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Smart Maintenance Program for Solar Photovoltaic (PV) with Cooling System

Loraine Angel B. Ladianghibong[1], **Bea Joana C. Llacuna**[1], **Aivee Ann H. Didulo-Baylon**[1]
[1]*Mindanao State University - General Santos, General Santos City, South Cotabato, Philippines*

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Email of Corresponding Author: aiveeann.didulo@msugensan.edu.ph

Abstract

This study developed and evaluated a Smart Maintenance Program for Solar Photovoltaic (PV) systems integrating automated cleaning and a temperature-based water-dripping cooling system to improve PV voltage output and operational performance. A quantitative experimental design was employed using two 150 W, 18 V monocrystalline solar PV systems, one equipped with the smart maintenance system and one unaltered. The developed system used Arduino IDE programming, a motorized wiper, temperature sensor, water pump, and associated control components. Voltage output was measured using a multimeter, while the temperature sensor was used to control the cooling mechanism according to the programmed temperature threshold. Data were collected at 10:00 A.M., 12:00 noon, and 2:00 P.M. for 20 days in General Santos City and analyzed using a paired two-tailed t-test at a 95% confidence level. Results showed that the smart PV panel consistently produced higher and more stable voltage outputs than the non-smart panel, with statistically significant differences at all observation periods. The findings indicate that integrating automated cleaning and temperature-based cooling can contribute to improved PV operational performance under actual outdoor conditions. The study concluded that the smart maintenance system provided a more favorable operating condition for the PV panel compared with the unaltered system. Recommendations included longer experimentation, larger PV panels, improved experimental controls, updated software, optimized panel positioning, enhanced cooling components, and more durable system materials. The study supports SDG 7—Affordable and Clean Energy, SDG 9—Industry, Innovation and Infrastructure, and SDG 12—Responsible Consumption and Production. Its sustainability contribution lies in improving renewable-energy utilization, reducing excessive water use through water recirculation, and supporting more effective and durable solar PV operation.

Keywords: Cleaning; Cooling System; Maintenance; Photovoltaic; Solar PV; Temperature; Voltage; Water-Dripping

1. Introduction

Solar PV technology depends on the ability of photovoltaic cells to absorb solar radiation and convert part of it into electricity. Although approximately 20% of incident solar radiation may be converted into electricity, more than 50% can become excess heat (Soliman et al., 2019). Excessive temperature can decrease solar-cell efficiency and power output and may adversely affect the silicon layer, potentially reducing the service life of the system. Environmental exposure also affects PV performance. Dust deposition, bird droppings, water stains, wiring losses, inverter losses, and debris can contribute to approximately 10-25% efficiency reduction (Gebrelibanos, 2013). Consequently, the continued expansion of solar technology increases the need for effective maintenance systems capable of minimizing contamination and maintaining efficient energy production. Demand is therefore increasing for cleaning solutions that support environmental standards and sustained PV performance (Abdulla et al., 2018). Temperature control is another important aspect of PV maintenance. Cooling can help sustain solar-cell efficiency and extend system life by reducing excessive surface temperatures. Previous investigation of PV cooling technologies found that reducing PV surface temperature can improve system output performance (Satpute & Rajan, 2018). These findings support the integration of cleaning and cooling functions into a smart maintenance system intended to address both surface contamination and thermal effects.

The literature incorporated in the manuscript centers on three related themes: maintenance management, environmental and thermal losses, and automated performance enhancement. First, organized maintenance is important because operation and maintenance constitute major phases of the solar PV life cycle, and insufficient maintenance can compromise system competence and cost-effectiveness (Mgonja & Saidi, 2017). Second, PV efficiency is affected by excess heat and accumulated contaminants. A substantial portion of incident solar radiation becomes heat rather than usable electrical energy (Soliman et al., 2019), while dust, debris, wiring, and inverter-related factors further contribute to efficiency losses (Gebrelibanos, 2013). Third, the literature suggests that technological interventions can address these performance limitations. Efficient cleaning methods are increasingly necessary to maintain peak PV performance (Abdulla et al., 2018), while cooling technologies can reduce PV surface temperature and improve electrical output (Satpute & Rajan, 2018). Collectively, these studies indicate that PV maintenance should address both cleanliness and temperature rather than treating either factor independently. Beyond solar PV systems, renewable-energy efficiency is also influenced by the optimization of system design parameters, as demonstrated by the effect of blade number on wind-turbine efficiency (Adeyeye et al., 2021).

At the broader level, the increasing use of renewable energy and solar PV technologies creates a need for more effective strategies for maintaining photovoltaic systems. Solar panels are continuously exposed to sunlight and outdoor environmental conditions, making maintenance essential to their sustained performance (Mgonja & Saidi, 2017). Studies on solar-cell heat generation and PV cooling further demonstrate that thermal effects on photovoltaic performance are relevant beyond a single installation or location (Soliman et al., 2019; Satpute & Rajan, 2018). Within the local context, the present study was conducted at Zone 3, Block 3, Fatima, General Santos City. Two solar PV systems were observed: one equipped with the smart maintenance, cleaning, and cooling system and another without these alterations. Voltage-output data were collected at 10:00 A.M., 12:00 noon, and 2:00 P.M. for 20 days to determine how the systems performed under local outdoor conditions. The manuscript does not provide a separate discussion of Philippine national-level solar PV statistics, policies, or national maintenance conditions. Accordingly, no additional national claims are introduced in this condensed Introduction.

The manuscript does not identify a formal named theory. Its conceptual basis is instead derived from the relationship among temperature, surface contamination, maintenance intervention, and PV electrical performance. Excess heat is associated with reduced solar-cell efficiency and power (Soliman et al., 2019), while dust and debris contribute to additional efficiency losses (Gebrelibanos, 2013). Cooling is expected to reduce surface temperature and improve PV output (Satpute & Rajan, 2018), while automated cleaning is intended to minimize contaminant buildup (Abdulla et al., 2018). Based on this relationship, the study treats the smart maintenance program as the intervention and solar PV voltage output as the principal indicator of comparative performance. The system integrates periodic automated cleaning and temperature-triggered water dripping to address the identified environmental and thermal factors affecting PV operation.

Existing literature establishes that inadequate maintenance, excessive heat, and surface contamination can reduce PV performance (Gebrelibanos, 2013; Mgonja & Saidi, 2017; Soliman et al., 2019), while cleaning and cooling technologies can help address these limitations (Abdulla et al., 2018; Satpute & Rajan, 2018). However, the manuscript identifies the practical need to determine whether combining automated cleaning and temperature-based cooling in a single smart maintenance program can produce measurable differences in PV voltage output under actual operating conditions. The study therefore compares voltage-output data from a solar PV panel equipped with the smart maintenance and cooling program against an unaltered solar PV panel. This comparative approach provides the rationale for assessing whether automated cleaning and localized temperature management can enhance PV operational performance.

The study is most directly aligned with SDG 7 – Affordable and Clean Energy because it seeks to improve the operational efficiency of solar photovoltaic technology through automated maintenance and cooling. Improving the ability of PV systems to sustain electrical output despite heat, dust, and debris supports more effective utilization of renewable solar energy. The manuscript specifically focuses on mitigating factors that reduce PV efficiency and on improving energy harvesting through proactive maintenance. It is also relevant to SDG 9 – Industry, Innovation and Infrastructure because the proposed system applies programmed automation, sensors, cleaning mechanisms, and temperature-based control to an existing renewable-energy technology. In addition, the study has relevance to SDG 12 – Responsible Consumption and Production insofar as improving PV maintenance and service performance can support more efficient use of installed renewable-energy equipment. These alignments are based on the study's stated emphasis on system efficiency, automated maintenance, and improved PV operational life rather than on any broader claims not examined in the manuscript.

The study contributes primarily to technological, environmental, energy, and innovation sustainability. Technologically, it demonstrates the integration of automated control, temperature sensing, motorized cleaning, and water-dripping cooling in PV maintenance. Such integration provides a practical approach for reducing dependence on purely manual maintenance while allowing the system to respond to operating conditions. From an environmental and energy-sustainability perspective, maintaining cleaner and cooler PV surfaces can help preserve the performance of renewable-energy systems affected by thermal buildup and environmental contaminants (Gebrelibanos, 2013; Satpute & Rajan, 2018; Soliman et al., 2019). The approach is therefore relevant to improving the continued usefulness of solar installations and supporting more efficient renewable-energy harvesting without introducing energy sources outside the scope of the study. From an innovation perspective, combining sensing, programmed control, cleaning, and cooling demonstrates how relatively simple automation may be applied to renewable-energy maintenance. The application of microcontroller-based monitoring and control has also been demonstrated in other renewable-energy systems, including an Arduino-based wind-energy harvesting system (Subhashini et al., 2018). The study consequently links engineering technology and sustainable-energy management by addressing practical factors that influence the reliability and efficiency of photovoltaic systems.

The study aimed to: (1) design and construct a smart maintenance program for solar PV using an automated cleaning system and a temperature-based water-dripping cooling system; and (2) evaluate and compare the voltage-output performance of a solar PV system equipped with the smart maintenance program against a solar PV system without maintenance and cooling alterations. The study specifically addressed temperature rise, dust, and debris that may adversely affect PV performance. Two 150W, 18V, 35cm × 35cm monocrystalline solar PV systems were used. One remained unaltered, while the other incorporated a motor-driven wiper and water-dripping cooling system. The wiper operated automatically at three-hour intervals, while the cooling mechanism was triggered when the monitored PV temperature reached 35°C and stopped as the temperature decreased according to the programmed threshold. Data were collected three times daily for 20 days in General Santos City, with the voltage outputs of the two panels compared under actual outdoor operating conditions.

2. Material and methods

2.1 Research Design

The study used a quantitative experimental research design to develop and evaluate an intelligent solar PV maintenance program incorporating automated cleaning and a temperature-based cooling method. The research process began with planning the system concept, materials, and electrical components, followed by preparation of the prototype design and electrical configuration. The system was subsequently fabricated by integrating the structural, mechanical, electrical, sensing, and control components. Experimental testing was then conducted to monitor and compare the voltage output of the two solar PV systems, while the temperature sensor controlled the cooling mechanism according to the programmed threshold. The final stage involved evaluating and comparing the voltage performance of the modified and unaltered PV systems under actual outdoor operating conditions. The smart system was programmed through the Arduino IDE using embedded C/C++ code. The program-controlled sensor-data acquisition, system logic, and actuator operation according to temperature thresholds and voltage readings. The developed configuration allowed the system to monitor PV temperature and automatically operate its cleaning and cooling mechanisms according to predetermined operating conditions.

2.2 Locale of the Study

The experiment was conducted at Zone 3, Block 3, Fatima, General Santos City, Philippines, where the two solar PV systems were exposed to actual outdoor operating conditions. Data were obtained consistently at 10:00 A.M., 12:00 noon, and 2:00 P.M. for 20 days. Environmental conditions affecting the experiment, including unexpected disturbances such as rain, were considered during the assessment.

2.3 Respondents of the Study

The study did not involve human respondents because it was an experimental evaluation of solar PV systems. The experimental units consisted of two 150W, 18V, 35 cm × 35 cm monocrystalline solar PV systems. One PV system served as the unaltered comparison setup without maintenance or cooling modifications, while the other was equipped with the developed smart maintenance program incorporating automated cleaning and temperature-based water-dripping cooling. The modified system monitored panel temperature using a sensor positioned at the back of the solar PV, while its electrical performance was monitored through voltage measurements. The unaltered system was evaluated under the same general experimental conditions to provide a basis for performance comparison.

2.4 Sample and Sampling Procedure

No respondent sampling procedure was employed because the study did not investigate a human population. Instead, the two solar PV systems constituted the experimental samples. Repeated measurements were obtained from both systems during the 20-day experimental period. Measurements were collected at three fixed times each day—10:00 A.M., 12:00 noon, and 2:00 P.M.—to provide comparable observations of PV performance under varying daytime environmental conditions. A total of 120 voltage-output observations were assessed, consisting of 60 observations from the smart PV system and 60 observations from the unaltered PV system.

2.5 Research Instrument

The primary research instrument was the developed smart maintenance program for solar PV with a cooling system. Its software component was developed through the Arduino IDE using embedded C/C++ programming to manage sensor acquisition, system logic, temperature thresholds, and actuator control. The prototype incorporated a 150W, 18V, 35 cm × 35 cm monocrystalline solar PV module, Arduino UNO microcontroller, 12V 40k mAh LifePO4 battery, charge controller, L293D H-bridge, inductive proximity sensor, step-up voltage regulator module, jumper and stranded wires, and a waterproof digital temperature sensor. The battery stored harvested solar energy, while the charge controller regulated the charging process. Voltage output was measured using a multimeter. The Arduino UNO controlled system operations, the H-bridge regulated motor direction and speed, and the proximity sensor assisted in controlling the movement of the cleaning mechanism. The structural and maintenance system included mounting brackets and steel angle bars, a customized 3D-printed roller gear and chain drive, a resin wiper, servo motor, water reservoir, mini micro diaphragm water pump, flexible hose, and perforated hose components. The angle bars formed the structural frame and supported the wiping mechanism. The motor-driven gear and chain moved the resin wiper across the panel surface, while the cooling mechanism pumped water through the hose and distributed it over the PV surface. During fabrication, the 35 cm × 35 cm monocrystalline PV panel was surrounded by steel angle bars that also supported the wiper assembly. The customized 3D-printed gear-and-chain mechanism was driven by a servo motor and operated with an inductive proximity sensor. A customized perforated hose was installed along the upper portion of the panel for water distribution. Water was supplied through a micro pump from a reservoir and returned to the storage container through the drainage system. Electrical circuitry and wiring were enclosed in a customized plastic housing attached beneath the PV assembly to provide a compact, waterproof, and protected installation. The system monitored panel temperature through the sensor and voltage output through the multimeter. These measurements and control functions supported the operation of the developed maintenance system, while voltage-output measurements provided the primary quantitative data used to evaluate its performance.

2.6 Data Gathering Procedure

The experiment compared the two solar PV systems for 20 days under the actual outdoor conditions in General Santos City. One panel operated without maintenance modifications, while the second panel incorporated the programmed smart maintenance and temperature-based water-dripping cooling system. The system operated according to the prescribed PV temperature condition, while voltage output was measured using a multimeter. The cleaning mechanism was programmed to operate automatically at three-hour intervals to remove accumulated dust and debris. The water-dripping cooling system operated in response to the PV temperature detected by the sensor attached to the back of the panel. The cooling mechanism was activated when the monitored panel temperature reached the programmed threshold of 35°C and automatically stopped when the programmed lower-temperature condition was reached. Voltage readings from the modified PV system and the unaltered PV system were recorded at 10:00 A.M., 12:00 noon, and 2:00 P.M. throughout the 20-day experimental period. Environmental disturbances encountered during experimentation, including rain, were noted and considered in the assessment. The collected voltage measurements were encoded and stored for subsequent statistical evaluation.

2.7 Data Analysis Techniques

The collected data were analyzed comparatively to determine differences in the voltage-output performance of the solar PV system equipped with smart maintenance and cooling and the solar PV system without these modifications. Each measurement from the smart PV system was paired with the measurement from the unaltered PV system taken on the same date and at the same observation time. A paired two-tailed t-test at a 95% confidence level was employed to determine whether a statistically significant difference existed between the voltage outputs of the smart and unaltered PV systems. The t-distribution was used to obtain the corresponding p-values for determining statistical significance. The analysis provided the quantitative basis for assessing the performance of the developed smart maintenance and cooling system.

3. Results and Discussion

3.1 Performance of the Smart Maintenance System

3.1.1 Developed Smart Maintenance and Cooling System

The developed system successfully integrated automated cleaning and temperature-based water-dripping cooling into the solar PV setup. The cleaning mechanism was designed to remove accumulated dust and debris, while the cooling system responded to increased panel temperature. The completed prototype provided simultaneous maintenance and thermal-management functions intended to reduce surface contamination and temperature rise without requiring extensive manual intervention. The successful operation of the integrated system demonstrated the feasibility of combining automated cleaning and temperature regulation in a single PV maintenance mechanism. The system directly addressed the two principal operational concerns identified in the study—surface contamination and excessive temperature—while allowing the PV panel to respond automatically to changing operating conditions.

3.1.2 Voltage Output of Smart and Non-Smart PV Panels

Across the 20-day monitoring period, the smart PV panel generally produced higher voltage outputs than the non-smart panel at all three observation times. Recorded smart-panel voltage values ranged from 12.81 V to 19.87 V at 10:00 A.M., from 13.59 V to 19.94 V at 12:00 noon, and from 13.10 V to 19.83 V at 2:00 P.M. Corresponding non-smart-panel values ranged from 9.89 V to 19.52 V, 13.10 V to 19.23 V, and 12.84 V to 19.14 V, respectively. The smart panel maintained higher outputs throughout the observations despite day-to-day changes in environmental conditions. These patterns indicate that the smart maintenance system provided more favorable operating conditions for the PV panel. The combination of automated cleaning and temperature-based cooling was designed to address accumulated debris and elevated panel temperature, potentially supporting more favorable operating conditions for the PV system, allowing the smart PV system to maintain higher voltage output. The observed consistency also suggests that proactive maintenance and temperature regulation contributed to the observed higher voltage output compared with the unaltered panel.

3.1.3 Statistical Difference in Voltage Output

Statistical analysis confirmed significant differences between the voltage outputs of the smart and non-smart PV panels. At 10:00 A.M., the mean voltage difference was 0.76650 V with a standard deviation of 0.79774, a t-value of 4.297, and a p-value of 0.00012. At 12:00 noon, the mean difference was 0.65450 V with a standard deviation of 0.46811, a t-value of 6.253, and a p-value of 0.00025. At 2:00 P.M., the mean difference was 0.77150 V with a standard deviation of 0.54499, a t-value of 6.331, and a p-value of 0.00033. All reported p-values were below the 0.05 significance level. The statistically significant results indicate that the higher voltage output of the smart PV panel was not limited to isolated observations. The manuscript therefore rejected the null hypothesis and concluded that the smart PV panel produced significantly higher values than the non-smart panel. The magnitude of the t-values relative to the observed variability further supports the reported performance difference between the two systems.

3.2 Integrated Effect of Smart Maintenance on PV Performance

3.2.1 Effectiveness of Automated Cleaning and Cooling

The overall 20-day results showed that the smart PV panel maintained higher voltage outputs than the non-smart panel across the three daily monitoring periods. At 10:00 A.M., the smart panel generally demonstrated higher and more stable output. At 12:00 noon, the smart panel continued to maintain stronger output while the non-smart panel showed comparatively lower values. The higher smart-panel voltage remained evident at 2:00 P.M., indicating improved operating performance of the integrated maintenance system. The results suggest that combining automated cleaning with temperature-based cooling can contribute to more stable PV voltage output under actual outdoor conditions. However, because cleaning and cooling were implemented as a combined intervention, the individual contribution of each component could not be isolated in the present experimental design.

4. Conclusion & Recommendations

The study demonstrated that the Smart Maintenance Program for Solar Photovoltaic (PV) with Cooling System improved the voltage output of the solar PV system compared with the unaltered panel. Statistical analysis at a 95% confidence level showed significant differences in voltage output at all three observation periods, with the smart PV panel maintaining higher voltage values than the non-smart panel. The results indicate that integrating automated cleaning and temperature-based cooling can contribute to improved PV operating performance under actual outdoor conditions. Because the cleaning and cooling mechanisms were implemented as a combined intervention, the individual contribution of each component could not be determined in the present study.

Future studies should extend the experimental period beyond 20 days, use larger solar panels, and separately evaluate the effects of automated cleaning and cooling. The software should be updated to incorporate newer developments, while panel angle and positioning should be optimized to improve solar exposure and water flow. The cooling mechanism may be improved using a higher-pressure pump without reducing harvested energy, and the use of 3D-printed or plastic-molded materials in the wiper mechanism should be minimized because of the socket malfunction encountered. The study further recommends using durable materials such as anti-reflective coatings, securing electrical components, improving the wiper design for more effective dust and debris removal, and protecting the metal frame against corrosion through protective coatings or corrosion-resistant materials.

Compliance with ethical standards

This study involved no human participants, animals, personal data, or sensitive information; therefore, informed consent and human-participant ethical approval were not applicable. The research consisted solely of experimental testing of solar photovoltaic systems using voltage, temperature, and weather-related measurements. The authors declare no conflict of interest.

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