Global Journal of Engineering and Technology Advances
eISSN: 2582-5003
Cross Ref DOI: 10.30574/gjeta
Journal homepage: https://gjeta.com/

(RESEARCH ARTICLE)

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A holistic framework for PV performance optimization: Integrating intelligent solar tracking and autonomous robotic cleaning

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Global Journal of Engineering and Technology Advances, 2025, 24(02), 050-058

Publication history: Received on 21 June 2025; revised on 28 July 2025; accepted on 31 July 2025

Article DOI: https://doi.org/10.30574/gjeta.2025.24.2.0231

Abstract

Maximizing the energy yield of photovoltaic (PV) systems requires a multi-faceted approach that addresses both optimal energy harvesting and proactive maintenance. This paper presents a holistic, intelligent framework that integrates two critical optimization strategies: dynamic dual-axis solar tracking to maximize incident irradiance and autonomous, rule-based robotic cleaning to mitigate soiling losses. The solar tracker, guided by a four-quadrant LDR sensor array, continuously adjusts the panel's orientation to maintain perpendicularity with the sun's rays, significantly boosting energy capture. Complementing this, the autonomous cleaning system leverages a differential data comparison between a soiled test panel and a clean reference panel to make informed decisions. Its rule-based engine triggers cleaning cycles only when performance degradation surpasses a defined threshold, avoiding unnecessary operations. A detailed design of the cleaning robot is presented, featuring a robust tracked locomotion system and a high-torque, dual-brush cleaning head. Experimental results demonstrate that the solar tracker increases daily energy generation by 30.1% on clear days and 115.4% on cloudy days. The cleaning algorithm effectively responds to soiling events while intelligently avoiding redundant cycles during natural cleaning events like rainfall. This integrated platform represents a comprehensive, practical solution for maximizing the lifecycle performance of PV installations.

Keywords: Solar tracking; Solar panel cleaning; Photovoltaic optimization; Autonomous robot; Rule- based system; IoT

1. Introduction

The global imperative for sustainable energy has established photovoltaic (PV) technology as a corner- stone of the renewable energy transition. The economic viability and performance of solar installations, however, are profoundly influenced by real-world operating conditions. To maximize the return on investment and achieve the nameplate capacity of these systems, a holistic optimization strategy is required. This strategy must address two fundamental and persistent challenges: maximizing the capture of avail- able solar irradiance and minimizing performance degradation due to environmental factors. This paper addresses both constraints through a single, integrated, intelligent framework.

The first challenge, maximizing irradiance capture, stems from the geometric relationship between the sun and a fixed PV panel. Conventional installations are typically mounted at a static tilt angle, a compromise optimized for peak performance at a specific time of day and season. As the sun traverses its daily and seasonal arcs, the angle of incidence deviates significantly from the optimal perpendicular, leading to substantial "cosine losses." These losses are most pronounced during the early morning and late afternoon, effectively narrowing the window of peak power generation [4]. Dual-axis solar trackers provide a direct mechanical solution, dynamically reorienting the panels to follow the sun, thereby minimizing cosine losses and significantly boosting the total daily energy yield [5].

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The second, and equally critical, challenge is the mitigation of soiling losses. Soiling refers to the accumulation of airborne particles—dust, industrial pollutants, pollen, bird droppings—on the panel surface. This layer of grime obstructs and reflects incident sunlight, leading to power losses that can range from a negligible amount in rainy climates to over 30% in arid or polluted regions, severely impacting the levelized cost of energy (LCOE) [1]. Regular cleaning is therefore not an option but a necessity for maintaining plant efficiency. While automated robotic cleaning systems are becoming more prevalent, the majority operate on simplistic, fixed schedules. This ”one-size-fits-all” approach is inherently inefficient, failing to adapt to the stochastic nature of soiling and weather events, often resulting in wasted resources or prolonged periods of suboptimal performance [3].

This paper proposes a holistic framework that tackles these dual challenges in a synergistic manner. We integrate an intelligent dual-axis solar tracker with an autonomous, rule-based cleaning robot. The system is designed not merely to perform tasks, but to make intelligent, data-driven decisions. The tracker maximizes the potential energy input, while the smart cleaning system ensures the panel surface remains in optimal condition to realize that potential. This synergy, governed by a unified data acquisition and control architecture, represents a significant step beyond isolated optimization strategies. Our work details the design of the control algorithms, the mechanical and electronic architecture of the robotic platforms, and presents experimental validation of the integrated system’s superior performance.

2. System Design and Methodology

The proposed platform is architected as a multi-layered, closed-loop, cyber-physical system. It is designed for modularity, scalability, and autonomous operation, comprising three core subsystems: a unified Data Acquisition Unit, an Intelligent Control Engine, and two Mechatronic Actuation Platforms (the tracker and the robot).

2.1. Overall Architecture and IoT Integration

The system operates on continuous feedback loops governed by the Intelligent Control Engine, which is implemented on a low power ESP32 microcontroller. The engine runs two parallel logic streams: a continuous, high frequency feedback loop for solar tracking and an event-driven, lower frequency rule- based algorithm for cleaning decisions.

The entire system is integrated with a custom IoT dashboard built on Node-RED, communicating via the lightweight MQTT protocol. This provides a user-friendly graphical interface for:

- Real-Time Monitoring: Visualization of all sensor data, power outputs, and system states.
- Manual Control: An operator can manually override the autonomous logic to command either the tracker or the cleaning robot, which is invaluable for diagnostics and testing.
- Data Logging: All data is logged for long-term performance analysis.

This architecture makes the platform an ideal tool for both practical deployment and academic research.

2.2. Mechatronic Platform 1: Dual-Axis Solar Tracker

The solar tracker is the first stage of optimization, designed to maximize the gross energy input.

2.2.1. Mechanical Design

The platform uses a dual-axis (azimuth and elevation) mechanism, capable of full hemispherical movement. The frame is constructed from lightweight aluminum to minimize the load on the driving motors. Two SG90 servo motors, chosen for their cost effectiveness and ease of control in a prototype setting, actuate the two axes. The gear train provides sufficient torque to orient the 5W panel against moderate wind loads.

2.2.2. Tracking Control Algorithm

The control logic is a closed-loop, proportional feedback system. Its goal is to nullify the error signal generated by a four-quadrant LDR sensor array. The LDRs are arranged in a cross pattern, separated by a cruciform baffle. Let LTL, LTR, LBL, LBR be the light values from the top-left, top-right, bottom-left, and bottom-right LDRs, respectively. The algorithm calculates two differential error signals:

- **Horizontal (Azimuth) Error (E_{hor}):**

$$E_{hor} = (L_{TR} + L_{BR}) - (L_{TL} + L_{BL}) \ldots\ldots\ldots\ldots (1)$$

- **Vertical (Elevation) Error (E_{ver}):**

$$E_{ver} = (L_{TL} + L_{TR}) - (L_{BL} + L_{BR}) \ldots\ldots\ldots\ldots (2)$$

The control loop, detailed in Algorithm 1, adjusts the servo positions based on these errors. A tolerance threshold ('dead_zone') is implemented to create a hysteresis band. If the absolute error is within this zone, no motor action is taken. This is critical to prevent constant, energy wasting micro adjustments ("jittering") and to reduce mechanical wear on the servos.

Table 1 Algorithm of Solar Tracking Control Loop

1: **Constants:** 'dead_zone' = 10, 'step_size' = 1 degree
2: **Variables:** 'azimuth_pos', 'elevation_pos'
3:
4: **loop**
5: Read $L_{TL}, L_{TR}, L_{BL}, L_{BR}$ from LDRs
6: $E_{hor} \leftarrow (L_{TR} + L_{BR}) - (L_{TL} + L_{BL})$
7: $E_{ver} \leftarrow (L_{TL} + L_{TR}) - (L_{BL} + L_{BR})$
8:
9: **if** $\lvert E_{hor} \rvert >$ 'dead_zone' **then**
10: **if** $E_{hor} > 0$ **then**
11: 'azimuth_pos' ← 'azimuth_pos' - 'step_size'
12: **else**
13: 'azimuth_pos' ← 'azimuth_pos' + 'step_size'
14: **end if**
15: **end if**
16:
17: **if** $\lvert E_{ver} \rvert >$ 'dead_zone' **then**
18: **if** $E_{ver} > 0$ **then**
19: 'elevation_pos' ← 'elevation_pos' + 'step_size'
20: **else**
21: 'elevation_pos' ← 'elevation_pos' - 'step_size'
22: **end if**
23: **end if**
24:
25: Set Azimuth Servo to 'azimuth_pos'
26: Set Elevation Servo to 'elevation_pos'
27: Wait for 200ms
28: **end loop**

2.3. Mechatronic Platform 2: Autonomous Cleaning Robot

The cleaning robot is the second stage of optimization, engineered to maintain the panel's surface transmittance. Its design emphasizes stability, low ground pressure, and effective cleaning action. The final assembled prototype, shown in Figure 1, integrates these design principles into a compact and functional platform.

2.3.1. Mechanical Design

The robot's design was guided by the unique constraints of operating on a delicate glass surface that may be inclined.

- Locomotion System: A tracked locomotion system was chosen over wheels. The two rubber tracks, featuring high grip treads, provide a large contact area. This distributes the robot's weight (approx. 2.5 kg) evenly, resulting in very low ground pressure to prevent panel micro-cracks, and ensures superior traction to prevent slippage on inclined or wet surfaces [12]. The drive mechanism consists of drive sprockets, idler wheels, and a spring-loaded tensioning system to keep the tracks taut.
- Chassis: The chassis is built from a laser-cut aluminum sheet, providing a rigid and lightweight structure. The design maintains a low center of gravity to maximize stability and prevent tipping during motion. The chassis features a modular layout with predefined mounting points for the electronic components, battery, and cleaning head, facilitating assembly and maintenance.
- Cleaning Head: The cleaning head employs a dual-brush design with two counter-rotating circular brushes. This configuration is highly effective: the scrubbing action dislodges dirt, and the counter rotation creates a central channel that efficiently ejects debris away from the robot's path. The brushes are driven by high-torque MG513 geared DC motors. The brush pads are made of soft, non- abrasive nylon bristles and are attached with a hook-and-loop system, allowing for easy replacement.
- Fluid Delivery System: The prototype incorporates a future-proofed design for a wet cleaning system. As seen in Figure 1, two flexible coolant pipes are mounted on articulated arms. These are positioned to deliver water or a cleaning solution directly in front of the brushes. This system, to be driven by a small peristaltic pump, will allow the robot to tackle more stubborn, caked on grime.

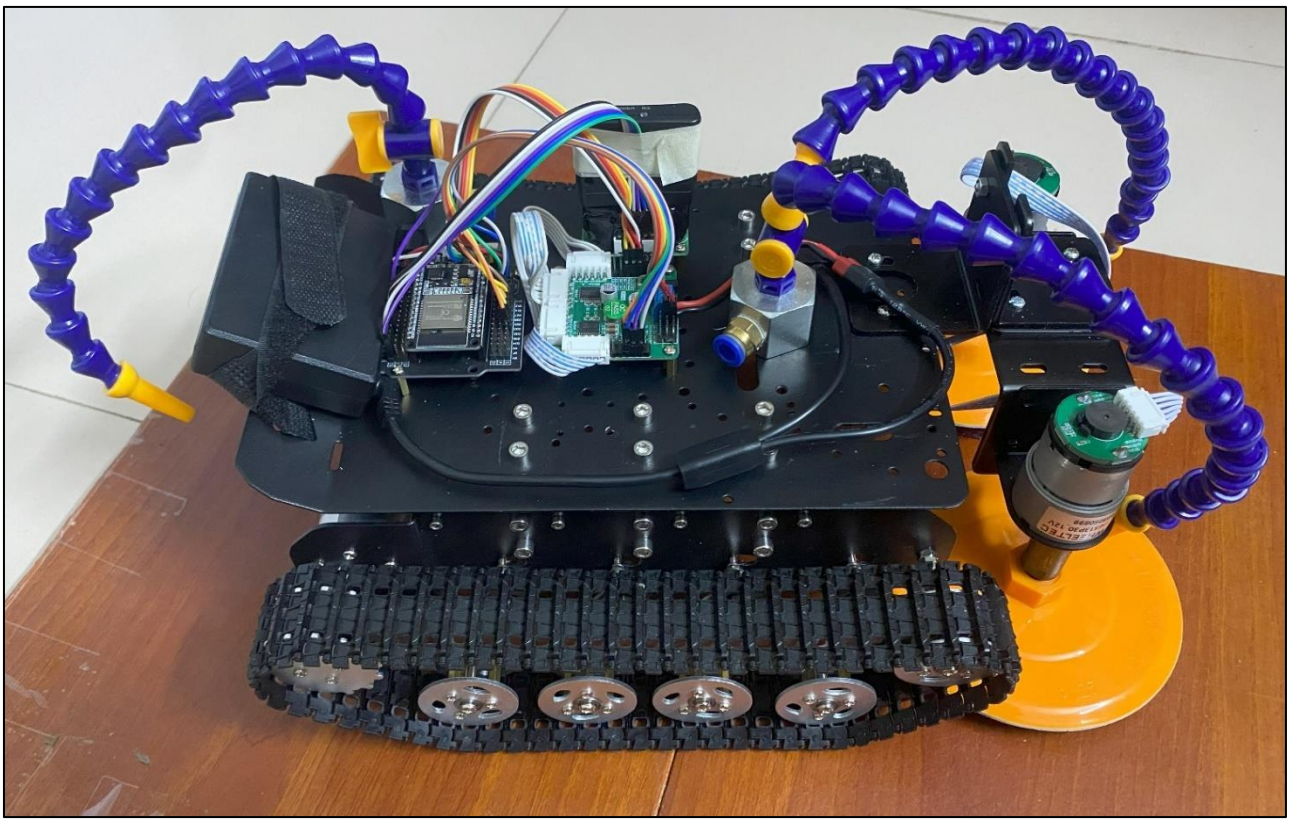


Figure 1 The assembled prototype of the autonomous cleaning robot. Key components visible include the tracked locomotion system for stability, the central ESP32 microcontroller and motor driver board, and the flexible coolant pipes repurposed for a future water/cleaning fluid delivery system

2.3.2. Electronics and Control Architecture

The robot's onboard systems are designed for efficiency and robust operation.

- Microcontroller (MCU): An ESP32 WROOM-32 module serves as the robot's brain. It was selected for its dual-core processor, integrated Wi-Fi and Bluetooth for communication with the main control unit, and extensive low-power modes to conserve battery life when idle.
- Motor Control: Four TB6612FNG H-bridge drivers are used to control the two track motors and the two brush motors independently. These MOSFET-based drivers are significantly more power efficient and

generate less heat than older BJT based drivers like the L298N, which is critical for a battery powered system.

- Power System: A 12V, 2550mAh 3S Li-ion battery pack provides the main power. The pack includes an integrated Battery Management System (BMS) for overcharge, over-discharge, and short-circuit protection, as well as cell balancing. A dedicated power distribution board with buck converters steps down the 12V supply to 5V for the motor driver logic and 3.3V for the ESP32 MCU.

2.4. Data Acquisition and Rule-Based Cleaning Engine

The intelligence of the cleaning system resides in its ability to interpret data and make decisions. This is achieved through a differential measurement setup and a hierarchical rule-based algorithm. Two identical 5W panels are used: a "Test Panel" (tracked and cleaned) and a "Reference Panel" (fixed-tilt, manually kept clean).

The rule-based engine, detailed in Figure 2, evaluates conditions sequentially. Safety and inhibit rules are checked first.

- **Night-time Inhibit (C_{Night}):** Cleaning is disabled between sunset and sunrise.
- **Rain Inhibit (C_{Rain}):** If relative humidity $H(t) > 95\%$, cleaning is inhibited [9].
- **Power Degradation Trigger ($C_{PowerDiff}$):** This is the primary trigger for uniform soiling. The relative power loss, $\Delta P(t)$, is calculated:

$$\Delta P(t) = \frac{P_{ref}(t) - P_{test}(t)}{P_{ref}(t)} \times 100\% \quad \text{.....(3)}$$

- A 'CLEAN_NOW' command is issued if $\Delta P(t)$ remains above a 20% threshold for a sustained period of 10 minutes. The time filter is crucial to prevent false triggers from transient shadows.
- **Obstruction Detection Trigger ($C_{VoltageDiff}$):** This rule detects acute, non-uniform soiling (e.g., a leaf) that can cause dangerous "hot spots" [10]. The relative voltage loss $\Delta V(t)$ is calculated:

$$\Delta V(t) = \frac{V_{ref}(t) - V_{test}(t)}{V_{ref}(t)} \times 100\% \quad \text{.....(4)}$$

If $\Delta V(t) > 20\%$, cleaning is triggered immediately.

3. Experimental Results and Analysis

To validate the performance of the integrated platform, a series of experiments were conducted in Hanoi, Vietnam. The analysis is presented in two parts: first, the energy gain from the solar tracker, and second, the effectiveness of the smart cleaning algorithm.

3.1. Performance of the Dual-Axis Solar Tracker

The tracker's performance was evaluated by comparing its power output against an identical panel mounted at a fixed, optimal tilt angle.

3.1.1. Clear Sky Conditions

Figure 3 illustrates the performance on a clear, sunny day. The fixed panel shows a typical parabolic power curve, peaking at solar noon. In contrast, the tracked panel achieves a much broader, flatter power curve, maintaining a near-peak output for over 6 hours. By integrating the area under both curves, the total energy generated was calculated. The tracked panel produced 13.31 Wh, while the fixed panel produced 10.23 Wh, representing a substantial "energy gain of 30.1%".

3.1.2. Cloudy Sky Conditions

Figure 4 shows the performance on a heavily overcast day. Under these conditions, a large portion of the available light is diffuse. The dual-axis tracker demonstrates a remarkable advantage by constantly adjusting to face the brightest point in the sky. The tracked panel generated 6.16 Wh, compared to just 2.86 Wh for the fixed panel. This represents a relative "energy gain of 115.4%", highlighting the tracker's crucial role in boosting performance in non-ideal weather.

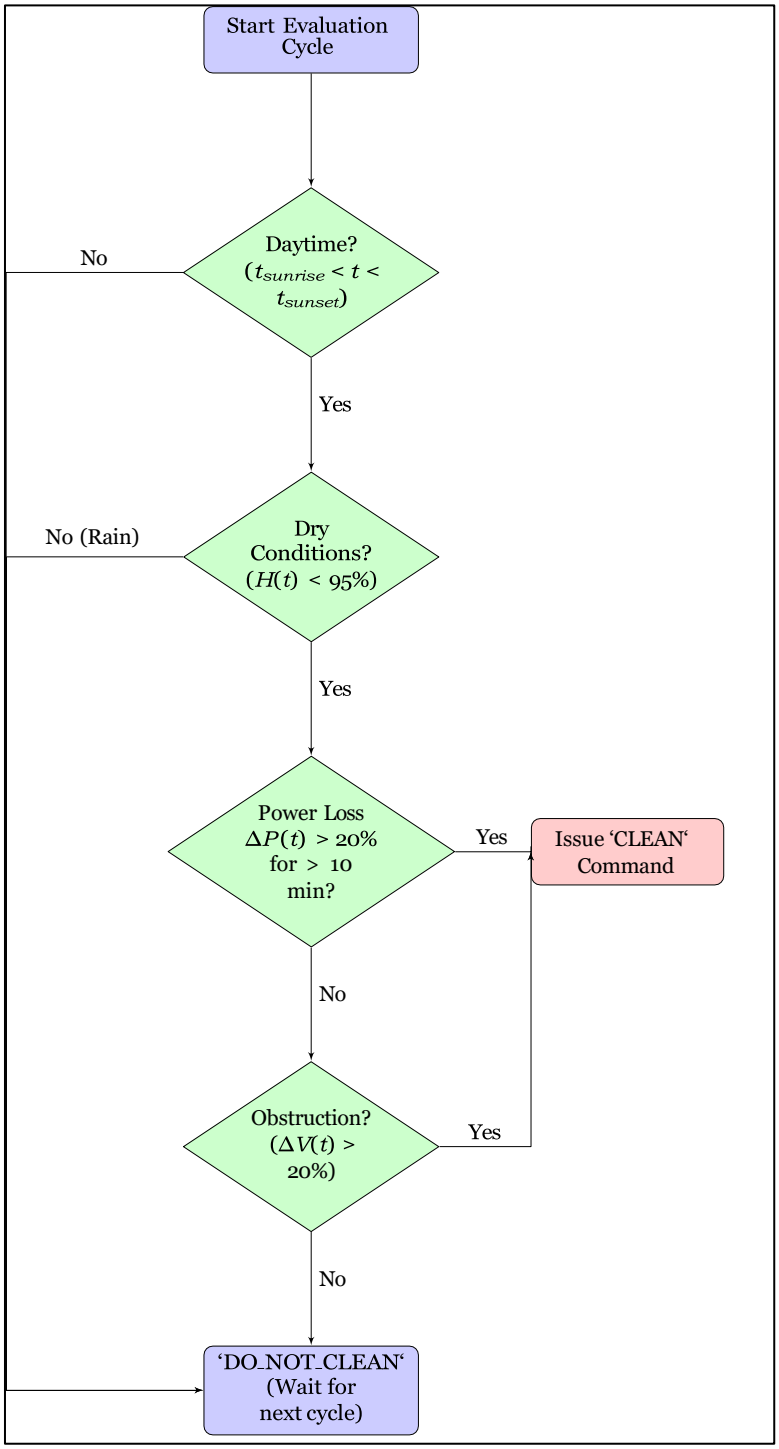


Figure 2 Flowchart of the hierarchical, rule-based decision-making algorithm for the cleaning robot

3.2. Effectiveness of the Smart Cleaning Algorithm

The cleaning algorithm was validated using the reference panel methodology. The system successfully demonstrated its intelligence by correctly inhibiting cleaning during a rain event (detected by humidity more than 95%), thus saving

energy and leveraging a natural cleaning process. On subsequent clear days, the system correctly identified when soiling caused the power loss to exceed the 20% threshold, triggering a cleaning cycle and restoring the panel's performance to its baseline. This event-driven approach ensures that the operational cost of cleaning is only incurred when the energy-yield benefit is guaranteed.

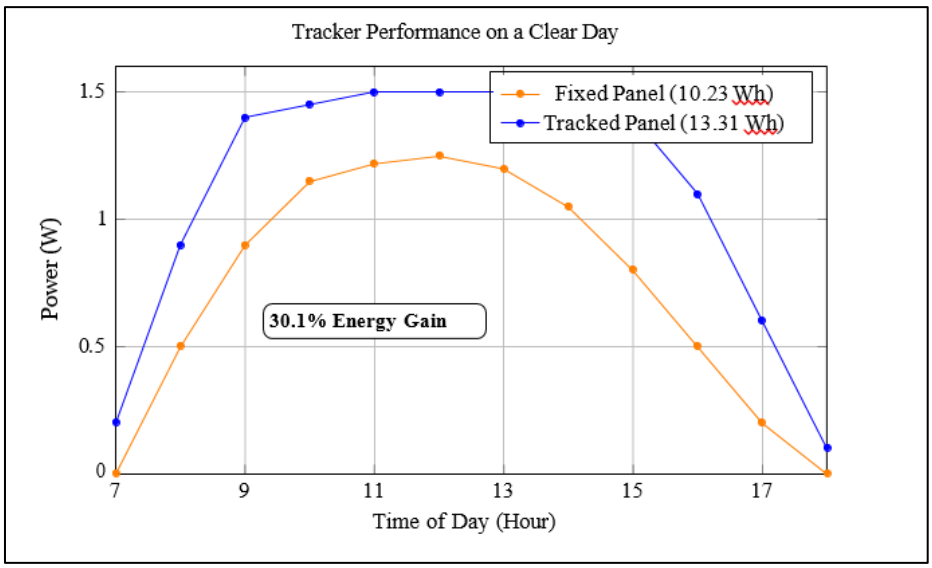


Figure 3 Power output comparison on a clear day. The tracked panel maintains peak power for a longer duration, resulting in a 30.1% increase in total energy generation

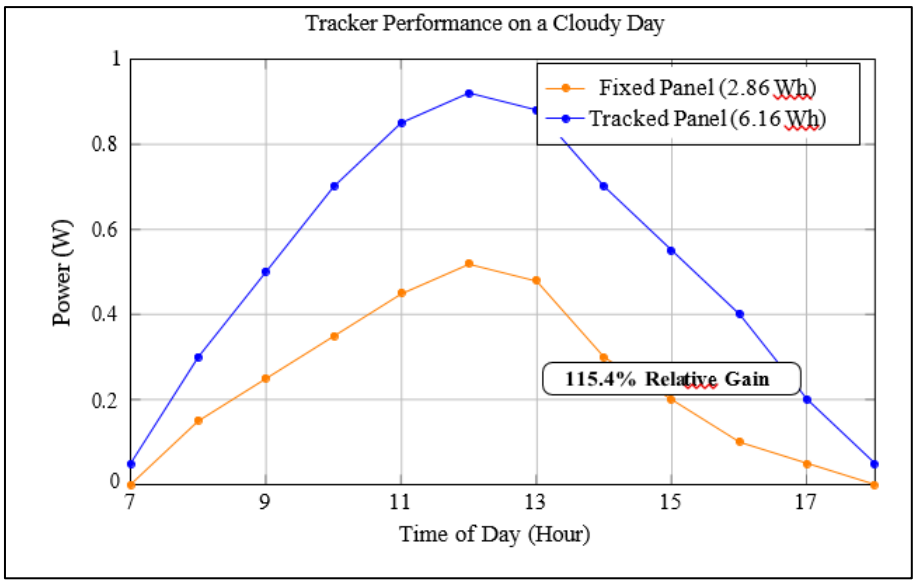


Figure 4 Power output comparison on a cloudy day. The tracker's ability to capture diffuse light results in a dramatic 115.4% relative increase in energy generation

3.3. Discussion of Integrated System Performance

The experimental results confirm the powerful synergy of the integrated platform. The solar tracker fundamentally increases the *potential* energy that can be harvested, while the smart cleaning robot ensures that this potential is consistently realized by maintaining the panel surface in an optimal state. The combined effect is a significant increase in the net energy yield compared to a standard, fixed-tilt, and schedule-cleaned system. The benefits are multiplicative: the percentage gain from cleaning is applied to the already higher baseline energy production provided by the tracker.

The rule-based approach for cleaning proved to be robust, reliable, and computationally efficient, making it suitable for implementation on low-cost microcontrollers. It provides a practical and accessible method for achieving intelligent maintenance without the complexity and data requirements of advanced

AI models. The main limitation of this study is the short-term nature of the data collection. A long- term, multi-season deployment would be required to quantify the precise annual energy gain and economic benefits.

4. Conclusion and Future Work

This paper has presented a holistic and intelligent framework for PV system optimization, successfully integrating dual-axis solar tracking with autonomous, rule based robotic cleaning. The system addresses the two primary sources of real-world performance loss suboptimal orientation and surface soiling within a single, cohesive platform. Experimental validation demonstrated that the solar tracker can increase daily energy capture by 30-115%, while the smart cleaning algorithm effectively mitigates soiling losses in a resource efficient manner. The combination of these technologies, governed by a data driven control engine, offers a practical and scalable solution to maximize the energy yield and economic viability of PV installations.

Future work will focus on deepening the integration between the system's components and enhancing its predictive capabilities. Key directions include:

- Long-Term Deployment and Site-Specific Calibration: A multi-season deployment is planned to build a comprehensive dataset. This data will be used to calibrate the rule thresholds (e.g., power loss percentage, humidity level) for the specific climatic and soiling conditions of the location.
- Predictive Control with Weather Integration: The system will be enhanced by integrating with weather forecasting APIs. This will enable predictive control logic, such as proactively cleaning
- "before" a predicted long stretch of sunny days or delaying cleaning if rain is imminent.
- Transition to Machine Learning Models: The rich dataset collected by the platform is an ideal foundation for training machine learning models. A Decision Tree or Random Forest model could be trained to learn the optimal decision boundaries, replacing the hard-coded rules with a more adaptive and self-optimizing control strategy [15].
- Economic Viability Analysis: A detailed economic analysis will be conducted, comparing the Levelized Cost of Energy (LCOE) of a system equipped with our platform against a conventional system. This will quantify the economic break-even point and return on investment.

These advancements will continue to drive the evolution of smart PV maintenance, contributing to a more efficient and reliable renewable energy infrastructure.

Compliance with ethical standards

Acknowledgments

The authors gratefully acknowledge the financial support for this research from Hanoi Open University under grant number MHN2024-03.44.

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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