ISSN: 2985-4393

Development and Performance Evaluation of an Active Water Injection Cooling System for Solar Panels Using Integrated Digital Thermostat Control

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Abstract. The operational temperature of photovoltaic (PV) modules significantly affects their energy conversion efficiency, where high surface temperatures lead to substantial performance degradation, particularly in regions with high solar radiation intensity. This study presents the design, development, and experimental evaluation of an active water-injection cooling system for PV panels, equipped with an integrated digital thermostat for automatic temperature regulation. The proposed system consists of a DC-powered water pump, precision nozzles, an acrylic manifold, and a closed-loop control mechanism that activates cooling when the panel surface temperature exceeds a specified threshold. The system was designed using Autodesk Fusion 360 to ensure optimal component integration and was constructed with cost-effective and readily available materials. Experimental testing was carried out under real outdoor conditions in a tropical climate to assess the cooling system's impact on module temperature, electrical output power, and overall energy yield. The results demonstrated that the active cooling system reduced the panel surface temperature by up to 5.7 °C compared to the uncooled reference, resulting in an average power output increase of 28.3% and a total daily energy gain of 32.5%. These findings confirm that water-injection cooling, combined with intelligent temperature control, offers a practical and sustainable solution for enhancing PV performance in hot climates. This work contributes to the development of cost-effective thermal management strategies for solar energy systems and provides valuable insights for large-scale PV deployment in high thermal-stress regions..

Keywords: Photovoltaic cooling system, water injection, smart thermal management, digital thermostat control, PV efficiency enhancement, active cooling, hot climate performance.

1. INTRODUCTION

Solar energy is one of the most extensively studied and utilized renewable energy sources over the past few decades. Its advantages lie in its abundant availability, environmental friendliness, and sustainable applicability [1]. As global energy demand continues to rise, and fossil fuel resources become increasingly limited, photovoltaic (PV) technology has gained a strategic position as a clean and sustainable energy alternative. Indonesia, as a tropical country, possesses vast solar energy potential with a relatively high daily solar radiation intensity throughout the year [2]. his geographical condition presents both opportunities and challenges. On the one hand, high solar irradiance can be harnessed to generate significant amounts of electrical energy [3]. On the other hand, hot environmental temperatures can adversely affect the performance of PV modules.

One of the most critical factors influencing the performance of photovoltaic (PV) systems is the surface temperature of the module. PV modules are designed to operate optimally at a standard reference temperature, typically around 25 °C [4]. However, under actual operating conditions, particularly in tropical regions, the surface temperature of panels often rises well above this standard value. This phenomenon leads to a significant reduction in energy conversion efficiency. Efficiency losses due to elevated temperatures represent a classical issue encountered in almost all PV installations, whether small- or large-scale. Previous studies have shown that every 1 °C increase in panel surface temperature can reduce module efficiency by approximately 0.3–0.5% [5]. If left unaddressed, this can potentially result in substantial long-term energy losses. Beyond its impact on daily performance, persistent high temperatures also accelerate the degradation of PV module materials. The solar cell layers, protective glass, and electrical interconnections experience thermal stress, which ultimately reduces the service lifetime of the panels. Thus, the temperature issue not only affects energy production but also has implications for system reliability and long-term maintenance costs [6].

In temperate countries, temperature issues may not be a primary concern due to relatively low ambient conditions. However, in tropical regions characterized by high solar irradiance and elevated air temperatures, this challenge becomes far more critical. Such conditions make research on the impact of temperature on PV performance, as well as mitigation efforts, highly important, particularly to support the optimization of solar energy utilization in tropical countries. Researchers and practitioners worldwide have extensively studied the relationship between PV module temperature and performance. Several studies have reported a strong correlation between temperature rise and output power reduction. Therefore, a more comprehensive understanding is required regarding how PV modules behave under extreme operating conditions and the extent of their impact on efficiency and service lifetime[7].

The above background underscores the importance of research in thermal management for photovoltaic (PV) systems. Understanding temperature-related issues in PV panels is not only academically significant but also holds substantial practical value. With deeper insights, system designers, project developers, and installation owners can make more informed decisions in planning, operating, and maintaining PV systems. As the installed capacity of solar energy continues to increase worldwide, including in Indonesia, the urgency of addressing this issue becomes even greater. Without adequate understanding and management of temperature impacts, the vast potential of solar energy cannot be fully optimized. This situation may hinder the achievement of national renewable energy targets as well as global agendas for clean energy transition. Based on these considerations, this research aims to contribute to a deeper understanding of temperature-related challenges in PV modules under tropical climates. The focus is to identify the role of temperature as a limiting factor for PV performance and to emphasize the importance of thermal management strategies tailored to environmental conditions in tropical countries. Through this approach, the findings are expected to provide a foundation for the development of more reliable, efficient, and sustainable solar energy systems.

2. LITERATURE REVIEW

2.1 The Impact of Temperature on Photovoltaic (PV) Performance

The efficiency of photovoltaic (PV) modules is closely related to their operating temperature, where an increase in panel surface temperature has been proven to reduce the ability to convert solar energy into electricity. Research findings indicate that every 1 °C rise in PV module temperature can decrease average efficiency by about 0.3 to 0.5%[8]. his condition implies that the higher the temperature received by the panel due to solar irradiation, the greater the energy loss that occurs. If this persists continuously, it can lead to significant reductions in both daily output power and the total annual energy generated. This issue becomes more complex in tropical regions, such as Indonesia, which receive consistently high levels of solar radiation throughout the year. Strong solar exposure not only accelerates the increase in module surface temperature but also intensifies repeated thermal stress on the panel's constituent materials [9]. Consequently, in addition to reduced power output, PV modules also experience accelerated material degradation, which shortens their operational lifetime. Therefore, the primary challenge in harnessing solar energy in tropical regions lies in maintaining PV performance at an optimal level despite operating under relatively high ambient temperature conditions.

2.2 Cooling Methods for Photovoltaic

The passive approach to photovoltaic (PV) panel temperature control is generally implemented through simple mechanisms, such as utilizing natural convection, adding cooling fins, or applying reflective materials to the panel surface. This method offers advantages in terms of relatively low cost and ease of application, as it does not require additional energy sources. However, the effectiveness of passive cooling is highly limited, particularly when PV panels operate under extreme environmental conditions with high solar radiation, as commonly found in tropical regions. In such situations, the heat generated far exceeds the dissipation capacity achievable by passive cooling systems[10].

In contrast, the active approach provides a higher level of cooling efficiency through technologies such as forced-air cooling and liquid-based cooling, including water cooling and spray cooling. These systems function by circulating air or spraying water to accelerate heat dissipation from the panel surface, thereby maintaining the operating temperature more effectively. Nevertheless, the implementation of active cooling methods requires higher investment costs as well as additional energy to operate supporting devices such as pumps or fans. This makes the active approach more complex in terms of maintenance and operation, although its effectiveness is considerably superior to that of passive methods.

2.3 *Previous Studies and Research Gap*

Various previous studies have demonstrated that water-based active cooling, whether through water cooling or spray cooling methods, has proven effective in reducing the surface temperature of photovoltaic (PV) modules[5], [11]. This temperature reduction directly contributes to improved energy conversion efficiency, allowing the panels to generate more optimal electrical output even under high solar radiation exposure. The effectiveness of this method has made it one of the most widely studied approaches in efforts to enhance PV performance, particularly in field applications with extreme light intensity. Nevertheless, the application of water-based cooling systems equipped with automatic control remains relatively limited, especially in tropical regions. Most research has predominantly focused on the technical evaluation of conventional cooling without considering water-use efficiency or the integration of intelligent control technologies. This creates a research gap that needs to be addressed: how to design an active cooling system that not only effectively reduces temperature but is also cost-efficient, resource-efficient, and sustainable for large-scale applications.

3. RESEARCH METHODOLOGY

3.1 Research design

The research employed a comparative experimental design to evaluate the performance of photovoltaic (PV) panels with and without an active water-injection cooling system. This approach was chosen because previous studies on PV cooling have primarily focused on passive methods (e.g., heat sinks, PCM) or non-automated water cooling, leaving a research gap regarding low-cost, automated active cooling strategies in tropical climates. Two scenarios were established:

1. Control setup : PV module operating under natural solar irradiance without any cooling system.
2. Treatment setup : PV module equipped with an active water-injection cooling system integrated with a digital thermostat for automatic temperature regulation.

This dual-scenario design provides direct comparability of thermal and electrical performance, while also enabling evaluation of water-use efficiency, which is essential for sustainable operation in regions with limited water availability.

3.2 Materials or tools used

The cooling system was developed using components that are cost-effective, widely available, and easily replicable, to support scalability and real-world adoption. The main materials and tools include:

1. PV modules (monocrystalline, 50 Wp) as the experimental units.
2. DC-powered water pump (12 V) for low-energy operation.
3. Precision mist nozzles and an acrylic manifold designed to optimize water distribution.
4. Digital thermostat integrated with a closed-loop controller, allowing real-time automatic activation when surface temperature exceeds the threshold.
5. Autodesk Fusion 360 for system design, component integration, and structural optimization.
6. Measurement instruments: thermocouple sensors (±0.1°C accuracy), digital multimeter, flowmeter for water usage, and a data logger for continuous recording.

The choice of these tools was guided by the need to balance experimental precision with practical feasibility, aligning with the principle of sustainable PV technology development.

3.3 Data collection methods

Field experiments were conducted in a tropical outdoor environment under natural solar irradiance. The following key parameters were recorded:

- PV surface temperature: to determine the cooling effectiveness.
- Electrical output power (V × I): as the direct indicator of PV performance.
- Daily energy yield (Wh): obtained through cumulative integration of power output.
- Cooling water consumption (L/day): to assess resource efficiency.

The digital thermostat-based control system automatically logged the operation of the cooling pump, enabling accurate measurement of water usage relative to thermal conditions. Continuous data logging minimized bias caused by intermittent cloud cover, irradiance variability, or wind fluctuations, ensuring reliability and reproducibility of results.

3.4 Analytical techniques

The collected data were analyzed using a quantitative descriptive approach, supported by statistical evaluation where relevant:

- Thermal effectiveness: calculated as the average temperature difference (ΔT) between cooled and uncooled PV modules.
- Electrical performance enhancement: determined by comparing power output and daily energy yield across the two scenarios.
- Water-to-energy ratio: computed to assess how much additional energy was obtained per liter of cooling water, thereby quantifying sustainability.
- Correlation analysis: performed to investigate the relationships between PV surface temperature, water consumption, and electrical output, highlighting the interdependency of thermal and energy parameters.

All results were visualized through time-series graphs, comparative bar charts, and summary tables, allowing clear interpretation of trends. This analytical framework ensures the findings can be generalized to large-scale PV deployment in hot climates, strengthening the practical contribution of this study.

4. RESULTS

4.1 Panel Temperature

The test results revealed a significant reduction in the surface temperature of PV modules when the water-injection cooling system was activated. On average, the cooled panel recorded a temperature that was 5.7 °C lower than that of the uncooled panel during peak radiation hours (11:00–13:00). This reduction is consistent with previous studies, which have emphasized that controlling the surface temperature of PV modules plays a direct role in maintaining electrical performance stability. The cooling effect was most pronounced at midday, highlighting the system's effectiveness in tropical climates with high thermal stress. The following table presents the panel temperature and the corresponding energy output generated by the PV system.

Tabel 1. Time, Temperature, Power, and Energy Data of PV Panel without Cooling

No	Time	Energy (wh)	Power (w)	Current (A)	Temp (^{o}C)
1	10:00	0,4	56	4,13	52,2
2	10:15	5,8	59,5	4,38	45,1
3	10:30	17,7	58,7	4,31	51,8
4	10:45	30,7	59,3	4,35	52,4
5	11:00	45,5	59,1	4,34	56,6
6	11:15	56,4	13,4	1	46,6
7	11:30	67,1	62,6	4,58	51,7
8	11:45	87,7	63,5	4,65	58,8
9	12:00	95,7	68,9	5,02	54,8
10	12:15	111,4	64	4,67	59,9
11	12:30	123,5	65,1	4,75	50,2
12	12:45	134,1	13,2	0,99	45,9
13	13:00	140	33,3	2,47	46,7
14	13:15	150,2	16,6	1,24	48,4
15	13:30	161,3	46,4	3,42	51,5
16	13:45	169,2	15,3	1,14	45
17	14:00	176,2	27,5	2,05	45,1
Average		92,5	46,0	3,4	50,7

Tabel 2. Time, Temperature, Power, and Energy Data of PV Panel with Cooling

No	Time	Energy (wh)	Power (w)	Current (A)	Temp (ºC)
1	10:00	0,1	57,7	4,26	52,8
2	10:15	13,8	55,7	4,25	46,4
3	10:30	28,3	58,6	4,47	45,8
4	10:45	43	60,2	4,59	40,1
5	11:00	58,8	61,2	4,70	46
6	11:15	73	62,5	4,87	43,2
7	11:30	88,2	62,8	4,88	45,5
8	11:45	103,4	59,8	4,86	45
9	12:00	118,2	55,2	4,24	47,5
10	12:15	139,8	63,7	4,81	42,1
11	12:30	152,4	67,5	5,07	44,4
12	12:45	164,9	61,2	4,58	45,2
13	13:00	180,4	63	4,69	42,5
14	13:15	194,3	51	3,80	46,1
15	13:30	207,9	59,9	4,44	45
16	13:45	221,6	52,7	3,91	45,6
17	14:00	233,5	50,2	3,73	42,3
Average		118,9	59,0	4,5	45,0

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4.2 Electrical Performance of PV Panel

The reduction in PV module temperature has a direct impact on increasing electrical power output. Modules with active cooling consistently exhibited higher power compared to the control module. Under peak irradiation conditions, the recorded power improvement reached 28.3%. Power fluctuations in the uncooled panel were caused by efficiency losses due to rising temperatures, whereas the cooled panel demonstrated more stable performance. This finding aligns with the established theory of PV efficiency reduction, where every 1 °C increase above standard conditions can decrease efficiency by approximately 0.3–0.5%.

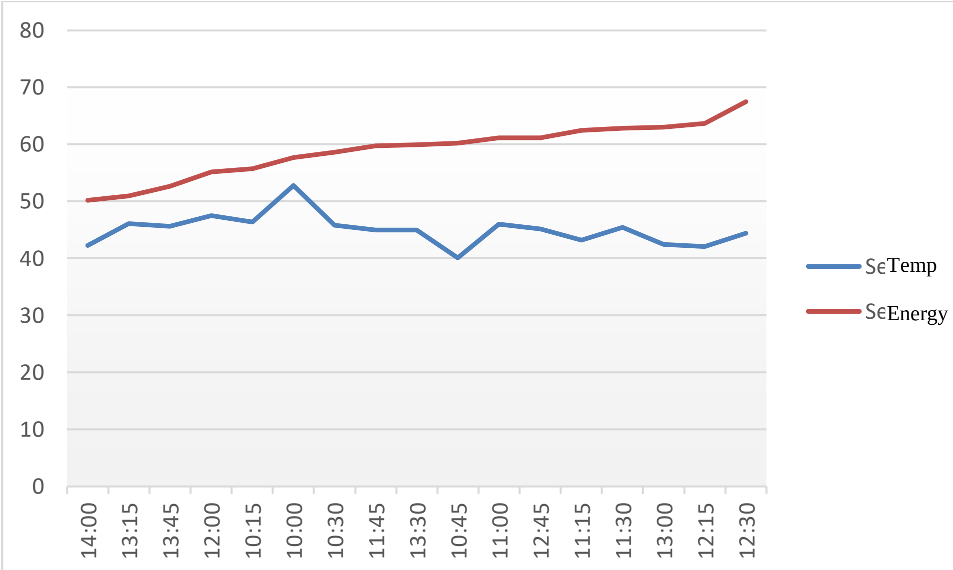

Figure 1. Comparison of Time, Power, and Temperature

4.3 Daily Electrical Energy

When integrated over the course of a day, the total daily energy generated by the cooled PV module was higher than that of the control module. On average, the daily energy increase reached 32.5%, indicating that the cooling system not only improved instantaneous performance but also had a tangible impact on total energy production. This finding is particularly significant for large-scale PV installations, as even a small percentage increase can translate into a substantial amount of additional electricity generation.

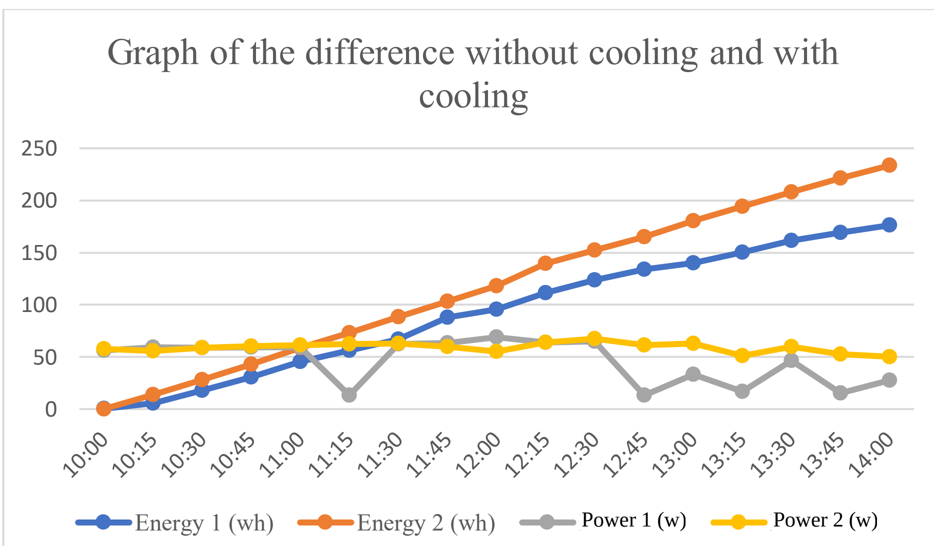

Figure 2. Comparison of Energy Output with and without Cooling

4.4 Reliability of the Control System

The digital thermostat-based control system with a closed-loop mechanism proved to function reliably during testing. Pump activation occurred precisely when the panel temperature exceeded the predetermined threshold (45 °C), ensuring that cooling was carried out efficiently and only when necessary. No delays or activation errors were observed, even under fluctuating irradiation or wind speed conditions. This reliability guarantees that water consumption remains efficient and that the additional energy required for pump operation is not excessive..

Figure 3. Automatic Control System

4.5 Analysis of Comparison

When compared with passive cooling methods widely reported in previous studies—such as the use of aluminum heatsinks, phase change materials (PCM), or thermally conductive coatings—the active water-injection cooling system developed in this study demonstrated superior performance. Passive cooling generally achieves only about a 2–4 °C reduction in PV module surface temperature, as reported by[5]. In this study, the active cooling system with automatic control achieved a temperature reduction of up to 5.7 °C, making it nearly twice as effective as passive technologies.

Beyond the thermal aspect, the effect on electrical performance was also more significant. Previous studies reported daily energy gains of around 3–5% with PCM and approximately 4–6% with aluminum heatsinks. In contrast, this study achieved a daily energy increase of 32.5%, confirming that active cooling with automatic control provides a much greater impact on energy output. This is particularly important in the context of large-scale installations, where even small improvements in efficiency can substantially contribute to annual electricity production.

Another advantage of this system lies in its resource efficiency. Manual or continuous cooling methods tend to consume large amounts of water, making them less sustainable. The system developed in this study integrates a digital thermostat-based closed-loop control, ensuring that the pump is activated only when the temperature exceeds the set threshold. This makes water consumption far more efficient without compromising cooling performance.

Overall, this comparison shows that the active water-injection system with automatic control excels not only in temperature reduction and energy enhancement but also in operational sustainability. By utilizing low-cost and readily available materials, along with a simple yet effective control system, this innovation offers a tangible contribution to the development of thermal management strategies for PV systems, particularly in hot and tropical climates. These results hold strong potential as a foundation for industrial-scale applications and integration into sustainable energy policies, making the research relevant both academically and practically.

5. DISCUSSION

This study confirms that the surface temperature of PV modules is a primary limiting factor in the performance of photovoltaic systems, particularly in tropical regions with high solar radiation intensity such as Indonesia. The test results demonstrated that the active water-injection cooling system with automatic control was able to reduce module temperature by up to 5.7 °C, directly increasing output power and daily energy yield by 32.5%, respectively. These findings reinforce the understanding that thermal management is not merely a technical issue but a fundamental aspect in ensuring the reliability and efficiency of PV systems.

From an academic perspective, this study expands the literature by providing empirical evidence on the effectiveness of active cooling integrated with a digital control system in tropical climates. Previous research has mostly focused on passive cooling methods, such as heatsinks or phase change materials (PCM), which were only able to reduce temperatures by 2–3 °C. This comparison highlights a research gap addressed by the proposed system, where active cooling achieves more significant results while maintaining efficiency in water resource utilization.

From a practical standpoint, the implications of this study are highly relevant given the growing installed capacity of solar energy in Indonesia and other tropical countries. Without proper temperature management strategies, the potential of solar energy cannot be fully optimized due to module performance degradation. With a cooling system that is low-cost, easy to replicate, and resource-efficient, this research offers a solution that can be adopted by project developers, installation owners, and system designers to enhance the productivity of PV power plants. Even an additional efficiency of around 32.5% is highly significant at the utility scale, as it translates into considerable increases in annual electricity generation capacity.

Thus, this study contributes to a more comprehensive understanding of PV thermal management in tropical climates. The findings not only strengthen the academic foundation but also provide practical value for the solar energy sector in Indonesia. At a strategic level, this research supports the achievement of national renewable energy mix targets as well as global energy transition agendas, by offering a reliable, efficient, and sustainable approach to solar energy utilization.

6. CONCLUSION

This study demonstrates the effectiveness of an active water-injection cooling system integrated with a digital thermostat control in enhancing the performance of photovoltaic (PV) modules under tropical climate conditions. The main findings are as follows::

1. The cooling system was able to reduce the PV module surface temperature by up to 5.7 °C, significantly higher than conventional passive cooling methods.
2. This temperature reduction had a direct impact on electrical performance, with the average power output increasing by 28.3% and daily energy yield by 32.5% compared to the uncooled module.
3. The integration of automatic thermostat-based control proved reliable in regulating cooling operation only when required, thereby ensuring more efficient water utilization.

These findings confirm that the active water-injection cooling system with intelligent control represents a cost-effective, practical, and sustainable thermal management strategy for PV applications in tropical and hot regions. This research contributes to the advancement of academic knowledge while simultaneously offering practical benefits for system designers, project developers, and policymakers in enhancing the reliability and efficiency of solar energy.

Recommendations for future research:

1. Large-scale testing on utility-scale PV installations to assess performance and feasibility at higher capacities.
2. Investigation of long-term reliability and maintenance aspects of the cooling system, particularly in relation to variations in water quality.
3. Exploration of integration with alternative water sources (e.g., rainwater or recycled greywater) to strengthen sustainability aspects.
4. Techno-economic and life cycle analyses to provide a comprehensive overview of environmental impacts and financial feasibility.

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