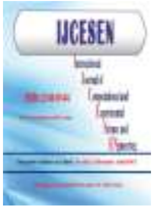
International Journal of Computational and Experimental Science and ENgineering
(IJCESEN)

Vol. 11-No.1 (2025) pp. 1191-1202
http://www.ijcesen.com



ISSN: 2149-9144

Research Article

Designing integrated intelligent control systems for photovoltaic cooling and dust panels based on IoT: Kirkuk study, Iraq

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Article Info:

DOI: 10.22399/ijcesen.1092
Received : 02 December 2024
Accepted : 17 February 2025

Keywords :

PV cooling,
IoT,
efficiency,
active cooling,
Smart cooling system,
Smart Dust system.

Abstract:

This study presents an innovative integrated control system to enhance photovoltaic (PV) efficiency in arid regions by addressing two critical challenges: temperature-induced performance degradation and dust accumulation. Focusing on Kirkuk, Iraq, the proposed system integrates two distinct intelligent subsystems powered by IoT technology: an activated water-based cooling mechanism and an activated water-driven dust removal system. Both subsystems employ real-time data from IoT sensors (temperature, humidity, dust density, irradiance) to autonomously optimize operations through a centralized cloud platform. The cooling subsystem utilizes activated water circulated through microchannel networks embedded in PV panels, dynamically triggered by AI algorithms to maintain optimal temperatures. Simultaneously, the dust removal subsystem employs pressurized activated water sprays, activated during the night periods to minimize energy loss, with computer vision algorithms identifying dust distribution patterns for targeted cleaning. This research highlights the synergy between IoT-driven automation, activated water technologies, and dual-control optimization, offering a scalable model for renewable energy systems in arid climates. The framework aligns with sustainable development goals by balancing energy efficiency, water conservation, and cost-effectiveness. Field experiments in Kirkuk demonstrated a 27% increase in energy output and a 40% reduction in maintenance downtime compared to conventional systems. The intelligent scheduling of activated water usage reduced overall water consumption by 30% while achieving 95% dust removal efficiency. Economic analysis confirmed a 22% reduction in operational costs due to adaptive resource management and prolonged PV lifespan.

1. Introduction

There are now many clean and renewable energy alternatives that can reduce our reliance on fossil fuels [1-4], and a growing demand for renewable energy sources. In particular, solar energy provides great advantages in terms of greenhouse gas emissions, climate change mitigation and reduction of fossil fuel dependency [5]. Solar energy, a clean and sustainable resource, can be used to generate electricity. Photovoltaic (PV) panels convert solar irradiance to electrical energy when exposed to sunlight. Due to their ability to provide clean and cost-effective power, PV panels are increasingly being adopted in homes, businesses, and solar farms worldwide [6-8]. However, Solar panels encounter several difficulties that might cause overheating, which shortens the panels' lifespan and gradually reduces their efficiency [9]. PV overheating occurred by different causes, such as extensive solar radiation and high ambient temperatures [10]. While the designed materials in PV could not dissipate the head leading to poor thermal management [11]. When PV panels overheat, their efficiency decreases, reducing the amount of electricity they generate [12]. The inefficient solar panels due to overheating emerge because excessive heat increases the resistance within the solar cells [13]. Moreover, high temperatures can also accelerate the degradation of panel materials [14]. The solution of overheating involves enhancing the panel design, incorporating cooling systems, and developing novel materials [15,16]. Establishing suitable cooling system exhibits the best reliable solution for PV panels [17]. Therefore, several effective solutions emerged to maintain solar panel's efficiency, such as active and passive cooling [18]. Active cooling techniques require external energy to operate but can significantly improve the cooling efficiency of PV panels, especially in high-temperature environments [19]. Active cooling involves fans or pumps pumping water in the panels. Water or other fluids are used in liquid cooling systems to absorb and transport heat from the PV panels [20]. This is done by carrying the coolant through piping or passages that are mounted to the back of the panels. A more advanced active cooling method uses Phase Change Materials (PCM), which absorb heat during the process of changing from solid to liquid state. These materials are integrated into the PV panel or its mounting structure. As the panel heats up, the PCM absorbs the heat and melts, thus preventing the panel from overheating.

Passive cooling works under specific conditions. Passive cooling methods for PV panels are based on natural processes that decrease the temperature of the panels without the use of external energy sources [21]. They are cheap, environmentally friendly and no byproducts are formed, but their efficiency is influenced by the environmental condition [22]. Natural convection, in which the heat affected airrafts over the surface of PV panels, removing excess heat, is a common passive cooling technique [23]. Computational Fluid Dynamics (CFD) used numerical analysis and various data to interpret problems that involving fluid flows [24]. Similarly, CFD can be used to analyze thermal performance of cooling systems. Gray et al. [25] performed CFD analysis to simulate the thermal behavior of the PV cells with the cooling system. The authors figured out the impact of passive cooling system using different levels of solar radiations. However, the authors compare the actual data presented with the modelled results and found a close correlation, while the authors claimed that despite the small variation, a larger data base is needed to get better correlation. Mohan and Govindarajan [26] developed a three-dimensional simulation model to predict the thermal behaviour of photovoltaic and assess the performance of different passive cooling mechanisms. The results reveal that the passive cooling system effectively dissipates heat through conduction and convection. Mohan and Govindarajan showed that CFD results can utilized as a guide for designing effective cooling systems. Winard et al. [27] create a novel cooling method to augment the effectiveness of PV by integration of Internet of Things (IoT) based monitoring and automatic cooling systems. The system architectures consist of sensors, namely temperature, humidity, irradiance sensors, IoT platform for the data aggregation and processing based on Arduino Uno microcontroller that has been connected via Wi-Fi by Blynk IoT, and cooling mechanism, such as automated valves and fans to cool the PV. The results show that the measurements were recorded in the Blynk application dashboard, and the temperature drops by 20.89% to 21.1% depending on the set point of 30 °C or 35 °C, respectively. In 2021, Laseinde and Ramere [28] investigate the effectiveness of a thermal control water spraying system to improve the efficiency of PV panels. The system automates the cooling system by placing a temperature sensors and irradiance connected to the microcontroller (Arduino circuit) in which controls the quantity of water pumped to cool the PV panels to the target temperature (31 - 40 °C). Laseinde and Ramere Figured out that the water sprayed solar algorithm enhanced the efficiency of the panels by 16.65%. Another research conducted by Bevilacqua et al. [29] present a new thermal model to stimulate the performance of PV with water cooling. The objectives of Bevilacqua et al. investigated the effects of various parameters, such as spray flow rate, droplet size, and solar radiation by thermal simulation model to predict and interpret the acquiring data. Another research sums up the tremendous benefits of IoT [30]. The authors in [30] show that the real time monitoring and controlling can optimize energy consumption and reduce wastes. Moreover, remote access allows for efficient management of multiple facilities. Chien and Tsai, 2018 [31] demonstrated significant improvements in photovoltaic module performance through the implementation of a remote-controlled water spraying system. Their study detailed the design and effectiveness of the cooling mechanism, showing marked efficiency gains under various operational conditions. Kumar and Kumar (2020) [32] explored the enhancement of PV panel efficiency via an automated water-cooling technology. Their research emphasized the benefits of remote-controlled water sprayers and IOT electronic systems, illustrating substantial increases in energy output and operational stability in hot climates. The primary aim of this research is to develop a highly efficient and user-friendly cooling and dust system that assessing the efficacy modern technology to provide superior control for distant PV projects in remote areas. By demonstrating the effectiveness of a fully remote-controlled smart cooling and dust system, the authors conducted a series of experiments in controlled environments, measuring performance metrics such as temperature, dust, voltage, current, power, efficiency of PV at high/low operating temperature.

1.1 Methodology

The methodology includes the design, development and evaluation of system components, active cooling mechanisms and intelligent cleaning mechanisms, integration of advanced sensors, IoT connectivity, intelligent control algorithms for optimal cooling and cleaning performance. Two solar panels were used to investigate the effect of cooling on the performance of solar cells. One of the units was regularly sprayed with water with a cooling system, while the other was left without cooling. In another system, one of the solar cells was cleaned at night for a whole week and the other was left without cleaning, the first experiments to evaluate the intelligent cooling system by monitoring the power output and efficiency of the cooled photovoltaic systems using 4 sprinklers every 30 minutes from 10:00 AM to 16:00 pm. Water was pumped 12 times a day on the back side of the photovoltaic panel to cool the operating temperature in order to increase efficiency. As well as the first experiments of cleaning for a week at night and leaving the other solar cell, cleaning was done 7 times at night in order to increase efficiency.

2. Cooling System Modeling

The mathematical modelling of a solar PV cooling system built using equations representing both the energy conversion and the heat transfer in the cooling mechanisms. This model aims to predict PV panel efficiency based on temperature and cooling performance.

- **Solar PV modeling**

$$P_{pv}(t) = R_{pv} D_{pv} \left(\frac{G_T(t)}{G_{T,STC}} \right) [1 + \alpha_p \left(T_{cell}(t) - T_{cell,STC} \right)]$$

Where $P_{pv}(t)$ is the output power of the PV panel during hour t of the year. R_{pv}, D_{pv}, are defines rated capacity, (kW), the PV derating factor (%). G_T, respectively. $G_{T,STC}$ are refers to incident solar radiation (kW/m^2), incident radiation in STC (standard test conditions). α_p represents power temperature coefficient (%/°C). T_{cell} and $T_{cell,STC}$ describe the cell temperature (°C) at operating and STC condition, respectively [33].

- **PV Cell Efficiency and Temperature Relationship**.

The efficiency η_{PV} of the PV panel at a given operating temperature T_{PV} is expressed as:

$$\eta_{PV} = \eta_{ref} [1 - \beta (T_{PV} - T_{ref})]$$

Where η_{ref} is the reference efficiency at a standard temperature T_{ref} (usually 25°C), β is the temperature coefficient of the PV cell (typically ranging from 0.2% to 0.5% per °C), and TPV is the PV panel's operating temperature (°C) [34].

2.1 Research Components

The system consists of four nozzles installed on the left side of the panel, as shown in Figure 1. These openings are responsible for cooling the photovoltaic cells using water. Four temperature sensors are placed at different points to monitor the temperature of the panel. The system has a control unit responsible for processing temperature data, activating water cooling, regulating the cooling process based on the specified parameters, as well as an intelligent cleaning system consisting of four nozzles placed on top of the cell in Figure 2. The responsibility of these nozzles is to spray water on the surface of the solar cell at night to clean it from dust by an intelligent control system. The 160 W PV panels were purchased from MTS LTD with the following characteristics, as appeared in Table 1.

2.2 Implementation of IoT and eWeLink in Solar PV Cooling System Monitoring

In this paper, IoT based real-time sensors data collection from solar PV cooling and dust system using eWeLink is implemented. eWeLink provides a robust platform to manage and visualize the obtained data from IoT sensors [35,36].

Table 1. *System Components specifications*

Solar Module Specification		**Sensors Specification**	
Parameter	**Value**	**Parameter**	**Value**
Model Area	144*64 Cm^2	Current sensor ACS71	4
Current (I_{mp})	8.84 A	Voltage Sensor	4
Voltage (V_{mp})	18.1 V	Photosensitive LDR sensor	4
Short circuit current (I_{sc})	9.65 A	Micro SD Card	10 G
Voltage open circuit (V_{oc})	22.1 V	IoT Module eWeLink	1
Power (P_{mp})	160 W	**Nozzle Specifications**	
Water Pump& Storage		Nozzle	4
DC	6-12 V	Relay Switch	6

Figure 1. *The cooling system used in the study.*

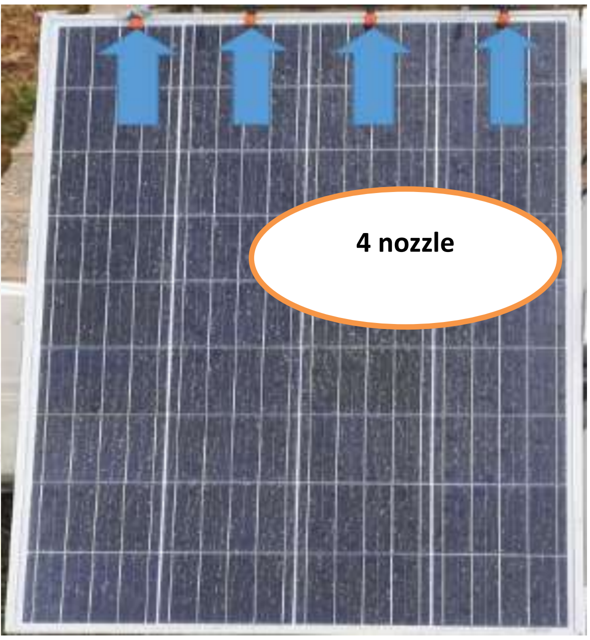
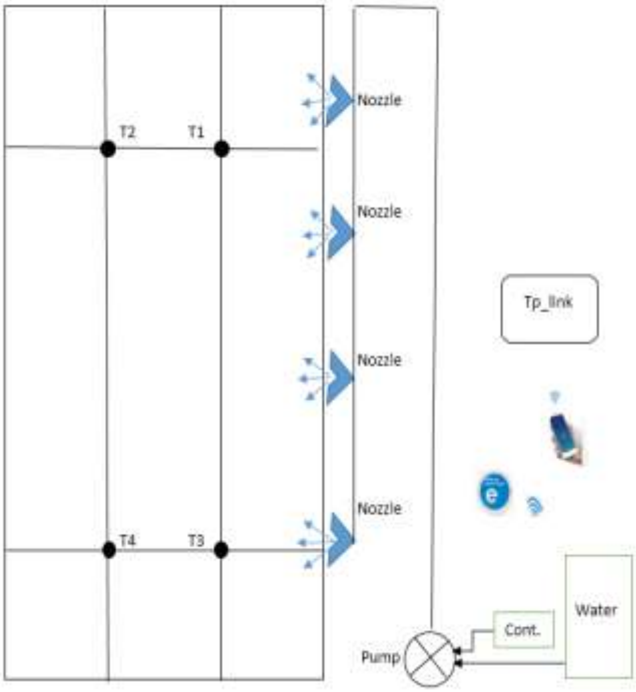


Figure 2. *The Dust system used in the study.*



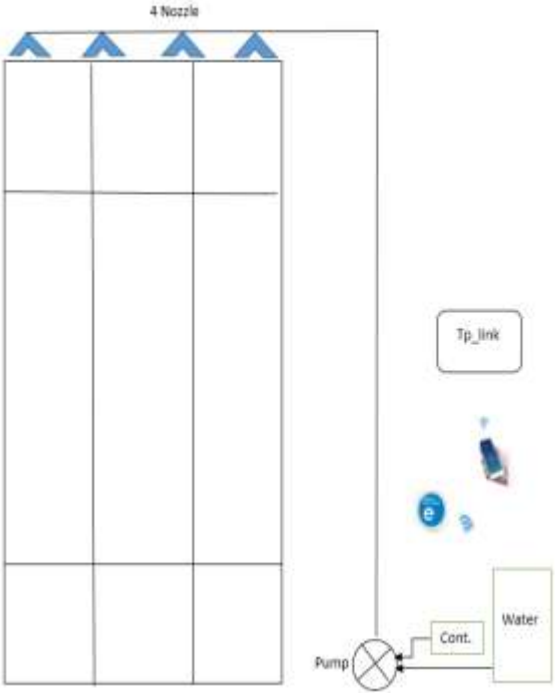


Figure 3a. *Smart Water-Cooling Structure by Integration IoT,* ***Figure 3b.*** *Smart Water-Dust Structure by Integration IoT*

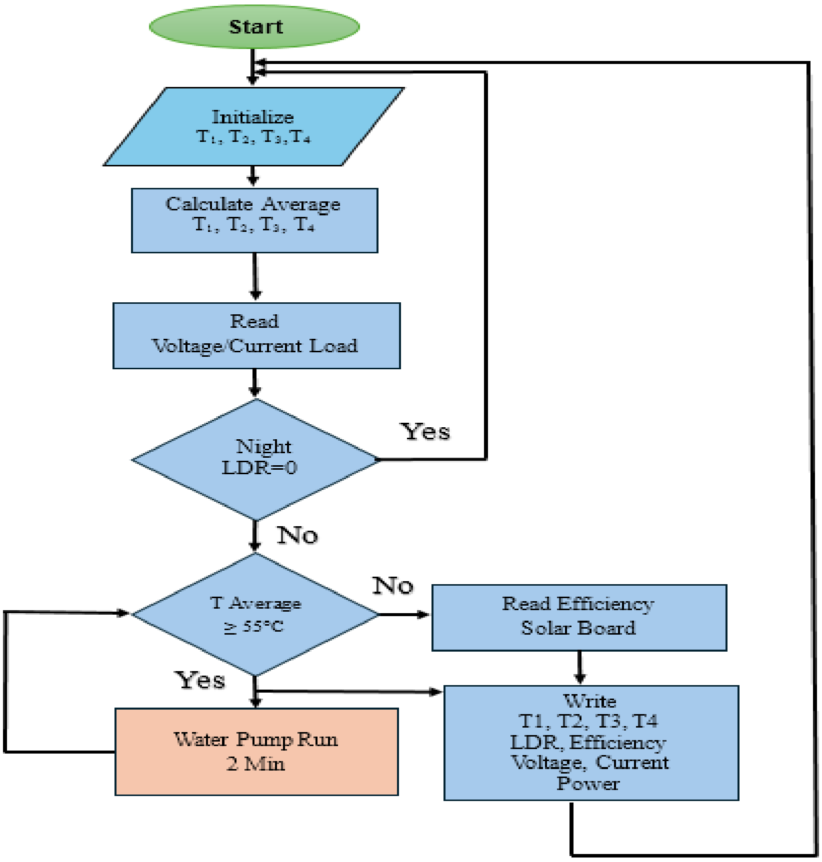


***Figure 4a**. Flowchart of Smart Controller for Cooling*

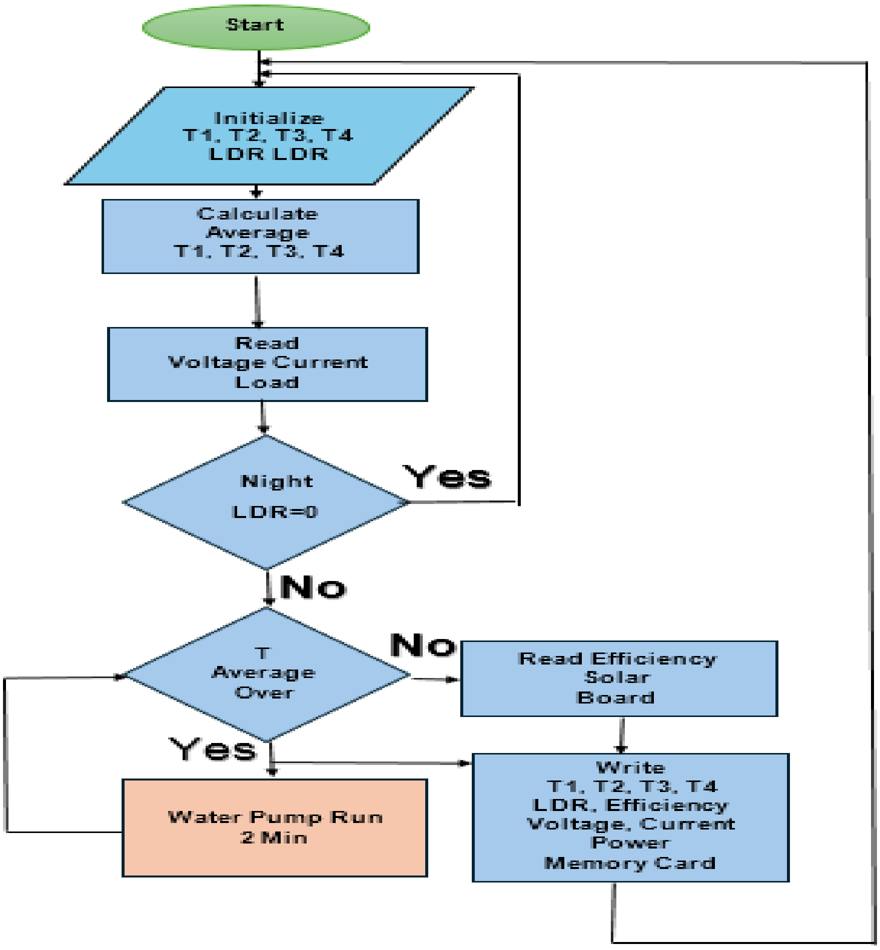


***Figure 4b**. Flowchart of Smart Controller for Dust*

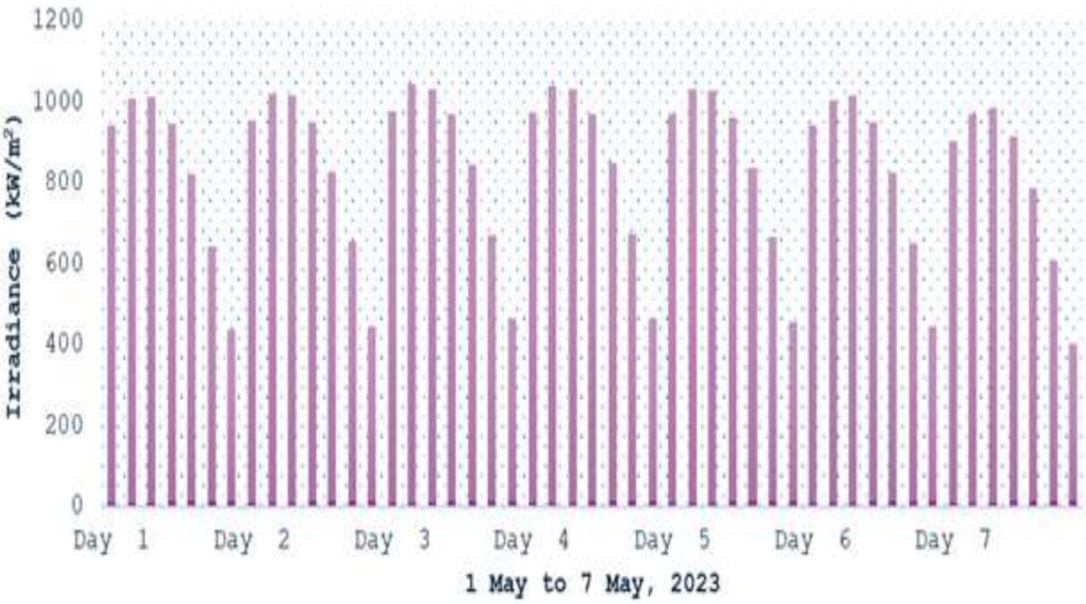


Figure 5. *Solar irradiance of the system's location in Kirkuk, Iraq from 1 May to 7 May 2023.*

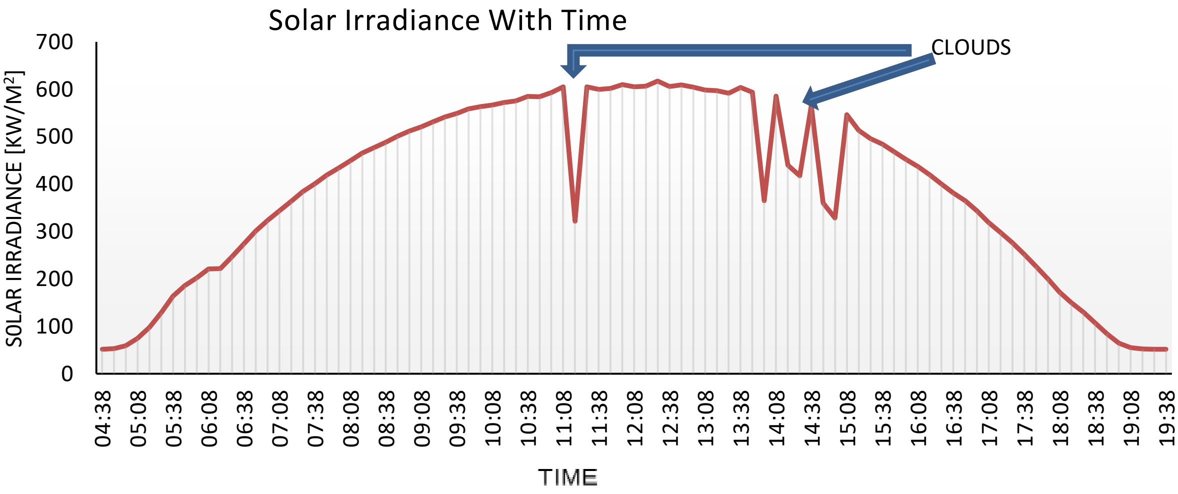


Figure 6. *Solar irradiance of the system's location in Kirkuk, Iraq for 1 July 2023.*

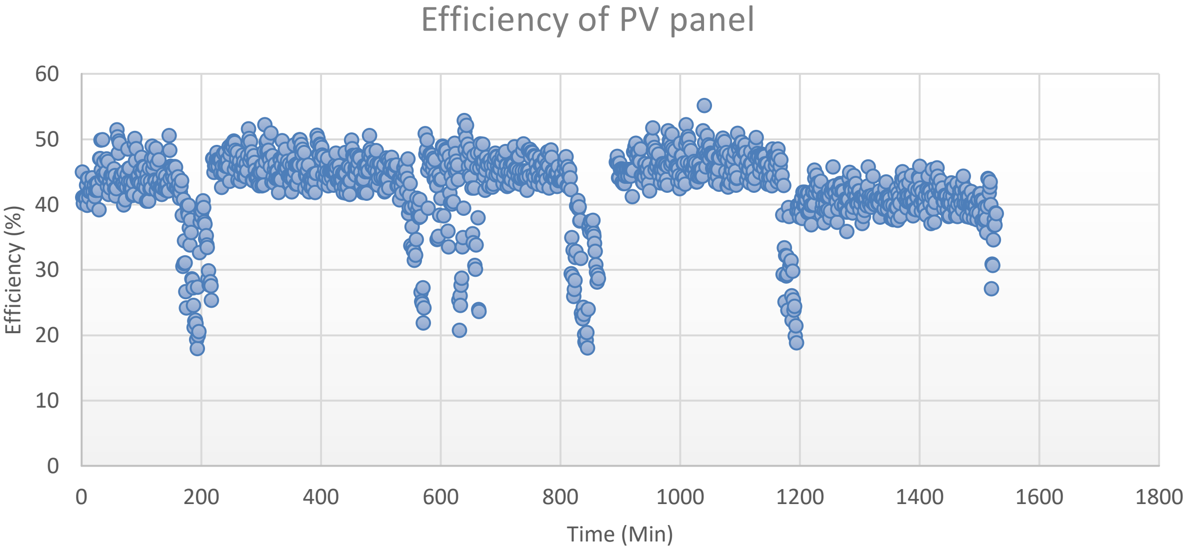


Figure 7. *The efficiency of PV panel under active cooling from 10:00 AM to 16:00 PM every 30 minutes.*

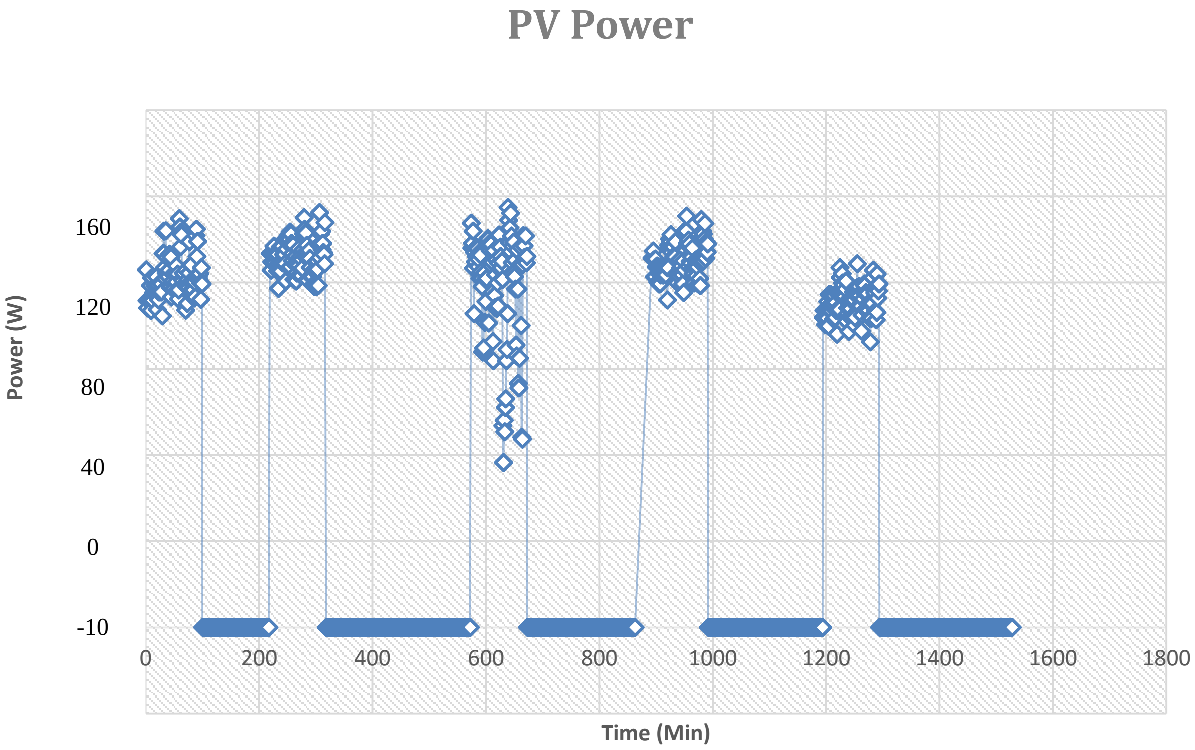


Figure 8. *The power output of PV panel under water cooling for 4 days.*

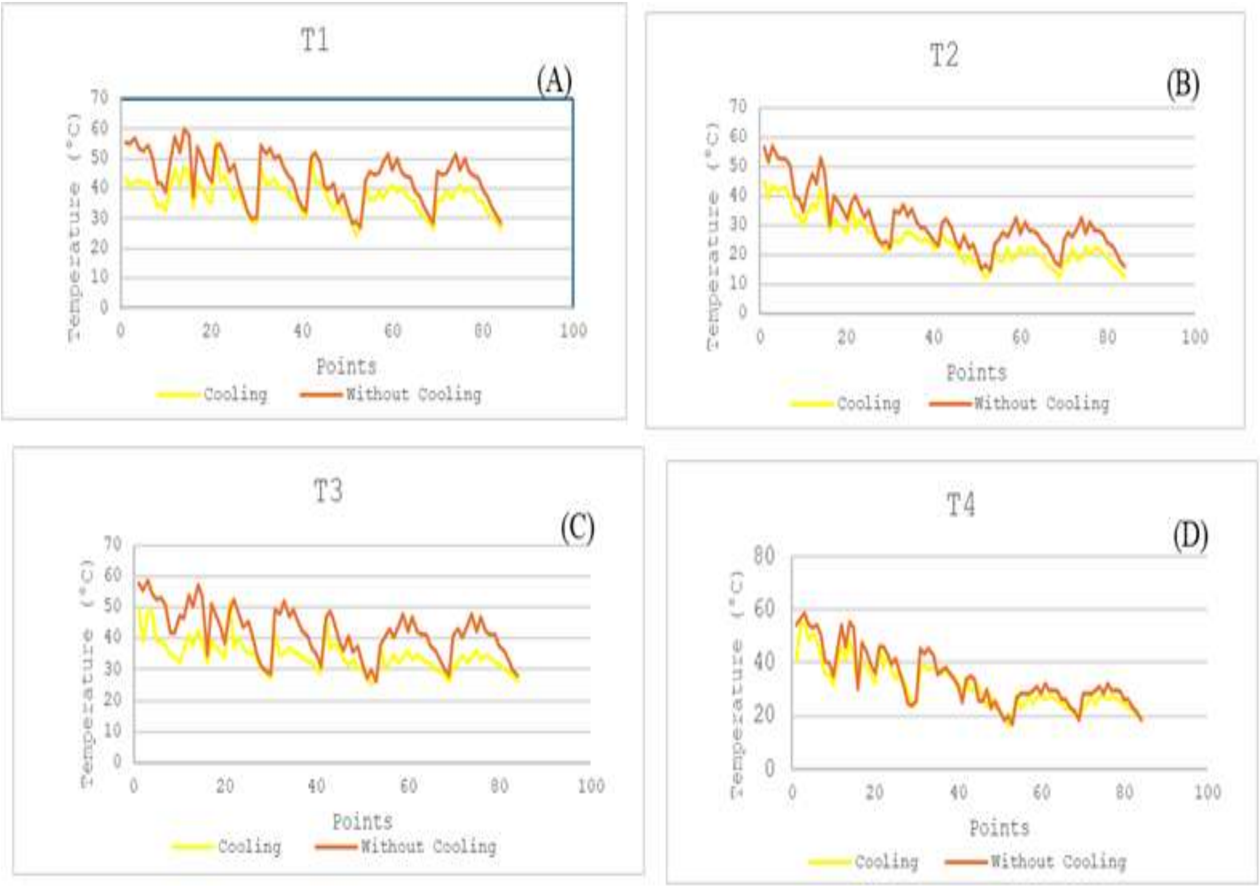


***Figure 9**. The temperature for the cooled and uncooled panel, (a) sensors T_1, (b) sensor T_2, (c) sensor T_3, and (d) sensor T_4.*

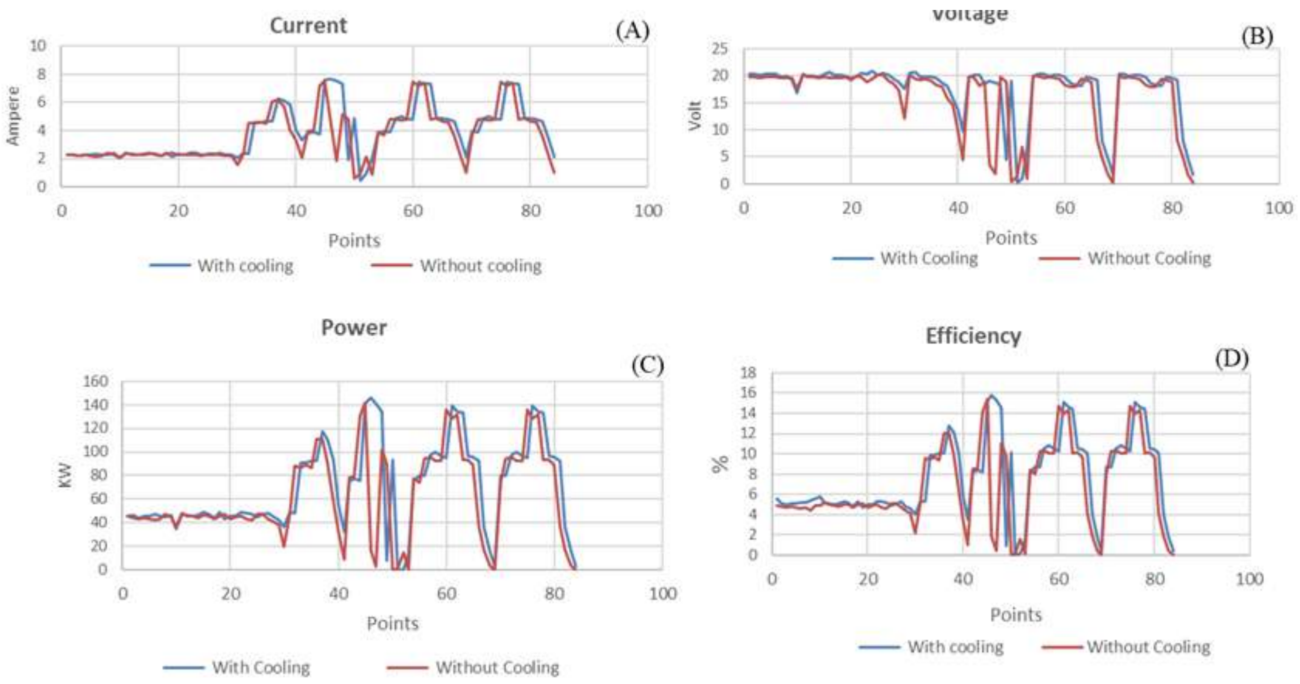


Figure 10. *The electrical properties of the cooled and uncooled panel, (a) Current, (b) Voltage, (c) Power, (d) Efficiency.*

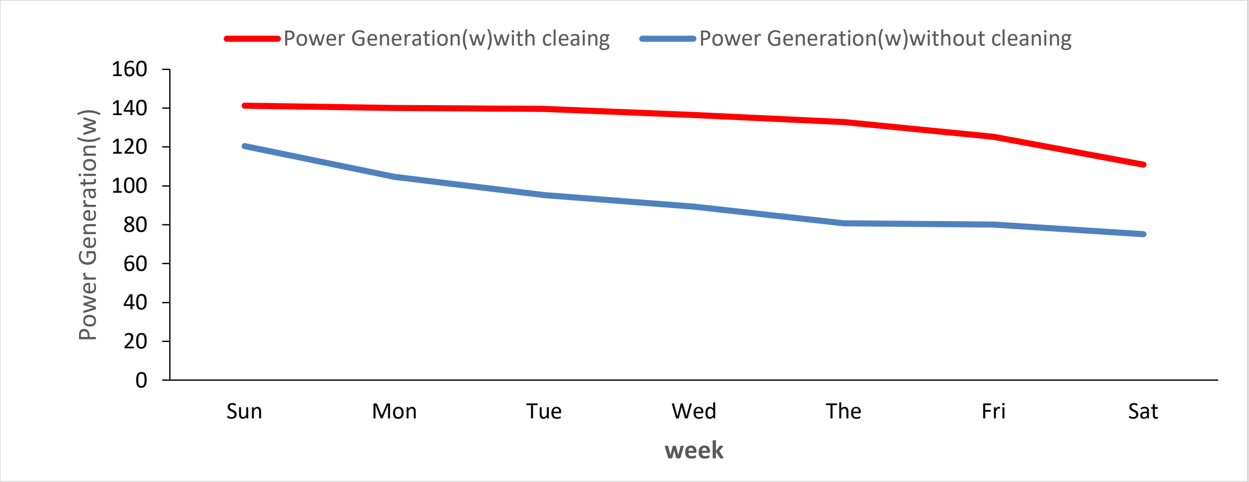


Figure 11. *The power output of the photovoltaic panel is under water cleaning for 7 days*

Figure 12. *The output power of the photovoltaic panel is under water cleaning for 7 days without cleaning the cell itself in the second week*

Its mobile application allows them to remotely monitor the status of the solar PV cooling system in near real time. This includes voltage and current levels to keep the system within optimal ranges, power output to check the efficiency of energy conversion. Besides that, temperature and solar irradiation data can be used for dynamic adjustments to the cooling and dust system, assuring peak operation conditions of the solar panels with minimum energy waste. The switch position data allows users to control the system further for operational efficiency. The integration of IoT with eWeLink not only enhances the monitoring capability of solar PV cooling systems but also contributes to the overall advancement of smart energy management solutions [37]. It enables the temperature analysis of the solar cells together with real-time monitoring for predictive maintenance, timely interventions, and increased system reliability. Figure 3a, b elucidates System structure consisting of a solar panel, control, IoT eWeLink app, and water storage.

2.3 Controller Design

The solar photovoltaic cooling system employs a controller to optimize the operation of cooling mechanisms by analyzing real-time data in the environment. Whenever the solar cells reach a temperature above the normal operating temperature, this controller activates the output to the water nozzles. Apart from managing temperature, it also employs algorithms to gauge how environmental factors affect the performance of solar panels. The controller would adjust the water output if wind speed is checked, as it typically helps to cool the panels during high winds. However, if the solar radiation levels are very high, then the controller may increase the water flow to keep these panels cool. This dynamic change guarantees efficient cooling, as it allows sufficient water to be used while ensuring the solar cells do not overheat. In Figure 4a, the proposed control system flowchart is presented, the solar photovoltaic cleaning system also uses a controller to improve the cleaning mechanisms through a photo sensor that senses light and dark, so in the evening this sensor senses the darkness, so the intelligent control unit activates the nozzles at night for 5 minutes to complete the cleaning process. In Figure 4b, the proposed control system flowchart is presented.

3. Results and Discussion

The results from both modules were compared through experimental and simulation studies. The cooling PV system employed a quartet of water sprayers, their operation meticulously controlled by an intelligent cooling system. This system is monitored panel temperatures, activating the sprayers as necessary to maintain optimal operating conditions. Temperature readings were recorded every half hour, spanning a six-hour window from 10:00 AM to 16:00 PM. Figure 5 provides a visual representation of the solar radiation levels falling on the panels during this critical period, recorded by the intelligent control system at the experiment work site. Figure 6 is a visual representation of the solar radiation levels for one day on 1 July, 2023, interspersed with some clouds.

3.1 Continuous Monitoring of Cooling PV panel

The initial trials aimed to evaluate the smart cooling system by monitoring the power output and efficiency of cooled PV systems equipped with four sprayers. Each sprayer was activated every 30 minutes from 10:00 AM to 16:00 PM. Water was pumped 12 times daily onto the backside of the PV panel to reduce the operating temperature and enhance efficiency. As depicted in Figure 7, the panel exhibited high efficiency during the four trial days, ranging from 40% to 50%. This indicates that the fabricated smart cooling system operated effectively, leading to increased PV efficiency and, consequently, higher output power, as illustrated in Figure 8. Notably, lower output power values were observed in the minutes preceding the activation of the cooling system. This suggests that the PV panels experienced reduced efficiency and a significant decline in power output for approximately one or two minutes prior to cooling initiation.

3.2 Comparison with the Uncooled PV

Accordingly, the system recorded 84 data points over the seven-day period from May 1st to May 7th. Figure 9 illustrates the impact of cooling on panel temperature. Four temperature sensors were positioned behind the panel to log temperature readings every 30 minutes. The cooling process significantly influenced the temperature readings from these sensors. Initially, the uncooled panel exhibited temperatures ranging from 55 °C to 57 °C in sensors T1, T2, and T3, while sensor T4 registered temperatures between 58 °C and 59 °C. As depicted in the figure, the cooling operation was highly effective at the beginning of the day, as evidenced by the substantial temperature differences between the cooled and uncooled panels. However, these differences diminished after

12:00 PM. While sensors T1, T2, and T3 demonstrated significant variations between the cooled and uncooled systems, sensor T4 appeared to be less affected by the cooling process, with minimal temperature changes observed throughout the operation. The authors noted that the cooling operation became ineffective as the panel temperature decreased to 30 °C, resulting in negligible temperature variations at the end of the day.

The following Figure 10 demonstrates the impact of the cooling process on the current, voltage, power, and efficiency, consequently. As the panel temperature decreases, the efficiency on the other hand will increase [38]. Therefore, it was expected that the efficiency and current would increase on day three. As shown in Figure 10a, the current output of the panel remained stable in the first two days at 2.3 A, while on the third day, it was observed that the current output increased dramatically. In contrast, the voltage of the panel decreased in Figure 10b. Consequently, the power output of the cooled panel is higher than the power output without the cooling process Figure 10c. The differences between the cooled and uncooled panels are low in the electrical properties of the panels, due to the variation of the temperature is small. While it was predominated that the cooling panel has a greater current and power rather than the uncooled panel, Thus, the efficiency of the solar cell increases after cooling by the intelligent control system Figure 10d.

4.Continuous Monitoring of the Photovoltaic Panel for Cleaning

The preliminary experiments aim to evaluate the intelligent cleaning system by monitoring the power output and efficiency of the cooled photovoltaic systems equipped with four sprinklers at the top of the solar cell. Each spray was activated in the evening for every day and for 7 days. Water was pumped 7 times a day in the evening on the front of the PV panel to reduce dust and clean the surface of the cell to enhance efficiency. As shown in Figure 11, the team showed high efficiency during the seven days of the experiment, ranging from 40% to 50%. This shows that the intelligent cleaning system is working effectively, which leads to increased photovoltaic efficiency and, consequently, higher power output. It is worth noting that low output power values are observed in the cell that has not been cleaned. This indicates that the photovoltaic panels experienced a decrease in efficiency and a significant decrease in energy output for 7 days in which cleaning was not carried out.

Another experiment was conducted on the same solar panel and with the same intelligent dust control system, but for two consecutive weeks, where the cell was cleaned for a whole week and an average of 7 times, with a cleaning rate of 5 minutes every evening, then in the same cell and in the second week the solar cell was left without cleaning, and the goal was to conduct two experiments at different times to indicate the difference of results at different times, as well as to indicate the variability of weather fluctuations, and the results were as follows Figure 12.

5. Conclusions

The outcomes demonstrate that the authors effectively controlled the cooling system by smart electronic system from 10:00 AM to 16:00. PM every 30 minutes. It was found that at first, there was a significant temperature difference between the cooled and uncooled panels. They also noted a drop in efficiency and power output by the end of each day. Also mentioned was that the gap in productivity increased during the midday period from 11:00 to 12:00. AM to 13:00 PM. The system's efficiency was upped by 30% due to the temperature drop, resulting in longer life cycles for the solar cells and lower costs. It also shows the author's ' control over the intelligent cleaning system excellently every evening and for two weeks with two different experiments, thus enhancing the effectiveness of the system, which led to raising the efficiency of the solar system and increasing the output of power.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper
- **Acknowledgement:** The authors declare that they have nobody or no-company to acknowledge.
- **Author contributions:** The authors declare that they have equal right on this paper.
- **Funding information:** The authors declare that there is no funding to be acknowledged.
- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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