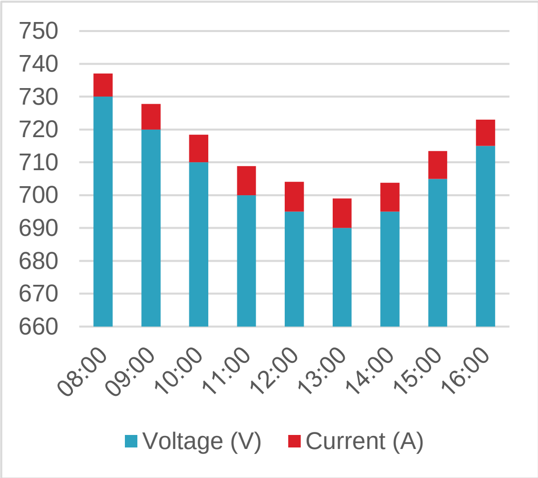

Fig. 6: Voltage Vs Current (cooled)

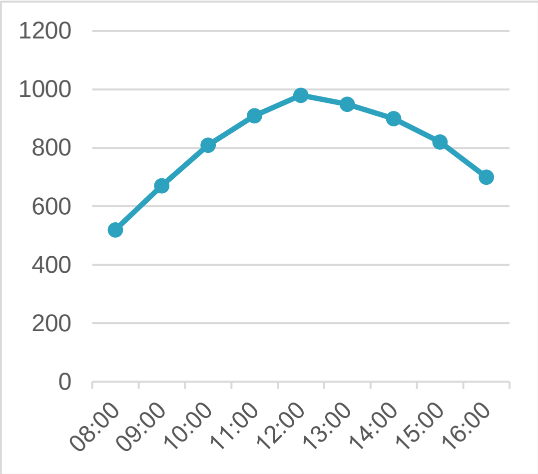

Fig. 7: Irridance Vs Time

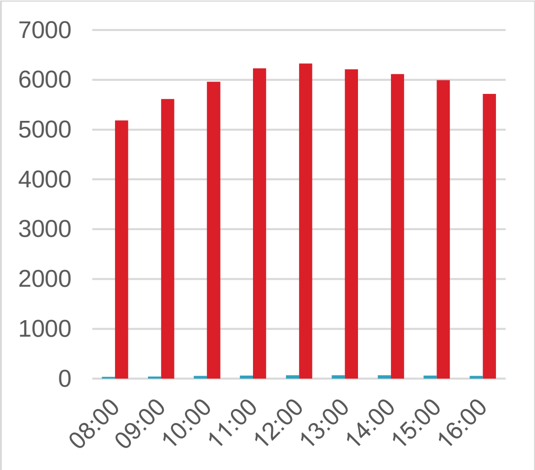

Fig. 8: Ambient and Modulated Temp. Vs Time

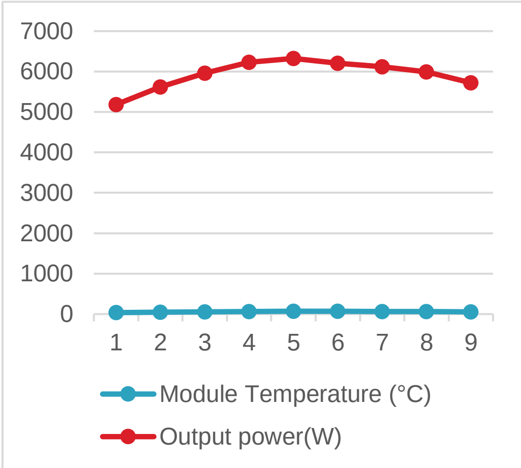

Fig. 9: Module Temp. Vs Voltage

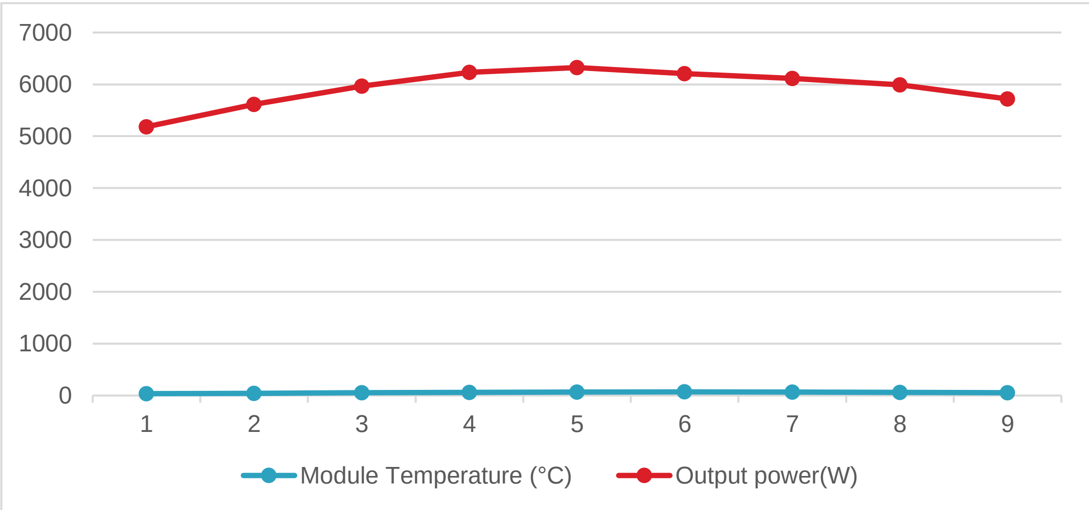

Fig. 10: Modulated Temp. Vs Output power

Effect of Heat Sink Cooling on Module Temperature

The effectiveness of heat sink cooling is demonstrated by a reduction in module temperature from 70 °C to 56 °C, a decrease of 14 °C. Reducing temperature is an important way to improve photovoltaic efficiency, as only a small fraction of incident solar energy is converted into electrical power. In contrast, the remaining energy is dissipated as heat (Ibrahim et al., 2023).

The reduction confirms that the heat sink arrangement enhanced natural convection between the photovoltaic modules and the surrounding atmosphere. Similar findings have been reported in recent investigations where passive cooling arrangements significantly lowered cell temperature and improved electrical efficiency (Journal of Cleaner Production, 2023; Solar Energy, 2023). Emerging studies have further demonstrated that thermal management plays an important role in prolonging module lifespan and minimizing thermal degradation (Renewable and Sustainable Energy Reviews, 2024).

The temperature reduction is given by:

$$\Delta T = \Delta T = T_a - T_b$$

At peak conditions,

$$\Delta T = 70 - 56 = 14\ °C$$

The 14 °C reduction in module temperature demonstrates the effectiveness of passive heat-sink cooling in promoting heat dissipation via natural convection.

Output Power Analysis

The output power increased from 6.324 kW before cooling to 6.958 kW after cooling, representing an improvement of approximately 10.02%. The increase in output power can be attributed to the lower operating temperature achieved after installing heat sinks.

Temperature-induced power losses have been widely reported in photovoltaic systems operating under high irradiance conditions (Sharaf et al., 2022). Ibrahim et al. (2023) further reported that increasing cell temperature causes a significant reduction in voltage and power output, thereby lowering system efficiency. Likewise, comparative analyses of photovoltaic cooling technologies have shown that temperature regulation directly enhances power output and improves energy harvesting (Journal of Cleaner Production, 2023).

The output power generated by the photovoltaic system was determined from

$$P = VI$$

The electrical output power before cooling was calculated as the product of the output voltage and current:

$$P_b = V_b \times I_b$$

At peak irradiance before cooling,

$$P_b = 695 \times 9.1$$

$$P_b = 6324.5\text{W}$$

Similarly, after the application of the cooling system, the output power was determined using:

$$P_a = V_a \times I_a$$

$$P_a = 710 \times 9.8$$

$$P_a = 6958\text{W}$$

Table 3: Output Power Comparison

S/N	Condition	Voltage (V)	Current (A)	Power (W)
1	Before Cooling	695	9.1	6324.5
2	After Cooling	710	9.8	6958

The power improvement obtained after cooling was calculated as

$$\Delta P = \frac{P_a - P_b}{P_b} \times 100$$

Substituting the given values:

$$\Delta P = \frac{6958\text{-}65324.5}{65324.5} \times 100$$

First, compute the difference:

$$6958 - 6324.5 = 633.5$$

Then divide by the initial value:

$$\frac{633.5}{6324.5} = 0.1002$$

The percentage increase in power:

$$\Delta P = 0.1002 \times 100 = 10.02\%$$

The increase in power output confirms that reducing temperature significantly enhances photovoltaic performance.

Module Efficiency Analysis

The module efficiency increased from 15.82% to 17.40% after cooling. This improvement is primarily due to reduced thermal losses resulting from the heat sink arrangement. The findings indicate that thermal regulation contributed positively to the energy conversion process.

According to recent investigations, photovoltaic efficiency decreases considerably when operating temperatures exceed standard test conditions (Renewable and Sustainable Energy Reviews, 2024). Some Authors have demonstrated that effective cooling techniques can restore some of the efficiency losses associated with elevated cell temperatures (Wang et al., 2021; Solar Energy, 2023). The efficiency magnitudes obtained in this study are consistent with those reported for monocrystalline photovoltaic modules operating under tropical conditions (Ibrahim et al., 2023).

The area of one photovoltaic module is given by:

$$A_m = 1.5 \times 0.68$$

$$A_m = 1.02\text{m}^2$$

Therefore, the total area of 40 modules is:

$$A = 40 \times 1.02\text{A} = 40.8\text{m}^2$$

The incident solar power at an irradiance of 980 W/m2 is:

$$Pin = 980 \times 40.8$$

$$Pin = 39{,}984\ \text{W}$$

Before cooling, the efficiency is calculated as:

$$\eta b = \frac{6324.5}{39984} \times 100$$

$$\eta b = 15.82\%$$

After cooling, the efficiency becomes:

$$\eta a = \frac{6858}{39984} \times 100$$

$$\eta a = 17.40\%$$

Table 4: Module Efficiency

S/N	Condition	Efficiency (%)
1.	Before Cooling	15.82
2.	After Cooling	17.40

The increase in efficiency demonstrates the beneficial effect of heat sink cooling in minimizing thermal losses.

Performance Ratio Analysis

The performance ratio increased from 79.05% before cooling to 86.98% after cooling. The performance ratio is an important indicator for assessing the quality and effectiveness of photovoltaic installations. Higher performance ratios indicate better utilization of installed capacity and reduced system losses.

Recent studies have shown that thermal regulation and proper maintenance significantly influence performance ratio values and overall energy yield (Milan et al., 2025). Improvements in performance ratio after cooling have also been reported in several investigations involving passive thermal management systems (Journal of Cleaner Production, 2023).

For an installed capacity of 8 kWp,

Before cooling, the performance ratio (PR) is calculated as:

$$PR_b = \frac{6.324}{8} \times 100$$

$$PR_b = 79.05\%$$

After cooling, the performance ratio becomes:

$$PR_a = \frac{6.958}{8} \times 100$$

$$PR_a = 86.98\%$$

Table 5: Performance Ratio

S/N	Condition	Performance Ratio (%)
1.	Before Cooling	79.05
2.	After Cooling	86.98

The increase in performance ratio indicates improved utilization of the installed capacity.

Daily Energy Yield and Capacity Factor

Assuming an average effective sunshine duration of six (6) hours per day:

Before cooling, the daily energy output is given by:

$$E_b = 6.324 \times 6$$

$$E_b = 37.94 kWh/day$$

After cooling, the daily energy output becomes:

$$E_a = 6.958 \times 6$$

$$E_a = 41.75 kWh/day$$

The capacity factor before cooling is calculated as:

$$CF_b = \frac{37.948}{8 \times 24} \times 100$$

$$CF_b = 19.8\%$$

After cooling, the capacity factor becomes:

$$CF_a = \frac{41.758}{8 \times 24} \times 100$$

$$CF_a = 21.7\%$$

Table 6: Daily Energy Yield and Capacity Factor

S/N	Condition	Energy Yield (kWh/day)	Capacity Factor (%)
1.	Before Cooling	37.94	19.8
2.	After Cooling	41.75	21.7

The increase in daily energy production further demonstrates the effectiveness of passive heat sink cooling.

Comparative Assessment

A comparative evaluation of the photovoltaic system performance before and after cooling is presented in Table 7.

Table 7: Overall Performance Comparison

S/N	Parameter	Before Cooling	After Cooling
1.	Peak Module Temperature (°C)	70	56
2.	Peak Output Power (W)	6324.5	6958
3.	Efficiency (%)	15.82	17.40
4.	Performance Ratio (%)	79.05	86.98
5.	Energy Yield (kWh/day)	37.94	41.75
6.	Capacity Factor (%)	19.8	21.7

The results obtained clearly show that passive heat sink cooling improves the thermal and electrical performance of the photovoltaic system. The reduction in operating temperature contributed to higher voltage levels, improved power generation, enhanced efficiency, and increased energy yield. These findings indicate that passive cooling provides an economical and practical solution for photovoltaic installations operating in tropical climates.

Conclusion

This study evaluates the effectiveness of passive heat-sink cooling on the thermal and electrical performance of the standalone photovoltaic system installed at the Diagnostic Center of Kwara State Polytechnic, Ilorin, Nigeria. The investigation was carried out under representative tropical weather conditions to assess the influence of module temperature on photovoltaic performance and to determine the effectiveness of passive thermal regulation.

Experimental measurements obtained before and after heat sink cooling showed that module temperature significantly influences the performance of photovoltaic systems. Under normal operating conditions, the module temperature increased progressively throughout the day, reaching a maximum of 70 °C. The installation of heat sinks effectively enhanced heat dissipation and reduced the peak module temperature to 56°C, corresponding to a temperature reduction of 14°C. This finding confirms that passive heat-sink cooling is an effective means of minimizing excessive heat accumulation in photovoltaic modules.

The reduction in module temperature led to noticeable improvements in the system's electrical characteristics. The peak output power increased from 6.324 kW before cooling to 6.958 kW after cooling, representing an enhancement of approximately 10.02%. Similarly, the conversion efficiency increased from 15.82 % to 17.40%, while the performance ratio improved from 79.05% to 86.98%. Furthermore, the daily energy yield increased from 37.94 kWh/day to 41.75 kWh/day, and the capacity factor increased from 19.8% to 21.7%. These improvements demonstrate that passive heat-sink cooling significantly enhances photovoltaic performance under tropical climatic conditions.

The results of this study are consistent with recent literature findings, which indicate that thermal management plays a critical role in mitigating temperature-induced losses and improving photovoltaic energy conversion efficiency. Consequently, low maintenance requirements and the absence of additional power consumption associated with passive heat sink cooling make the technique particularly suitable for standalone photovoltaic systems deployed in developing countries and regions with high ambient temperatures.

The findings of this study further demonstrate the importance of thermal regulation for ensuring the reliable operation of photovoltaic systems used in critical applications, such as healthcare facilities. Improved energy yield and enhanced system efficiency contribute to greater energy availability, reduced operational costs, and improved reliability of the medical services provided by the Diagnostic Center.

Conclusively, passive heat sink cooling can be considered a practical, economical, and sustainable solution for improving the performance of photovoltaic systems operating in tropical environments. Future studies should investigate the combined effects of heat sinks and other cooling techniques such as phase change materials, forced-air cooling, and water-based cooling systems. In addition, long-term experimental investigations that account for seasonal variations and different module technologies are recommended to provide further insight into optimizing thermal management strategies for photovoltaic applications.

References

1. International Energy Agency (IEA). (2023). *Renewables 2023: Analysis and forecast to 2028*. IEA.
2. International Renewable Energy Agency (IRENA). (2023). *World energy transitions outlook 2023*. IRENA.
3. Ibrahim, H., Luk, P. C., & Luo, X. (2023). Cooling of concentrated photovoltaic cells: A review and the perspective of pulsating flow cooling. *Energies*.
4. Jiao, X., & Li, Y. (2023). An updated review of solar cooling systems driven by photovoltaic–thermal collectors. *Energies*.
5. Kumar, S., & Singh, R. (2022). Passive cooling techniques for photovoltaic modules: A review and performance assessment. *IEEE Access*, *10*, 1–15.
6. Milan, F., et al. (2025). The PV performance ratio paradox. *International Energy Agency Report*.
7. Ojo, J. A., Bello, T. K., & Yusuf, M. A. (2023). Energy audit and performance improvement of institutional buildings using renewable integration. *Energy Reports*, *9*, 1120–1134.
8. Oladipo, A. S., & Adeyemi, T. J. (2023). Assessment of photovoltaic adoption in Nigeria’s off-grid communities. *Solar Energy*, *230*, 112–124.
9. REN21. (2024). *Renewables 2024 global status report*. REN21 Secretariat.
10. Sharaf, M. A., Yousef, A., & Huzayyin, M. (2022). Review of cooling techniques used to enhance photovoltaic system efficiency. *Environmental Science and Pollution Research*, *29*, 1–20.
11. Comparative Review and Evaluation of State-of-the-Art Photovoltaic Cooling Technologies. (2023). *Journal of Cleaner Production*.
12. Emerging Trends in Cooling Technologies for Photovoltaic Systems. (2024). *Renewable and Sustainable Energy Reviews*.

13. Effects of Cooling on Performance of Photovoltaic/Thermal Solar Panels: A Comprehensive Review. (2023). *Solar Energy*.
14. Wang et al. (2021). A systematic review of recent air source heat pump systems assisted by photovoltaic and photovoltaic/thermal sources. *Renewable and Sustainable Energy Reviews*.
15. Wang, Y., Li, X., & Zhang, H. (2021). A review of photovoltaic/thermal systems and cooling strategies. *Renewable and Sustainable Energy Reviews, 149,* 111–130.