UDC 621.383.51
DOI: 10.15587/1729-4061.2025.327590

DEVELOPMENT OF PASSIVE COOLING WITH PERFORATED PLATES AND REAL-TIME MONITORING FOR PV EFFICIENCY IMPROVEMENT

This study focuses on enhancing photovoltaic (PV) module performance through the development of a passive cooling method using perforated aluminum plates, supported by a real-time monitoring system. The core problem addressed is the thermal inefficiency of PV modules operating in hot, humid environments, where heat accumulation lowers energy output. A real-time data acquisition system was developed using Arduino to monitor voltage, current, surface temperature, humidity, and solar irradiance. Four identical polycrystalline PV modules were tested; three were equipped with aluminum plates of varying perforation diameters (10 mm, 12.5 mm, 15 mm), while one remained uncooled as a control. The results showed that the module with 15 mm perforations had the best performance, achieving a 61.04 W output under peak irradiance (1404 W/m^2) and reducing surface temperature by nearly 10°C. These outcomes demonstrate that enhanced natural convection and evaporative effects, enabled by the larger perforations, significantly improved thermal regulation. The synchronized monitoring system validated the temperature-power relationship by capturing environmental dynamics in real time. Due to its energy independence, low cost, and simplicity, this integrated solution is particularly applicable in tropical regions or off-grid installations. The findings establish a practical basis for scalable deployment of passive cooling in PV systems, especially where active cooling is unfeasible

Keywords: passive cooling, perforated aluminum plate, real-time monitoring, solar energy efficiency, natural convection, thermal regulation

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Received 28.03.2025
Received in revised form 20.05.2025
Accepted 06.06.2025
Published 25.06.2025

How to Cite: *Sofijan, A., Sipahutar, R., Pradana, W. A., Siregar, B. O., Bizzy, I., Sailah, S., Ardianto, F., Darma, S., Kamila, A. P., Dhafia, V. A. (2025). Development of passive cooling with perforated plates and real-time monitoring for PV efficiency improvement. Eastern-European Journal of Enterprise Technologies, 3 (5 (135)), 30–38. https://doi.org/10.15587/1729-4061.2025.327590*

1. Introduction

The growing global demand for clean and sustainable energy has intensified the development of renewable energy systems, especially photovoltaic (PV) technology, which offers a scalable and modular solution for electricity generation from solar radiation without fuel combustion or moving parts [1]. PV systems are particularly attractive due to their low operational cost and decreasing installation prices. However, a key limitation in real-world applications is their temperature-dependent performance; excessive heat buildup on PV modules can significantly reduce their efficiency and lifespan [2, 3].

Studies have shown that for every 1 °C increase in the operating temperature of a PV module, efficiency can drop by approximately 0.4–0.6% [4]. This is especially problematic in tropical and subtropical regions, where high solar irradiance is accompanied by elevated ambient temperatures for most of the year [5]. In such climates, the effect of thermal accumulation not only leads to energy losses but also accelerates material degradation, ultimately reducing the return on investment for PV installations [6].

To address this issue, researchers have explored thermal management strategies aimed at reducing module temperatures. Active cooling techniques such as water circulation, heat pipes, phase change materials, or forced convection have demonstrated potential in enhancing energy output [7]. However, these approaches typically demand external power sources, incur additional costs, and require regular maintenance, which limits their practicality for rural or off-grid applications [8].

In contrast, passive cooling methods have emerged as a promising alternative due to their energy independence and low complexity. These methods rely on natural convection, radiation, and conduction to dissipate heat without any auxiliary power input [9]. One notable passive cooling technique involves the use of perforated aluminum plates placed behind the PV modules to enhance convective airflow and promote evaporative cooling [10]. Experimental investigations have indicated that such configurations can reduce module temperature by up to 30°*C* and improve power output by more than 10% under certain conditions [11].

However, a major gap in most of the existing literature lies in the lack of real-time monitoring systems. Many previous studies have relied on manual or periodic temperature measurements, which are insufficient to capture transient thermal behaviors or dynamic efficiency variations throughout the day [12]. This limitation hinders the understanding of thermal response under real operating conditions and restricts the development of data-driven cooling optimization strategies.

The integration of real-time monitoring technologies, such as microcontroller-based data loggers (e.g., Arduino or Raspberry Pi) and Internet of Things (IoT) platforms, has gained traction in PV applications due to their low cost, flexibility, and ability to provide continuous environmental and performance data [13]. Such systems enable researchers and operators to monitor irradiance, temperature, voltage, and current in real time, thus allowing for better performance assessment, early fault detection, and intelligent control mechanisms [14].

This combination of passive cooling with perforated plates and real-time data acquisition offers a novel approach to improve PV module performance, particularly in hot climate regions. Moreover, it aligns with global renewable energy goals, where thermal efficiency and durability of PV systems are increasingly prioritized to support large-scale solar integration [8, 15].

Given these challenges, the development of reliable, passive cooling mechanisms integrated with real-time monitoring systems is not only technically significant but also highly relevant in addressing both current and future demands for efficient solar energy utilization. By mitigating temperature-induced losses without incurring additional energy consumption or operational burdens, such innovations support the broader goals of energy sustainability, particularly in regions where solar energy holds the greatest untapped potential. Therefore, the exploration of passive thermal regulation solutions such as perforated aluminum plate configurations combined with accurate environmental monitoring stands as a critical and timely research direction within the global renewable energy agenda.

2. Literature review and problem statement

Numerous studies have been conducted to address the thermal limitations of photovoltaic (PV) modules under high solar irradiance conditions. The paper [16] presents the effects of temperature and wind speed on PV performance and confirms that elevated module temperatures lead to reduced voltage and overall system efficiency. It is shown that solar module temperature is one of the most critical factors affecting electrical output. However, this research focused primarily on external environmental factors and did not provide a solution for internal thermal regulation of the modules.

Further work [17] analyzed various active cooling methods, including water spray and air circulation systems, to enhance PV performance. These approaches demonstrated significant improvements in temperature reduction and energy output. However, unresolved issues remain related to energy consumption, cost, and maintenance complexity of such active systems, especially in developing regions or remote areas. The reason for this is the objective difficulty in supplying auxiliary energy sources for cooling where power infrastructure is limited, which makes large-scale deployment of active systems economically impractical.

To overcome these limitations, passive cooling strategies have been proposed. Research [18] examined the use of perforated aluminum plates placed behind PV modules to enhance natural convection. It showed moderate success in reducing surface temperature without additional energy consumption. However, this work did not explore variations in geometric parameters (such as hole diameter) nor did it incorporate real-time monitoring, limiting its adaptability to changing environmental conditions.

A more recent study [19] explored the influence of evaporative cooling enhanced by humidity in tropical regions. While promising, the setup relied on external water sources and did not test its integration with existing PV support structures. This introduces fundamental constraints for areas with limited water availability. In addition, the research lacked a continuous, multi-parameter data collection system for thermal and electrical behavior.

This paper [20] demonstrated the effectiveness of an Arduino-based data logger for monitoring PV performance. The results confirmed the ability to gather high-resolution environmental and electrical data simultaneously. However, the focus was solely on monitoring and did not combine this capability with any thermal management intervention, leaving the effect of combined real-time sensing and passive cooling untested.

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The study [22] explores the real-time monitoring of temperature and humidity using LabVIEW and machine learning algorithms to enhance data acquisition efficiency and prediction accuracy in environmental applications. Their system leverages graphical programming for sensor interfacing and incorporates intelligent data analysis for trend forecasting. However, despite the integration of advanced software tools, the research focuses on software-side optimization and lacks hardware deployment for field-based applications, such as PV systems in varying environmental conditions.

The study [23] present the development of an Arduino-based data logging system designed for monitoring on-grid photovoltaic systems, with real-time data streamed and recorded through Microsoft Excel. The study emphasizes ease of use, low cost, and integration with familiar software platforms, making the system accessible for small-scale installations. Nevertheless, the monitoring was limited to basic electrical parameters and did not include thermal or humidity sensors, which are essential for assessing the environmental effects on PV performance.

The research [24] a low-cost, open-source microcontroller-based temperature data logger was developed and evaluated. The logger demonstrated high precision in recording temperature changes, showing the feasibility of using open-source tools for scientific measurement. While the system proved effective for laboratory and general environmental monitoring, it did not extend its application to integrated PV system monitoring or include additional parameters such as current, voltage, or humidity that are vital in assessing solar module performance under dynamic conditions.

Some author researchers [25] used mesh or aluminum fin structures to support passive heat dissipation. However, such structures are often rigid or complex in design, limiting their scalability and cost-effectiveness in field deployment. These approaches also lack dynamic adaptability, as they are not paired with feedback systems to monitor effectiveness in changing climate scenarios [26].

All this suggests that there remains an open niche for a simple, scalable passive cooling method integrated with real-time monitoring, specifically optimized for warm, humid environments. The gap lies in evaluating the cooling efficiency of various perforated geometries, measured dynamically using a synchronized environmental and electrical data acquisition system, which would bridge both the mechanical and digital optimization of PV performance [27].

3. The aim and objectives of the study

The aim of this study is to develop a passive cooling method using perforated aluminum plates and integrate it with a real-time Arduino-based monitoring system in order to investigate its effect on the thermal and electrical performance of polycrystalline photovoltaic (PV) modules under hot climate conditions, thereby providing a practical and energy-independent solution for improving PV efficiency.

To achieve this aim, the following objectives are accomplished:

– to design, implement, and validate an Arduino-based real-time data logging system integrated with passive cooling structures using perforated aluminum plates of varying hole diameters (10 mm, 12.5 mm, and 15 mm) mounted behind multiple PV modules;

– to analyze the impact of passive cooling configurations on PV module temperature, efficiency and power output under varying environmental conditions, including solar irradiance and humidity.

4. Materials and methods

The object of this study is the polycrystalline PV module system equipped with a passive aluminum plate cooling system. The main hypothesis is that increasing the perforation diameter on the aluminum plate enhances natural cooling and improves PV module performance. This study was conducted using an experimental approach involving hardware implementation and simulation validation to examine the thermal and electrical behavior of photovoltaic (PV) modules under passive cooling treatment [15]. The methodology included the design and deployment of a data acquisition system, construction of experimental cooling configurations, and implementation of environmental measurement protocols under controlled field conditions. To explore the influence of passive cooling on photovoltaic (PV) module performance, the study introduced a set of configurations that varied solely in terms of thermal regulation design [28–37]. Each configuration represented a unique structural intervention aimed at enhancing natural convective airflow, without relying on active energy inputs. These setups allowed for direct comparison under equal environmental exposure, establishing a foundation for evaluating how physical design affects thermal and electrical behavior. The cooling variants consisted of perforated elements positioned at the rear of three modules, with the fourth serving as an unmodified baseline. The perforation diameters 10 mm, 12.5 mm, and 15 mm were selected to create a gradient of airflow potential, facilitating observation of how geometric variation impacts thermal dissipation. By controlling all other installation parameters, any observed performance shifts could be confidently attributed to these structural differences.

This configuration scheme played a central role in the study's comparative logic. Each cooling design was not just a physical attachment but a defined experimental condition, enabling an assessment of passive cooling as a functional intervention. The goal was not to assess the mechanical integrity of the materials themselves, but to evaluate how such variations influence temperature stability and electrical consistency when exposed to naturally fluctuating irradiance and humidity. The use of multiple cooling configurations enabled the formation of parallel performance baselines under matched conditions. This approach improved the reliability of comparative analysis and ensured that trends identified in the data could be systematically linked to differences in thermal treatment. The consistency in module characteristics and installation geometry further strengthened this comparative structure. The significance of these configurations lies in their simplicity and relevance to scalable applications. By documenting how passive thermal modifications affect PV module operation over time, the study establishes a model for low-cost enhancement strategies suitable for deployment in regions with limited access to active cooling technologies. This lays the groundwork for evaluating the broader practical viability of such systems in future solar infrastructure development.

5. Results of the study on passive cooling of PV modules and data logging

5. 1. Design, implementation and validate of an Arduino-based real-time data logging system integrated with passive cooling structures using perforated aluminum plates

Four identical 100 Wp polycrystalline PV modules were used in this experiment. These modules were installed outdoors in an open space to ensure uniform solar exposure throughout the day. One module (PV1) was used as the control, without any cooling plate. The remaining three modules (PV2, PV3, and PV4) were each equipped with a perforated aluminum plate mounted behind them. The aluminum plates had different hole diameters: 10 mm for PV2, 12.5 mm for PV3, and 15 mm for PV4. These variations were used to determine the most effective configuration for reducing operating temperature and enhancing performance.

To enhance the functionality and reliability of the monitoring system, the datalogger code was structured in modular blocks using the Arduino IDE [32]. This allows flexible control over sampling intervals and easy integration of additional sensors if necessary. Each data set collected is timestamped using the internal clock, allowing accurate time-correlation of PV performance with changing environmental conditions. Data are logged in CSV format, compatible with spreadsheet analysis tools, and temporarily visualized via serial monitor and LCD display [22].

Special care was taken in sensor layout and wiring to reduce electromagnetic interference (EMI), with shielded wires and proper grounding. Temperature sensors were mounted directly behind each PV module to capture realistic operating temperatures. The design also supports scalability, enabling future extension to more modules or inclusion of IoT connectivity.

Fig. 1 describe an Arduino Uno microcontroller was used as the core of the data logging system. This microcontroller was connected to several sensors to monitor critical parameters. Voltage was measured using a voltage divider circuit, while current was measured with an ACS712 current sensor. A DS18B20 digital temperature sensor was used to monitor the surface temperature of each PV module, and a DHT22 sensor was employed to measure ambient humidity. All sensor data were recorded in real-time and stored on an SD card for later analysis.

The datalogger was powered by a 5V regulated power supply and programmed to sample data at regular intervals throughout the day. The accuracy of the sensors was calibrated prior to the experiment, ensuring precise measurements with minimal tolerance: 0.025% for voltage and humidity, and 0.0081% for temperature [38].

The circuit simulation process using Proteus 8 Professional was essential for validating circuit stability, pin compatibility, and functional accuracy of sensor readings. This step minimized hardware errors by enabling pre-deployment testing of signal flow, sensor polling rates, and SD card storage functionality. The LCD module was also simulated to ensure real-time output feedback.

The block diagram created not only illustrated the component architecture but also served as a guide for troubleshooting and system expansion. It shows the path from PV module energy conversion, through sensor acquisition, to data processing and storage. This clear workflow simplifies future upgrades, such as adding wireless telemetry or machine learning based analysis.

To validate the hardware design before physical implementation, in the Fig. 2 describe the circuit was first simulated using Proteus 8 Professional software. The simulation included all major components sensors, Arduino, SD card module, and LCD display and allowed the researchers to visualize system behavior and troubleshoot possible errors in sensor readings or wiring.

The simulation phase played a crucial role in ensuring system functionality and integration before physical deployment. It provided a safe and efficient environment to validate sensor interactions, data flow, and hardware response, thereby minimizing potential implementation errors and reducing development time.

A block diagram design in Fig. 3 was also created to illustrate the overall working principle of the system.

Solar energy is absorbed by the PV modules, and performance data including voltage, current, temperature, and humidity are transmitted to the Arduino-based datalogger. The system is capable of recording data from all four PV modules simultaneously, providing comparative insights into the effect of different cooling configurations.

This configuration ensures efficient real-time monitoring and data acquisition, which is essential for evaluating the effectiveness of each passive cooling approach. By enabling direct comparison between modules under identical environmental conditions, the system enhances the reliability of the performance analysis and supports a more comprehensive assessment of temperature reduction impacts on PV efficiency.

The experiment was carried out on a clear day to ensure stable solar radiation. Measurements were taken from morning to afternoon, focusing on the hours when solar irradiance peaked. Data collected included solar radiation intensity, open-circuit voltage (*Voc*), short-circuit current (*Isc*), module surface temperature, and ambient humidity. The recorded data were processed and visualized using graphing software to analyze the correlation between environmental factors, cooling configurations, and PV module performance. This method allowed for an accurate, real-time evaluation of the cooling effects of perforated aluminum plates and the efficiency of the datalogger system in monitoring solar PV systems.

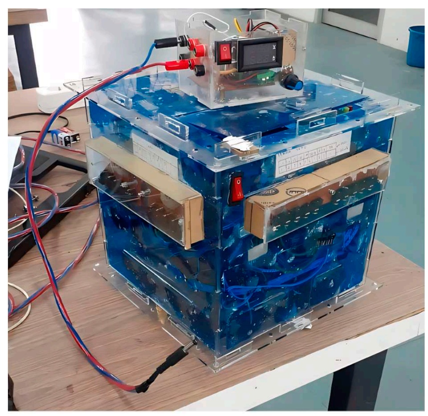

Fig. 1. Design of datalogger based on Arduino Uno

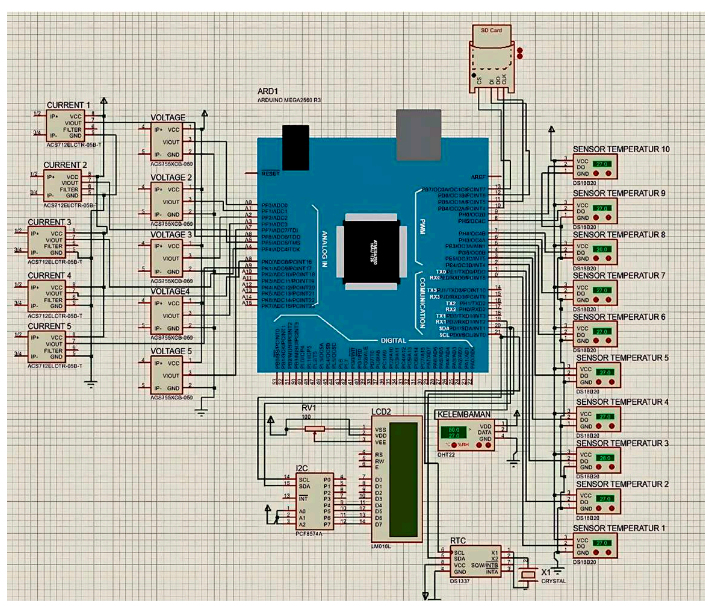

Fig. 2. Circuit simulation of datalogger

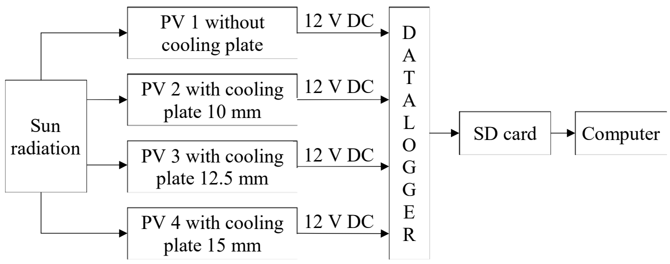

Fig. 3. Datalogger working system block diagram design

A custom-built data acquisition system was meticulously developed using the Arduino Uno microcontroller as the central processing unit, aimed at enabling real-time monitoring and recording of key environmental and electrical parameters associated with photovoltaic (PV) module performance. This system was specifically engineered to support the simultaneous acquisition of multiple data types voltage, current, surface temperature, and ambient humidity essential for comprehensive analysis of solar energy systems operating under dynamic environmental conditions. The voltage of each PV module was measured through a precision voltage divider circuit designed to safely scale down the electrical potential to levels readable by the Arduino's analog input. Current measurements were captured using the ACS712 Hall-effect sensor, which offers non-intrusive, accurate current sensing with minimal signal interference. To assess thermal behavior, DS18B20 digital temperature sensors were employed, known for their high accuracy and digital output that minimizes analog noise. Ambient humidity was continuously recorded using the DHT22 sensor, which combines temperature and humidity readings in a compact and reliable format. These sensors were strategically placed to reflect both module-specific and environmental conditions, allowing for a nuanced interpretation of external influences on PV performance.

All sensor data were acquired and logged automatically to a microSD card in CSV format, enabling structured and timestamped data storage for post-experimental analysis. The system operated on fixed time intervals, ensuring consistent sampling and high-resolution data acquisition throughout the day. An integrated 16×2 LCD display provided real-time visual feedback of key readings, including voltage, current, and temperature, which proved highly beneficial during on-site setup, diagnostics, and observation. One of the distinguishing features of this system was its autonomous operation. It was programmed to begin recording data daily from 08:00 to 16:00, aligning with peak solar irradiance hours to capture the most relevant variations in PV output. Once powered, the system required no manual intervention, thereby eliminating the risk of human error and ensuring continuous, unbiased data collection. Prior to deployment, each component of the system was rigorously calibrated in a controlled laboratory environment. Calibration procedures ensured that sensors performed within predefined tolerance levels – ±0.025% for voltage and humidity sensors, and ±0.0081% for the temperature sensor – thus providing high reliability and measurement stability under diverse outdoor conditions. This level of precision was essential to ensure that subtle changes in environmental conditions or cooling effects could be accurately detected and quantified.

The modular and low-power architecture of the Arduino-based system makes it particularly well-suited for field deployment in remote or off-grid locations, where energy efficiency and simplicity are critical. Its scalability allows additional sensors or modules to be added with minimal modifications, supporting future expansion for more complex monitoring tasks or integration with Internet of Things (IoT) platforms. In summary, the development and deployment of this real-time data acquisition system provided a powerful, cost-effective, and reliable solution for capturing high-fidelity environmental and performance data from PV modules. Its successful implementation not only validated its functional design but also contributed significantly to the accurate assessment of passive cooling strategies and their impact on PV efficiency under real-world conditions [28].

A series of controlled experiments were conducted to evaluate the performance of four identically rated polycrystalline photovoltaic (PV) modules under high solar irradiance conditions, with peak radiation intensity reaching up to 1404 W/m^2. The purpose of the test was to assess the effectiveness of passive cooling using perforated aluminum plates with varying hole diameters, and how such configurations influenced the modules' power output and thermal behavior [28]. The experimental setup consisted of one reference module and three modified units to isolate the impact of the passive cooling systems. PV1 was designated as the control module and was operated without any cooling mechanism. It served as the baseline for comparison to evaluate the influence of passive cooling. In contrast, the other three modules PV2, PV3, and PV4 were each equipped with custom-fabricated perforated aluminum plates mounted on their rear surfaces. These plates featured circular perforations of different diameters: 10 mm on PV2, 12.5 mm on PV3, and 15 mm on PV4. All other experimental parameters such as tilt angle, orientation, and location were kept constant to ensure data validity.

5. 2. Analysis of the impact of passive cooling on PV module performance under varying environmental conditions

Real-time experimental data revealed consistent performance trends across photovoltaic (PV) modules under varying environmental conditions. As solar irradiance increased during the day, the benefits of passive cooling became increasingly evident, especially in modules fitted with larger perforated aluminum plates. The Arduino-based monitoring system enabled continuous measurement of temperature, voltage, current, and humidity, allowing for detailed performance analysis.

Fig. 4 illustrates the surface temperature of the PV modules in relation to the solar irradiance values. The temperature values are plotted on the y-axis, and the corresponding solar irradiance readings are on the x-axis. The graph includes data from all four modules, each tracked simultaneously to observe how their surface temperatures responded as solar energy levels varied throughout the test duration. The plot is based on raw sensor data recorded in real time.

Fig. 5 presents a time-series plot comparing the power output of each photovoltaic (PV) module against the corresponding levels of solar irradiance recorded during the observation period. The x-axis indicates the solar irradiance in watts per square meter (W/m^2), while the y-axis displays the electrical power output in watts (W) generated by each module. All modules were monitored concurrently, and the data points reflect real-time conditions captured at regular intervals throughout the day.

Fig. 6 displays the relationship between surface temperature of the PV modules and ambient humidity measured during the experimental period. The x-axis represents humidity in percentage (%), and the y-axis represents module surface temperature in degrees Celsius (°C). The data points represent simultaneous measurements of temperature and humidity taken from the same time intervals, allowing for visual comparison of how these two environmental variables aligned during the experiment.

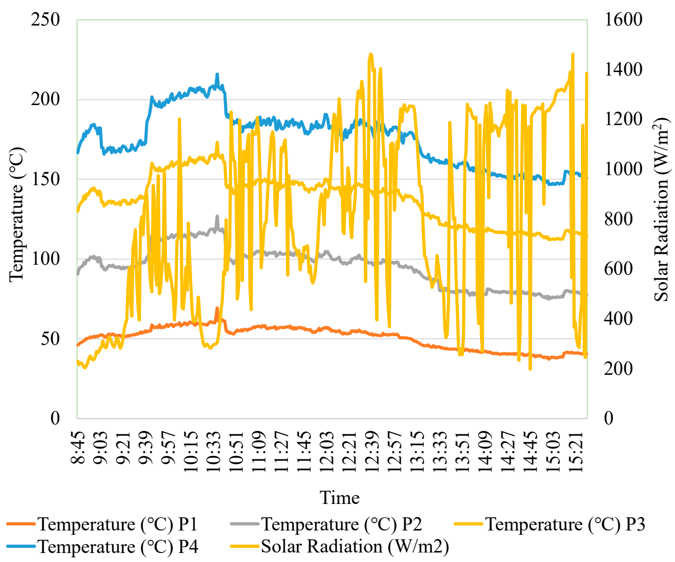

Fig. 4. Result of temperature versus solar radiation

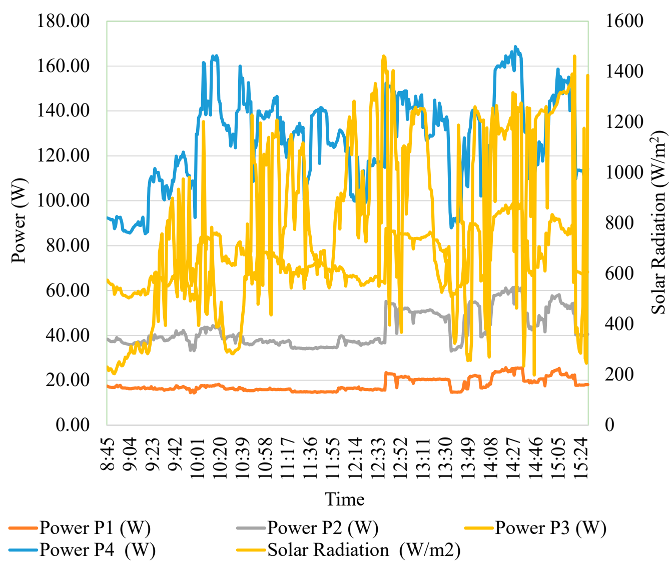

Fig. 5. Result of power output versus solar radiation

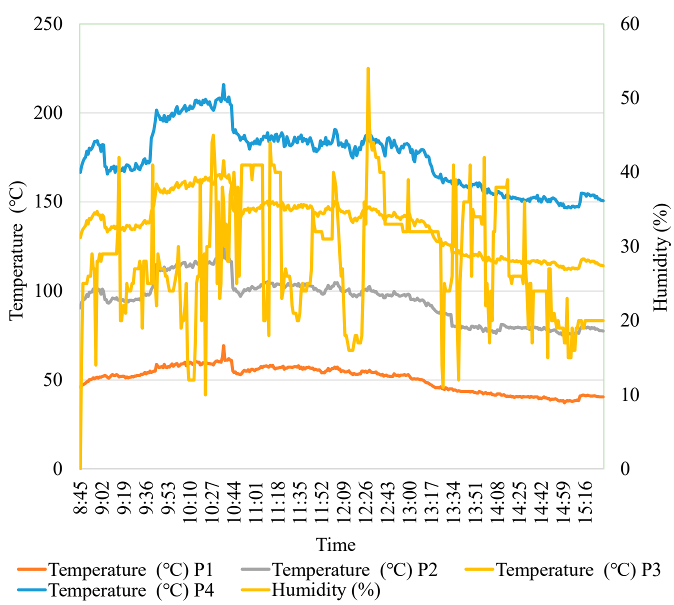

Fig. 6. Result of humidity versus temperature

6. Discussion of the results of the study on the effectiveness of passive cooling and real-time monitoring on PV module performance

The evaluation of photovoltaic (PV) module behavior under outdoor conditions required a structured and continuous monitoring strategy. To support this, a real-time data acquisition system was incorporated into the study framework, enabling parallel tracking of thermal and electrical variables. This system operated throughout peak solar hours, generating a time-aligned dataset reflecting module performance as ambient conditions evolved. Fig. 1–3 represent the core technical implementations that enabled this monitoring. Fig. 1 illustrates the datalogger hardware configuration built around the Arduino Uno microcontroller. This schematic demonstrates how voltage, current, temperature, and humidity sensors were connected to the Arduino, forming the basis for the real-time monitoring setup. Fig. 2 provides the Proteus-based simulation model of the system, which was used to validate the circuit design, check pin compatibility, and confirm that each sensor component functioned properly before physical deployment. Fig. 3 presents the functional block diagram of the complete data logging system, summarizing the data flow from sensor acquisition to data processing and storage. These figures serve not only as visual support but also represent the technical foundation upon which real-time environmental monitoring was achieved. The inclusion of the simulated design in Fig. 2 and functional logic in Fig. 3 ensures reproducibility and scalability of the system for future work.

Central to the monitoring approach was the ability to capture dynamic interactions between surface temperature, humidity, irradiance, voltage, and current. These variables were observed simultaneously across all modules to ensure uniformity and reduce interpretive bias. The monitoring platform functioned not merely as a passive recorder but as a diagnostic tool, offering temporal granularity that manual methods could not achieve. This resolution was critical in detecting subtle shifts in temperature or electrical output that might occur over short intervals, especially during sharp irradiance peaks or environmental transitions. By enabling synchronized data capture across all experimental configurations, the system enhanced the validity of performance comparisons among the differently cooled PV modules. The structured hardware and software setup validated in Fig. 1–3 ensured minimal error and high fidelity in the measurements, which supports the robustness of the analysis presented.

The results obtained in this study can be explained by analyzing the interaction between passive cooling configurations and environmental variables, supported by synchronized real-time monitoring. The use of perforated aluminum plates significantly enhanced the thermal regulation of photovoltaic (PV) modules, which directly impacted their electrical performance. The uncooled PV module (PV1) consistently recorded the highest surface temperatures and lowest power output, with a maximum of only 22.72 W under peak solar irradiance (1404 W/m^2). This module serves as a control to compare the thermal and electrical behavior of modules with passive cooling. In contrast, PV modules equipped with perforated plates

(PV2, PV3, PV4) demonstrated improved temperature profiles and higher power outputs. Specifically, PV4 equipped with a 15 mm perforated plate, achieved the highest power output of 61.04 W and the lowest module surface temperature of 40.2°C. This confirms the role of larger perforations in facilitating more effective airflow and heat dissipation via natural convection.

The correlation between temperature reduction and performance improvement is further visualized in Fig. 4, which plots solar radiation versus power output across all PV modules. The curve for PV4 shows a distinct upward shift compared to PV1, reflecting a 54% increase in output at the same irradiance level. This performance boost is explained by the reduced thermal resistance and greater convective air movement allowed by the 15 mm holes. Fig. 5 supports this conclusion by showing solar irradiance versus module temperature. PV4 consistently maintained lower surface temperatures throughout the day, with a maximum gap of nearly 10°C compared to PV1 at 1:10 PM. This thermal gradient confirms that passive cooling effectively mitigates temperature buildup, which would otherwise decrease voltage and shift the maximum power point (Mpp), as discussed in the literature [7, 9]. Humidity also played a role in amplifying the cooling effect. Fig. 6 illustrates the relationship between ambient humidity and module temperature. Under high humidity (54%), the cooling performance of PV4 was most pronounced, reaching a temperature differential (ΔT) of 16.2°C compared to PV1. This suggests an additional mechanism of evaporative cooling, where moisture-laden air passing through the perforations enhanced latent heat transfer, thereby improving heat dissipation beyond what convection alone could achieve. Under low humidity (11%), the temperature gap narrowed to 9.5°C, indicating that while convection remains effective, the absence of evaporation slightly reduces overall cooling efficiency. The accuracy of these findings is supported by the high-resolution data recorded by the Arduino-based data logger system and validated through the circuit model in Fig. 1–3. The system captured synchronized voltage, current, temperature, and humidity data from four modules simultaneously, eliminating time-based data inconsistencies. This level of integration allowed precise correlation between environmental conditions and electrical performance, reinforcing the reliability of the conclusions drawn.

In summary, the superior results obtained from PV4 are explained by the synergistic effect of large-diameter perforations (15 mm), which enhanced both natural convection and evaporative cooling. The combined reduction in surface temperature directly improved electrical output and efficiency, confirming the thermal sensitivity of PV modules. These outcomes demonstrate that passive cooling using perforated aluminum plates especially when monitored in real time provides a scalable, energy-independent solution for increasing PV performance in hot and humid climates.

However, this study is limited to short-term daytime measurements under clear weather conditions. Long-term performance under varying climatic conditions, such as rain or dust accumulation, was not evaluated. While the proposed system is designed for industrial applicability, it has not yet been implemented at an industrial facility. At this stage, the system has been validated under controlled experimental conditions. Plans are currently underway to conduct a pilot-scale implementation in collaboration with a regional solar farm to assess operational feasibility and long-term reliability under real-world industrial conditions.

7. Conclusions

1. A real-time data acquisition system using Arduino Uno was successfully designed and implemented to monitor key performance parameters of photovoltaic (PV) modules, including voltage, current, temperature, and humidity. The system demonstrated high accuracy, with measurement tolerances of ±0.025% for voltage and humidity and ±0.0081% for temperature. It enabled continuous, synchronized data logging from four PV modules, proving its effectiveness in replacing manual measurements and the application of perforated aluminum plates as a passive cooling method led to a significant improvement in PV module performance. Under peak solar irradiance (1404 W/m^2), the module equipped with a 15 mm perforated plate produced 61.04 W, while the control module without cooling generated only 22.72 W. This represents a 54% increase in output power, confirming that larger perforations enhance natural convection and improve thermal dissipation.

2. The relationship between environmental conditions and PV module performance was clearly demonstrated. The module with the 15 mm perforated plate consistently exhibited lower surface temperatures, especially under high humidity conditions, where the temperature difference with the uncooled module reached up to 16.2°C. These findings validate the dual cooling effect convection and evaporation of the perforated structure and confirm the system's suitability for deployment in hot and humid environments.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this study, whether financial, personal, authorship or otherwise, that could affect the study and its results presented in this paper.

Financing

The research was performed without financial support.

Data availability

Manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Acknowledgements

I would like to thank the Coordinator of the Energy Technology Laboratory at Sriwijaya University, especially the Faculty of Engineering, for their assistance in this research, particularly the resource persons, observers, and even those who provided moral and material support throughout this process.

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