Real-Time Monitoring and Adaptive Control of Solar Panel Cooling for Enhanced Power Harvest Through IoT Integration

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https://doi.org/10.5109/7323279

出版情報：Proceedings of International Exchange and Innovation Conference on Engineering & Sciences (IEICES). 10, pp.312-318, 2024-10-17. International Exchange and Innovation Conference on Engineering & Sciences
バージョン：

Real-Time Monitoring and Adaptive Control of Solar Panel Cooling for Enhanced Power Harvest Through IoT Integration

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Abstract: *With the growing demand for renewable energy, solar power's efficiency is hindered by environmental factors like temperature. This study explores real-time monitoring and adaptive control systems for cooling solar panels to enhance power harvest. Analyzing current cooling techniques, it highlights the limitations of passive methods and introduces IoT-based active cooling systems for continuous temperature monitoring. Using temperature, voltage, and current sensors, the system enables precise monitoring of panel performance. Experimental validation in real-world installations shows an approximately 9.39% improvement in power harvest efficiency, disregarding system power consumption. This study demonstrates the feasibility of real-time monitoring and adaptive control for enhancing solar panel efficiency, offering a scalable and flexible approach for sustainable energy generation through IoT integration.*

Keywords: IoT Monitoring, Adaptive Control of Cooling System, Active & Passive Cooling System, Solar Panel, Web Application

1. INTRODUCTION

As the global use of renewable energy sources grows and evolves to help mitigate global warming [1], solar photovoltaic (PV) collection is becoming increasingly important [2]. Many studies where are already conducted to explore the technical and economic feasibility of the technology, emphasizing the advantages and environmental benefits of solar energy, and its potential for reducing carbon emissions [3].

In the Philippines, 77% of energy comes from fossil fuels, with the rest from hydro, geothermal, wind, and solar [4]. Given the country's high levels of sunlight [5], the Department of Energy is advocating for more solar projects. The International Energy Agency predicts significant growth in global solar PV capacity, potentially exceeding 8519 GW by 2050 [6-7].

High solar intensity and rising ambient temperatures in the Philippines enhance PV panel temperatures, reducing efficiency [8]. For instance, Butuan City's heat index reached 48°C in early 2023, heating panels up to 60°C [9]. Operating temperatures of 45 to 65°C are common, much higher than the standard 25°C [10]. Cooling strategies are necessary to maintain optimal temperatures. Active cooling methods like fans and water-cooling increase convective heat transfer but require external resources, making passive cooling methods, such as wind-driven convection, more appealing [11].

The growing demand for solar energy has made enhanced monitoring systems essential. The National Grid Corporation of the Philippines reported a peak demand exceeding 10,000 MW in 2017[12]. Effective monitoring can increase solar PV system accuracy and performance [13]. Wireless monitoring systems, less affected by environmental factors, offer real-time decision-making capabilities [14]. IoT-based real-time monitoring and adaptive control systems provide continuous monitoring and management of cooling processes, optimizing performance [15]. This research focuses on leveraging IoT technology for real-time monitoring and adaptive control to enhance power harvest and improve solar energy system efficiency.

2. LITERATURE REVIEW

2.1 PV Operation

Solar energy stands out as a leading renewable energy source due to its cleanliness, accessibility, sustainability, and limitless potential [16]. Photovoltaic (PV) technology is pivotal in converting solar energy directly into electricity, offering noiseless operation and low maintenance. However, high operational temperatures can degrade solar panel performance and reduce power output, necessitating effective cooling strategies to maintain efficiency and extend the panels' lifespan [17]. This literature review covers the fundamental concept of solar panels, the environmental factors affecting their efficiency, the importance of monitoring and adaptive control systems for cooling, and current technologies used in these systems.

Solar panels consist of PV cells, which are p-n junction diodes that convert sunlight into electrical power. The performance of these cells is heavily influenced by their operating temperature, with higher temperatures leading to decreased efficiency. Only a small percentage of incoming solar radiation is converted to electricity, with the rest being absorbed as heat, raising the panel temperature to detrimental levels [18]. Studies have shown that effective cooling methods can significantly improve PV cell performance and longevity [19]. Dust accumulation and high temperatures are major environmental challenges that further necessitate the implementation of cooling systems to optimize solar panel output and lifespan [20-21].

2.2 PV Cooling

Effective cooling strategies and monitoring systems are critical for maintaining the performance of solar panels, especially in hot climates. IoT-based technologies offer real-time monitoring and adaptive control, enabling remote management and optimization of cooling processes [22]. Various methods, such as water-based cooling and advanced heat dissipation techniques, are being explored to improve efficiency [23-24]. Recent studies have focused on developing low-cost, efficient cooling systems that can adapt to environmental conditions, demonstrating significant potential in enhancing the reliability and output of solar energy systems [25-28].

2.3 Summary of Contribution

Table 1. Summary of Relevant Literature

Related Works	Parameters/Features Considered				
	A	B	C	D	E
A. Hamied et al. [27]	✔	✗	✗	✔	✗
V. Guivarch et al. [25]	✔	✔	✔	✗	✔
K.M. Moharram et al. [26]	✔	✗	✗	✗	✔
O.H. Mohammed et. Al [28]	✔	✗	✗	✗	✔
Proposed Approach	✔	✔	✔	✔	✔

Note: A- Temperature, B-Humidity, C-Dust Accumulation, D-IoT based Monitoring, E-Adaptive Control Cooling System

Table 1 shows that the proposed system addresses the gaps and characterizes the necessary aspects for implementing real-time monitoring and adaptive control of solar panel cooling. This integration through IoT enhances power harvesting compared to existing solar panel cooling systems and the methods found in the literature.

3. DEVELOPMENT OF THE SYSTEM

3.1 System Overview

In the solar panel monitoring system (Fig. 1), a single configuration includes one solar panel, a PWM solar charge controller, a battery, a Wi-Fi modem serving as a load, and a device known as the solar panel monitoring device. This monitoring device is responsible for measuring various parameters such as voltage, current, panel temperature, humidity, and ambient temperature. The solar panel's output is linked to the PWM, which charges the battery. Subsequently, the battery powers the Wi-Fi modem and a 12V DC water pump, both of which act as loads. This charging and discharging cycle are carefully managed to ensure a continuous flow of current from the solar panel, resulting in a measurable power output. For the adaptive cooling system, the setup comprises an ultrasonic sensor, a 12V DC water pump, and a 12V relay module. When the panel temperature exceeds 50 degrees Celsius, the ESP32 microcontroller triggers the 12V relay module to activate the 12V DC water pump, directing water onto the panel's surface. The water is then redirected back to the water tank through a gate, utilizing gravity to facilitate the cycle. This setup operates passively without the need for additional power. Additionally, the ultrasonic sensor functions as a water level monitor for the tank, indicating whether it is empty, half-full, or full.

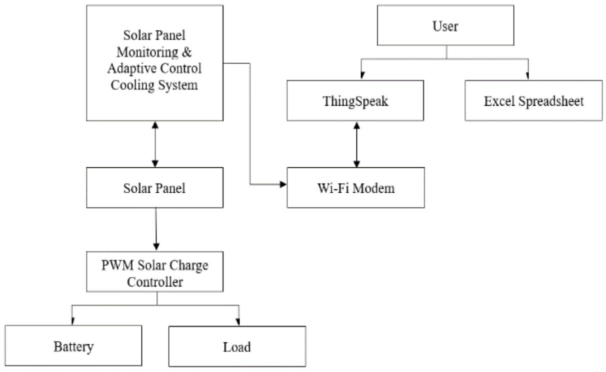

Fig. 1. Block Diagram of the Whole System

3.2 Solar Panel Monitoring System

The solar panel monitoring system seen in Figure 2 comprises an ESP32 WROOM microcontroller, a voltage sensor based on a voltage divider and an ACS712-20A Current Sensor, a DS18B20 temperature sensor, a DHT11 temperature and humidity sensor, an ADS1015 external ADC, and a LM2596S-HW-688 DC-to-DC Stepdown Buck Converter. These four sensors function as inputs to the ESP32 WROOM. Upon completion of all readings, the microcontroller transmits these readings to ThingSpeak.

The outputs of both the current sensor and voltage sensor were fed to the external ADS1015 12-bit ADC. The outputs of the DS18B20 temperature sensor and DHT11 temperature and humidity sensor were directly fed to the ESP32. A buck converter was utilized to provide a 5V power supply for the system.

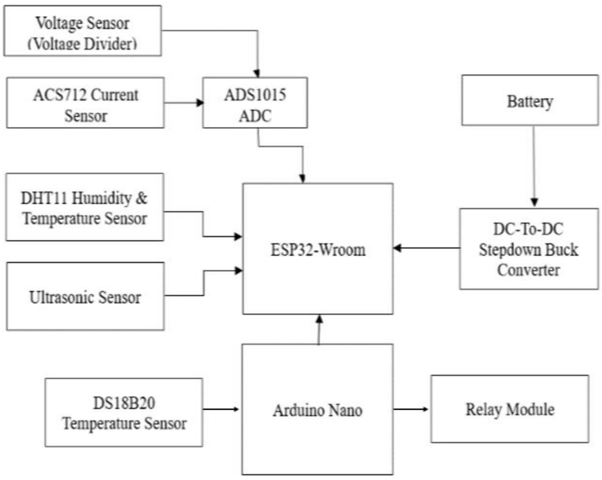

Fig. 2. Block Diagram of Solar Panel Monitoring System

The Solar Panel Monitoring System can also be presented as an Input, Process, Output (IPO) Diagram, as seen in Figure 3. All sensors are the inputs of the system, while the two microcontrollers (Arduino and ESP32) are responsible for processing, analysis, and decision-making based on the readings. The outputs of the microcontrollers are the control signals for the cooling system and the data to be sent to the cloud server, respectively.

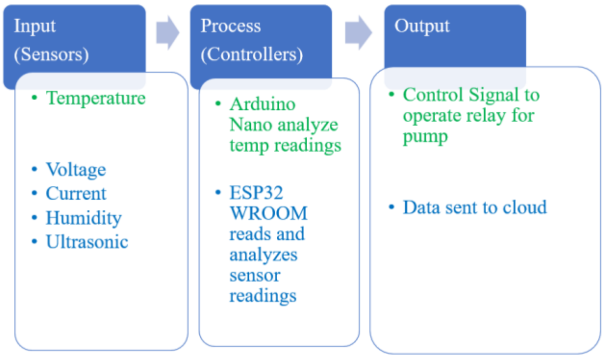

Fig. 3. Input, Process, Output Diagram of the System

3.3 Adaptive-Control Cooling System and Water Level Monitoring

The adaptive-control cooling and water level monitoring system is primarily composed of essential components including temperature sensors, relay modules, a 12V DC submersible water pump, an ultrasonic sensor, Arduino Nano, and ESP-32-WROOM-32 microcontrollers. Each microcontroller serves a distinct purpose within the system framework. The Arduino Nano serves as the data aggregator, collecting pertinent information, while the ESP32 microcontroller facilitates the transmission of data to the internet.

The DS18B20 temperature sensor, responsible for monitoring panel temperature, is connected to the Arduino Nano, alongside the relay module that controls the water pump. Upon reaching predefined temperature thresholds, the relay module triggers the water pump accordingly. Concurrently, the ultrasonic sensor monitors the water level within the tank.

These collected data are automatically channeled to a data conversion unit, subsequently transmitted to the ESP32-WROOM-32U microcontroller. The ESP32 microcontroller then relays the data to the internet, where it is stored on a cloud platform, notably ThingSpeak. The systematic architecture is visually depicted in the accompanying Figure 4 below.

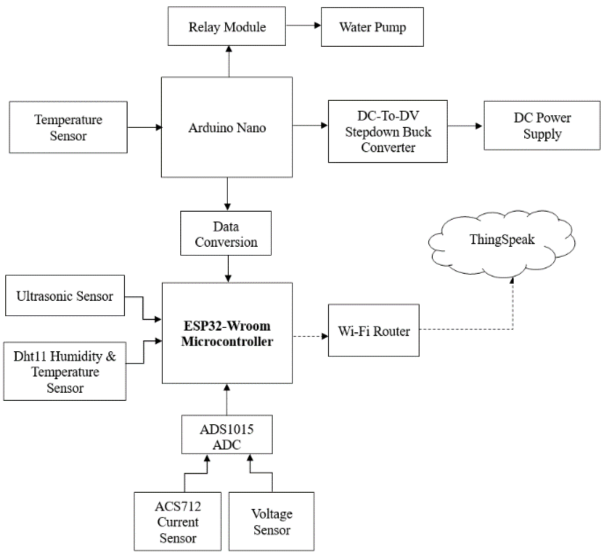

Fig. 4. Systematic Architecture of Adaptive-Control Cooling System and Water Level Monitoring

3.4 Operational Sequence of the System

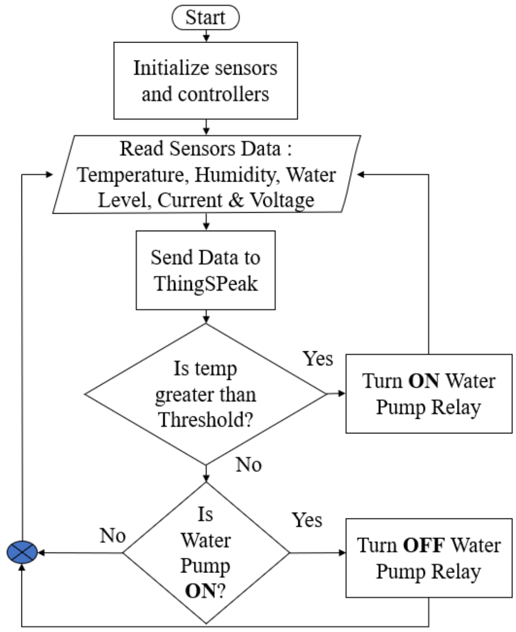

Fig. 5. Flowchart of the System

Figure 5 illustrates the operational sequence of the adaptive-control cooling and water level monitoring system. Upon system activation, both the Arduino Nano and ESP32 microcontrollers commence sensor and Wi-Fi initialization procedures. Subsequently, data from the temperature and ultrasonic sensors are acquired, together with the panel temperature and the water tank levels. Before data transfer, the ESP32 verifies its connection to a wireless network. Upon establishing connectivity, the ESP32 utilizes the internet to transmit data to cloud storage.

Upon reaching predefined temperature thresholds, the relay module is activated, enabling control over the water pump. Conversely, if the temperature remains below the threshold, the relay module deactivates. Collected data is then serially transferred and stored within the Arduino Nano. If a successful serial conversion between the Arduino Nano and ESP32 microcontroller is established, the gathered data is transmitted and archived within the ESP32 microcontroller, and the process repeats again.

4. RESULTS AND DISCUSSIONS

4.1 Prototype Development

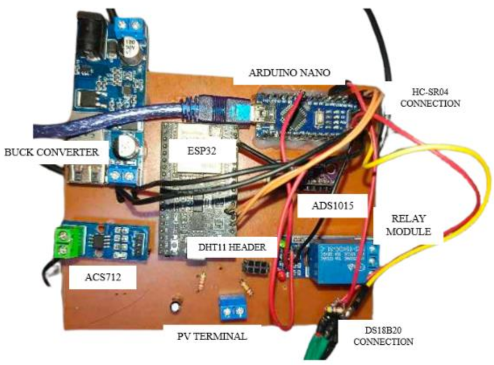

Fig. 6. Prototype of the Developed System

Illustrated in Figure 6 is the prototype of the monitoring system. The PCB design process was executed using EasyEDA, a user-friendly platform renowned for circuit design, simulation, and PCB layout. The trace width utilized in the design was set at 1.5 mm to optimize conductivity and reliability.

Following the fabrication of the device, the respective code was uploaded to the ESP32 and Arduino Nano microcontrollers. The programming process was conducted utilizing the Arduino IDE and Arduino code, ensuring compatibility and seamless integration with the microcontroller platforms.

To validate the functionality of the devices, two 12V 100AH Gel-Type Battery were series together connected with a potentiometer was employed for testing purposes. This setup facilitated the variation of voltage, enabling comprehensive testing of the devices under varying conditions.

Careful testing procedures were executed to verify that the devices operated as anticipated. This encompassed validating the accuracy of sensor readings and ensuring the successful transmission of data to the cloud platform. Through precise testing and validation, the reliability and efficacy of the devices were confirmed, validating their suitability for the intended application.

4.2 Overall System Deployment

Fig. 7. System Deployment

Seen in Figure 7 is the actual deployment of the entire system. The solar panel is integrated with a Pulse Width Modulation (PWM) solar charger controller, positioned underneath the solar panel. This controller manages the energy flow to the connected 12V 100-AH battery, employing PWM technology to regulate current delivery gradually. PWM charge controllers are proficient at maintaining battery charge levels by providing a minimal power supply once the battery reaches full capacity.

A protective insulation sheet is utilized to shield the PWM controller, offering accessibility for maintenance purposes. Additionally, an enclosure is provided beneath the panel to house the device securely. Visible wire connections within the enclosure facilitate the integration of additional components, including temperature and ultrasonic sensors, alongside connections to the battery and PWM controller.

The system's design emphasizes durability and reliability in various environmental conditions. This comprehensive approach ensures that the solar panel monitoring system remains efficient, user-friendly, and capable of meeting the energy needs of small-scale applications effectively.

4.3 Dashboard with Data

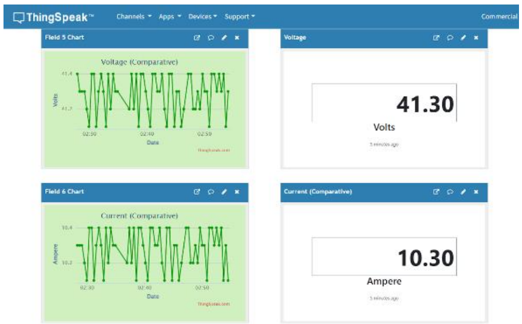

Fig. 8. ThingSpeak Dashboard

Figure 8 below illustrates a snapshot of the real-time data obtained from the system, as presented via the ThingSpeak platform. This platform provides users with the capability to visualize data through various graphical representations. Within the dashboard, pertinent metrics such as the current and voltage output from the solar panel are prominently displayed. Upon establishing an internet connection, data generated by the system is seamlessly integrated into the dashboard interface. Furthermore, users are afforded the convenience of exporting this data to Microsoft Excel for in-depth analysis and further processing.

The dashboard offers comprehensive monitoring functionalities, encompassing critical parameters essential for system performance evaluation. These include but are not limited to, the temperature of the solar panel, ambient environmental temperature, humidity levels, solar power output, and the water level within the designated tank. Such detailed insights empower users to make informed decisions and undertake proactive measures in optimizing system efficiency and functionality.

4.4 System Power Output

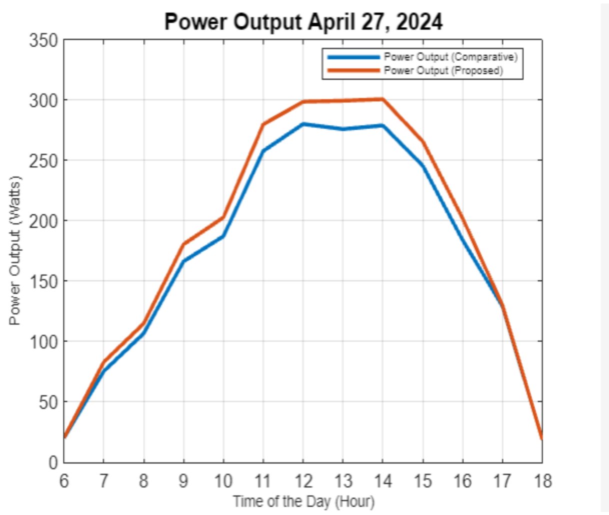

Fig. 9. Power Output - April 27, 2024

The graph depicted in Figure 9 illustrates the power output in watts on the y-axis and the time of day in hours on the x-axis for April 27, 2024. It features two lines: one representing the comparative power output and the other the proposed power output. It is notable that both panels reach peak power output between 12 noon and 2 PM. However, the power output of the panel with the proposed system surpasses that of the typical solar panel.

The maximum power output for the proposed system reaches 300 watts, whereas the comparative system achieves approximately 280 watts. From 6 AM to the peak hour at 12 PM, the power output steadily increases, maintaining stability until 2 PM, after which it begins to decline. During this period, from 6 AM to nearly 7 AM, both systems exhibit nearly identical power output due to the inactive cooling system. Similarly, from about 5 PM to 6 PM, the power output of both systems becomes equal as the cooling system is switched off, indicating optimal temperature conditions for the panels.

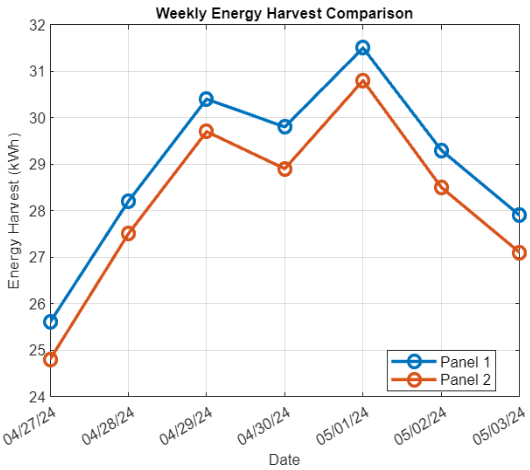

Fig. 10. One Week Energy Harvest

Figure 10 summarizes the power output of each day for both panels. It highlights that the power output of the proposed system is higher than that of the comparative system in terms of energy harvest in kWh per day. Panel 2 is the comparative system, whereas Panel 1 is the panel with proposed system. Overall, the proposed system yields a harvest of 16.715 kWh during the week, whereas the comparative system yields 15.283 kWh.

4.5 Power Consumption of the System per Day

Table 2. Power Consumption of the Proposed System

Components	Power Consumption	Qty	Working Hrs.	Total
Water Pump	42W	1	4	168Wh
ESP32 Module	1.1W	1	12	12.2Wh
Arduino Nano	1.1W	1	12	13.2Wh
ACS712-20A	55mW	1	12	.66Wh
ADS1015 ADC	.825 mW	1	12	9.9mWh
DS18b20	55 mW	1	12	0.66Wh
DHT11	11mW	1	12	0.132Wh
HC-SR04	110mW	1	12	1.32Wh
Mechanical Relay	360mW	1	4	1.44Wh
DC-DC Stepdown Buck Converter	100mW	1	12	1.2Wh
Total				0.1998 kWh

In this section, the calculation of the overall system for this study is explored. Understanding the power consumption is crucial for determining the power harvest efficiency, especially when comparing it to the typical panel setup. By quantifying the power consumption, researchers can assess the effectiveness of the proposed system in maximizing energy harvest compared to conventional panel setups.
As presented in Table 2, the components utilized in the proposed system are listed along with their respective power consumption in watts. This information provides an insight into the overall power consumption, which is then quantified in kilowatt-hours (kWh) per day. Given the focus of the study on power generation by the PV panel, understanding this consumption is vital. The data reveals a daily consumption of 0.1998 kWh, amounting to a total of 1.3986 kWh per week.

4.6 Power Harvest Efficiency

A comprehensive analysis of the total energy harvest from two solar panels with distinct setups is conducted, one integrating the proposed system and the other representing a typical PV panel setup.
To facilitate comparison, the researchers calculate the average daily energy production for each panel. Given that the proposed system yields a weekly energy production of 16.715 kWh and the comparative setup yields 15.283 kWh, Equation 1 is employed to determine the average daily energy production for each setup.

Average Daily Energy Production = Total energy produced in a week ÷7 days *Equation 1.*

The calculated average daily energy production for the panel with the proposed system is approximately 2.388 kWh, whereas for the typical panel, it is 2.183 kWh. This calculation reveals that the panel with the proposed system exhibits a higher average daily energy production, suggesting potentially superior power harvest efficiency compared to the typical panel.
Furthermore, considering the power consumption of each setup, the researchers ascertain the final power harvest. The power consumption per day for the panel with the proposed system is 0.1998 kWh, resulting in a net daily harvest of 2.1882 kWh. In contrast, the typical setup yields 2.183 kWh.
To assess power harvest efficiency in percentage terms, the percentage increase of the week in energy production of the panel with the proposed system relative to the typical panel setup is compared. The percentage increase is calculated using Equation 2.

Percentage Increase = (Energy produced by Panel 2-Energy produced by Panel 1)Energy Produced by Panel 1×100% *Equation 2.*

Consequently, the panel with the proposed system achieves an approximately 0.23% higher energy production, indicating a slight but notable improvement in power harvest efficiency. However, if one were to base the assessment solely on the overall power harvest, disregarding the power consumption of the systems, a notable improvement in power harvest efficiency of 9.39% is observed.

4.7 Panel Temperature

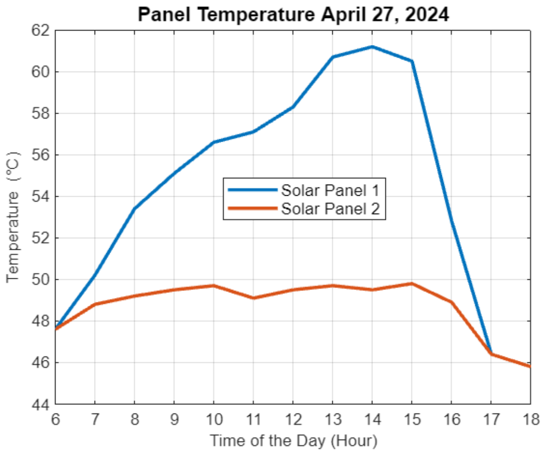

Figure 11. Panel Temperature - April 27,2024

The panel temperature readings for April 27, 2024, are depicted in Figure 11, sourced from Appendix F. Analysis of the graph reveals that Solar Panel 2, equipped with the proposed system, maintains a stable temperature throughout the day, without exceeding 50 degrees Celsius. Conversely, Solar Panel 1, representing the typical setup, experiences a temperature increase from 6 AM until 2 PM, followed by a gradual decrease.
Comparing the two setups, the average panel temperature of Solar Panel 2 during the day is 48.73 degrees Celsius, while that of Solar Panel 1 is notably higher at 54.28 degrees Celsius. The maximum temperature recorded for Solar Panel 2 is 49.8 degrees Celsius, whereas Solar Panel 1 reaches a peak of 61.2 degrees Celsius. Conversely, both setups exhibit a minimum temperature of 45.8 degrees Celsius.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

The comprehensive analysis conducted from April 27 to May 3, 2024, provides valuable insights into the performance of solar panel setups with and without the proposed system, as well as the impact of environmental factors on their operation. Across the observed period, the panel equipped with the proposed system consistently demonstrated leading power output, with maximum readings surpassing those of the comparative panel. This highlights the effectiveness of the proposed system in maximizing energy harvest and resilience to weather fluctuations.
Additionally, the analysis of power consumption and energy production underscored the higher average daily energy production of the proposed system, indicating its potential for increased power harvest efficiency. Despite marginal differences in daily energy production, the proposed system exhibited consistent performance, contributing to enhanced reliability and effectiveness of solar energy systems. The proposed system achieves an approximately 0.23% higher energy production. While this increase may seem modest, it signifies a notable improvement in power harvest efficiency and underscores the potential benefits of the proposed system in optimizing energy production. However, if one were to base the assessment solely on the overall power harvest, disregarding the power consumption of the systems, a notable improvement in power harvest efficiency of 9.39% is observed.

Furthermore, the analysis of panel temperatures revealed that the proposed cooling system effectively regulated panel temperature, preventing overheating and prolonging the lifespan of the panels. The disparity in temperature between the setups underscores the importance of effective thermal management in optimizing solar panel performance. Moreover, the analysis of environmental temperature and humidity highlighted dynamic patterns that influence solar panel operation, emphasizing the need for understanding and adapting to climatic conditions.
In addition to the innovative cooling solution, the proposed system incorporates an IoT monitoring system, which plays a pivotal role in optimizing solar panel performance. The IoT monitoring system provides real-time data on various parameters, including power output, panel temperature, environmental conditions, and water levels. This real-time monitoring allows for proactive management and timely intervention to maximize energy harvest and mitigate potential issues. Furthermore, the IoT monitoring system facilitates data-driven decision-making by providing insights into system performance trends and patterns. This allows stakeholders to identify opportunities for optimization and fine-tuning, ensuring the system operates at peak efficiency under varying conditions.

5.2 Recommendations

The study successfully achieved its objectives, but there are opportunities for system enhancement. One key enhancement could involve streamlining the system's microcontroller setup to reduce power consumption. Currently, the use of two microcontrollers, the ESP32 and the Arduino Nano, was necessitated by compatibility issues between the ESP32 MCU and the relay. Consolidating sensor readings and pump control into a single microcontroller would not only simplify the system but also minimize power usage. In addition to the improvements, optimizing the system's circuitry and selecting a water pump with lower power consumption are recommended. These steps will reduce overall energy usage without compromising functionality, enhancing the system's sustainability and cost-effectiveness.
Moreover, optimizing the power supply mechanism by directly connecting the system to the solar panel could enhance efficiency. By incorporating a DC power supply switch, along with a DC-to-DC stepdown converter and voltage regulator, the system could automatically activate during daylight hours when sunlight is available and deactivate during nighttime. This automated approach would eliminate the need for manual intervention, improving overall system convenience and energy efficiency. Furthermore, enhancing the cooling system could be achieved by implementing a passive cooling system in conjunction with an additional tank for water outlet from the solar panel. By utilizing passive cooling methods, such as natural convection or radiation, in combination with water circulation, heat dissipation could be improved, thereby enhancing the system's performance and longevity. By implementing these suggested improvements, the system could achieve greater efficiency, reliability, and sustainability in harnessing solar energy for various applications.

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