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Implementation of Monitoring and Cooling System to Improve Solar Power Plant Efficiency Based IoT

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ABSTRACT

Solar power plants are one of the renewable energy solutions with great potential for development in tropical regions. The efficiency of solar panels decreases as surface temperature of modules increases, resulting in suboptimal performance of the solar power plant and affecting amount of electricity generated. The study aims to design a real-time, automated Internet of Things based solar panel monitoring and cooling system to maintain a constant level of electrical energy. The system measures panel temperature, light intensity, voltage, current, input power, output power, efficiency, and the status of cooling pump; the data is then analyzed across five tests based on average value of each parameter. The data is used as a reference to control the cooling system's operation if temperature parameter reaches maximum limit of 38°C. The results show that panel temperatures recorded by the system ranged from approximately 31°C to 38.64 °C, with a maximum light intensity of 24,040 lux. The first test recorded highest average temperature 38.64 °C an average light intensity of 7,363 lux and an average output power of 6.64 W. Under these conditions, cooling system operated optimally and achieved an average efficiency of 77.18%. In the second through fifth tests, panel temperature decreased, with an average value ranging from 34.59 °C to 31.97 °C, and light intensity was approximately 700–900 lux, indicating that the cooling system was operating normally. These conditions affected average efficiency, with the highest average value recorded in second test at 82.64% and lowest in the fourth test at 69.56%.

INTRODUCTION

Solar energy is one of the renewable energy sources widely developed to reduce dependence on fossil fuels. Solar Power Plants convert solar radiation into electrical energy through photovoltaic modules. Tropical regions receive sunlight throughout the year, so SPPs have the potential to be widely developed there. However, intense sunlight also raises the module surface temperature.

Module temperature strongly affects solar panel performance. Part of the radiation received by the cell is not converted into electricity but is absorbed as heat, so the cell temperature rises. Higher temperatures reduce the output voltage and conversion efficiency. The temperature coefficient of crystalline silicon modules is in the range of about −0.4 to −0.5% per °C (Sharaf et al., 2022). Field measurements in Indonesia also show that higher panel temperatures reduce output voltage (Nurdin et al., 2026). The effect of temperature on the efficiency of monocrystalline and polycrystalline modules has been studied experimentally (Hudișteanu et al., 2024). The effect of variations in solar radiation on the efficiency of modules equipped with passive cooling has also been reported (Rubaiee & Fazal, 2022).

Various cooling techniques have been developed to curb this temperature rise. These techniques include passive cooling, active cooling with water or air, and phase change materials (T. Ibrahim et al., 2024; Sharaf et al., 2022; C. Wang et al., 2025). The effectiveness of air, water, and porous-media cooling has also been modeled thermally and electrically (Menacer et al., 2025). Passive cooling with aluminum fins under tropical conditions reduced module temperature by about 3.25 °C and increased power by up to 14.2% (Ahmad et al., 2022). Active cooling requires energy to drive pumps or fans. This energy reduces the net power produced by the panel (Sharaf et al., 2022). For this reason, active cooling should only be run when the panel temperature exceeds a certain threshold.

Internet of Things (IoT) technology enables remote monitoring and control of power plant systems. Several studies have developed low-cost SPP monitoring systems that measure current, voltage, temperature, and irradiance (Demir, 2023; Ftirich et al., 2024; Hamied et al., 2023). Wireless data acquisition systems have also been designed to analyze the performance of photovoltaic modules (Boulemzaoud et al., 2022; Radia et al., 2023). ESP32-based monitoring with a web dashboard has also been developed (Silaban et al., 2024). A recent review discusses the application of IoT in photovoltaic systems under extreme climatic conditions (Y. Wang et al., 2024). Some studies

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combine IoT monitoring with active cooling. (Kamarudin et al., 2021) developed automatic active cooling with *real time* energy monitoring. (Reddy et al., 2026) activated a fan and water pump when the temperature exceeded a certain threshold. In Indonesia, an IoT-based solar panel cooling prototype using a Peltier module and a fan was reported to lower panel temperature and raise output power in a seven-day test (Azhari et al., 2026). Automatic temperature-triggered pumps were also compared with manual pumps and uncooled panels on a single sunny day (Abdillah et al., 2026).

However, most studies focus on only one aspect, namely monitoring or cooling. Studies that combine the two generally report temperature and power output. Analyses that link complete per-sample monitoring data, the operating status of the cooling pump, and the operating temperature limit have rarely been presented in detail. This study fills that gap by implementing a single integrated system. The system measures eight parameters in *real time* and controls the cooling pump at a temperature limit of 38 °C. Its performance is analyzed through five tests based on the average value of each parameter.

This study aims to design and implement an IoT-based solar panel monitoring and cooling system. It also aims to analyze panel temperature, power, and efficiency across five tests and to evaluate system performance against the 38 °C temperature limit. The contribution of this study is an integrated system design and test data that can serve as a reference for applying automatic cooling in small-scale SPPs.

LITERATURE REVIEW

Studies on the effect of temperature show that the performance of photovoltaic modules is determined by operating temperature and the radiation received. (Hudișteanu et al., 2024) experimentally analyzed the impact of temperature on the efficiency of monocrystalline and polycrystalline panels. (Rubaiee & Fazal, 2022) reviewed the effect of variations in solar radiation on the efficiency of modules equipped with a passive cooling system. These studies confirm the relationship among temperature, radiation, and module efficiency.

Cooling techniques have been widely reviewed. (T. Ibrahim et al., 2024) reviewed water-, air-, and phase-change-material-based cooling technologies, along with an assessment of environmental and economic aspects. The review positions thermoelectric cooling as a promising approach. (C. Wang et al., 2025) presented a comprehensive review of solar panel cooling methods. (Soliman, 2023) numerically investigated the performance of photovoltaic-thermal systems with several cooling configurations. (K. A. Ibrahim et al., 2023) reviewed the cooling of concentrated photovoltaic cells and the prospects of pulsating flow. These reviews show the diversity of cooling approaches that can be chosen according to the application conditions.

On the monitoring side, (Ftirich et al., 2024) built a low-cost IoT prototype for monitoring solar panels connected to a battery. The prototype measured current, voltage, temperature, humidity, and irradiance, then stored the data in a database via a Raspberry Pi 4 and displayed it on a web interface. (Hamied et al., 2023) designed low-cost SPP monitoring for greenhouse farmland in an arid region. (Demir, 2023) developed a low-cost monitoring system for a stand-alone SPP along with its power estimation. (Radia et al., 2023) and (Boulemzaoud et al., 2022) discussed wireless data acquisition for the performance analysis of photovoltaic modules and installations.

(Y. Wang et al., 2024) reviewed IoT-based photovoltaic systems under extreme climatic conditions, including climate sensing and data processing for monitoring system conditions. (Silaban et al., 2024) built an ESP32-based prototype with a web dashboard. The prototype monitored the electrical quantities of the solar panel and allowed users to control the load.

Studies in tropical regions are also relevant to the conditions of this study. (Ahmad et al., 2022) tested aluminum fins on the back side of a photovoltaic module. This passive cooling reduced module temperature by about 3.25 °C and increased power by up to 14.2%. (Nurdin et al., 2026) tested a 50 Wp module in Cimahi City. The module's output power followed irradiance, and higher panel temperatures reduced voltage.

Studies that combine monitoring and cooling are more relevant to this study. (Kamarudin et al., 2021) reported an automatic active cooling system with IoT-based energy monitoring. The system assessed panel efficiency and battery charging conditions and compared active cooling with passive cooling. (Reddy et al., 2026) used an Arduino UNO microcontroller and a DS18B20 sensor to activate a fan and water pump when the temperature exceeded a threshold. Their tests showed an efficiency improvement of about 10–12% under peak conditions. The system used hysteresis logic and sent data to a cloud service via an ESP8266. (Azhari et al., 2026) built an IoT prototype with sensors, a microcontroller, a Peltier module, and a fan. Seven-day tests showed lower panel temperatures and higher output power. (Abdillah et al., 2026) compared uncooled panels, manual pump cooling, and automatic temperature-triggered pump cooling. Automatic cooling lowered panel temperature the most and increased daily output, but the testing covered only one sunny day.

These studies show that IoT monitoring and active cooling have developed, both separately and in an integrated manner. This study builds on them by presenting data on eight parameters, including pump status, from five tests. The data are analyzed against the 38 °C temperature limit so that the relationships among temperature, light intensity, power, and efficiency can be examined in more detail.

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METHOD

This study is experimental with a prototype design-and-build approach. The choice of a threshold-based active cooling strategy refers to (Abdillah et al., 2026; Kamarudin et al., 2021; Reddy et al., 2026), while the design of data acquisition and *real time* monitoring refers to (Demir, 2023; Ftirich et al., 2024).

System Design

The system consists of a solar panel, a panel temperature sensor, a light intensity sensor, voltage and current sensors, a microcontroller, a relay module, a cooling pump, and an IoT platform. Figure 1 shows the relationships among the components. The sensors measure the panel conditions. The microcontroller reads the sensor data, calculates power and efficiency, sends the data over a wireless network to the IoT platform, and controls the pump through the relay module. The pump delivers cooling water to the panel surface when needed.

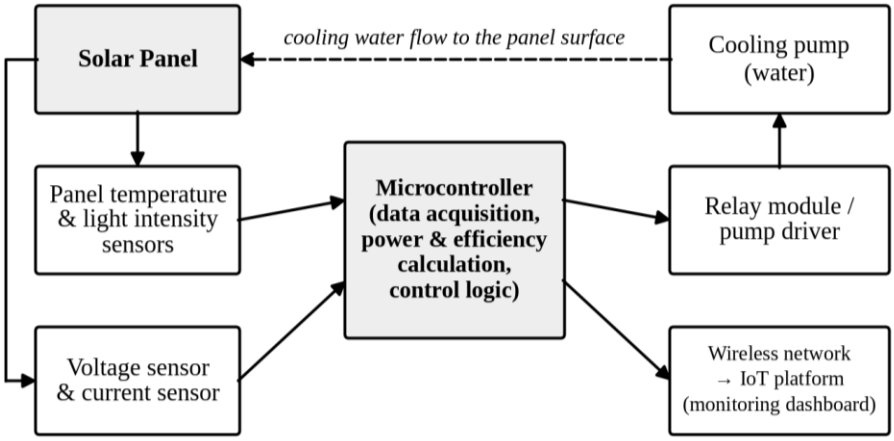


Figure 1. Block diagram of the IoT-based solar panel monitoring and cooling system

Control Logic

The control logic uses a maximum temperature limit of 38 °C. In each reading cycle, the microcontroller compares the panel temperature with this limit. The pump is activated if the panel temperature reaches or exceeds 38 °C. The pump remains on standby if the panel temperature is below the limit. Figure 2 presents this control flow.

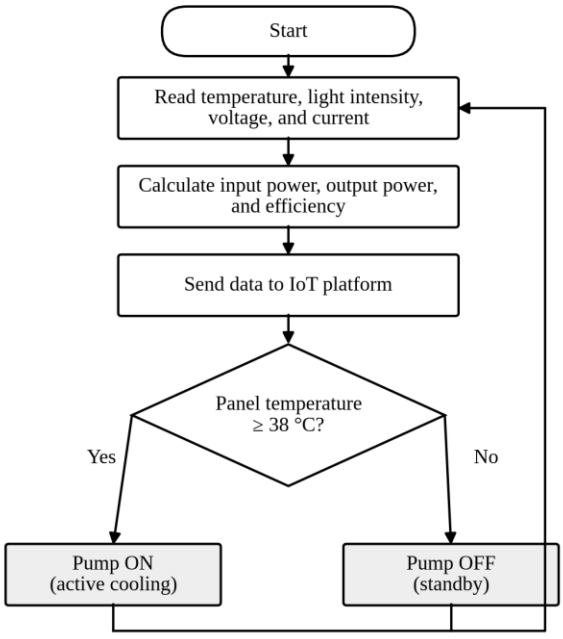


Figure 2. Flowchart of cooling pump control based on the 38 °C temperature limit

Based on figure 2 can be explained that IoT-based solar panel monitoring and cooling system measures temperature, light intensity, voltage, and current to calculate the panel's power and efficiency. The collected data are transmitted to the IoT platform in real time. When the panel temperature reaches or exceeds 38 °C, the cooling pump is

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activated; otherwise, the pump remains off. This process operates automatically and continuously to monitor performance and help maintain solar panel efficiency.

Measurement Parameters

Eight parameters are recorded at each sampling. Table 1 summarizes the parameters, units, and how they are obtained. Output power is calculated from voltage and current using equation (1). Input power is estimated from light intensity using a fixed conversion factor in equation (2). Efficiency is calculated as the ratio of output power to input power using equation (3) and is capped at a maximum of 100%.

Table 1. Parameters Recorded by the System

Parameter	Unit	How obtained
Panel temperature	°C	Measured by temperature sensor; pump trigger at the 38 °C limit
Light intensity	lux	Measured by light intensity sensor
Input power	W	Estimated from light intensity, equation (2)
Voltage	V	Measured by voltage sensor
Current	mA	Measured by current sensor
Output power	W	Calculated from voltage and current, equation (1)
Efficiency	%	Ratio of output power to input power, equation (3)
Pump status	–	Standby or active according to the temperature limit

$$P_{\text{out}} = \frac{V \times I}{1000} \quad (1)$$

$$P_{\text{in}} = k \times E \quad (2)$$

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} \times 100\% \quad (3)$$

where P_{out} is output power (W), V is voltage (V), I is current (mA), P_{in} is input power (W), E is light intensity (lux), k is the conversion factor (W/lux), and η is efficiency (%). The value of k read from the test data is approximately 1.358×10^{-3} W/lux, i.e., the ratio of input power to light intensity.

Testing Procedure

Testing was carried out five times under different lighting conditions. Data were obtained from the system's sampling logs saved for each test. Each test produced 118 to 119 sampled data points. The procedure for each test proceeded sequentially. First, the system was switched on and the sensors began reading data. Second, the microcontroller calculated power and efficiency at each sampling. Third, the data were sent and displayed on the IoT platform. Fourth, the pump was controlled based on the 38 °C temperature limit. After each test was completed, the data for each parameter were averaged to obtain a representative value for each test.

Data Evaluation

The data were evaluated using descriptive statistics in the form of mean, minimum, and maximum values. The number of readings reaching or exceeding 38 °C was counted to assess how often the temperature touched the control limit. The relationships among parameters were examined through graphs of temperature against sampling sequence and efficiency against light intensity. System performance was assessed from the average temperature and average efficiency in each test.

RESULT

Table 2 presents the average parameter values from the five tests. Each test consisted of 118 to 119 data points.

Table 2. Average Parameter Values in the Five Tests

Test	Number of data	Temp. (°C)	Intensity (lux)	Input power (W)	Voltage (V)	Current (mA)	Output power (W)	Efficiency (%)
1	119	38.64	7,363	10.00	13.36	486.50	6.64	77.18
2	118	34.59	720.0	0.98	12.54	66.78	0.84	82.64
3	118	31.97	707.9	0.96	12.40	56.77	0.70	74.70
4	118	31.26	763.8	1.04	12.33	57.46	0.71	69.56
5	118	31.38	892.4	1.21	12.34	77.35	0.96	78.08

Panel Temperature and Light Intensity

The table 2 shown that he highest average temperature occurred in test 1, at 38.64 °C. The average temperatures in Tests 2 to 5 were 34.59 °C, 31.97 °C, 31.26 °C, and 31.38 °C, respectively. Table 3 shows that the temperature in Test 1 ranged between 35.75 °C and 40.56 °C. A total of 72 of the 119 readings in this test reached or exceeded the 38 °C

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limit. In the other tests, no readings reached this limit. The highest temperature outside Test 1 was 37.50 °C, recorded at the start of Test 2.

Figure 3 shows the temperature changes in each test. In Test 1, the temperature rose from 35.75 °C to a peak of 40.56 °C, then fell to 37.56 °C at the last reading. In Test 2, the temperature decreased gradually from 37.50 °C to 32.44 °C. In Tests 3 to 5, the temperature was relatively stable in the range of 31 °C to 32 °C.

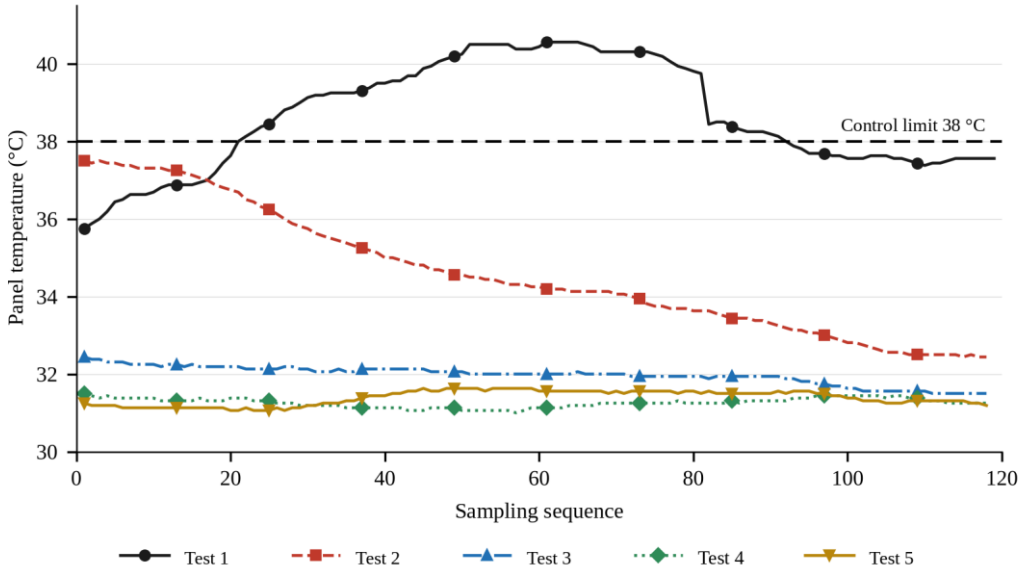


Figure 3. Panel temperature changes across the five tests relative to the 38 °C control limit (black dashed line)

The average light intensity in Test 1 reached 7,363 lux with a maximum value of 24,040 lux. Tests 2 to 5 took place at much lower light intensities, averaging 720.0 lux, 707.9 lux, 763.8 lux, and 892.4 lux.

Table 3. Ranges of Temperature, Light Intensity, and Efficiency Values

Test	Temperature min–max (°C)	Intensity min–max (lux)	Efficiency min–max (%)	Readings with temperature ≥ 38 °C	Readings with efficiency 100%
1	35.75–40.56	616–24,040	12.05–100.00	72 of 119	78
2	32.44–37.50	477–883	66.59–100.00	0 of 118	18
3	31.50–32.44	413–949	57.69–100.00	0 of 118	6
4	31.00–31.50	608–1,138	51.20–79.62	0 of 118	0
5	31.06–31.63	372–1,276	64.05–100.00	0 of 118	7

Power and Efficiency

Base on table 3, it can be explained that the average input power in test 1 was 10.00 W with an average output power of 6.64 W. In tests 2 to 5, the average input power ranged between 0.96 W and 1.21 W, while the average output power ranged between 0.70 W and 0.96 W. The average voltage in Test 1 was 13.36 V and the average current was 486.5 mA. In the other tests, the average voltage ranged between 12.33 V and 12.54 V, and the average current ranged between 56.77 mA and 77.35 mA.

Figure 4 shows (a) the average efficiency and (b) the average output power of each test. The highest efficiency was recorded in Test 2 at 82.64% and the lowest in Test 4 at 69.56%. The efficiencies of Tests 1, 3, and 5 were 77.18%, 74.70%, and 78.08%, respectively. Table 3 also shows that some readings reached the 100% efficiency cap: 78 readings in Test 1, 18 in Test 2, 6 in Test 3, and 7 in Test 5. Test 4 had no readings reaching 100%, with a maximum efficiency of 79.62%.

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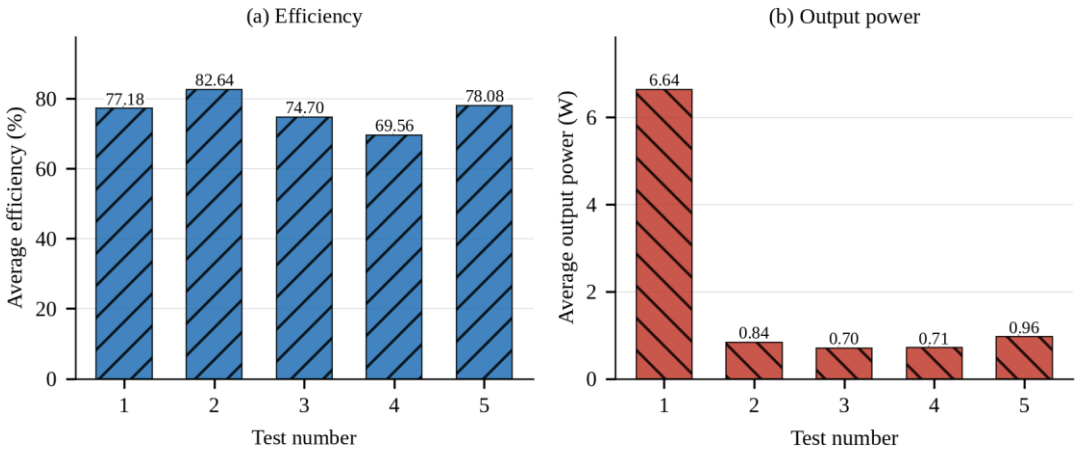


Figure 4. Average efficiency (a) and average output power (b) across the five tests

Test 1 under Two Light Intensity Conditions

The data from Test 1 were divided into two light intensity groups, as seen in Figure 5. A total of 38 readings were at intensities above 3,000 lux, with an average of 20,772 lux, an average temperature of 39.44 °C, and an average efficiency of 31.66%. A total of 81 readings were at intensities up to 3,000 lux, with an average of 1,072 lux, an average temperature of 38.26 °C, and an average efficiency of 98.53%.

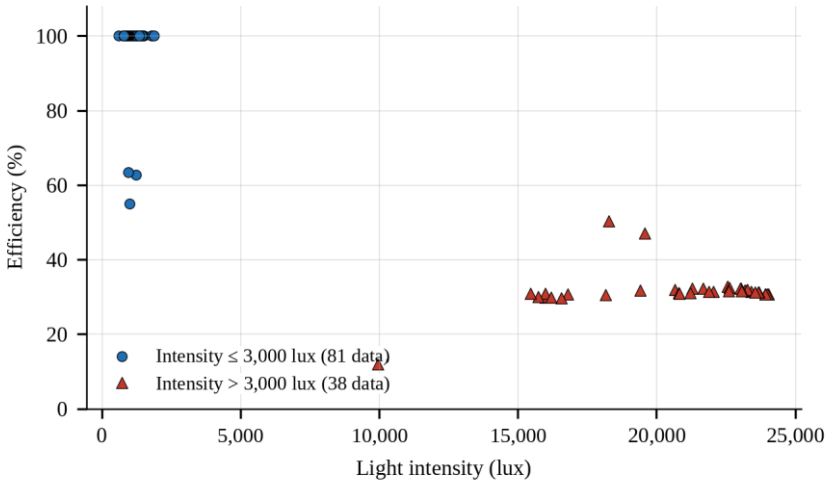


Figure 5. Relationship between light intensity and efficiency in Test 1 for the two light intensity groups

The pump status column in the log showed the standby value in all 591 samples from the five tests.

DISCUSSION

The results show that panel temperature follows lighting conditions. Test 1 had the highest average light intensity and the highest average temperature. However, the relationship between temperature and light intensity within each test was not uniform. The correlation coefficient between the two ranged from −0.63 to 0.87. This is reasonable because panel temperature is also influenced by air temperature, wind, and heating time, which were not recorded as separate parameters in this study.

The average temperature of 38.64 °C in Test 1 exceeded the control limit, so this condition was the most severe scenario for the cooling system. The peak temperature of 40.56 °C then fell to 37.56 °C at the end of the test. A similar decreasing pattern was seen in Test 2, from 37.50 °C to 32.44 °C. This decrease is consistent with the system's goal of suppressing panel temperature after it reaches the upper limit. However, the temperature decrease may also be influenced by changes in weather and light intensity. The cause cannot be determined without an uncooled reference for comparison.

The average efficiency of 77.18% in Test 1 needs to be read with caution. This figure is a combination of two different groups of data. At low light intensity, the average efficiency reached 98.53% because many readings touched the 100% cap. At intensities above 3,000 lux, the average efficiency was only 31.66%. Input power in the data is calculated linearly from light intensity, whereas output power does not increase proportionally. A possible cause is a

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load limitation or the system's output settings, but this assumption needs to be verified in further research. Thus, the high average efficiency in Test 1 does not automatically mean that power conversion at high intensity is efficient.

In Tests 2 to 5, the average temperature was below 38 °C, so the system was in a normal condition. The highest efficiency in Test 2 (82.64%) coincided with a higher average temperature than in the other tests (34.59 °C). Conversely, the lowest efficiency in Test 4 (69.56%) occurred at a nearly constant temperature of 31.00–31.50 °C. Differences in efficiency between tests therefore cannot be explained by temperature alone. At a light intensity of around 700–900 lux, input and output power are very small, so their ratio changes easily due to variations in current and voltage measurements. In addition, the efficiency in Test 2 was affected by 18 readings capped at 100%, whereas Test 4 had no such readings.

These results are consistent with the literature that temperature and radiation affect module efficiency (Hudișteanu et al., 2024; Rubaiee & Fazal, 2022). The designed system is able to record electrical parameters, temperature, and light intensity in real time, as with the low-cost IoT systems in (Demir, 2023; Ftirich et al., 2024; Hamied et al., 2023; Radia et al., 2023). The temperature-threshold-based cooling trigger is similar to the approach of (Reddy et al., 2026) and automatic active cooling (Kamarudin et al., 2021). Both studies evaluated the effect of cooling on efficiency, and (Reddy et al., 2026) reported an improvement of about 10–12% under peak conditions. This study cannot yet report a similar magnitude of improvement because it has no uncooled reference panel. In addition, active cooling requires energy for the pump (Sharaf et al., 2022). Activating the pump only when the temperature reaches 38 °C may limit this energy consumption, but the pump power was not measured in this study.

Studies in tropical regions give a similar picture. (Ahmad et al., 2022) reported a module temperature reduction of about 3.25 °C and a power increase of up to 14.2% with passive cooling. (Azhari et al., 2026) and (Abdillah et al., 2026) that module output power follows irradiance.(Nurdin et al., 2026) bahwa daya keluaran modul mengikuti iradiansi.

This study has several limitations. First, there was no uncooled reference panel, so the contribution of cooling to efficiency cannot yet be quantified. Second, the pump status column in the log was entirely standby, so direct evidence of pump activation is not available in the analyzed data. This needs to be verified, for example by recording the relay output and pump current. Third, input power was estimated from light intensity with a fixed factor rather than from irradiance measurements, and efficiency was capped at 100%. Fourth, only five tests under different lighting conditions were analyzed, so the results do not yet represent long-term weather variations. Fifth, water consumption and pump power were not measured.

CONCLUSION

This study designed and implemented an IoT-based solar panel monitoring and cooling system that monitors eight parameters in real time and controls the cooling pump at a temperature limit of 38 °C. Based on the five tests, Test 1 recorded the most severe condition, namely an average temperature of 38.64 °C at an average light intensity of 7,363 lux, with an average output power of 6.64 W and an average efficiency of 77.18%. In Tests 2 to 5, the average temperature fell to 31.26–34.59 °C and the average efficiency ranged between 69.56% and 82.64%, with the highest value in Test 2 and the lowest in Test 4. Efficiency is not determined by temperature alone, but also by light intensity and the way efficiency is calculated.

The contribution of this study is an integrated system design and test data that can serve as a reference for automatic cooling in small-scale SPPs. Future research should add an uncooled reference panel, measure irradiance with a calibrated sensor, record pump power and water consumption, and verify pump status. Longer-duration testing under various weather conditions is also needed.

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