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Optimization of Internet of Things-Based Solar Panel Cooling Using Splash Fill

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Abstract: Solar panel performance is strongly affected by module surface temperature because a large portion of incident solar radiation is converted into heat rather than electrical energy. Although water-based photovoltaic cooling has been widely investigated, many existing systems still rely on open-loop or manually activated cooling and provide limited integration between thermal recovery, adaptive control, and real-time monitoring. This study proposes an Internet of Things-based automatic solar panel cooling system that combines closed-loop water circulation, splash fill-assisted water temperature reduction, MQTT communication, and Home Assistant monitoring for tropical operating conditions. The system was evaluated using two 100 Wp monocrystalline photovoltaic panels under identical environmental conditions, where one panel was equipped with the proposed cooling system and the other was operated without cooling. Key parameters, including panel temperature, water temperature, voltage, current, output power, irradiance, daily energy, and efficiency, were measured at 10-minute intervals over two experimental days. The results show that the proposed system reduced panel temperature by 19.22-20.10°C, increased output power by 26.35-28.89 W, and improved average efficiency by 3.42-4.18%. Net daily energy increased by 154.88-167.04 Wh after considering pump consumption. These findings demonstrate that integrating splash fill cooling with Internet of Things-based adaptive monitoring provides a practical and scientifically relevant approach for improving photovoltaic performance in tropical environments.

Keyword: Efficiency, Internet of Things, Solar Panel, Splash Fill, Water Cooling

INTRODUCTION

Photovoltaic technology is an important option for increasing renewable energy utilization in tropical countries because solar radiation is available throughout the year. Indonesia, which is located near the equatorial region, has strong potential for solar power development. However, high ambient temperature and continuous solar exposure create operating conditions that can reduce photovoltaic conversion efficiency and weaken the expected benefit of solar energy deployment (Karjadi, 2025; Jaya, Rahmat, & Asrori, 2024).

One of the most critical factors affecting photovoltaic performance is the increase in module surface temperature during operation. Under real outdoor conditions, only a portion of incoming solar radiation is converted into electrical energy, while the remaining energy is absorbed as heat by the module. The resulting temperature rise reduces output voltage more significantly than it increases current, causing overall power output to decline, particularly in crystalline silicon modules (Humairi, Asri, Al Hemyari, & Jung, 2025; Sya'rani Denk, Azis Pandria, & Syukri, 2025).

In addition to thermal effects, environmental factors such as dust, dirt, and surface contamination can reduce the amount of light reaching the solar cells. These effects are important in outdoor photovoltaic installations because they interact with temperature, irradiance, and electrical load conditions. Therefore, performance improvement strategies should not only focus on energy conversion but also consider operational monitoring and environmental control (Wicaksono, Daud, & Mursid, 2023).

Various cooling strategies have been proposed to reduce photovoltaic operating temperature, including passive cooling, water spray cooling, water circulation, heat sinks, phase change materials, and hybrid approaches. Water-based cooling is attractive because water has a relatively high specific heat capacity and can remove heat directly from the panel surface. Experimental studies have shown that water cooling can reduce module temperature and increase power output, but system effectiveness depends on cooling configuration, water use, pump consumption, and control strategy (Attia, Hossin, & Hazza, 2023; Sornek, Goryl, Figaj, Dabrowska, & Brezden, 2022).

Despite these developments, several limitations remain in existing photovoltaic cooling systems. Manually operated cooling cannot respond consistently to changes in irradiance and panel temperature. Open-loop water cooling may increase water consumption, while simple pump-based systems may consume energy even when cooling is not required. In addition, many previous systems focus mainly on temperature reduction and do not sufficiently integrate cooling control with real-time data acquisition, monitoring, or communication platforms (Abdullah, Putri, Iriani, Hulu, & Cholish, 2023; Rahajoeningroem & Jatnika, 2022; Kamal & Jati, 2025).

Internet of Things-based monitoring provides an opportunity to overcome these limitations by enabling real-time measurement, data transmission, remote visualization, and automatic control. In photovoltaic systems, IoT monitoring supports continuous observation of voltage, current, power, temperature, and system status. MQTT-based communication is widely used in lightweight monitoring systems because it supports efficient data exchange between sensors, controllers, and dashboards (He, Aziz Baig, & Iqbal, 2025; Nath et al., 2023; Mohammed, Sarban Singh, Aslam, & Wong, 2026).

Splash fill cooling media are commonly used to increase the contact area between water and air. When applied to a closed-loop photovoltaic cooling system, splash fill can help reduce the temperature of recirculated water before it returns to the panel surface. This mechanism is important because closed-loop water circulation reduces water waste, but the water must be cooled again to maintain heat removal effectiveness. Therefore, combining splash fill media with automatic control may improve both thermal performance and operational sustainability.

Previous studies have reported improvements using water spray or splash fill cooling under tropical conditions, but many systems still lack integration among closed-loop recirculation, water temperature reduction, MQTT-based communication, and real-time monitoring in a single experimental platform. As summarized in Table 1, existing approaches provide useful contributions, but the proposed work advances the state of the art by combining thermal management and digital monitoring in an adaptive cooling framework.

The novelty of this study lies in the integration of closed-loop water circulation, splash fill-assisted water temperature reduction, MQTT communication, and Home Assistant-based real-time monitoring for automatic photovoltaic cooling. This combination is expected to reduce the panel temperature, improve electrical output, and provide operational data for intelligent energy management. The objective of this study is to evaluate the effect of the proposed system on panel temperature, voltage, current, output power, daily energy, efficiency, and statistical significance under tropical outdoor conditions.

Table 1. Summary of Previous Photovoltaic Cooling and Monitoring Studies

Study	Approach	Main Limitation	Contribution of Proposed Study
Attia et al. (2023); Sornek et al. (2022)	Water-based photovoltaic cooling	Limited integration with adaptive IoT monitoring	Combines water cooling with real-time control and monitoring
Rahajoeningroem and Jatnika (2022); Kamal and Jati (2025)	Automatic water spraying or microcontroller cooling	Limited recirculated water temperature recovery	Adds splash fill media for cooling recirculated water
Daniar et al. (2026); Wibowo et al. (2024)	Splash fill or nozzle-based cooling	IoT communication and monitoring are not fully emphasized	Integrates splash fill, MQTT communication, and Home Assistant dashboard
He et al. (2025); Mohammed et al. (2026)	IoT-based photovoltaic monitoring	Focuses primarily on monitoring, not active thermal management	Combines monitoring, decision control, cooling actuation, and performance evaluation

Source: Literature review, processed (2026)

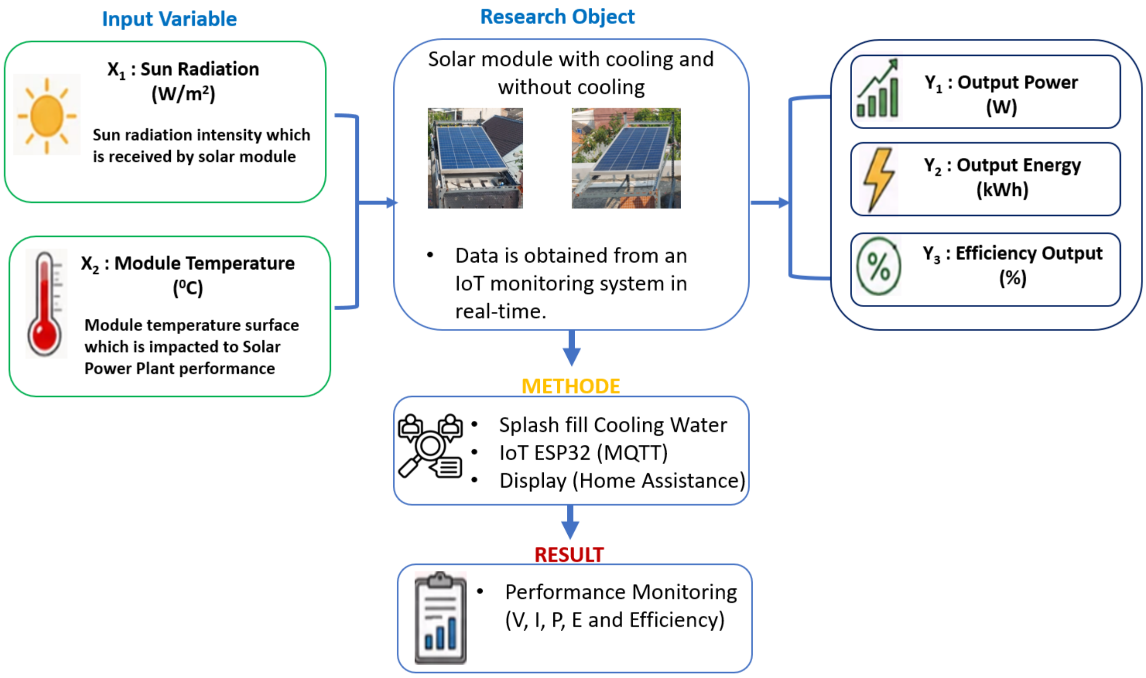
METHOD

Research Design

This study used a comparative experimental design to evaluate the effectiveness of the proposed cooling system. Two 100 Wp monocrystalline photovoltaic panels were installed under the same location and orientation. One panel was equipped with the Internet of Things-based splash fill cooling system, while the other panel was used as an uncooled reference. This paired comparison strategy was selected to reduce environmental bias because both panels were exposed to similar irradiance and ambient conditions during the same observation period.

System Architecture

The proposed system consists of sensing, control, actuation, cooling, and monitoring layers. The sensing layer measures panel temperature and electrical output. The control layer uses an ESP32 microcontroller to process sensor data and compare the panel temperature with the cooling threshold. The actuation layer controls the pump and valve through a relay. The cooling layer circulates water over the panel surface and sends the heated water back to the reservoir through splash fill media. The monitoring layer transmits data through MQTT and displays the system status in Home Assistant.



Source: Research Results

Figure 1. Concept of the Internet of Things-based splash fill cooling system

Experimental Setup

The experimental setup used two 100 Wp monocrystalline solar panels, a solar charge controller, a 12 V battery, a 22 W direct current pump, DS18B20 temperature sensors, a PZEM-017 voltage and current sensor, an RS485 module, ESP32, relay, water level sensor, electric valve, reservoir, and splash fill media. The DS18B20 sensor was used to measure panel and water temperature, while the PZEM-017 sensor measured voltage, current, and output power. The system was tested in Bekasi on 6-7 June 2026 from 08:00 to 17:00.

Data Acquisition and Measurement

Data were collected every 10 minutes for panel temperature, water temperature, voltage, current, output power, and solar irradiance. The measurement interval was selected to capture outdoor performance variations while maintaining manageable data storage and monitoring frequency. Before the field test, sensor readings were checked to ensure stable measurement response. Data from the ESP32 were transmitted to the monitoring dashboard to support real-time observation and later analysis.

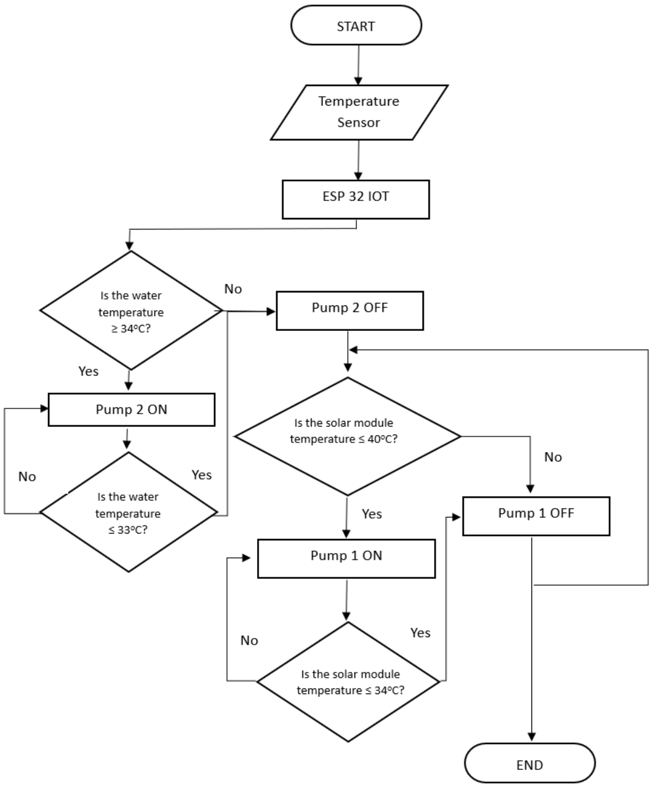
Table 2. Measured Parameters

No.	Parameter	Symbol	Unit	Sensor/Instrument
1	Panel output voltage	Vps	V	PZEM-017
2	Panel output current	Ips	A	PZEM-017
3	Panel output power	Pps	W	PZEM-017
4	Panel temperature	T	°C	DS18B20
5	Light intensity	G	W/m²	Solar power meter

Source: Research design, processed (2026)

Temperature Control Procedure

The cooling control process begins with sensor initialization and continuous data acquisition. The ESP32 reads the panel temperature and electrical parameters, then sends the data to Home Assistant through MQTT. When the panel temperature exceeds the predefined threshold, the relay activates the direct current pump and valve so that water is sprayed onto the panel surface. The heated water flows into the reservoir and passes through the splash fill media, where water-air contact helps reduce the water temperature before recirculation. If the panel temperature is below the threshold, the pump remains inactive and the system continues monitoring.



Source: Research Results

Figure 2. Temperature Control Flowchart

Performance Evaluation

Input power, output power, and panel efficiency were calculated using the following equations. For the cooled panel, pump consumption was included so that net efficiency represented the actual useful electrical gain after subtracting cooling energy demand.

$Pin = G \times A$

$\eta = (Pout / Pin) \times 100\%$

$\eta net = [(Pout - Ppump) / Pin] \times 100\%$

Statistical Analysis

The paired t-test was used to evaluate whether the difference between the cooled and uncooled panels was statistically significant. This method was selected because both panels were measured under comparable time-based outdoor conditions. The null hypothesis stated that there was no significant difference between the cooled and uncooled panel performance. A p-value below 0.05 was interpreted as evidence of a statistically significant difference. In addition to p-values, effect size and confidence interval interpretation were included to strengthen the practical meaning of the statistical results.

RESULTS AND DISCUSSION

Summary of Experimental Findings

The proposed cooling system produced clear improvements in thermal and electrical performance. The cooled panel operated at an average temperature of 35.61-35.94°C, while the uncooled panel reached 54.84-56.04°C. This difference indicates that the combination of direct water cooling and splash fill-assisted recirculation effectively removed heat from the photovoltaic surface. The lower temperature helped maintain output voltage and increased average output power. The main experimental findings are summarized before further discussion to improve readability.

Table 3. Comparison of Panel Temperature

Date	With Cooling (°C)	Without Cooling (°C)	Reduction (°C)	Reduction (%)
6 June 2026	35.94	56.04	20.10	35.86
7 June 2026	35.61	54.84	19.22	35.05

Source: Research data, processed (2026)

Table 4. Comparison of Solar Panel Electrical Performance

Parameter	With Cooling	Without Cooling	Difference
Average voltage	20.25-20.54 V	17.70-17.73 V	2.55-2.81 V
Average current	2.10-2.18 A	0.90-0.92 A	1.18-1.28 A
Average power	42.40-44.60 W	15.71-16.05 W	26.35-28.89 W
Average efficiency	8.10-8.81%	4.63-4.68%	3.42-4.18%

Source: Research data, processed (2026)

Table 5. Daily Energy of Solar Panels

Date	Energy With Cooling	Energy Without Cooling	Energy Increase
6 June 2026	283.28 Wh	128.40 Wh	154.88 Wh
7 June 2026	292.72 Wh	125.68 Wh	167.04 Wh

Source: Research data, processed (2026)

Thermal and Electrical Interpretation

The temperature reduction of 19.22-20.10°C is scientifically important because photovoltaic output voltage is highly sensitive to temperature. When the module temperature decreases, the semiconductor junction operates under more favorable conditions, resulting in higher operating voltage. Although current may change with irradiance, the voltage improvement contributes substantially to the increase in power output. Therefore, the observed power increase is consistent with the theoretical relationship between photovoltaic temperature and electrical performance.The use of splash fill media improves the closed-loop cooling process by increasing water-air contact area before recirculation. Without this stage, water that has absorbed heat from the panel may return to the surface at a higher temperature, reducing cooling effectiveness. The splash fill stage therefore functions as a passive heat rejection component within the active cooling loop. This explains why the cooled panel temperature remained far below the uncooled panel temperature during the observation period.

Comparison with Previous Studies

The proposed system differs from conventional water spray cooling because it combines surface heat removal, recirculated water cooling, automatic pump control, and real-time monitoring. Compared with cooling systems that only activate water spraying, the proposed configuration provides a more complete framework for intelligent photovoltaic management. Compared with monitoring-only IoT systems, the proposed system adds a direct control function that links measured temperature to cooling actuation.

Table 6. Comparison of the Proposed System with Existing Approaches

Aspect	Previous Cooling Approaches	Proposed System
Cooling mechanism	Water spray, water flow, or passive heat removal	Closed-loop water circulation with splash fill heat rejection
Control strategy	Manual or simple threshold-based control	ESP32-based automatic control using real-time temperature data
Monitoring	Often limited or separated from cooling control	MQTT communication and Home Assistant dashboard
Water management	May use open-loop water supply	Recirculated water with reservoir and splash fill media
Contribution	Temperature reduction and power improvement	Integrated thermal control, monitoring, and net-energy evaluation

Source: Literature comparison, processed (2026)

Statistical Results and Practical Significance

The paired t-test results indicate statistically significant differences between the cooled and uncooled panels for temperature, output power, and efficiency. The temperature comparison produced a two-tailed p-value of 1.86819E-27, while output power and efficiency produced two-tailed p-values of 1.32357E-17 and 1.08206E-19, respectively. These values are far below 0.05, confirming that the observed improvements were statistically significant. The effect sizes were also large, indicating that the differences were not only statistically significant but also practically meaningful for photovoltaic operation.

Table 7. Statistical Interpretation of Paired t-test Results

Parameter	Mean Difference	t-statistic	p-value (two-tail)	Approx. 95% CI	Effect Size (dz)	Interpretation
Panel temperature	21.06°C reduction	21.744	1.86819E-27	19.12 to 23.01°C	3.02	Significant and very large thermal effect
Output power	27.77 W increase	12.841	1.32357E-17	23.43 to 32.11 W	1.78	Significant and large power improvement
Efficiency	0.0329 increase	14.472	1.08206E-19	0.0284 to 0.0375	2.01	Significant and large efficiency improvement

Source: Statistical analysis, processed (2026)

Limitations of the Study

Although the results show strong improvements, several limitations should be acknowledged. First, the experimental period was limited to two days, which may not fully represent long-term seasonal variation. Second, outdoor conditions such as irradiance fluctuation, wind speed, humidity, and cloud cover may influence the measured performance. Third, measurement accuracy depends on the selected sensors and calibration procedure. Fourth, the scalability of the system for larger photovoltaic arrays has not yet been evaluated. These limitations suggest that additional long-term testing is required before large-scale implementation.

CONCLUSION

This study developed and evaluated an Internet of Things-based automatic photovoltaic cooling system that integrates closed-loop water circulation, splash fill-assisted water temperature reduction, MQTT communication, and Home Assistant real-time monitoring. The scientific contribution of this work is the integration of thermal management and digital monitoring into a single adaptive cooling framework for photovoltaic operation under tropical conditions. The proposed system reduced panel temperature by 19.22-20.10°C, increased output power by 26.35-28.89 W, improved efficiency by 3.42-4.18%, and increased net daily energy by 154.88-167.04 Wh after accounting for pump consumption. The practical implication of the proposed system is that photovoltaic installations in tropical regions can benefit from automatic cooling that operates based on real panel conditions rather than manual intervention. The use of MQTT and Home Assistant also enables real-time monitoring, historical data storage, and future integration with intelligent energy management systems. However, this study was limited by the short experimental duration, environmental variability, sensor accuracy, and testing at small panel scale. Future research should conduct long-term field validation, improve sensor calibration, optimize pump energy consumption, evaluate economic feasibility, test different temperature thresholds, and assess scalability for larger photovoltaic systems.

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