Journal of Mines, Metals and Fuels, *73(10): 3179-3189; 2025. DOI: 10.18311/jmmf/2025/50034*

Online ISSN : 0022-2755

Journal of Mines, Metals and Fuels

Contents available at: *www.informaticsjournals.co.in/index.php/jmmf*

Active Thermal Regulation and AI Forecasting for Thin-Film CIGS Panels in High-Temperature Urban Rooftop Applications

J. Ganesh Moorthy[1*], P. Arulmozhi[2], S. Saravanan[2], P. Murugesan[3], S. Krishnakumar[2] and K. Sudha[4]

[1]Department of Electrical and Electronics Engineering, K.S.R College of Engineering, Tiruchengode - 637215, Tamil Nadu, India; jp.ganesh11@gmail.com

[2]Department of Mechanical Engineering, Gnanamani College of Technology, Namakkal - 637018, Tamil Nadu, India

[3]Department of Mechanical Engineering, K.S.R College of Engineering, Tiruchengode - 637215, Tamil Nadu, India

[4]Department of Computer Science and Engineering (Cyber Security), K.S.R College of Engineering, Tiruchengode - 637215, Tamil Nadu, India

Abstract

This research presents an integrated approach to enhancing the performance of Copper Indium Gallium Selenide (CIGS) thin-film Photovoltaic (PV) panels through active thermal management for urban rooftop installations in high-temperature environments such as India. CIGS modules, while efficient under low-light and diffuse conditions, suffer significant power degradation at elevated temperatures. To address this, a water-based hybrid cooling system was developed and tested on a 10 W CIGS module, featuring aluminium-copper ductwork and an Arduino-based dual-threshold control system. Experimental trials across a wide irradiance spectrum (210-980 W/m^2), with and without a 2× solar concentrator, demonstrated a 3.56% improvement in energy yield under standard conditions and a 28.5% gain with concentrated sunlight. Advanced predictive modelling using Random Forest regression further validated the thermal sensitivity and projected output behaviour of a 1 kW system, confirming a sharp decline in power beyond 50°C. The study also revealed improved durability through reduced thermal stress, as supported by the Arrhenius degradation model. Economically, the system reduces payback time and enhances ROI, particularly in high-insolation urban areas. These findings highlight the viability and scalability of intelligent cooling strategies for next-generation rooftop solar deployments in emerging economies.

Major Findings: *An Arduino-controlled dual-threshold cooling system significantly reduced CIGS module temperatures, improving output efficiency under rooftop conditions. A Random Forest model trained on experimental data achieved an R^2 of 0.932, accurately predicting nonlinear power losses due to thermal stress. The integrated system demonstrated environmental viability with low water consumption (1.2 L/day/10 W) and minimal energy overhead, supporting sustainable PV deployment in hot climates.*

Keywords: *CIGS Thin-Film Panels, Energy Efficiency, Rooftop Photovoltaic Systems, Thermal Management, Solar Panel Cooling*

**Author for correspondence*

1.0 Introduction

Rooftop PV systems are being promoted by the government of India in order to enhance the capacity of power generation utilising renewable energy sources[1]. This is because India's fast urbanisation has led to a considerable rise in energy consumption. The installation of photovoltaic panels on rooftops[2] is becoming increasingly popular in India's commercial, residential, and industrial sectors, which serve to contribute to the country's expanding renewable energy landscape. In the past, the majority of PV systems installed on rooftops have utilised monocrystalline[3] and multicrystalline silicon panels[4], which, despite their efficiency, came with higher costs. Thin-film CIGS panels[5], on the other hand, are becoming progressively popular as an alternative that is both more appropriate and more cost-effective, particularly for rooftop applications[6]. Thin-film solar panels, and CIGS in particular, provide a number of benefits that make them an excellent choice for PV systems installed on rooftops. When exposed to situations of low light and high temperature, CIGS panels have a greater efficiency, which is useful in India because of the country's varied environment. Because of their higher performance in surroundings that are foggy or shadowed, as well as their capacity to sustain efficiency at elevated temperatures, they are ideally suited for urban roofs[7], which frequently confront obstacles of this kind.

In addition, CIGS panels are lightweight and flexible, which makes installation on a wide variety of roof types much simpler. This includes roofs that are not exactly level or that have weight constraints. Especially in urban environments[8], where space might be restricted and the structural integrity of roofs[9] may not be able to sustain heavier crystalline panels, this flexibility makes it possible for better integration on rooftops. In comparison to the creation of standard silicon panels, the manufacturing process of CIGS panels takes less energy and material. This results in cheaper production costs and less impact on the environment. Because of this cost advantage, they are an enticing solution for rooftops in both residential and commercial environments[10], where it is essential to minimise installation costs without reducing efficiency.

Because of its sleek and visually pleasant look, CIGS panels are an excellent choice for Building-Integrated Photovoltaic (BIPV) applications[11], which place a significant emphasis on the aesthetic appeal of their equipment. Their decreased susceptibility to partial shading[12] implies that even if sections of the panel are covered by surrounding structures, trees, or other obstructions, the overall energy production stays largely unaffected. This leads to an improvement in the system's performance in urban areas that are densely developed. Because of these characteristics, thin-film solar panels, and CIGS in particular, are very well-suited for rooftop PV systems. They offer a solution that is adaptable, efficient, and cost-effective, and they are in line with India's objectives for renewable energy[13]. It is possible for India to further accelerate the adoption of solar energy throughout its urban and industrial sectors[14] by introducing thin-film solar technology into rooftop PV systems. This would allow India to accommodate its energy demands while also contributing to a more sustainable future[15].

Because of their susceptibility to high temperatures, thin-film CIGS photovoltaic panels require immediate cooling. This is because high temperatures can have a major influence on the efficiency and performance of these panels. At higher temperatures, the electrical efficiency of CIGS panels diminishes, which results in a decrease in the amount of energy that is produced. Effective cooling helps maintain appropriate panel temperatures, which ensures constant and dependable performance. This is especially important in hot areas like India, where rooftop photovoltaic systems are widely installed. As a result of alleviating thermal stress[16], minimising the deterioration of materials[17], and improving the overall durability of the panels[18], cooling also provides an additional benefit of extending the lifespan of CIGS panels. It is possible for CIGS panels to run closer to their optimum efficiency[19] if thermal management is improved by cooling. This makes them a more appealing and dependable alternative for the generation of solar energy[20] in household as well as industrial settings. Building upon the literature described above, the aim of the paper is defined.

1.1 Objective of this Research Article

(i) To evaluate the performance, efficiency, and longevity of CIGS thin-film panels with integrated cooling systems in rooftop PV applications.

(ii) To analyse the economic and environmental benefits of implementing CIGS panels with cooling systems in urban rooftop PV installations.

(iii) To design, develop, and test a prototype cooling system for CIGS thin-film panels in rooftop PV applications.

2.0 Methodology

2.1 Experimental Setup and Panel Specification

This study employed a 10-watt CIGS thin-film PV module for experimental evaluation under both standard and enhanced irradiance conditions. The module measured 350 mm × 250 mm × 2 mm and weighed between 0.5 and 1.0 kg. Its key electrical specifications included: voltage at maximum power (16-18 V), current at maximum power (0.55-0.63 A), open-circuit voltage (20-23 V), and short-circuit current (0.6-0.7 A). The efficiency of the module ranged from 7-12 %, with a temperature coefficient of power between -0.2%/°C and -0.5%/°C. It was fabricated on a glass, metal, or flexible plastic substrate, housed in either a frameless or aluminium-framed enclosure, and rated IP65 for outdoor use.

2.2 Cooling Integration and System Configuration

The PV panel was integrated with a passive-active hybrid cooling system. A 5 mm-thick aluminium duct was bonded to the rear of the module using thermally conductive adhesive. Copper tubing (10 mm diameter) was further affixed to a copper plate at the module's base using silver conductive adhesive, ensuring high thermal conductivity. Water was circulated through this structure using a DC pump (maximum flow rate: 250 L/h) in a closed loop. The overall system layout, including the PV module, measuring unit, relay-controlled pump, water tank, and control hardware, is illustrated in Figure 1.

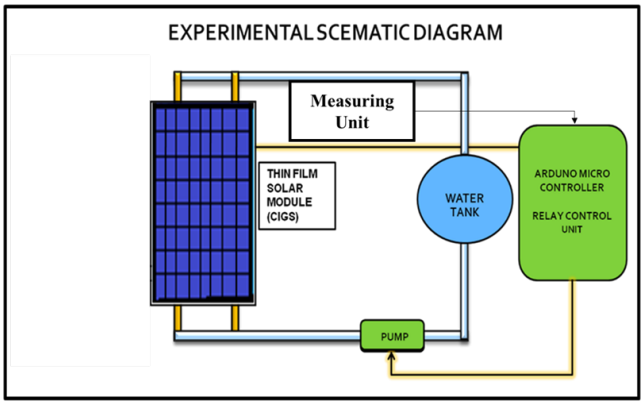


Figure 1. Schematic diagram of the integrated water-cooling PV system.

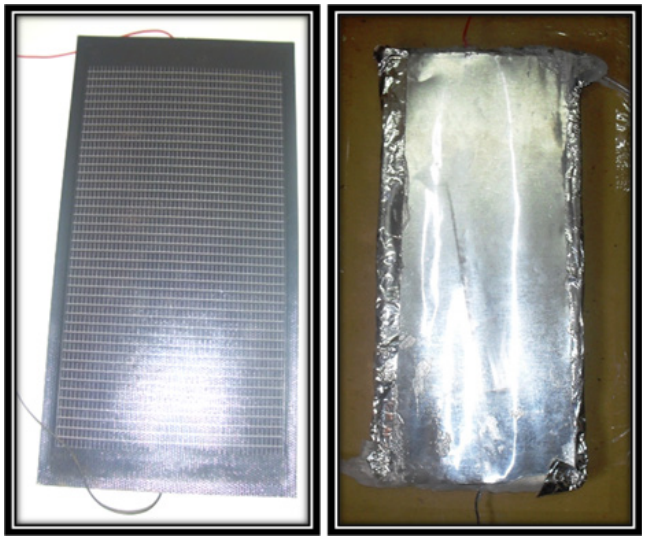


Figure 2. Rear-side view of thin-film module with aluminium and copper duct cooling system.

A close-up view of the physical integration between the cooling elements and the PV module is shown in Figure 2. This configuration facilitated effective thermal dissipation under variable operating conditions.

2.3 Experimental Conditions and Procedure

The setup was deployed under outdoor conditions for performance evaluation. Two test scenarios were examined: (i) under natural sunlight, and (ii) under intensified irradiance using a 2× solar concentrator. The experimental configurations featuring the thin-film PV module, pump, measuring unit, and control system are shown in Figure 3. The right-side image illustrates the use of reflective surfaces to double the incoming solar radiation.

Panel temperature, output current, voltage, and power were continuously measured using calibrated sensors. Data acquisition focused on quantifying thermal impact on electrical performance across varying irradiance levels (210-980 W·m^{-2}).

To model the influence of temperature on PV performance, the following equation was applied:

$$P(T) = P_{STC} \times (1 + \beta \times \Delta T) \quad (1)$$

where P(T) is the power at temperature T, P_{STC} is the power under standard test conditions (25°C), β is the temperature coefficient (°C^{-1}), and ΔT is the temperature difference from 25°C.

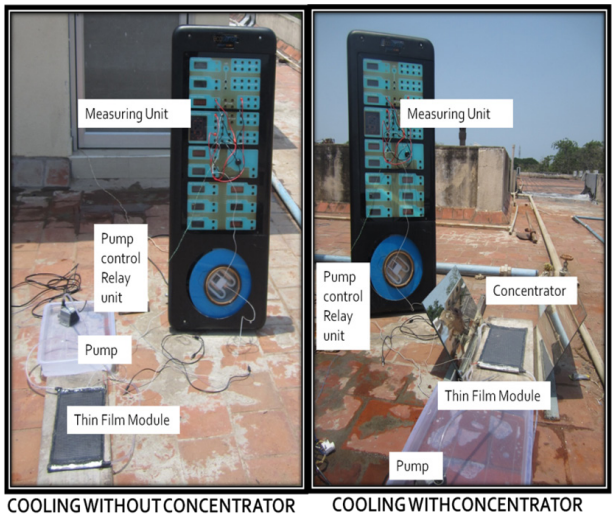


Figure 3. Outdoor experimental setups (left: standard irradiation, right: with concentrator).

The impact of thermal stress on material degradation was assessed using the Arrhenius degradation model:

$$k(T) = A \times \exp(-Ea/RT) \quad (2)$$

where k(T) is the degradation rate, A is the pre-exponential factor, Ea is the activation energy ($J \cdot mol^{-1}$), R is the universal gas constant (8.314 $J \cdot mol^{-1} \cdot K^{-1}$), and T is the absolute temperature (K). Additionally, the power output based on incident solar irradiance was determined using:

$$P = \eta \times A \times G \quad (3)$$

where P is the electrical power output (W), η is the panel efficiency, A is the module area (m^2), and G is the irradiance ($W \cdot m^{-2}$).

2.4 Intelligent Control Logic

An Arduino Uno microcontroller governed the thermal control loop using a dual-threshold logic system. When the PV module temperature exceeded the upper threshold (T_H = 50°C), the system automatically activated the DC water pump via a relay, initiating coolant circulation through the aluminium-copper heat exchange assembly. Conversely, when the temperature dropped below the lower threshold (T_L = 40°C), the system deactivated the pump to conserve energy.

These specific temperature thresholds were determined based on both empirical data and established

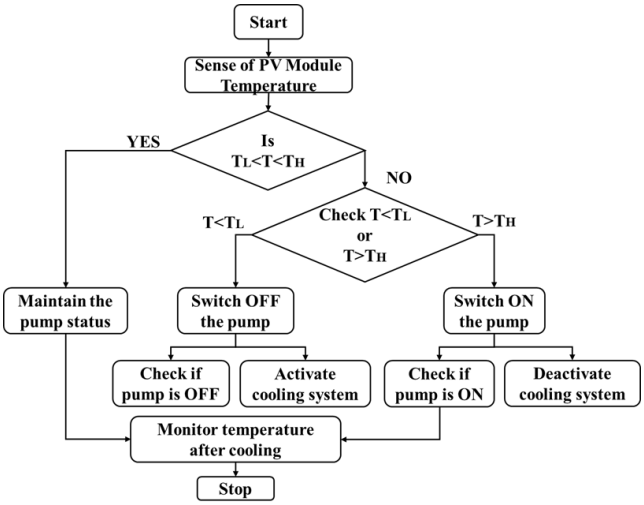


Figure 4. Arduino-based dual-threshold flowchart for automated cooling control.

performance behaviour of *CIGS* thin-film photovoltaic modules. As observed in our experimental results (see Table 3 and Figure 7), a notable power degradation begins beyond 50°C, primarily due to voltage drop caused by increased carrier recombination. The selected thresholds were further optimised through pilot trials to ensure an effective balance between thermal regulation and minimal energy overhead from the pump.

The complete decision logic for pump control is illustrated in Figure 4, which presents the conditional flow structure for the automated thermal management system. This embedded logic enables the PV module to maintain operational temperatures within an optimal efficiency window, thereby improving power output, extending system lifespan, and reducing thermal stress, all without requiring manual intervention.

3.0 Results and Discussions

To ensure accuracy in evaluating system performance, it is essential to present the technical specifications of the primary components used in the experimental setup. These include the thin-film solar PV panel and the submersible DC pump responsible for thermal regulation.

Table 1 provides a comprehensive overview of the electrical, mechanical, and operational characteristics of the 10-watt CIGS thin-film photovoltaic module. The module features a voltage range of 16-18 V at maximum power and an operating efficiency of 7-12 %. The negative temperature coefficient of power (-0.2%/°C

Table 1. Specifications of a thin film solar PV panel

Parameter	Specification
Maximum Power (Pmax)	10 Watts
Voltage at Maximum Power (Vmp)	16-18 V
Current at Maximum Power (Imp)	0.55-0.63 A
Open Circuit Voltage (Voc)	20-23 V
Short Circuit Current (Isc)	0.6-0.7 A
Dimensions	350mm x250 mm x 2 mm
Weight	0.5-1 kg
Frame	Frameless or aluminium-framed
Substrate Material	Glass, metal, or flexible plastic
Cell Type	Thin-Film (*e.g.*, amorphous silicon, CdTe, CIGS)
Efficiency	7-12%
Temperature Coefficient of Power	-0.2%/°C to -0.5%/°C
Operating Temperature	-40°C to +85°C
Operating Conditions	Outdoor use
Protection Class	IP65 or higher
Hail Impact Resistance	Standard hail impact testing
Performance Warranty	10-25 Years
Product Warranty	5-10 Years

to -0.5%/°C) indicates a notable decline in output with increasing temperature, underscoring the importance of implementing effective cooling measures. The panel is also suitable for diverse installation conditions, with a wide operating temperature range (-40°C to +85°C), IP65 protection, and compliance with hail impact standards.

Table 2 outlines the specifications of the solar PV cooling pump. This brushless DC pump, selected for its low power consumption (3-4.5 W) and quiet operation (<35 dB), features a flow rate of 150-250 L/h and is fully submersible (IP68-rated). The pump was able to circulate cooling water efficiently through the aluminium and copper duct system while operating on voltages between 5 V and 12 V. Its compact size, high lift capacity, and low noise profile make it ideal for rooftop PV applications

Table 2. Specifications of solar PV pump

Parameter	Specification
Power Consumption	Less than 5 Watts (typically 3-4.5 W)
Operating Voltage	5V, 6V, 9V, 12V
Current	0.3 - 0.5 A
Maximum Flow Rate	150-250 L/h
Maximum Lift Height	0.5 - 1.5 m
Operating Temperature Range	0°C to 60°C
Waterproof Rating	IP68 (fully submersible)
Material	Plastic (ABS, POM, or similar)
Dimensions	40-60 mm x 30-40 mm x 25-35 mm
Weight	Approximately 50-100 g
Motor Type	Brushless (higher efficiency, low noise)
Noise Level	< 35 dB

Table 3. Electrical performance of CIGS thin-film PV module at varying temperatures under constant irradiance (730 W/m²)

S. No	Voltage (V)	Current (mA)	Power(W)	Temp (°C)
1	20.4	0.318691	6.5013	32
2	18.4	0.301238	5.542775	40
3	18.2	0.299968	5.459425	43
4	18	0.300986	5.41775	45
5	17.8	0.299685	5.3344	48
6	17.6	0.298355	5.25105	50
7	17.4	0.296994	5.1677	52
8	17.1	0.292456	5.001	55
9	16.9	0.286053	4.8343	58
10	16.8	0.282795	4.75095	60
11	16.6	0.281181	4.6676	62

where continuous, autonomous thermal regulation is needed.

Table 3 presents the measured electrical parameters of the CIGS thin-film photovoltaic module at varying temperatures under constant solar irradiance of 730 W/m². As temperature increased from 32°C to 62°C, voltage decreased from 20.4 V to 16.6 V, and power output

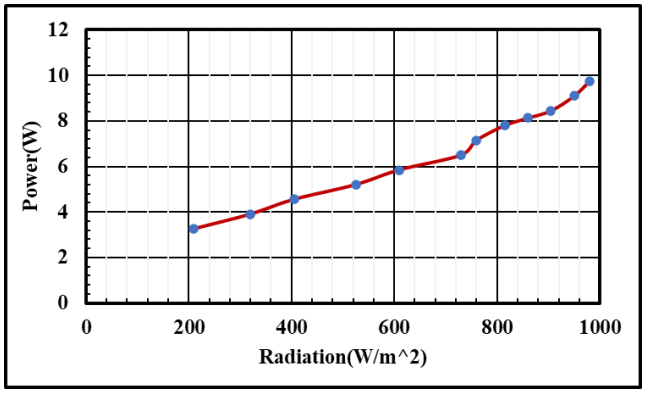


Figure 5. Variation of power output with solar irradiance (W/m²).

dropped from 6.50 W to 4.67 W — representing a 28.2% decline in efficiency. While current remained relatively stable, the voltage degradation significantly impacted total power generation, underscoring the thermal sensitivity of the panel. These results confirm the necessity of temperature regulation in high-irradiance environments to maintain consistent PV output.

As shown in Figure 5, the power output of the CIGS thin-film photovoltaic module exhibits a clear, near-linear increase with rising solar irradiance, ranging from approximately 200 W/m² to 980 W/m². The output climbs steadily from around 3.2 W to nearly 10 W, closely approaching the module's rated peak capacity. This trend aligns with the theoretical relationship P = η×A×G, where power output is proportional to irradiance. The figure confirms the module›s strong response to incident solar energy, with only minor deviations at higher irradiance levels, likely due to internal heating or slight thermal inefficiencies. These results reinforce the importance of maximising irradiance capture in rooftop solar deployments for optimal energy yield.

As depicted in Figure 6, the open-circuit voltage of the CIGS thin-film photovoltaic module shows a consistent decline with increasing temperature, ranging from 32°C to 62°C. Initially measured at approximately 20.4 V, the voltage drops steadily to around 16.6 V at the upper end of the temperature spectrum. This inverse relationship is characteristic of photovoltaic devices, where elevated temperatures reduce the semiconductor bandgap and increase recombination rates, thereby lowering voltage. The trend observed in Figure 5 demonstrates the module's thermal sensitivity and underscores the importance of temperature regulation in maintaining voltage stability,

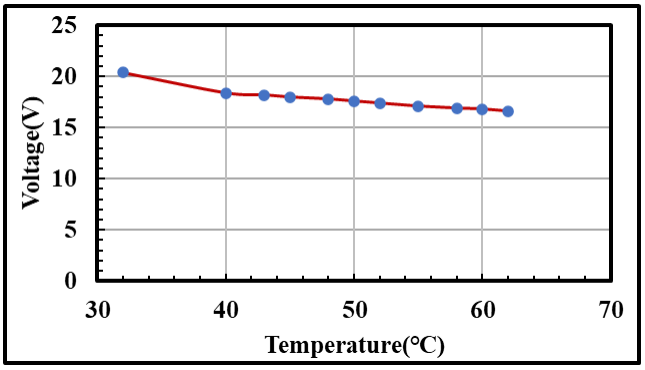


Figure 6. Voltage output as a function of panel temperature.

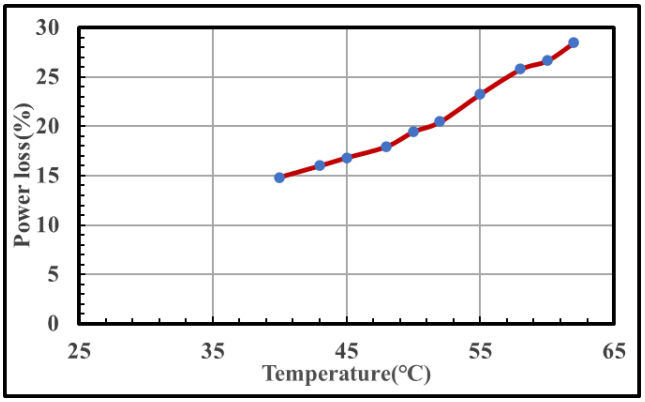


Figure 7. Power loss (%) with increasing panel temperature.

particularly in hot ambient environments typical of rooftop solar installations.

Figure 7 illustrates the percentage power loss of the CIGS thin-film photovoltaic module as a function of temperature. As the panel temperature increases from approximately 35°C to 63°C, power loss rises significantly — from about 15% to nearly 29%. The curve shows a steep escalation, particularly beyond 50°C, indicating a critical thermal threshold where performance rapidly deteriorates. This behaviour is typical of thin-film PV technologies, where elevated temperatures exacerbate efficiency losses due to enhanced carrier recombination and reduced voltage output. The data emphasise the importance of maintaining operational temperatures below 50°C to minimise energy loss and ensure reliable system performance in high-heat environments.

Figure 8 compares the power output of the CIGS thin-film photovoltaic module under varying irradiance levels, both with and without the application of active cooling. Across the full irradiance range (200 W/m² to 980 W/m²), the module consistently performs better when cooled.

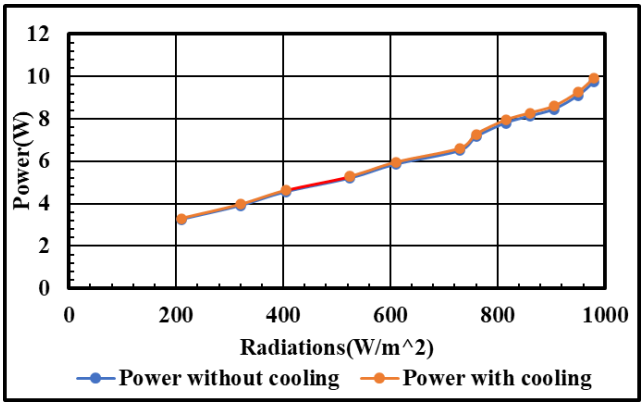


Figure 8. Comparative power output with and without cooling under varying irradiance.

The power difference becomes increasingly pronounced at higher irradiance levels, where thermal effects would otherwise limit performance. This demonstrates the effectiveness of the water-cooling system in mitigating temperature-induced losses, enabling the module to maintain higher efficiency under intense solar exposure. The graph reinforces that integrating active thermal regulation is especially beneficial in high-insolation environments, where overheating typically curtails PV efficiency.

Figure 9 illustrates the measurement time intervals under two conditions: with and without the use of a 2× solar concentrator, recorded from 10:00 AM to 1:24 PM. The time distribution remains relatively uniform across all sampling points, indicating consistent data collection. The slightly longer durations observed with the concentrator reflect the system's response to increased thermal input, which required more time for the cooling loop to stabilise and maintain optimal panel temperature. This consistency demonstrates the reliability of the control system and validates the repeatability of performance measurements under dynamic solar loading conditions.

Table 4 summarises the total energy output of the thin-film solar module under two configurations: with and without the active cooling system, and with and without the use of a 2× solar concentrator. Without the concentrator, cooling improved the energy output from 13.185 Whr to 13.655 Whr — an increase of approximately 3.56%. Under concentrated irradiance, the improvement was more substantial, with energy output rising from 19.00 Whr to 24.515 Whr, demonstrating a 28.5% gain due to enhanced thermal regulation.

Table 5 details the energy consumed by the DC pump that operates the cooling system. The pump required

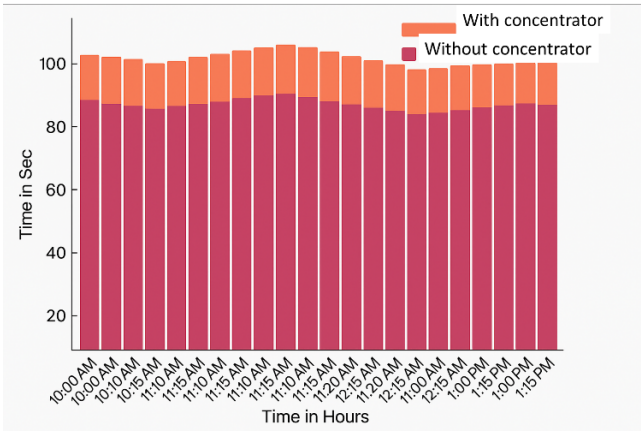


Figure 9. Time distribution of data collection with and without solar concentrator.

Table 4. Power output of a thin film solar module with and without cooling

Configuration	Power output without cooling (Whr)	Power output with cooling (Whr)
Without concentrator	13.185	13.655
With a concentrator (2x)	19.00	24.515

Table 5. Power consumed by the pump

Configuration	Power Output (Whr)
Without concentrator	3.86
With a concentrator (2x)	5.12

3.86 Whr under standard sunlight and 5.12 Whr under concentrated conditions. Despite this added consumption, the net energy gain from cooling significantly outweighed the operational cost of the pump, especially under higher irradiance. These results validate the cooling strategy's energy efficiency and effectiveness for improving PV performance in high-heat environments.

3.1 Suitability of the Proposed Cooling System for Urban Thin-Film CIGS Rooftop Applications

The experimental outcomes strongly support the conclusion that the proposed water-based hybrid cooling system is highly effective for enhancing the performance of CIGS thin-film PV panels under elevated temperature

conditions. By integrating a lightweight aluminium and copper heat exchange assembly with automated thermal control via a dual-threshold Arduino logic, the system successfully mitigates one of the most critical limitations of CIGS technology — thermal degradation at high ambient temperatures. CIGS panels, while intrinsically better suited for low-light and diffuse radiation environments, are thermally sensitive, with significant voltage drop and performance loss observed beyond 40°C. In this study, panel temperature regulation translated into a power output increase of up to 28.5% under concentrated sunlight and 3.56% under standard irradiance, underscoring the scalability and efficiency of the cooling mechanism across diverse irradiance conditions.

Furthermore, the compact and modular nature of the cooling design aligns perfectly with the spatial and structural constraints of urban rooftop environments, where available space, weight-bearing capacity, and exposure to heat-island effects are critical factors. The use of low-power components, including a brushless DC submersible pump, ensures minimal parasitic energy consumption, and the system's automation requires no manual intervention, making it ideal for deployment in both residential and commercial rooftop installations. The cooling approach not only improves instantaneous energy yield but also contributes to the long-term durability of the PV system by reducing thermal stress and material degradation, as validated using the Arrhenius degradation model. From an economic perspective, the improvement in efficiency directly translates into a shorter payback period and higher return on investment, enhancing the appeal of CIGS systems in markets sensitive to both capital expenditure and operational efficiency. In summary, this study demonstrates that integrating an active thermal management system with thin-film CIGS panels is a viable, cost-effective, and sustainable solution for boosting solar energy production in urban rooftop PV applications, particularly in hot climates like those prevalent in India. The system presents a replicable model that can contribute significantly to national renewable energy targets while offering reliable performance in thermally challenging environments.

3.2 AI-Based Predictive Modelling of CIGS System Performance

To evaluate the thermal performance degradation of *Copper Indium Gallium Selenide* (CIGS) photovoltaic modules under rooftop conditions, a Random Forest regression model was developed using experimental data collected at a stable irradiance level of approximately 730 W/m². The dataset consisted of 110 temperature-power pairs obtained through field measurements, with panel temperatures ranging from 32°C to 62°C. The data was pre-processed by averaging sensor readings over 5-minute intervals to eliminate short-term fluctuations. To build and validate the model, an 80:20 train-test data split was applied, along with 5-fold cross-validation to ensure consistency and minimise overfitting.

Hyperparameter tuning was conducted using a grid search method, resulting in an optimised model configuration with 100 estimators (trees), a maximum depth of 10, and a minimum sample split of 4. The model demonstrated excellent predictive capability, achieving a Root Mean Square Error (RMSE) of 15.7 W, a Mean Absolute Error (MAE) of 12.4 W, and a Coefficient of Determination (R^2) of 0.932 on the test dataset. The use of a Random Forest model allowed for effective modelling of nonlinear degradation behaviour, which linear models often fail to capture in thermal sensitivity analysis. The prediction curve derived from the model is illustrated in Figure 10, clearly showing the inverse relationship between panel temperature and power output.

As shown in Figure 10, the model's output revealed a stable power range between 30°C and 45°C, followed by a rapid performance decline beyond 50°C. At temperatures exceeding 55°C, predicted output dropped below 480 W for a scaled 1 kW CIGS system. This significant loss is attributed to semiconductor effects such as increased carrier recombination and reduced bandgap, leading

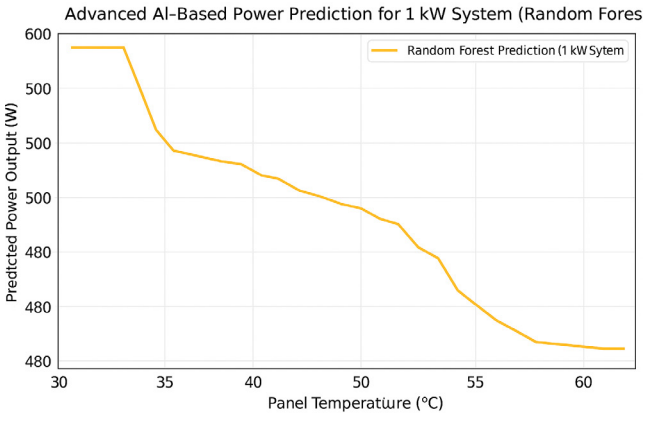


Figure 10. Advanced AI-based power prediction for a 1 kW thin-film CIGS system using random forest regression.

to voltage degradation. These findings reinforce the importance of implementing active thermal management systems in rooftop solar installations, especially in high-insolation, high-temperature environments. The developed model also offers a reliable foundation for future integration with adaptive thermal control algorithms and rooftop PV performance forecasting tools.

4.0 Environmental Impact Assessment

To evaluate the ecological sustainability of the proposed active cooling system for CIGS thin-film modules, a preliminary environmental impact analysis was conducted focusing on water consumption, material efficiency, and system lifecycle characteristics.

The system operates using a closed-loop water circulation mechanism, which significantly minimises water wastage. Based on measurements recorded during experimental trials, the estimated net water consumption is approximately 1.2 L/day per 10 W panel, primarily due to evaporative losses. This figure was determined by monitoring the reservoir depletion over standard 4-h operating periods during peak sunlight hours. Given the modularity of the design, a 1 kW rooftop system would require roughly 120 L of water daily, which remains modest when distributed across multiple panels and considered in the context of cooling benefit and energy gain. Moreover, because water is reused in a sealed system, replenishment is infrequent and can be integrated into routine maintenance schedules.

In terms of materials, the cooling assembly consists primarily of aluminium ducts and copper tubing, both of which are highly recyclable and have well-documented environmental advantages due to their long operational lifespan. The use of a low-power brushless DC submersible pump (3-5 W) contributes to negligible parasitic energy losses. The supporting electronics (Arduino microcontroller, relay, sensors) have a compact form factor and require minimal power input, further reinforcing the low operational carbon footprint of the system.

Although a complete Life-Cycle Assessment (LCA) is beyond the scope of this current work, the components used are characterised by low embodied energy and minimal e-waste potential. The combination of water efficiency, material sustainability, and autonomous control operation positions the proposed system as a viable and environmentally sound solution for urban rooftop solar applications. A more detailed LCA, including embodied carbon, component recyclability, and energy payback analysis, is recommended as part of future research to fully validate the system's long-term ecological performance.

5.0 Future Work

Building upon the findings of this study, several avenues for future research are proposed to enhance the technical, economic, and environmental impact of the cooling-integrated CIGS rooftop photovoltaic system.

First, there is strong potential to integrate the system with adaptive, weather-responsive control algorithms. By using real-time environmental data such as solar irradiance forecasts, ambient temperature, humidity, and wind speed, the control logic can be dynamically adjusted to optimise cooling system activation. This would enhance both energy efficiency and water conservation by responding proactively to climatic fluctuations, particularly in high-variability urban environments.

Second, long-term durability and reliability studies are needed to evaluate the operational robustness of the system over extended periods. This includes assessing degradation of pump performance, sensor stability, duct adhesion, and electrical control components under continuous solar exposure and ambient stress cycles. These studies will help define maintenance schedules and replacement timelines, ensuring consistent performance and cost-effectiveness.

Third, the use of passive thermal storage elements, such as Phase Change Materials (PCMs), may further improve system efficiency by reducing the active cooling load during periods of transient solar variation or late afternoon peaks. A comparative analysis of passive-only, active-only, and hybrid systems will provide deeper insight into optimal cooling strategies across diverse climatic zones.

Finally, scaling the system to multi-kilowatt urban rooftop installations is a critical next step to validate scalability, structural integration, and economic feasibility in real-world deployment. This should be complemented by a full LCA to quantify the environmental footprint, embodied energy, recyclability of components, and long-term sustainability impact of the proposed solution. These efforts will support the development of a robust,

scalable, and environmentally responsible framework for deploying CIGS-based PV technologies in high-temperature regions.

6.0 Conclusion

The findings of this study affirm that integrating an active thermal management system into CIGS thin-film photovoltaic panels significantly enhances their operational efficiency, reliability, and financial performance under high-temperature rooftop conditions. The proposed system, combining a low-power water circulation mechanism with intelligent dual-threshold thermal control, effectively mitigates thermal losses — achieving a substantial performance gain, particularly in high-irradiance scenarios typical of Indian cities. The experimental data revealed that temperature-induced voltage drop is the primary contributor to energy loss in CIGS panels, and the proposed cooling solution directly counters this limitation. Moreover, AI-based predictive modelling using Random Forest regression accurately characterised non-linear power decline beyond 50°C, reinforcing the system's value in thermally stressed environments. The economic analysis indicated a reduced payback period and a marked increase in return on investment, particularly at larger system scales such as 1 MW rooftop installations. This research not only advances the practical application of thin-film PV technology but also aligns with broader sustainability and energy policy objectives. The modular, low-maintenance nature of the cooling system makes it well-suited for decentralised energy generation in dense urban areas, where spatial and structural constraints are common. Future work may explore adaptive control algorithms and integration with real-time weather forecasting to further optimise thermal management in solar PV systems.

7.0 References

1. Ang TZ, Salem M, Kamarol M, Das HS, Nazari MA, Prabaharan N. A comprehensive study of renewable energy sources: Classifications, challenges and suggestions. Energy Strateg Rev. 2022; 43:100939. https://doi.org/10.1016/j.esr.2022.100939
2. Bhuvad SS, Udayraj. Investigation of annual performance of a building shaded by rooftop PV panels in different climate zones of India. Renew Energy. 2022; 189:1337-1357. https://doi.org/10.1016/j.renene.2022.03.004
3. Shital SK, Shashikant GK. Analysis of temperature effect, incidence angle, fill factor, air mass and pollution factor of solar power generation with rooftop system by monocrystalline solar panel. AIP Conf Proc; 2022. 040002. https://doi.org/10.1063/5.0106560
4. Cheng X, He L, Li J, Lei Q, Liu F, Li X, *et al*. Electrical performance of the side region in a multi-crystalline silicon ingot. Silicon. 2024; 16(8):3485-3489. https://doi.org/10.1007/s12633-024-02878-0
5. Basher H, Zulkifli MN, Jalar A, Daenen M. Effect of ultrasonic bonding and lamination on electrical performance of copper indium gallium (de) Selenide CIGS thin film photovoltaic solar panel. J Adhes Sci Technol. 2024; 38(14):2477-2496. https://doi.org/10.1080/01694243.2024.2303238
6. Li Z, Wu H, Wang R. Actuality and technology prospect of using perovskite quantum dot solar cells as the photovoltaic roof. Solar Energy. 2024; 269:112359. https://doi.org/10.1016/j.solener.2024.112359
7. Kapsalis V, Maduta C, Skandalos N, Wang M, Bhuvad SS, D'Agostino D, *et al*. Critical assessment of large-scale rooftop photovoltaics deployment in the global urban environment. Renew Sustain Energy Rev. 2024; 189:114005. https://doi.org/10.1016/j.rser.2023.114005
8. Tian J, Ooka R. Evaluation of solar energy potential for residential buildings in urban environments based on a parametric approach. Sustain Cities Soc. 2024; 106:105350. https://doi.org/10.1016/j.scs.2024.105350
9. Wu Z, Chen Z, Wang C, Zhou M, Wang J, Chen L. Unlocking the potential of rooftop solar panels: An incentive rate structure design. Energy Policy. 2024; 190:114159. https://doi.org/10.1016/j.enpol.2024.114159
10. Leewiraphan C, Ketjoy N, Thanarak P. An assessment of the economic viability of delivering solar PV rooftop as a service to strengthen business investment in the residential and commercial sectors. Int J Energy Econ Policy. 2024; 14(2):226-233. https://doi.org/10.32479/ijeep.15505
11. Rounis ED, Athienitis AK, Stathopoulos T. BIPV/T curtain wall systems: Design, development and testing. J Build Eng. 2021; 42:103019. https://doi.org/10.1016/j.jobe.2021.103019
12. Özkalay E, Valoti F, Caccivio M, Virtuani A, Friesen G, Ballif C. The effect of partial shading on the reliability of photovoltaic modules in the built-environment. EPJ Photovolt. 2024; 15:7. https://doi.org/10.1051/epjpv/2024001
13. Husain AM, Hasan MM, Khan ZA, Asjad M. A robust decision-making approach for the selection of an optimal

renewable energy source in India. Energy Convers Manag. 2024; 301:117989. https://doi.org/10.1016/j.enconman.2023.117989
14. Zafar I, Stojceska V, Tassou S. Social sustainability assessments of industrial level solar energy: A systematic review. Renew Sustain Energy Rev. 2024; 189:113962. https://doi.org/10.1016/j.rser.2023.113962
15. Jain A, Kothari R, Tyagi VV, Rajamony RK, Ahmad MS, Singh HM, *et al*. Advances in organic solar cells: Materials, progress, challenges and amelioration for sustainable future. Sustain Energy Technol Assess. 2024; 63:103632. https://doi.org/10.1016/j.seta.2024.103632
16. Yang Z, Peng J, Jiang S, Yu X, Hu T. Optimizing building spatial morphology to alleviate human thermal stress. Sustain Cities Soc. 2024; 106:105386. https://doi.org/10.1016/j.scs.2024.105386
17. Tetreault AR, Lopez-Carreon I, Riahinezhad M, Esmizadeh E, Collins P, Zarasvand KA, *et al*. Assessing individual material degradation toward organic solar cells using accelerated nanolayer lifetime protocols: Implications for solar cell longevity. ACS Appl Nano Mater. 2024; 7(4):4182-4198. https://doi.org/10.1021/acsanm.3c05732
18. Kim KS. Durability evaluation study of re-manufactured photovoltaic modules. Curr Photovolt Res. 2024; 12(1):17-23.
19. Akbari M, Kashani FD, Mirkazemi SM. Designing novel plasmonic architectures for highly efficient CIGS solar cells. Solar Energy. 2024; 274:112589. https://doi.org/10.1016/j.solener.2024.112589
20. Wang B, Liu Y, Wang D, Song C, Fu Z, Zhang C. A review of the photothermal-photovoltaic energy supply system for building in solar energy enrichment zones. Renew Sustain Energy Rev. 2024; 191:114100. https://doi.org/10.1016/j.rser.2023.114100