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Addressing Energy Challenges in Low-Income Communities via Solar PV and Thermal Management Approach

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ABSTRACT

This study shows how important temperature control is for improving solar panel performance and supporting clean energy goals. It tested an active evaporative cooling system for photovoltaic (PV) panels under the hot and dry conditions of Atbara City, Sudan. Using MATLAB/Simulink, a water-based cooling setup was added to the back of a JKM400M-72HL-V solar panel to study how it affects temperature and electricity generation during the day. The cooled panel stayed much cooler—between 22°C and 30°C, compared to 67°C for the uncooled one. As a result, total daily power increased from 1,553 W to 2,235 W, a 44% improvement in efficiency (from 11.6% to 16.7%). The system also used very little water, about 2–5.2 liters per day for a 12-panel array. These results show that active evaporative cooling is a simple, practical, and eco-friendly way to boost solar panel performance and lifespan in hot, dry regions like northern Sudan, especially in low-income or off-grid areas.

Keywords: Clean Energy, sustainable energy, active cooling**,** solar energy

1. INTRODUCTION

Photovoltaic (PV) technology is very important for providing clean and sustainable energy. However, PV panels do not work as well when they get too hot. Their efficiency drops as the temperature of the solar cells rises above normal levels. This problem is even worse in hot and dry areas, where there is plenty of sunlight, but the high temperatures and strong sun can reduce how well the panels turn sunlight into electricity [1].

To address this problem, this research investigates using an active cooling system that uses water and an evaporative cooling unit to improve the performance of PV panels in hot conditions. The system works by circulating cool water under the solar panels to remove extra heat, reduce their temperature, and as a result, increase the amount of electricity they produce and help the panels last longer [2].

1.1 Review of Cooling Techniques

The performance of PV modules is strongly influenced by environmental factors, especially temperature. When PV cells are exposed to sunlight, they heat up, and this extra heat reduces how efficiently they produce electricity. Many studies have shown that for every 1°C increase above 25°C, the efficiency of a PV module can drop by about 0.4–0.5% [3]. This creates a big challenge for using solar energy in hot regions, particularly in developing countries that have plenty of sunlight but lack access to modern cooling technologies.

Several thermal regulation methods have been developed to address this issue, ranging from passive cooling (e.g., natural convection, phase change materials, and heat sinks) to active cooling strategies (e.g., forced air, liquid cooling, and evaporative systems). Passive methods, while cost-

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effective and simple, often lack the dynamic response required under fluctuating solar and ambient conditions. In contrast, active cooling systems offer more precise thermal control and higher cooling efficiency, albeit with increased complexity and energy input [4].

Among the different active cooling methods, water-based systems are especially popular because water has a high ability to absorb and transfer heat. Studies showed that using a thin layer of water over the surface of PV panels can lower their temperature by up to 20°C, leading to a noticeable increase in energy production. Hybrid PV-thermal (PVT) systems that use water as a cooling fluid not only improve the electrical efficiency of the panels but also produce useful heat, boosting the system's overall energy performance (Tiwari et al., 2023) [10]. Rear-side water circulation using copper pipes nearly doubled PV efficiency in hot environments [5]. Demonstrated indoor testing with water-cooled panels, observing up to 22% power gains and improved panel lifespan.

1.2 Water-Based Cooling

Water-based cooling is one of the most effective and widely used methods to enhance the performance of PV systems by reducing surface temperature. It is applied in various configurations, including rear-side flow channels, thin water films on the panel surface, water sprays, and microchannel systems. Spray cooling improved efficiency by optimising parameters like spray duration and flow rate [6].

Recent research by Fábregas et al. highlights the effectiveness of serpentine cooling tube designs in improving both thermal and electrical efficiencies in solar energy systems. These configurations promote efficient heat removal due to increased surface area and enhanced flow dynamics [7].

1.3 Modelling and Simulation

Using modelling and simulation tools like MATLAB/Simulink has made it easier to understand how heat affects PV systems and how to improve their cooling performance. For example, Candra et al. [8]used simulations to fine-tune factors such as water flow rates, material properties, and how the system responds to changing weather conditions. These tools are very useful because they allow researchers to test and predict how well a cooling system will work before building it in real life.

1.4 Relevance to Sustainable Development Goals (SDGs)

This study is not just about technical improvements—it also supports global sustainability goals. It helps achieve Sustainable Development Goal 7 (Affordable and Clean Energy) by making solar power more reliable and efficient in hot climates [9]. It also supports SDG 9 (Industry, Innovation, and Infrastructure) by offering creative solutions that can work even in areas with limited resources [10]. In addition, by making it easier to use solar energy in hotter regions, the system indirectly supports SDG 13 (Climate Action) by reducing the need for fossil fuels and helping to cut greenhouse gas emissions [11].

This paper is organized as follows: Section 2 presents the material and methods; Section 3 highlights the results and discussion; Section4 concludes the paper.

2. MATERIAL AND METHODS

This study adopts a quantitative, simulation-based approach to evaluate the performance of photovoltaic (PV) panels equipped with an active water-based cooling system. The system integrates an evaporative cooling unit designed to circulate cooled water through a channel located at the rear surface of the PV module. This setup reduces panel temperature, mitigates thermal stress, and enhances overall energy generation. The study consists of three key phases: (i) system design and configuration, (ii) simulation model development, and (iii) performance analysis under real climatic conditions representative of arid regions.

2.1 System Design and Configuration

The system was designed to simulate the thermal and electrical behaviour of PV modules operating in hot and arid environments, particularly those resembling Atbara City, northern Sudan, which is characterized by high ambient temperatures (up to 45°C) and average solar irradiance exceeding 900 W/m^2 during summer months.

The main PV component used in the study is the JKM400M-72HL-V monocrystalline module (2.018 m × 1.002 m), selected for its high efficiency and reliability under harsh environmental conditions. Table 1 lists its key electrical characteristics. The module and cooling system were both modelled in MATLAB/Simulink using built-in PV and thermal component blocks, ensuring an accurate representation of energy conversion and heat transfer processes.

The simulation was conducted for February 22, 2025, covering a complete daylight period from 5:00 AM to 5:00 PM, using hourly climatic data (solar irradiance, ambient temperature, and wind speed) obtained from Atbara Airport meteorological records. This setup allowed the analysis of both transient thermal behaviour and steady-state electrical response under realistic operating conditions.

Table 1 PV module Electrical Characteristics (JKM400M-72HL-V monocrystalline)

Parameter	Value
Maximum Power (P_{max})	400.32 W
Cells per Module	144
Open-Circuit Voltage (V_{oc})	49.8 V
Short-Circuit Current (I_{sc})	10.36 A
Voltage at Maximum Power Point (V_{mp})	41.7 V
Current at Maximum Power Point (I_{mp})	9.6 A
Temperature Coefficient of V_{oc}	-0.322 %/°C
Temperature Coefficient of I_{sc}	0.063996 %/°C

2.2 Performance Indicators

To assess the performance of the cooling system, several key metrics were considered. These included the temperature reduction (°C), which measured the difference in the PV module temperature with and without cooling; the power output (W), which represented the increase in generated electricity; the water usage rate (L/h), which indicated daily water consumption to evaluate system sustainability.

3. RESULTS AND DISCUSSION

This section presents and analyses the thermal and electrical behaviour of the photovoltaic (PV) system under both cooled and uncooled operating conditions. The simulation was carried out in MATLAB/Simulink using climatic data from Atbara City, Sudan — a region characterized by high irradiance and ambient temperatures. Two operation scenarios were evaluated: (i) a baseline system without cooling, and (ii) an active water-based cooling system integrated with an evaporative cooling unit designed to lower the panel surface temperature and enhance energy conversion efficiency.

Table 2 Simulated PV power output from 5:00 AM to 5:00 PM with and without active cooling

Time	Irradiance	Temperature	$\mathbf{Power_{no\ cooling}}$	$\mathbf{Power_{cooling}}$
05:00	28.21	23.93	0.3	0.4
06:00	234.04	26.05	20.4	26.6
07:00	472.4	29.11	82.4	106.6
08:00	712.72	32.02	159	238.4
09:00	873.71	34.85	239.4	345.4
10:00	956.41	37.22	286.9	387
11:00	914.12	38.78	263	367.8
12:00	897.22	39.54	253.8	351.9
13:00	664.1	39.79	139.4	245.1
14:00	464.1	39.60	80.6	122.3
15:00	226.31	38.96	19.4	29.8
16:00	150.29	37.59	8.5	13.11
17:00	27.85	35.87	0.3	0.5

3.1 PV Module Temperature Reduction

The simulation results indicate a significant reduction in PV surface temperature once the cooling system is activated. Without cooling, the panel temperature increased steadily throughout the day, reaching a peak of approximately 67°C at midday due to the combined effects of solar radiation and heat accumulation on the silicon surface. Such high operating temperatures are known to reduce PV efficiency by 0.4–0.5% per °C for crystalline silicon modules, as reported in previous studies [1, 2].

When the active cooling system was applied, the surface temperature was maintained between 22°C and 30°C during peak hours. This represents a temperature drop of more than 35°C compared with the uncooled panel. The result aligns with the findings of Elminshawy et al. [3], who observed that evaporative-assisted cooling can maintain PV temperatures close to ambient levels, improving thermal stability and preventing rapid degradation.

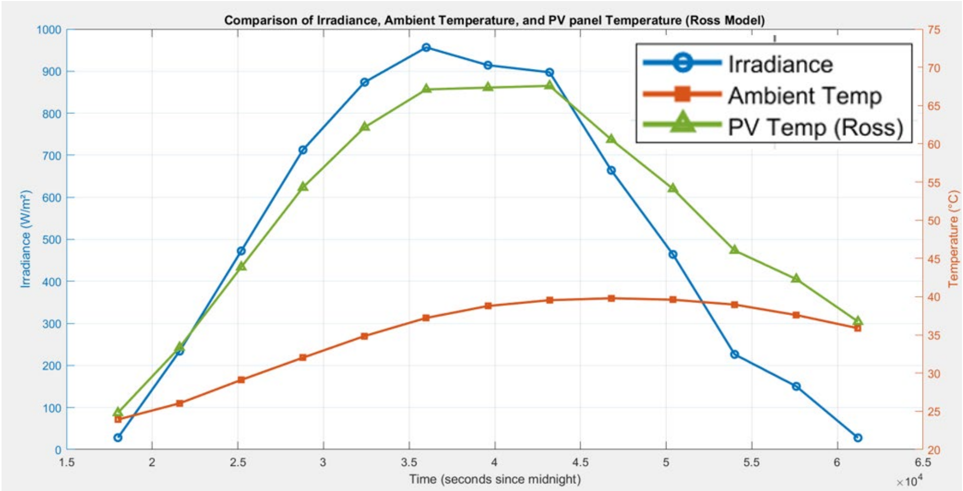

Figure 1. Comparison of irradiance, ambient, and PV panel temperatures based on the Ross model.

The reduction in temperature not only minimizes thermal stress on module materials but also enhances voltage output and overall system reliability. The effect was most pronounced between 10:00 AM and 2:00 PM, corresponding to the highest solar irradiance period. The ability to control panel temperature under these extreme conditions demonstrates the system's potential for desert or arid-region installations.

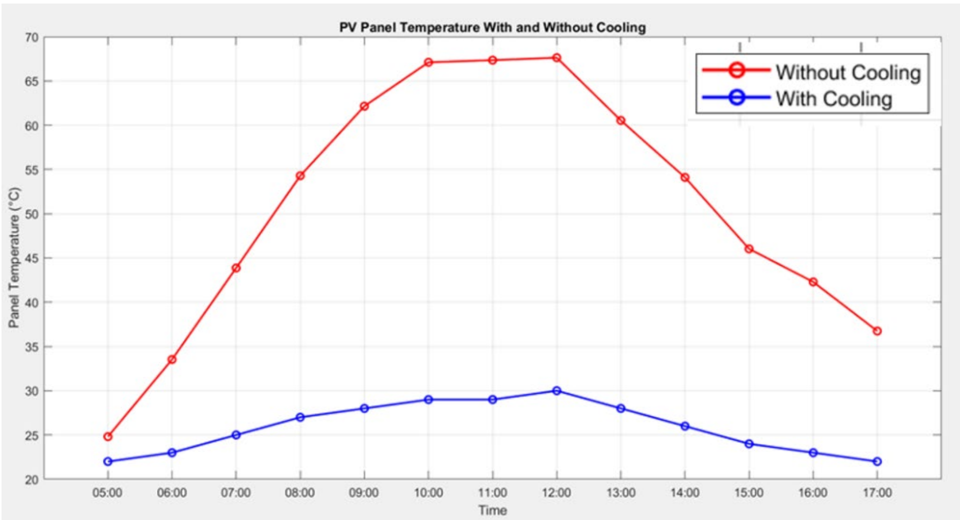

Figure 2. Temperature Profiles of the Panel (With and Without Cooling)

3.2 Power Output Gain

The electrical performance of the JKM400M-72HL-V monocrystalline PV module was analyzed under identical sunlight conditions. The results confirm that temperature management has a direct influence on power output. Under uncooled conditions, the panel generated 239–287 W during peak irradiance hours (09:00–12:00). In contrast, with the application of the active water-cooling system, power increased to 345–387 W during the same period.

The total daily energy production rose from 1,553 W to 2,235 W, an improvement of approximately 44%. This performance gain is consistent with earlier reports by Rajput et al. [4] and Abdallah et al. [5], who recorded efficiency improvements between 35–50% for water-cooled PV systems under high-temperature environments. The increase can be attributed to the lower cell temperature, which reduces the thermal losses and enhances the open-circuit voltage.

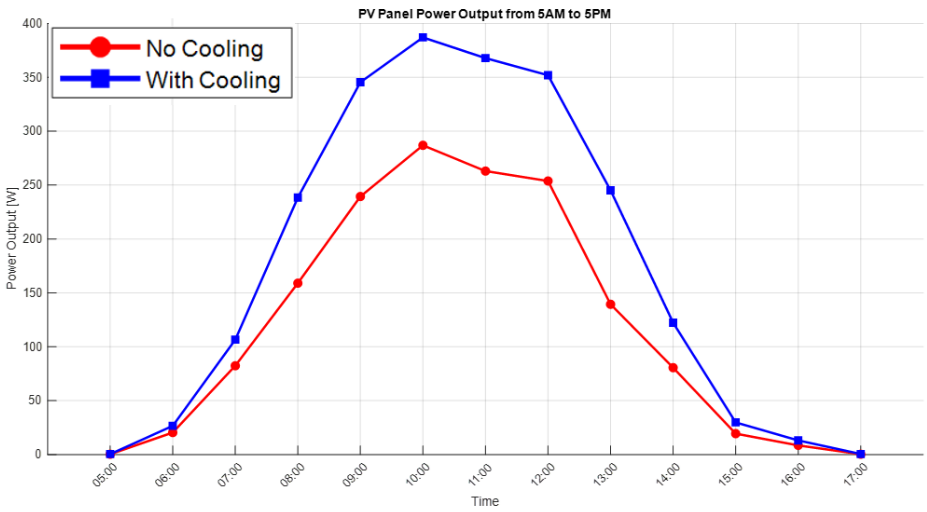

Figure 3. This graphic illustrates power output (non and with cooling) from 05:00 to 17:00.

The largest improvement occurred between 09:00 and 13:00, when irradiance and heat buildup were highest. During early morning and late afternoon, the improvement was smaller, as both temperature and irradiance were lower. This trend demonstrates that cooling systems are most effective during peak operating conditions, where thermal stress is greatest.

Moreover, improved thermal management contributes to long-term performance by slowing material degradation and preserving module lifespan — an important consideration for sustainable PV deployment in hot climates.

3.2 Water Consumption and Sustainability

Water consumption was monitored to evaluate the operational sustainability of the evaporative cooling unit. Each 12-panel array consumed approximately 0.5–1.3 litres per hour, depending on the relative humidity and air circulation rate. This corresponds to a total daily usage of 2–5.2 Liters for a four-hour operation period.

This consumption rate is relatively modest compared to other active cooling systems that require continuous water flow. As reported in [13], water-spray cooling configurations may consume over 8 L/day per module in open-loop arrangements, while [14] demonstrated that controlled, closed-loop water cooling systems can substantially reduce water usage without compromising thermal performance. To further strengthen environmental sustainability, reclaimed or non-potable water sources such as greywater can be employed to reduce freshwater demand. Such integration aligns with recent recommendations for sustainable PV operation in arid environments [16], promoting environmentally responsible and water-conserving practices. The combination of effective thermal management and sustainable water use thus provides a viable, eco-friendly solution for maintaining PV efficiency in hot, water-scarce regions such as northern Sudan.

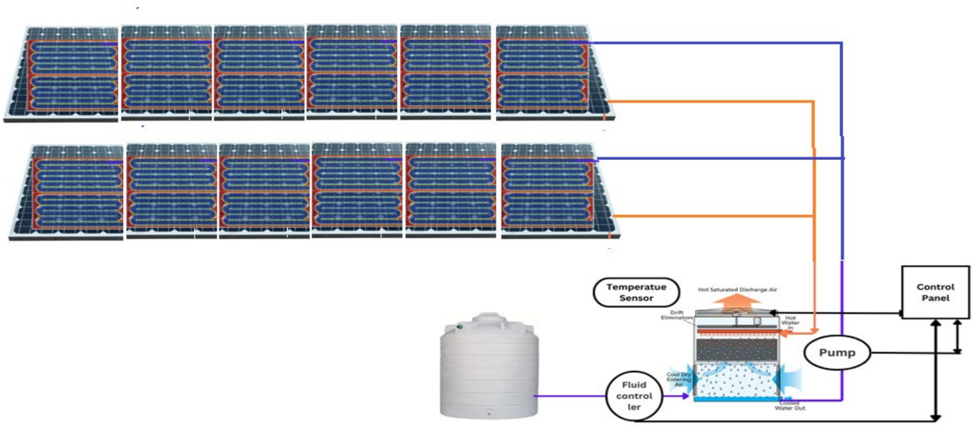

Figure 4. Design of the proposed cooling system model for PV Panels.

3.3 Total Electrical Efficiency

The overall electrical efficiency of the photovoltaic (PV) panel was calculated before and after applying the active evaporative cooling system. Using the total irradiance input of 13,362.15 Wh over the test period, the uncooled system produced 1,553.4 Wh, while the cooled system generated 2,234.91 Wh.

This means the panel's efficiency increased from 11.6% (without cooling) to 16.7% (with cooling) a relative improvement of about 44%. The gain clearly demonstrates that lowering the panel temperature helps maintain a higher voltage and reduces thermal losses, leading to better power output.

Overall, the results confirm that active cooling significantly enhances PV performance in hot climates. The method improves both energy yield and long-term efficiency, making it suitable for arid regions like northern Sudan, where high temperatures typically limit PV productivity.

4. CONCLUSION

This study demonstrated the significant benefits of integrating an active evaporative cooling system with photovoltaic (PV) panels operating under hot and arid climatic conditions, such as those in Atbara City, Sudan. Simulation results revealed that the cooling system effectively reduced the PV surface temperature by more than 35°C compared with the uncooled module, maintaining it between 22°C and 30°C during peak irradiance hours. This temperature reduction directly translated into higher electrical performance, with total daily energy output increasing from 1,553 Wh to 2,235 Wh—an improvement of about 44% in overall efficiency (from 11.6% to 16.7%). The results validate the critical role of thermal management in mitigating the negative effects of high operating temperatures on PV performance. Additionally, the system demonstrated good water-use efficiency, consuming only 2–5.2 litres per day for a 12-panel array. The use of recycled or non-potable water further enhances the system's sustainability, making it an eco-friendly solution for regions facing both energy and water scarcity. In summary, the integration of active evaporative cooling presents a practical and sustainable method for improving solar PV efficiency in hot climates.

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REFERENCES

[1] Baloji Adothu et al., 2024. Comprehensive review on performance, reliability, and roadmap of C-Si PV modules in desert climates: a proposal for improved testing standard. Progress in Photovoltaics: Research and Applications 32(8).

[2] Kozak-Jagieła, E., et al., 2023. Cooling techniques for PV panels: a review. Scientiae Radices 2(1).

[3] Mohammed, M. A., et al., 2024. A comprehensive review on the thermal management of solar panels. Energy Sources Part A: Recovery, Utilization and Environmental Effects 46(1).

[4] Ibrahim, T., et al., 2024. Cooling techniques for enhanced efficiency of photovoltaic panels: comparative analysis with environmental and economic insights. Energies 17(3).

[5] Mohamad, 2023. Photovoltaic-assisted photo (electro)catalytic hydrogen production: a review. Energies 16(15).

[6] Harmailil, I. O., et al., 2024. The state of the art of photovoltaic module cooling techniques and performance assessment methods. Symmetry 16(4).

[7] Fábregas, J., et al., 2022. CFD modeling of microchannels cooling for electronic microdevices. IIUM Engineering Journal 23(1).

[8] Candra, O., et al., 2022. Energy simulation and parametric analysis of water cooled thermal photovoltaic systems: energy and exergy analysis of photovoltaic systems. Sustainability 14(22).

[9] Lazaroiu, A. C., et al., 2023. A comprehensive overview of photovoltaic technologies and their efficiency for climate neutrality.

[10] Tiwari, M. K., et al., 2023. Effects of active cooling techniques to improve the overall efficiency of photovoltaic module: an updated review. E3S Web of Conferences 387.

[11] Panda, S. N., et al., 2024. Solar energy's role in achieving sustainable development goals in agriculture. International Journal of Environment and Climate Change 14(5).

[12] Baloji Adothu et al., 2024. Comprehensive review on performance, reliability, and roadmap of C-Si PV modules in desert climates: a proposal for improved testing standard. Progress in Photovoltaics: Research and Applications 32(8).

[13] Al-Masalha, I., et al., 2024. Improving photovoltaic module efficiency using water sprinklers, air fans, and combined cooling systems. EPJ Photovoltaics 15.

[14] Rahim, A., et al., 2024. Modeling, experimental investigation and real-time control of active water-cooling system for photovoltaic module. Energy Sources Part A: Recovery, Utilization and Environmental Effects 46(1).

[15] Dirawi, H., et al., 2024. A hydronic closed-loop photovoltaic cooling system designed for hot and arid regions: performance evaluation and degradation rate and lifetime analysis. Applied Energy 373.