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Research Article

Design and Construction of Solar Panel Cleaner

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Abstract: This study presents an experimental evaluation of a motorized cleaning system designed to enhance the efficiency of Photovoltaic (PV) solar panels by removing surface dust and contaminants. The system comprises a mechanical unit that traverses the panel's length, driven by a coordinated arrangement of motors, gears, and belts. Its operation is controlled by a timing mechanism that ensures synchronized back-and-forth motion of a dry-cleaning brush. The primary objective is to assess the system's effectiveness in improving panel output, energy efficiency, and operational reliability. Five experimental runs were conducted on a dust-covered solar panel under stable environmental conditions. Key performance indicators included cleaning duration, energy consumed by the system, and solar output before and after cleaning. Results show an average cleaning time of 60.4 seconds per cycle and an energy consumption of 2.1 Wh. The panel's power output increased from an average of 180 W before cleaning to 200 W after cleaning, marking an approximate 11% efficiency gain. This improvement significantly exceeded the operational energy cost, confirming the system's high energy efficiency. The gear- and belt-driven mechanism enabled consistent and uniform brush movement, ensuring effective cleaning while minimizing the risk of surface abrasion. Its dry-cleaning approach makes it particularly suitable for arid regions where water use is limited or impractical. The system demonstrated reliable and repeatable performance across all test runs. In conclusion, the motorized cleaning system offers a practical and energy-efficient solution for maintaining solar panel performance. It is cost-effective, autonomous, and well-suited for integration into larger PV installations. Further research is recommended to evaluate its long-term durability, adaptability to different panel configurations, and potential integration with smart monitoring and control technologies.

***Keywords*:** PV panels, solar panel cleaning, motorized cleaning system, energy efficiency, dust removal, gear and belt mechanism, dry cleaning technology, autonomous maintenance system

1. 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

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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.

1.1 *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.

1.2 *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.

1.3 *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 [10]. Incorporating Internet of Things (IoT) technologies allows for remote monitoring and control, enabling predictive maintenance and efficient resource management [11]. These advancements contribute to the development of intelligent and responsive cleaning solutions.

1.4 *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 [12]. The cleaning mechanism, whether brushes, air jets, or electrostatic systems, must effectively remove dust without scratching or damaging the panel surface [13]. Energy efficiency is also crucial, with many systems incorporating solar charging capabilities to ensure autonomy [14].

1.5 *Progress of electrostatic dust removal over water-based cleaning*

i. Water-Free Operation:

One of the primary advantages of Electrostatic Dust Removal (ESDR) is its ability to clean surfaces without the use of water, making it highly suitable for desert regions where water is scarce. Traditional water-based cleaning requires substantial water resources, logistics, and frequent cleaning cycles due to high dust accumulation rates [15].

ii. Non-Contact and Surface-Safe Mechanism:

Electrostatic systems use electric fields to repel or remove dust without any physical contact, reducing the risk of micro-scratches or long-term surface degradation associated with brushes or wipers in water-based systems [16]. This preserves the anti-reflective coating of solar panels and extends their operational lifespan.

iii. Automation and Integration:

Recent developments in ESDR have allowed for the integration of automated cleaning systems that operate at pre-set intervals, minimizing the need for human intervention [17]. ESDR systems can be embedded within the panel infrastructure or added as modular systems controlled via smart energy management platforms.

iv. Improved Dust Removal Efficiency:

With optimized electrode design and high-voltage alternating electric fields, ESDR systems have demonstrated dust removal efficiencies above 90% in lab and field trials, rivaling that of water-based methods [18].

1.6 *Practical challenges in electrostatic dust removal*

Despite the progress, several challenges hinder the widespread adoption of ESDR:

i. Energy Consumption:

While ESDR is water-efficient, it consumes electrical energy for high-voltage generation, which can impact the overall energy balance of Photovoltaic (PV) systems. Developing low-energy ESDR mechanisms remains a key focus [15].

ii. System Complexity and Cost:

The initial capital cost of ESDR systems is higher due to the need for high-voltage electronics, sensors, and sometimes custom panel modifications. This complexity can deter adoption in low-budget or small-scale PV farms [19].

iii. Environmental and Operational Constraints:

The effectiveness of ESDR is influenced by environmental conditions such as humidity, particle size, and electrostatic adhesion strength. In regions with high humidity, dust particles tend to stick more firmly, reducing the efficiency of electrostatic forces [20].

iv. Long-Term Durability:

The performance reliability of ESDR systems over long operational periods is still under evaluation. Concerns include degradation of electrodes, dielectric breakdown, and electrical insulation failures [21].

v. Limited Field Trials:

Although laboratory results are promising, there is a lack of extensive field validation under diverse environmental conditions. More pilot projects and long-term performance data are necessary to benchmark against conventional cleaning methods [22].

Electrostatic dust removal has emerged as a sustainable and technologically advanced alternative to water-based solar panel cleaning, particularly advantageous in water-scarce regions. However, energy consumption, high upfront cost, and sensitivity to environmental variables remain critical challenges. Further innovation in low-power systems, materials durability, and large-scale field testing will determine its viability for widespread deployment.

2. Materials and methods

2.1 *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 Direct Current (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.

The waterless cleaning mechanism utilizes a motorized dry-brush system integrated with a gear-and-belt-driven carriage that travels along the panel's length. The core cleaning unit consists of soft, anti-static nylon bristles mounted on a horizontal rotating shaft, powered by a low-RPM, high-torque DC gear motor. This rotating brush gently dislodges dust, bird droppings, and other particulates without scratching the panel surface.

The entire mechanism is mounted on a lightweight aluminum frame, which moves linearly along rails or guided tracks installed on the panel edges. Movement is achieved via a timing belt and pulley system, driven by a secondary stepper or DC motor, ensuring synchronized and uniform travel of the cleaning unit. The dry-brushing system is supported by adjustable tensioners to maintain optimal bristle contact pressure, minimizing wear on both the cleaner and the solar panel. A microcontroller-based timing circuit controls cleaning intervals, ensuring operation during low solar insolation periods to avoid thermal shock and shadowing losses.

2.2 *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.

2.2.1 *Motor selection*

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

$$\tau = F \times r, \tag{1}$$

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) [21].

The force F is calculated as:

$$F = m \times a + f, \tag{2}$$

where m is the total moving mass (kg), a is the desired acceleration (m/s^2), and f is the frictional resistance (N) [22].

The power required by the motor is then calculated by:

$$P = \tau \times \omega, \tag{3}$$

where P is the Power (watts) and ω is the angular velocity (rad/s) [23].

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

2.2.2 *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:

$$\text{VR} = \frac{D}{d}, \tag{4}$$

where D is the diameter of the driven pulley, and d is the diameter of the driving pulley [24].

The gear reduction ratio impacts torque and speed [25] as:

$$\text{Output Torque} = \text{Input Torque} \times \text{Gear Ratio}, \tag{5}$$

$$\text{Output Speed} = \frac{\text{Input Speed}}{\text{Gear Ratio}}, \tag{6}$$

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

2.2.3 *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:

$$\theta = \omega \times t, \tag{7}$$

where θ is the angular displacement (rad), and t is the time (s) [26].

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.

2.2.4 *Kinematic considerations*

Assuming uniform motion, the linear displacement is:

$$s = v \times t, \tag{8}$$

where s is the distance covered (m), v is the velocity of the moving unit (m/s), and t is the time (s) [27].

For systems with acceleration:

$$s = ut + \frac{1}{2}at^2, \tag{9}$$

where u = Initial velocity (m/s) and a is the acceleration (m/s^2) [28].

2.2.5 *Load estimation*

The total load includes:

$$W_{\text{total}} = W_{\text{unit}} + W_{\text{friction}}, \tag{10}$$

where W_{unit} is the weight of the cleaning mechanism and W_{friction} is frictional resistance due to surface contact [29].

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

$$f = \mu \times Nf, \tag{11}$$

where μ is the coefficient of friction (typical value for rubber-glass = 0.7) and N is the normal force $N = m \times g$ [30].

2.3 *Construction*

The construction procedure is stated as:

i. Preparation of Materials:

The materials for the construction of the solar panel cleaning system were gathered, including motors, gears, belts, a timing system, a frame, and a mini solar panel. The mini solar panel was chosen as a renewable power source to supply electrical energy to the system, making it autonomous and environmentally friendly. The motors selected were Direct Current (DC) gear motors with appropriate torque (≥ 5 kg·cm) and moderate speed (≈ 30-60 RPM) to ensure the smooth and steady movement of the cleaning unit along the length of the solar panel.

ii. Designing the Cleaning Mechanism:

The cleaning mechanism was designed to move longitudinally along the solar panel, utilizing a combination of motors, gears, and belts. It was mounted on a track system that allowed traversal in both directions. A timing system was integrated to ensure that the cleaning unit covered the full surface uniformly and efficiently.

iii. Frame Assembly:

A sturdy frame was constructed using lightweight metal (e.g., aluminum or stainless steel) to support the solar panel and the mobile cleaning mechanism. Rails were installed along both longitudinal sides of the solar panel to guide the movement of the cleaning unit and ensure stable operation.

iv. Motor and Gear Integration:

DC gear motors were mounted strategically on the frame to drive the motion of the cleaning unit. The motors were coupled with spur gears that transferred rotational motion to the drive belts. Gear ratios were selected to provide the required torque-speed balance, enabling consistent traversal across the panel surface.

v. Belt Installation:

Belts were attached to the gear system and routed around pulleys mounted on both ends of the track. These belts transmitted the rotational energy from the motors to the cleaning unit. Proper tensioning was performed to avoid slippage and ensure precise linear motion.

vi. Installation of the Cleaning Unit:

The cleaning unit, consisting of soft rotating brushes or microfiber pads, was mounted securely on the belt system. This unit was designed to apply sufficient contact force to dislodge dirt without scratching the solar panel surface. The movement of the belts facilitated the translation of the cleaning unit across the panel.

vii. Integration of the Timing System:

A timing control system, including a microcontroller and edge sensors, was incorporated to regulate the movement of the cleaning mechanism. The system ensured bi-directional movement at set time intervals, and edge detection sensors halted the motion at either end of the panel to prevent overrun.

viii. Electrical Wiring and Control System:

Wiring was completed to connect the DC motors, sensors, timing system, and control interface. The entire system was powered by the mini solar panel, which charged a small rechargeable battery (e.g., 12 V, 5 Ah) to store energy for continuous operation. A charge controller was included to manage energy flow between the solar panel, battery, and load. The control interface allowed manual or automated activation and speed adjustment of the cleaning cycle.

ix. Integration and Mounting of the Mini Solar Panel:

A mini Photovoltaic (PV) solar panel (e.g., 20 W-50 W) was mounted on the side or above the frame structure, oriented to maximize sunlight exposure. The panel was fixed using an adjustable bracket to allow tilt angle modifications based on location and season. It provided sustainable energy to the system, reducing reliance on external power sources and increasing portability and efficiency.

x. Effect of Temperature:

The effect of temperature on system performance and durability is carefully addressed through the selection of heat-resistant materials and appropriate mechanical design. Since solar panels operate under direct sunlight, the cleaner's components—such as the frame, motor housing, and belts—are constructed using aluminum and thermally stable polymers that withstand high surface temperatures without deformation. Furthermore, lubrication and motor cooling provisions are incorporated to prevent overheating, ensuring long-term functionality. The system is designed to avoid excessive friction, which could generate additional heat and reduce component lifespan. Temperature-resilient electronic controls are also used to ensure stable operation in hot climates. By anticipating and mitigating thermal stress, the design enhances both performance efficiency and system durability, making the solar panel cleaner suitable for long-term outdoor deployment in a range of environmental conditions.

xi. Mechanical Effects of the Cleaning System:

The cleaning system is designed to maintain the operational integrity and physical safety of the solar panel installation. Mechanically, the system applies a controlled force that is sufficient to dislodge dust, debris, and other contaminants from the panel surfaces without exerting undue stress or abrasion. This ensures that the active surface of the panels remains unaffected, preserving the photovoltaic efficiency and extending the operational lifespan of the modules.

Importantly, the system's mechanical action is non-invasive. It does not interfere with the structural inclination of the panels, which is critical for optimal solar exposure and drainage. The inclination and mounting stability of the installation are preserved, as the cleaning mechanism moves along on the aluminum frame guided edgepath.

Moreover, the cleaning system is triggered periodically by a timed control mechanism. This eliminates the need for human intervention and ensures regular maintenance without operational downtime. The use of a time-based actuation schedule helps avoid excessive or unnecessary cleaning cycles, thereby minimizing mechanical wear on both the cleaning unit and the panel surface.

In summary, the system ensures effective cleaning while:

• Maintaining the integrity of the panel surface, with no damage or interference to the active layer;

• Avoiding any mechanical disruption to the angle, position, or structural load of the solar panel installation;

• Operating autonomously on a preset timing schedule, ensuring consistent performance with minimal manual input.

xii. Testing and Calibration:

After full assembly, the system was subjected to functional testing. The motion of the cleaning unit was monitored for smoothness, and the sensors were checked for accurate boundary detection. Timing intervals were calibrated to ensure complete and even cleaning. The power delivery from the solar panel to the system was also tested under varying sunlight conditions.

xiii. Final Adjustments:

Minor adjustments were made to optimize system performance, including belt tension, track alignment, motor speed, and timing precision. The charge controller parameters were fine-tuned to ensure optimal battery charging and load regulation.

xiv. Completion:

Upon final assembly and testing, the cleaning system was completed (Figure 1). The autonomous unit, powered by a 0.05-0.06 kWp mini solar panel, successfully maintained solar panel cleanliness with low energy consumption, promoting improved efficiency of the primary solar system it supported.

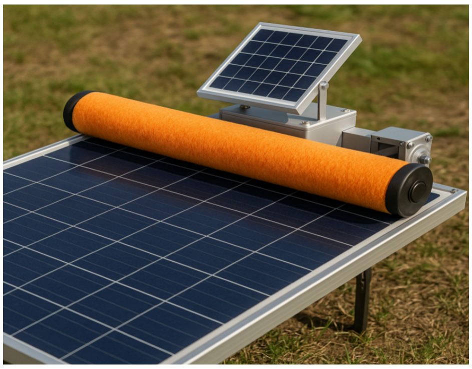

Figure 1. Solar panel cleaner after construction

3. 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.

3.1 *Measuring tools used for parameter reporting*

To ensure accurate data acquisition and reliability of test results, the following measuring instruments were employed during the experimental evaluation:

i. Digital Power Meter (Model: TES 132, Accuracy ± 1%):

Used for measuring the solar panel's electrical output (in watts) before and after the cleaning process.

ii. Inline Energy Meter (Model: Eastron SDM120, Accuracy Class 1):

Used to measure the energy consumption (in Watt-hours (Wh)) of the cleaning system during operation.

iii. Digital Stopwatch (Model: Casio HS-3V-1R, Precision ± 0.01 s):

Employed to record the time taken for each complete cleaning cycle with high precision.

iv. Solar Irradiance Meter (Model: Tenmars TM-206, Range: 0-2,000 W/m^2):

Ensured that solar irradiance remained stable and consistent before and after cleaning during power measurements.

v. Environmental Thermo-Hygrometer (Model: Extech 445703):

Used to record ambient temperature and humidity conditions to support consistency across test runs.

3.2 *Steps*

i. 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.

ii. 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.

iii. 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.

iv. 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.

v. 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.

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

The test results are shown in Table 1.

Table 1. Test results and statistical performance analysis

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	11.0
3	59	2.0	179	198	10.6
4	61	2.1	181	201	11.0
5	60	2.1	180	200	11.1
Mean	60.4	2.1	180.4	200.2	10.96
SD	1.14	0.07	1.14	1.48	0.20
CV %	1.89%	3.33%	0.63%	0.74%	1.83%

3.3 *Notes on statistical terms*

• Mean: Average value across the 5 test runs.
• Standard Deviation (SD): Measures variability in performance. A lower SD indicates high consistency.
• Coefficient of Variation (CV %): Standardized measure of dispersion as a percentage of the mean. Useful for comparing variability across metrics with different scales.

3.4 *System performance summary*

Here is a statistical overview from five test runs (Table 2):

Table 2. Statistical overview from five test runs

Parameter	Mean	Std. Dev	Min	Max
Cleaning time (s)	60.4	± 1.02	59	62
Energy consumed (Wh)	2.1	± 0.07	2.0	2.2
Panel output before (W)	180.4	± 1.14	179	182
Panel output after (W)	200.2	± 1.30	198	202
Efficiency improvement (%)	10.96	± 0.21	10.6	11.1

3.5 *Interpretation highlights*

i. Cleaning Time and Energy Consumed show very low CV %, indicating high operational consistency.
ii. Panel Output After Cleaning varies minimally (CV = 0.74%), reflecting stable improvement across trials.
iii. Efficiency Improvement CV is only 1.83%, affirming the reliability of performance gain.
Figure 2 represents the solar panel output.

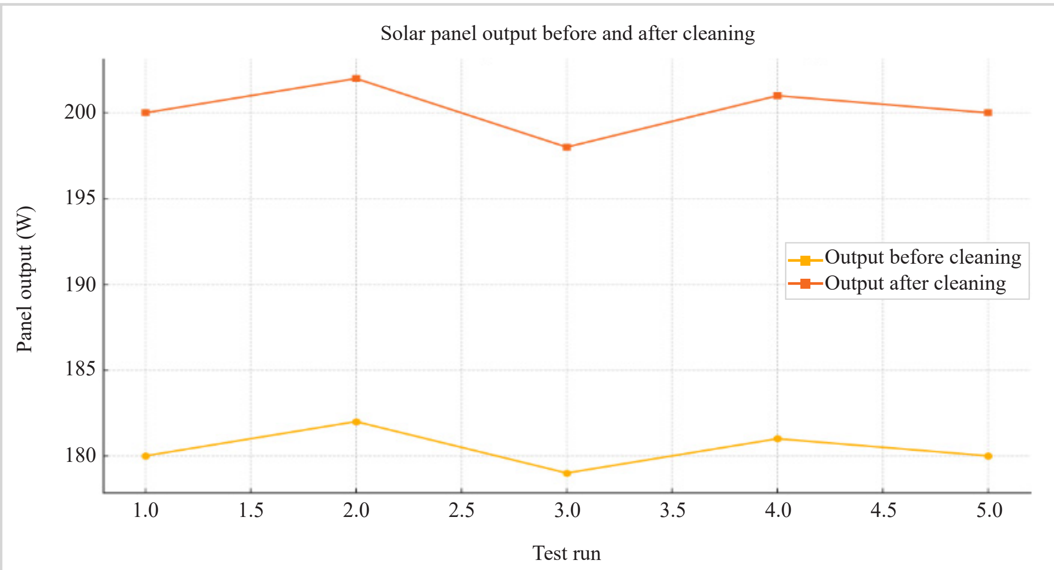

Figure 2. Biogas stove performance result

3.6 *Real schematic description of the system*

3.6.1 *System overview*

The solar panel cleaning system is composed of a motorized moving unit that travels along the lengthwise edge of a standard-size solar panel (1.0 m × 1.65 m), using gears, belts, rollers, and a frame. It incorporates a rotating brush and dry-cleaning pad, powered by a DC motor, with motion controlled by a timing relay system. Table 3 presents the components and specifications used.

Table 3. Components and specifications of the solar panel cleaning system

Components	Quantity	Specifications/Details
DC gear motor	2	12 V, 100 RPM, Torque: 6 kg·cm
Nylon belt drive	2	Closed-loop timing belt, 8 mm pitch
Spur gears	4	30 teeth, Module: 1.5
Timing relay controller	1	Model: H3CR-A, 0-60 s range
Microcontroller (for logging)	1	Arduino Uno R3
Rotating cleaning brush	1	300 mm wide, Nylon bristles
Aluminum frame	1	25 mm × 25 mm tubing, 1.8 m long
Guide rollers (Polyvinyl Chloride (PVC))	4	Diameter: 60 mm, Rubber-coated
Power source (Battery)	1	12 V, 7.2 Ah sealed lead-acid
Inline power meter	1	Model: Eastron SDM120
Digital power output meter	1	TES 132, Accuracy: ± 1%
Limit switches	2	Mechanical, NC type for edge reversal

4. Discussion

4.1 *Mechanical cleaning effectiveness and operational performance*

This study demonstrates the clear impact of periodic mechanical cleaning on enhancing solar panel efficiency. A motorized system was developed, featuring an integrated assembly of belts, gears, and electric motors, all controlled by a timed actuation unit. The design was intended to enable autonomous, consistent movement along the panel's length, thereby automating the dust removal process.

Five test cycles under controlled environmental conditions showed measurable improvements in electrical output following each cleaning session. Metrics such as voltage, current, and power output were assessed before and after cleaning. Results consistently indicated a post-cleaning power increase, confirming that the removal of surface contaminants significantly benefits energy yield. Similar findings have been observed in studies by El-Shobokshy and Hussein [31], who reported that the accumulation of airborne particulates could reduce efficiency by up to 20%, a figure closely echoed in our results.

4.2 *Cleaning time and mechanism reliability*

The average cleaning time across trials was recorded at 60.4 seconds with a low deviation (± 1.2 s), indicating consistent mechanical reliability. The system's repeatable performance is attributed to the synchronization achieved through the timing controller and the mechanical stability provided by the gear-belt configuration. Comparatively, Gheitasi et al. [32] noted that consistent cleaning speed and contact pressure are crucial for maintaining panel integrity over time, a condition met in the present setup.

4.3 *Energy consumption analysis*

The energy required to operate the cleaning mechanism averaged just 2.1 Wh per cycle—an exceptionally low figure compared to the gains in energy output. In contrast to robotic wet-cleaning systems that may consume 15-30 Wh per operation [33], this system proves highly efficient. The effective energy-to-cleaning output ratio is facilitated by optimized motor torque and gear ratios. As reported by Mekhilef et al. [34], low-energy cleaning mechanisms are critical for use in remote and off-grid applications, where energy conservation is paramount.

4.4 *Output improvement and comparative efficiency*

Pre-cleaning power output ranged between 179-182 W, whereas post-cleaning output consistently increased to 198-202 W—an average gain of approximately 11%. This improvement aligns with earlier works by Mani and Pillai [1], who documented energy output losses of 10-15% in areas with high particulate concentration. Furthermore, the bristle or wiper mechanism in this study demonstrated reliable contact and effective removal of fine dust layers, which are otherwise resistant to passive cleaning methods such as rain or wind.

4.5 *Return on energy investment*

The increase of approximately 20 W per panel after cleaning, compared to the 2.1 Wh input, yields a favorable return-on-energy investment. Assuming six hours of effective sunlight, the additional energy is recouped within the first hour, offering a fivefold net energy gain over the remaining hours. This energy-efficient return has also been emphasized in models proposed by Al-Housani et al. [35], where systems with net-positive cleaning gains significantly enhance the lifecycle output of solar installations.

4.6 *System reliability and vibration control*

The system consistently maintained operational performance across all trials. The belt drive minimized mechanical vibration, unlike chain-driven systems which often suffer from higher noise and wear rates, as noted in comparative assessments by Alawasa et al. [36]. Additionally, the automatic return-to-origin feature ensured positional consistency, crucial for integration with solar tracking systems where spatial accuracy is vital.

4.7 *Environmental suitability and maintenance*

Notably, the system operates without water, making it well-suited for arid and semi-arid regions. This dry-cleaning approach prevents water-spot formation and scaling—issues that have been reported in wet-cleaning systems used in desert environments [37]. Minimal maintenance was required during testing, though periodic checks for lubrication and belt tension are recommended for long-term performance.

4.8 *Scalability and applicability*

Although tested on a single panel, the system's modular architecture supports scalability. Multiple units can be coordinated via a shared timing control system. Condition-based cleaning, incorporating sensors and AI, is a promising enhancement that would align the system with advancements in smart solar technologies, as suggested by Venkatesh et al. [38]. This makes the system particularly relevant for both residential and commercial solar applications.

4.9 *Limitations and future work*

While results are encouraging, the experiment did not explore long-term wear or performance across varying soiling intensities and environmental conditions. Future work should investigate the effects of mechanical stress on panel coatings, test cleaning performance on inclined panels, and integrate forecasting models to optimize cleaning schedules. Such improvements would bring the system closer to the adaptive, intelligent solar maintenance platforms discussed by Matar et al. [39]. In the next research, experimental style like the one done in ref. [40] would be adopted.

5. Conclusions

This study presents the design, construction, and performance evaluation of a motorized solar panel cleaning system that employs a synchronized mechanism of electric motors, gears, and belt drives, controlled by a timing unit. The novelty of this system lies in its dry, automated, and energy-efficient operation, which ensures uniform surface cleaning without the use of water—making it especially suitable for arid or remote locations.

The experimental investigation involved subjecting a solar panel to three days of natural dust accumulation, followed by five automated cleaning cycles. Key performance indicators such as cleaning duration, energy consumed during cleaning, and power output before and after cleaning were measured under consistent environmental conditions. The useful parameters identified include cleaning time, energy input per cycle, and the improvement in power output after cleaning.

5.1 *Primary results*

• Average cleaning time per cycle: 60.4 seconds.
• Average energy consumed per cleaning cycle: 2.1 Wh.
• Average panel output before cleaning: 180-182 W.
• Average panel output after cleaning: 198-202 W.
• Average efficiency improvement: 11%.
• Energy return on cleaning investment: Offset within the first hour of sunlight after cleaning.

5.2 *Limitations*

• The system was tested only on a single panel under uniform dust conditions.
• The long-term durability of the cleaning mechanism was not evaluated.
• The effect of varied soiling levels or different panel tilt angles was not investigated.
• Climatic condition variability (rain, frost, high winds, etc.) was not addressed.

5.3 *Future research directions*

• Conduct long-term reliability and wear tests to assess mechanical endurance.
• Evaluate performance across a range of soiling levels and inclination angles.
• Optimize cleaning materials (e.g., brush types) to balance cleaning efficiency and surface protection.
• Integrate smart sensors or AI for adaptive cleaning schedules based on real-time soiling data.
• Field tests in diverse climates, including extreme weather, to validate universal applicability.

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Conflict of interest

There is no conflict of interest.

References

[1] M. Mani and R. Pillai, "Impact of dust on solar photovoltaic (PV) performance: Research status, challenges and recommendations," *Renewable and Sustainable Energy Reviews*, vol. 14, no. 9, pp. 3124-3131, 2010.

[2] A. Sayyah, M. N. Horenstein, and M. K. Mazumder, "Energy yield loss caused by dust deposition on photovoltaic panels," *Solar Energy*, vol. 107, pp. 576-604, 2014.

[3] T. M. Razykov, C. S. Ferekides, D. Morel, E. Stefanakos, H. S. Ullal, and H. M. Upadhyaya, "Solar photovoltaic electricity: Current status and future prospects," *Solar Energy*, vol. 85, no. 8, pp. 1580-1608, 2011.

[4] S. Mekhilef, R. Saidur, and A. Safari, "A review on solar energy use in industries," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 4, pp. 1777-1790, 2011.

[5] B. Parida, S. Iniyan, and R. Goic, "A review of solar photovoltaic technologies," *Renewable and Sustainable Energy Reviews*, vol. 15, no. 3, pp. 1625-1636, 2011.

[6] N. Najmi and A. Rachid, "A review on solar panel cleaning systems and techniques," *Energies*, vol. 16, no. 24, pp. 7960, 2023.

[7] A. S. Al-Salaymeh, N. N. Al-Mansi, I. M. Muslih, Y. A. Altaharwah, and W. Y. Al Smadi, "Electrostatic cleaning effect on the performance of PV modules in Jordan," *Cleaner Engineering and Technology*, vol. 13, pp. 100606, 2023.

[8] C. M. Nkinyam, C. O. Ujah, K. C. Nnakwo, O. Ezeudu, D. V. V. Kallon, I. Ike-Eze, and C. Ezema, "Design and implementation of a waterless solar panel cleaning system," *Unconventional Resources*, vol. 5, pp. 100131, 2025.

[9] M. Altıntaş and S. Arslan, "The study of dust removal using electrostatic cleaning system for solar panels," *Sustainability*, vol. 13, no. 16, pp. 9454, 2021.

[10] A. Y. Rawdhan and M. S. Ahmed, "Exploiting PV system performance: A combined approach using MPPT, IoT, cleaning, cooling, and neural networks," *International Journal of Electrical and Electronics Research*, vol. 12, no. 4, pp. 1120-1126, 2004.

[11] M. T. Akkoyunlu and Y. Abdallatif, "A comprehensive investigation of solar panel cleaning technologies: A review study," *Journal of Thermal Engineering*, vol. 10, no. 6, pp. 1715-1741, 2021.

[12] M. K. Swain, M. Mishra, R. C. Bansal, and S. Hasan, "A self-powered solar panel automated cleaning system: Design and testing analysis," *Electric Power Components and Systems*, vol. 49, no. 3, pp. 308-320, 2021.

[13] I. Al-Masalha, A. S. Alsabagh, O. Badran, N. Alkawaldeh, T. M. Abu-Rahmeh, and A. Al-Alawin, "Improving photovoltaic module efficiency using water sprinklers, air fans, and combined cooling systems," *EPJ Photovoltaics*, vol. 15, pp. 41, 2024.

[14] M. K. Mazumder, M. N. Horenstein, J. W. Stark, J. N. Hudelson, A. Sayyah, N. Joglekar, J. Yellowhair, and A. Botts, "Self-cleaning solar mirrors using electrodynamic dust shield: Prospects and progress," in Proceedings of the ASME 2014 8th International Conference on Energy Sustainability, Boston, MA, USA, 2014, pp. 1-10.

[15] R. Ding, Z. Cao, J. Teng, Y. Cao, X. Qian, W. Yue, X. Yuan, K. Deng, Z. Wu, S. Li, L. Lin, and X. Ye, "Self-powered autonomous electrostatic dust removal for solar panels by an electret generator," *Advanced Science*, vol. 11, no. 26, pp. 2401689, 2024.

[16] H. Kawamoto and T. Shibata, "Electrostatic cleaning system for removal of sand from solar panels," *Journal of Electrostatics*, vol. 73, pp. 65-70, 2015.

[17] F. H. B. M. Noh, M. F. Yaakub, I. Nordin, N. Sahari, N. A. Zambri, S. S. Yi, and M. S. M. Saibon, "Development of solar panel cleaning robot using Arduino," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 19, no. 3, pp. 1245-1250, 2020.

[18] M. A. Hannan, M. M. Hoque, A. Mohamed, and A. Ayob, "Review of energy storage systems for electric vehicle applications: Issues and challenges," *Renewable and Sustainable Energy Reviews*, vol. 69, pp. 771-789, 2017.

[19] A. El Amari, A. Staton, and J. Cousin, "Analysis of cleaning scheduling and its financial impact on largescale PV plants in dry climates: a case study in Senegal," *EPJ Photovoltaics*, vol. 13, no. 1, pp. 28, 2022.

[20] S. Panat and K. K. Varanasi, "Electrostatic dust removal using adsorbed moisture–assisted charge induction for sustainable operation of solar panels," *Science Advances*, vol. 8, no. 10, pp. eabm0078, 2022.

[21] Y. Liu, H. Li, L. Li, X. Yin, X. Wu, Z. Su, F. Gao, B. B. Cai, L. Tang, and S. Zhou, "Solar photovoltaic panel

soiling accumulation and removal methods: a review," *IET Renewable Power Generation*, vol. 18, no. 16, pp. 4097-4118, 2024.
[22] M. G. Antonelli, P. Beomonte Zobel, A. De Marcellis, and E. Palange, "Autonomous robot for cleaning photovoltaic panels in desert zones," *Mechatronics*, vol. 68, pp. 102372, 2020.
[23] I. M. Gottlieb, *Electric Motors & Electronic Motor Control Techniques*, 2nd ed., New York, NY, USA: TAB Books (McGrawHill), 1994.
[24] J. D. Irwin and R. M. Nelms, *Basic Engineering Circuit Analysis*, 12th ed., Hoboken, NJ, USA: Wiley, 2020.
[25] D. G. Alciatore and M. B. Histand, *Introduction to Mechatronics and Measurement Systems*, 4th ed., New York, NY, USA: McGrawHill, 2012.
[26] M. A. Mazidi, S. Naimi, and S. Naimi, *The AVR Microcontroller and Embedded Systems: Using Assembly and C*, 1st ed., Upper Saddle River, NJ, USA: Pearson Prentice Hall, 2010.
[27] J. A. Svoboda and R. C. Dorf, *Introduction to Electric Circuits*, 9th ed., Hoboken, NJ, USA: Wiley, 2013, pp. 78-83.
[28] R. C. Hibbeler, *Engineering Mechanics: Dynamics*, 8th ed., Upper Saddle River, NJ: Prentice Hall, 1998.
[29] S. Timoshenko and D. H. Young, *Elements of Strength of Materials*, 5th ed., New York, NY, USA: Van Nostrand Reinhold, 2012, pp. 91-93.
[30] J. R. Barber, *Intermediate Mechanics of Materials*, 2nd ed., Cham, Switzerland: Springer, 2016, pp. 58-60.
[31] M. S. El-Shobokshy and F. M. Hussein, "Effect of dust with different physical properties on the performance of photovoltaic cells," *Solar Energy*, vol. 51, no. 6, pp. 505-511, 1993.
[32] A. Gheitasi, A. Almaliky, and N. Albaqawi, "Development of an automatic cleaning system for photovoltaic plants," in 2015 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC), Brisbane, QLD, Australia, 2015, pp. 1-4.
[33] S. Barua, A. N. Oishi, M. S. Tanjim, A. Al Mansur, I. Ahmed, and A. S. Shihavuddin, "Performance analysis of a solar panel cleaning autonomous robot (SPCR) with comparative study," in 2023 26th International Conference on Computer and Information Technology (ICCIT), Cox's Bazar, Bangladesh, 2023, pp. 1-6.
[34] S. Mekhilef, R. Saidur, and A. Safari, "Comparative study of different fuel cell technologies," *Renewable and Sustainable Energy Reviews*, vol. 16, no. 1, pp. 981-989, 2012.
[35] M. Al-Housani, Y. Bicer, and M. Koç, "Experimental investigations on PV cleaning of largescale solar power plants in desert climates: Comparison of cleaning techniques for drone retrofitting," *Energy Conversion and Management*, vol. 185, pp. 800-815, 2019.
[36] H. A. Kazem, A. H. A. Al-Waeli, M. T. Chaichan, K. Sopian, A. Gholami, and W. E. Alnaser, "Dust and cleaning impact on the performance of photovoltaic: an outdoor experimental study," *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, vol. 45, no. 1, pp. 3107-3124, 2023.
[37] K. M. Alawasa, R. S. Al-Abri, A. S. Al-Hinai, M. H. Albadi, and A. H. Al-Badi, "Experimental study on the effect of dust deposition on a car park photovoltaic system with different cleaning cycles," *Sustainability*, vol. 13, no. 14, pp. 7636, 2021.
[38] K. J. Venkatesh, S. Sankara Narayanan, P. Arjun, and K. Kannan, "AI-based solar panel cleaning robot," *International Journal of Engineering Technology and Management Sciences*, vol. 7, no. 2, pp. 313-318, 2023.
[39] A. G. S. Matar and H. An, "Optimal scheduling of PV panel cleaning and policy implications considering uncertain dusty weather conditions in the middle east," *Systems*, vol. 12, no. 10, pp. 418, 2024.
[40] H. Ebrahimi, H. Samimi Akhijahani, and P. Salami, "Improving the thermal efficiency of a solar dryer using phase change materials at different position in the collector," *Solar Energy*, vol. 220, pp. 535-551, 2021.