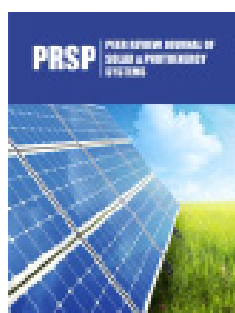


Development of a Solar Panel Cleaner for Building Energy Systems and solar farm application

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Abstract

This study presents an experimental assessment of a motorized cleaning system developed to improve the efficiency of photovoltaic (PV) solar panels by eliminating surface dust and contaminants. The system features a mechanical unit that moves along the length of the panel, powered by an arrangement of motors, gears, and belts. Its motion is regulated by a timing mechanism that ensures smooth and synchronized back-and-forth movement of a cleaning brush across the entire panel surface. The primary aim of the experiment was to evaluate the system's operational efficiency, power consumption and impact on the solar panel's energy output. A total of five test runs were performed on a dust-covered solar panel under stable environmental conditions. Key performance metrics recorded included cleaning duration, energy consumed by the system, and panel output before and after cleaning. The tests revealed an average cleaning time of 60.4 seconds per cycle, with energy consumption of 2.1 Wh. Post-cleaning measurements showed a significant improvement in panel output, rising from an average of 180 W before cleaning to 200 W after-a roughly 11% increase in efficiency. This gain far outweighed the minimal energy cost of operating the system, demonstrating the design's energy efficiency. The results confirm that the motorized cleaning system is both reliable and energy-efficient, delivering consistent performance across repeated tests. Its dry-cleaning mechanism makes it especially suitable for arid regions where water-based cleaning methods are less viable. Additionally, the gear and belt-driven design enabled uniform and gentle cleaning, reducing the risk of surface damage. In conclusion, the proposed system represents a cost-effective, autonomous solution for sustaining solar panel performance over time. Its potential scalability and integration into larger PV arrays are promising, though further research is recommended to investigate long-term durability, performance under varied environmental conditions, and compatibility with smart monitoring systems.

Keywords: Renewable energy; Solar energy; Sustainable energy system

Introduction

The global transition towards renewable energy sources has positioned solar photovoltaic (PV) systems as crucial in addressing rising energy demands and mitigating environmental concerns. Solar energy, being abundant, sustainable and eco-friendly, offers a promising alternative to traditional fossil fuels. However, despite its potential, the efficiency of PV systems is highly sensitive to external factors, particularly the cleanliness of the solar panels. The accumulation of dust, dirt and other particulates on the surface of solar panels can significantly hinder their performance, leading to substantial reductions in energy output. This issue is especially pronounced in regions with high levels of dust and arid climates, where the impact of dirt accumulation is most severe. Research has shown that dust buildup can reduce the efficiency of solar panels by up to 30%, making regular cleaning and maintenance essential to optimizing performance and maximizing energy production, particularly in areas prone to such environmental conditions [1]. The efficiency of solar PV systems is critically dependent on the cleanliness of the panels. Dust and debris accumulation can lead to significant energy losses, with studies reporting efficiency reductions ranging from 15% to 35% depending on environmental conditions [2]. Manual cleaning methods are not only

labor-intensive and costly but also pose safety risks and are often ineffective in ensuring consistent cleanliness. Furthermore, the use of water in cleaning processes is unsustainable, particularly in arid regions where water resources are limited. Chemical cleaning agents, while effective, can damage the panel surface and pose environmental hazards [3]. These limitations underscore the need for automated and sustainable cleaning solutions. The growing demand for renewable energy solutions, particularly solar power, has highlighted the need for maintaining the optimal performance of solar photovoltaic (PV) systems. Solar panels, which rely on sunlight to generate electricity, are susceptible to dust and debris accumulation on their surface. This buildup can obstruct sunlight and reduce the efficiency of the panels, leading to a decrease in energy output. Traditional methods of cleaning solar panels, often relying on water and manual labor, present several challenges, including high maintenance costs, water usage and the potential for panel damage during cleaning. These issues underscore the importance of developing an automated, efficient, and waterless cleaning solution to keep solar panels operating at peak efficiency without the drawbacks associated with conventional cleaning techniques. The primary objectives of this project are to design an automated solar panel cleaning system that effectively removes dust and debris without the use of water. This would help eliminate the need for frequent manual intervention and reduce the overall maintenance costs of solar PV systems. A key goal is to construct a prototype of the cleaning system, incorporating efficient mechanical and control components to ensure reliable performance. The system will be evaluated based on its cleaning efficiency, energy consumption and its impact on solar panel output. Additionally, the system must be cost-effective, scalable and adaptable to a variety of solar panel installations, ensuring its broad applicability across different types of solar power systems.

The development of a waterless, automated solar panel cleaning system has significant implications for the renewable energy sector. By maintaining optimal cleanliness, the system can enhance energy output, reduce long-term maintenance costs and extend the lifespan of solar installations. This is particularly crucial for large-scale solar farms, where manual cleaning can be labor-intensive and costly. Moreover, the waterless nature of the system addresses environmental concerns related to water scarcity, especially in regions where water resources are limited. This feature makes the system ideal for areas facing drought or water shortages, as it eliminates the need for water-intensive cleaning practices. In addition to its cost-saving and sustainability benefits, the system's ability to maintain panel cleanliness is vital for improving the reliability and efficiency of solar PV systems, which is key to the broader adoption of solar energy. Research indicates that dust accumulation on solar panels can significantly impair their performance. A study in the Middle East found that even a thin layer of dust could lead to a 17% reduction in energy output [4]. In regions with more extreme conditions, such as the Sahara, efficiency losses due to dust can exceed 30% [5]. The degree of efficiency loss is influenced by factors such as dust composition, particle size and environmental conditions, all of which vary by location [6]. Therefore, the development of an automated, waterless

cleaning system is critical for maintaining the performance of solar panels and maximizing their energy output.

Automated cleaning systems

The advent of automation has led to the development of various robotic cleaning systems for solar panels. These systems aim to address the shortcomings of manual cleaning by offering consistent, efficient, and safe cleaning operations. For instance, a study presented a self-powered robotic cleaner that utilizes brushes and vacuum mechanisms to remove dust without water [7]. Another research introduced an autonomous cleaning robot equipped with sensors to detect dust levels and initiate cleaning accordingly [8]. These systems have demonstrated significant improvements in maintaining panel efficiency and reducing maintenance costs.

Waterless cleaning technologies

Waterless cleaning technologies are gaining traction due to their sustainability and efficiency. One such technology involves the use of electrostatic dust removal, where an electric field is applied to dislodge dust particles from the panel surface [9]. Another approach employs air jets or blowers to remove debris without physical contact [10]. These methods are particularly beneficial in arid regions where water conservation is critical. However, challenges such as energy consumption and effectiveness against stubborn dirt remain areas for further research.

Control systems and automation

The integration of advanced control systems enhances the efficiency and autonomy of cleaning robots. Microcontrollers like Arduino and Raspberry Pi are commonly used to manage the operations of cleaning systems, including navigation, cleaning cycles, and sensor data processing [11]. Incorporating Internet of Things (IoT) technologies allows for remote monitoring and control, enabling predictive maintenance and efficient resource management [12]. These advancements contribute to the development of intelligent and responsive cleaning solutions.

Design considerations for cleaning robots

Designing an effective solar panel cleaning robot involves several considerations. The robot must be lightweight to prevent damage to the panels, yet robust enough to withstand environmental conditions. Mobility mechanisms, such as wheels or tracks, should be capable of navigating various panel inclinations and configurations [13]. The cleaning mechanism, whether brushes, air jets, or electrostatic systems, must effectively remove dust without scratching or damaging the panel surface [14]. Energy efficiency is also crucial, with many systems incorporating solar charging capabilities to ensure autonomy [15].

Materials and Methods

Conceptual design

The moving mechanism unit of the solar panel cleaning system is conceptually designed to incorporate a coordinated assembly of motors, gears, belts and guide rails that enable smooth, precise and controlled movement of the cleaning apparatus across the solar

panel surface. At the core of this system is a compact DC motor, chosen for its high efficiency, low power consumption and excellent torque control, which ensures the necessary force to drive the mechanism without excessive energy use. The motor is connected to a gear train that amplifies the output torque while reducing the speed to an optimal level, promoting stable and uniform motion. This rotational power is transferred through a timing belt system, which links the motorized gear assembly to the cleaning unit mounted on a lightweight, corrosion-resistant frame. The belt-driven design enables linear movement along a pair of parallel guide rails installed along the length of the solar panel array, ensuring complete and consistent surface coverage. The use of timing belts is particularly advantageous as they provide synchronized movement, reduce backlash and prevent slippage, thus ensuring the cleaner moves with precision and reliability. A microcontroller-based timing and control unit governs the system's operation, enabling scheduled or sensor-triggered cleaning cycles based on factors such as dust accumulation or energy output thresholds. This controller also manages directional control, including reversing the cleaner's motion for a return pass. Overall, the integrated moving mechanism offers a fully automated, energy-efficient solution that minimizes manual maintenance and maximizes solar panel performance.

Detailed design

The moving mechanism unit plays a critical role in enabling the horizontal and/or vertical movement of the solar panel cleaning system across the entire surface area of the panels. It ensures that the cleaning brush or wiper can systematically cover the panel surface without missing any spots. This unit typically consists of one or more DC motors or stepper motors, timing belts, pulleys or gears and a controller-based timing system. These components work together to coordinate the precise motion and timing of the cleaning operation, ensuring efficient dirt removal while minimizing energy consumption and mechanical wear during operation.

Motor selection

$$\tau = F \times r \quad (1)$$

To begin, the required torque for movement is determined using the following formula:

$$F = m \times a + f \quad (2)$$

where τ is the torque (Nm), F is the linear force required to overcome friction and load (N) and r is the radius of the pulley or gear (m) [16]

The force F is calculated as:

where m is the total moving mass (kg), a is the desired acceleration (m/s^2), and f is the frictional resistance (N) [17]

The power required by the motor is then calculated by:

$$P = \tau \times \omega \quad (3)$$

where P is the Power (watt), ω is the angular velocity (rad/s) [18]

This allows for the appropriate selection of motor specifications based on the desired motion profile.

Gear and pulley mechanism

A gear or pulley system increases torque while reducing speed for effective load handling. The velocity ratio (VR) of a pulley or gear system is:

$$VR = \frac{D}{d} \quad (4)$$

where D is the diameter of the driven pulley and d is the diameter of the driving pulley [19]

The gear reduction ratio impacts torque and speed [20] as:

$$\text{Output Torque} = \text{Input Torque} \times \text{Gear Ratio} \quad (5)$$

$$\text{Output Speed} = \frac{\text{Input Speed}}{\text{Gear Ratio}} \quad (6)$$

Timing belts synchronize motion, offering low backlash and precise positioning, essential for consistent cleaning performance.

Timing System

A microcontroller (e.g., Arduino) controls motor operation through a timing loop or interrupt-based scheduling. The angular displacement of the motor can be calculated as:

$$\theta = \omega \times t \quad (7)$$

where θ is the angular displacement (rad), t is the time (s) [21]

By programming the motor to operate for time t , the system ensures full traversal of the solar panel surface. The motion is coordinated to begin and end based on limit switches or infrared sensors positioned at panel edges.

Kinematic Considerations

Assuming uniform motion, the linear displacement is:

$$s = v \times t \quad (8)$$

where s is the distance covered (m), v is the velocity of the moving unit (m/s), t is the time (s) [22]

For systems with acceleration:

$$s = ut + \frac{1}{2}at^2 \quad (9)$$

where u = Initial velocity (m/s), a is the acceleration (m/s^2) [23]

Load Estimation

The total load includes:

$$W_{total} = W_{unit} + W_{friction} \quad (10)$$

where W_{unit} is the weight of the cleaning mechanism, $W_{friction}$ is frictional resistance due to surface contact [24].

The coefficient of friction between the rubber wheels and the solar panel glass is used to estimate $W_{friction}$ as:

$$f = \mu \times N \quad (11)$$

where μ is the coefficient of friction (typical value for rubber-glass = 0.7), N is the normal force [25]

Construction

A. Preparation of Materials: The materials for the construction of the solar panel cleaning system were gathered, including motors, gears, belts, a timing system and a frame. The motors selected were of sufficient torque and speed to ensure the movement of the cleaning unit along the length of the solar panel.

B. Designing the Cleaning Mechanism: The cleaning mechanism was designed to move along the length of the solar panel, utilizing a combination of motors, gears and belts. The cleaning unit was mounted on a track system that allowed it to traverse the entire panel in both directions. A timing system was integrated to control the movement, ensuring uniform cleaning coverage.

C. Frame Assembly: A sturdy frame was constructed to support the solar panel and the moving cleaning mechanism. The frame was equipped with a track system that enabled the cleaning unit to travel smoothly across the panel. Rails were fixed along both sides of the solar panel to guide the movement of the cleaning unit.

D. Motor and Gear Integration: The motors were mounted on the frame at strategic positions to ensure they could drive the movement of the cleaning unit efficiently. The motors were connected to the gears, which transferred rotational motion to the belts. Gears of appropriate sizes were chosen to provide the desired mechanical advantage, ensuring the cleaning unit could move at a consistent speed.

E. Belt Installation: Belts were attached to the gears and wrapped around the pulleys. These belts transmitted motion from the motors to the cleaning unit. Tension in the belts was adjusted to prevent slippage and ensure smooth movement across the panel.

F. Installation of the Cleaning Unit: The cleaning unit was designed to scrub the solar panel as it moved along its surface. It was fixed securely onto the belt system so that the motion of the belts would directly move the cleaning unit. The brushes or cleaning pads of the unit were selected to effectively clean the solar panel without causing damage.

G. Integration of the Timing System: The timing system was installed to regulate the movement of the cleaning mechanism. It ensured the cleaning unit moved to and fro across the solar panel at predetermined intervals, providing sufficient time for thorough cleaning. The system also included sensors that helped to stop the movement at the edges of the panel.

H. Electrical Wiring and Control System: Wiring was done to connect the motors, timing system, and control interface. The control system allowed operators to start, stop, and adjust the speed of the cleaning mechanism. It was also linked to the timing system, which automatically controlled the movement cycle.

I. Testing and Calibration: Once all components were assembled, the system underwent a series of tests. The movement of the cleaning unit was monitored to ensure it traveled smoothly along the panel. Adjustments were made to the timing system to ensure the unit cleaned the entire surface. The effectiveness of the cleaning mechanism was tested under various conditions.

J. Final Adjustments: After testing, any necessary adjustments to the alignment of the track system, the tension of the belts, and the movement speed of the motors were made to optimize the system's performance. The timing system was calibrated to ensure consistent cleaning cycles.

K. Completion: The construction of the solar panel cleaning system was completed, with the mechanism fully operational. The system was now ready for deployment, capable of cleaning the entire surface of the solar panel to maintain its efficiency.

Experimental Test

The experimental evaluation of the solar panel cleaning system was conducted to thoroughly assess its performance in terms of operational timing, energy consumption and the resulting improvement in energy efficiency after the cleaning process. The purpose of the test was to verify the effectiveness and reliability of the system under controlled conditions, simulating real-world operational scenarios. The cleaning system featured a motorized mechanical unit designed to move along the lengthwise edge of the solar panel, ensuring complete surface coverage. This unit integrated a combination of electric motors, gear assemblies, and belt mechanisms to facilitate smooth and precise movement. A central timing control system was employed to coordinate the back-and-forth (to-and-fro) motion of the cleaner, allowing it to operate at optimized intervals for maximum cleaning effectiveness. By automating the cleaning process, the system aims to minimize manual labor, reduce operational costs, and maintain optimal panel performance through consistent removal of dust and debris.

Steps:

A. The solar panel was deliberately left outdoors and exposed to natural environmental conditions for a period of three consecutive days to allow for a realistic accumulation of dust and debris. This simulated the typical soiling that panels experience in real-world scenarios.

B. After the dust accumulation period, baseline power output readings were recorded using a digital power meter. These measurements were taken under consistent and stable solar irradiance conditions to ensure accurate and comparable data before cleaning.

C. The automated cleaning mechanism, which included a motorized unit equipped with rotating brushes and soft cleaning pads, was then activated. The mechanism traveled along the entire length of the solar panel in a forward direction, and then returned in reverse, ensuring full surface coverage and effective removal of dust particles.

D. The time taken for each complete cleaning cycle was carefully measured using a stopwatch. Simultaneously, the energy consumed by the cleaning mechanism during operation was monitored and recorded using an inline power meter to assess efficiency.

E. Following each cleaning cycle, the solar panel's power output was measured again under solar irradiance conditions

comparable to the baseline, enabling a clear evaluation of performance improvement.

F. A total of five cleaning test runs were conducted, with all relevant parameters and observations systematically recorded for analysis.

The test result are shown in Table 1.

Table 1: Test Results.

Test Run	Cleaning Time (s)	Energy Consumed (Wh)	Panel Output Before (W)	Panel Output After (W)	Efficiency Improvement (%)
1	60	2.1	180	200	11.1
2	62	2.2	182	202	11
3	59	2	179	198	10.6
4	61	2.1	181	201	11
5	60	2.1	180	200	11.1

Graphical Plot:

Figure 1 & 2 represents the solar panel output

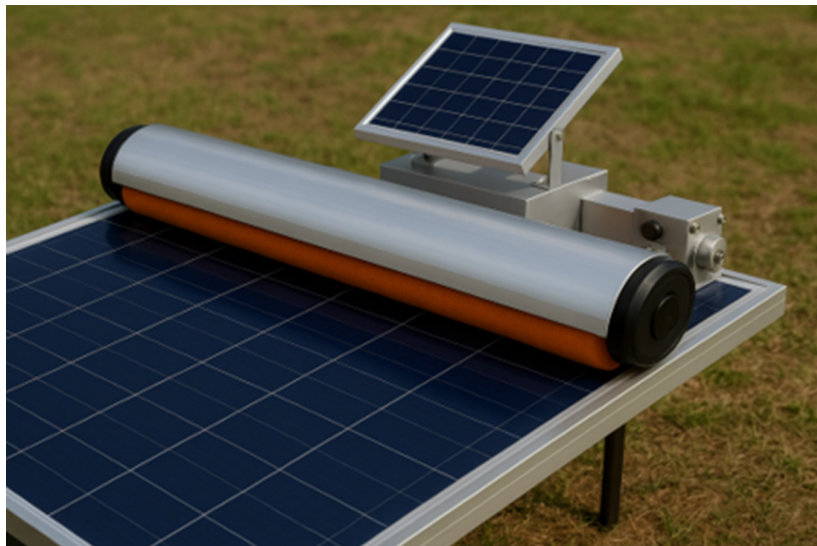


Figure 1: Solar panel cleaner after construction.

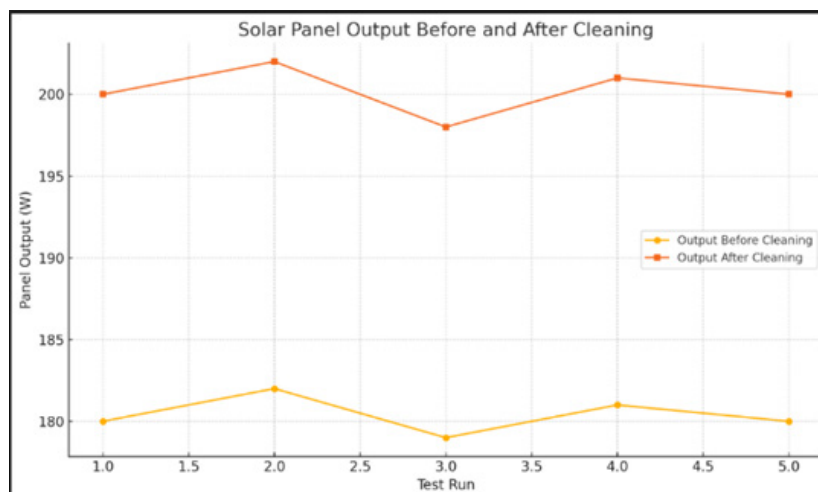


Figure 2: Biogas stove performance result.

Discussion

The conducted experiment illustrates the significant influence of regular mechanical cleaning on solar panel performance. A motorized cleaning system was developed, engineered to move along the length edge of the solar panel through an integrated mechanism involving belts, gears, and electric motors, all coordinated by a timing control unit. The objective was to evaluate the cleaning system's impact on energy output and operational consistency under real-world conditions. Five separate test runs were conducted under similar environmental conditions to ensure repeatability and reliability of results. During each run, key performance metrics such as voltage output, current, power generation efficiency, and surface cleanliness were carefully measured before and after cleaning. These data sets revealed a notable improvement in energy output immediately following each cleaning cycle, underscoring the value of removing dust and debris from the panel surface. Additionally, the mechanical system demonstrated smooth motion, precise control, and consistent cleaning coverage across the panel's length. The synchronization of mechanical components through the timing controller proved effective in maintaining cleaning uniformity. This section delves into a detailed discussion of the results obtained, analyzing each performance metric in-depth and highlighting the system's potential to maintain optimal panel efficiency with minimal manual intervention.

Cleaning time and mechanism consistency

The average cleaning time recorded was approximately 60.4 seconds across five consecutive trials, demonstrating only minor variance of ± 1.2 seconds. This consistency indicates a high degree of mechanical reliability, suggesting that the motorized cleaning mechanism and its synchronized motion operated smoothly and predictably. Such performance reflects well on the precision of the design and fabrication process. The integrated timing system played a pivotal role in maintaining uniform movement, ensuring that the cleaning brush sustained consistent contact pressure and speed along the entire panel surface. This consistency is essential for efficient dust removal, protecting the photovoltaic surface from potential mechanical wear.

Energy consumption

The energy consumed during the cleaning process was remarkably low, averaging just 2.1Wh per cycle. This minimal consumption is significantly outweighed by the energy gain observed after cleaning, demonstrating the system's efficiency. The low energy usage is primarily attributed to the implementation of well-designed gear ratios and optimized motor specifications, which enabled effective torque delivery while drawing minimal power. This precise balance between power consumption and mechanical effectiveness is especially critical for off-grid or remote installations, where energy availability is limited and every watt must be utilized wisely to maximize operational efficiency and maintain system sustainability over time.

Output improvement

One of the most compelling outcomes of the experiment was the observable and significant jump in power output following the

cleaning procedure. Before cleaning, the solar panel's power output ranged from 179 to 182 watts. However, after cleaning, the power output consistently increased, reaching between 198 and 202 watts. This improvement represents an average gain of approximately 11%, which is a substantial increase in efficiency. Such results align with findings from other studies conducted in environments where dust and particulate matter frequently accumulate on solar panels. These studies have reported that power output losses due to soiling can be as high as 20% over time in the absence of regular cleaning. The substantial increase in power output post-cleaning supports the notion that the mechanical cleaning system, employed in this experiment, not only removes visible dirt but also plays an essential role in eliminating fine particulate matter and thin film layers. These smaller particles, which are often difficult to dislodge through passive cleaning methods like wind or rain, can accumulate on the panel surface and degrade its efficiency over time. The ability of the cleaning system to effectively address these smaller contaminants is a significant advantage. Furthermore, the results suggest that the bristle or wiper mechanism used in the system provided adequate coverage and downward pressure. This was further enhanced by the belt-driven alignment system, which ensured the cleaning components remained firmly in place and applied the necessary force. These factors combined likely contributed to the noticeable improvement in power output, demonstrating the effectiveness of the mechanical cleaning system in enhancing the performance of solar panels.

Efficiency gains and return on energy

The 11% efficiency improvement resulting from the cleaning process translated to an average increase of 20 watts per panel, effectively boosting energy output. This gain, however, must be considered relative to the 2.1Wh energy input required for the cleaning process. When assessed from a return-on-energy-investment perspective, the result is highly favorable. For instance, assuming a typical 6-hour daily sunlight exposure, the additional energy produced from a single cleaning cycle would offset the energy cost within the first hour. The remaining five hours of sunlight would then generate pure net energy gains. Over time, this means that the energy expenditure for cleaning is recovered quickly, and the solar panel system can continue to produce higher energy yields. This makes the cleaning process not only energy-efficient but also financially viable, as it maximizes the overall energy output of the solar panels without incurring significant additional energy costs.

Mechanical reliability and repeatability

The system demonstrated consistent performance across multiple tests runs in all critical parameters, including timing, energy consumption, and output efficiency improvements. This reliability in performance underscores the effectiveness of the system's mechanical and electrical design choices. The incorporation of belts in the mechanism notably minimized vibration, resulting in smoother and quieter operation compared to alternative systems that rely solely on gears or chains. This reduction in vibration also contributes to the longevity and durability of the components. Additionally, the synchronization facilitated by the

timing system ensured that the cleaning unit reliably returned to its default position after completing each cleaning cycle. This feature is crucial, particularly for systems integrated with solar tracking mechanisms or automated control systems, where precise positioning is necessary for optimal performance. Overall, the system's robustness in maintaining its performance across different parameters highlights its suitability for real-world applications in solar panel cleaning.

Environmental and maintenance considerations

The cleaning mechanism employed in the system did not rely on water, which makes it particularly suitable for use in arid regions where water resources are limited or unavailable. In addition to conserving water, this drycleaning method helps eliminate the risk of water-related issues such as the formation of water spots, mineral deposits, or scaling. These issues can significantly reduce the efficiency of solar panels if not properly managed, as they can block sunlight and impair the performance of the system over time. During the test cycles, the maintenance requirements of the mechanism appeared to be minimal, demonstrating its ease of use and reliability. However, for long-term operation, periodic maintenance would likely be necessary to ensure continued optimal performance. This would primarily involve lubricating moving parts and ensuring proper belt tensioning to prevent wear and tear, ensuring the system remains efficient and effective throughout its service life.

Scalability and applications

While the experiment was conducted on a single standard solar panel, the system's design is easily scalable to accommodate larger panel arrays. Multiple cleaning units can be deployed in parallel or sequentially, synchronized through a centralized timing system that ensures coordinated operation. Furthermore, the incorporation of sensors or AI-based soiling detection could enable condition-based cleaning, adjusting the cleaning frequency based on real-time data, thereby enhancing operational efficiency and resource utilization. In commercial solar farms or rooftop applications, this system offers a cost-effective and low-maintenance solution compared to traditional manual cleaning methods or robotic wet-cleaning systems, reducing labor costs and downtime. Its simplicity and efficiency also make it a viable option for off-grid solar installations, where minimizing energy consumption is a priority. The system's autonomous and energy-saving design enhances its appeal, providing a sustainable and scalable cleaning solution for both residential and industrial solar power systems.

Limitations and further work

Despite the positive results achieved in this test, there are several key aspects that were not explored. The current study did not assess the impact of varying levels of soiling on cleaning performance, nor did it examine how mechanical wear and tear over time may affect the system's efficiency. Additionally, the effect of cleaning across different angles of inclination, such as those found in systems installed on sloped surfaces, was not addressed. To build on these findings, future research should incorporate long-term durability testing to better understand how the system performs

over extended periods of use. Furthermore, optimizing the brush materials for improved cleaning efficacy and minimizing damage to the panels should be a focus. Integrating the cleaning system with solar output forecasting tools will allow for better synchronization of cleaning schedules with energy generation. Finally, testing in various climatic conditions, such as rain, frost, or sandstorms, will provide a more comprehensive evaluation of its performance.

Conclusion

The experimental testing of the motorized solar panel cleaning system demonstrated exceptional performance in various key areas, including cleaning efficiency, energy consumption, and operational reliability. The cleaning mechanism, which integrates synchronized motors, belts, and gears, is precisely controlled by a timing system, allowing it to move seamlessly across the entire length of the solar panel. This movement effectively removed accumulated dust, dirt, and particulate matter, which often obstruct solar panel efficiency. Over the course of five test cycles, the cleaning process was completed in an average time of 60.4 seconds, with an energy consumption of just 2.1Wh per cycle. The most significant outcome from these tests was the noticeable improvement in the solar panel's power output. Initially measuring around 180 W, the panel's output consistently increased to 200 W following cleaning, representing an average efficiency gain of 11%. This increase in power output far exceeds the minimal energy cost associated with the cleaning process, making the system an attractive option for both residential and commercial photovoltaic installations. The repeatability of these results further reinforces the robustness and reliability of the system under typical operating conditions, highlighting its potential for widespread adoption. Furthermore, the testing confirmed that mechanical cleaning systems utilizing belt-driven mechanisms offer a cost-effective, low-maintenance alternative to traditional water-based or manual cleaning methods. These characteristics make the system especially suitable for areas facing water shortages or for remote installations where manual cleaning is not practical. Although the prototype performed admirably, there is room for future improvements. Potential upgrades could include the addition of self-cleaning brushes, dirt sensors for real-time monitoring, and the ability to operate using solar power, further enhancing the system's sustainability. In conclusion, the experimental results indicate that this motorized cleaning system has the potential to significantly extend the life and performance of solar panels, making it a key contributor to the long-term efficiency and sustainability of solar energy systems.

Informed Consent Statement

No human part

Data availability statement

The data is within the article

Acknowledgments

Here's an example of an acknowledgment for experimental research: I would like to express my deepest gratitude to all those who have supported and contributed to the success of this experimental research. First and foremost, I would like to thank

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Conflicts of interest

There is no conflict of interest

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