GREEN ECONOMICS
Vol.4, No.1, 2026, pp.53-67
https://doi.org/10.62476/ge.41.53

Jomard Publishing

DUST DETECTION & PROTECTION SYSTEM (DDPS) FOR LOW-COST SUSTAINABLE WATERLESS SOLAR MAINTENANCE: ECONOMIC AND ENVIRONMENTAL BENEFITS

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Abstract. Dust accumulation severely reduces the efficiency of photovoltaic (PV) panels, particularly in arid and conflict-affected regions where water, labor and safe maintenance access are limited. In areas such as Gaza and Ukraine, decentralized solar energy systems have become critical for civilian communication and essential services, highlighting the need for reliable, low-maintenance cleaning solutions. This study presents a cost-effective, waterless solar panel cleaning system that enhances energy yield, reduces operational costs and conserves water resources. Economic analysis demonstrates a favorable payback period and potential for large-scale deployment. The system contributes to circular economy objectives and promotes equitable energy access, supporting SDGs 6 and 7. Policy incentives for sustainable cleaning technologies could accelerate adoption in arid and conflict-affected regions. The proposed system employs sensor-based dust monitoring and a Predictive Reflex control architecture implemented on an Arduino Uno microcontroller, activating an air-fan-based cleaning mechanism only when required. The system draws power directly from the host PV panel, eliminating the need for external energy sources and human intervention. Experimental results demonstrate a significant performance improvement, with an average power output increase of 56.055% after cleaning. The DDPS provides a low-cost, scalable and environmentally sustainable solution for maintaining solar panel efficiency in water-scarce and high-risk environments.

Keywords: *Solar panel, waterless solar panel cleaning, economic viability, efficiency, dust accumulation, automatic cleaning.*

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Received: *21 September 2025;* ***Accepted:*** *26 November 2025;* ***Published:*** *14 January 2026.*

1. Introduction

Solar energy systems face a major challenge due to dust accumulation on photovoltaic (PV) panels (Bessa *et al*., 2021). Studies show that dust can reduce solar panel efficiency by 6-7% within two months and up to 40% in regions with heavy soiling (Adekanbi *et al*., 2024). Uncleaned panels incur lost revenue, higher operational costs and additional water consumption, which can be particularly burdensome in water-scarce regions. Soiling-related efficiency degradation has been shown to cause global revenue losses between USD 3-5 billion annually, corresponding to an average efficiency drop of 3-4% across large-scale photovoltaic installations (Hooshyar *et al*., 2025). Therefore, regular cleaning of the panels is essential to maintain the required power output.

Amid the ongoing war in Gaza, widespread electricity outages have forced civilians to seek alternative ways to meet basic communication needs. Many Palestinians rely on solar panels to charge mobile phones in order to stay in contact with family members, particularly as displacement has separated communities across the region. Solar energy had already become a coping mechanism in Gaza prior to the conflict due to chronic blackouts and the war has further highlighted its role as a critical source of decentralized electricity for civilians during infrastructure collapse (Min, 2024).

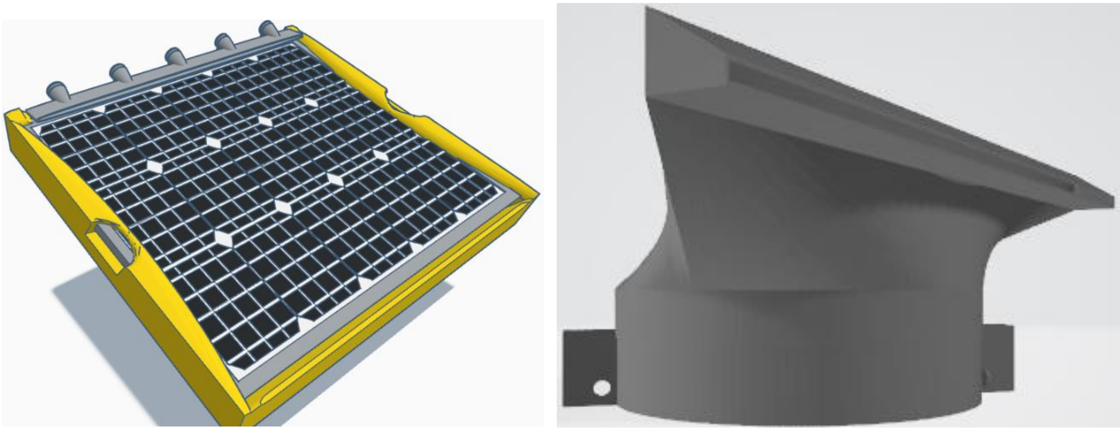
Beyond emergency use, the war in Ukraine has underscored the long-term strategic importance of renewable energy. Attacks on centralized power infrastructure have demonstrated the vulnerability of conventional energy systems, while renewables - especially solar - offer a pathway toward greater energy security and independence. Analysts note that expanding renewable capacity can also support Ukraine's integration with the European Union and accelerate the decarbonization of its energy system, positioning solar energy as both a wartime resilience tool and a post-conflict recovery strategy (Schonhardt & E&E News, 2023).

Modern armed conflicts such as the Ukraine-Russia and Gaza-Israel wars have demonstrated the vulnerability of civilian energy infrastructure. In such environments, solar panels often become the primary source of electricity for hospitals, shelters, communication systems and water pumps. However, war-generated contaminants - explosive dust, ash, concrete particles, soot and debris - rapidly degrade solar panel performance, while water, skilled labor and safe access for maintenance are unavailable. Existing automated solar cleaning systems are not designed for these conditions.

From a climate and energy justice perspective, access to decentralized renewable energy in conflict-affected regions represents a critical form of social equity, as vulnerable populations (despite bearing minimal responsibility for global emissions) face disproportionate risks from infrastructure collapse, energy poverty and climate-related stressors. Ensuring affordable, resilient energy access through low-cost solar technologies directly addresses this "double inequality" by supporting basic human needs, enhancing community resilience and aligning climate action with principles of responsibility sharing and justice for marginalized populations (Topaloglou & Nikolaidou, 2025).

The proposed design Figure 1 significantly reduces the need for frequent maintenance and routine system inspections required to sustain long-term performance. This feature makes the system particularly suitable for small- and medium-scale solar installations, where continuous manual intervention is often impractical or unsafe. In this study, an efficient, fully automated, waterless solar panel cleaning system is developed for small photovoltaic (PV) arrays. The system is built around an Arduino Uno microcontroller and integrates a motor-driven air fan with a Predictive Reflex control architecture to enable autonomous operation. Unlike conventional cleaning systems that rely on manually scheduled cleaning cycles using real-time clocks, the proposed system autonomously determines when cleaning is required based on environmental conditions, thereby eliminating the need for human involvement. By eliminating the need for human intervention and water consumption, the system reduces operational and maintenance costs, conserves water and shortens the payback period, supporting both economic and environmental sustainability. These benefits align with the UN Sustainable Development Goals (SDG 6: Clean Water; SDG 7: Affordable and Clean Energy) and offer a framework for policy incentives promoting resilient, sustainable solar energy systems in conflict-affected or water-scarce regions. The Dust Detection and Protection System

(DDPS) continuously monitors dust accumulation on the PV surface and automatically activates the cleaning mechanism to restore panel efficiency without manual intervention. This paper presents the overall system architecture, electronic design, control algorithms and experimental results demonstrating the performance of a functional DDPS-based prototype.



(a) (b)

Figure 1. (a) Illustration of the cleaning device positioned beside the PV panel (dimensions exaggerated for clarity); (b) Cleaning device

1.1. Problem Statement

Dust accumulation creates a barrier between sunlight and the PV surface, reducing power output (Bessa *et al*., 2021). Traditional water-based cleaning systems require large amounts of clean water and frequent maintenance (Crawford, 2022). In contrast, air-jet cleaning is environmentally friendly, maintenance-free and suitable for dry climates. Additionally, existing cleaning solutions often lack enough protection for outdoor conditions, leading to failures when components are not properly sealed against weather exposure and many systems require external power sources rather than drawing energy directly from the host panels. Furthermore, current industry options tend to involve complex setups and costly components, making them less accessible and economically inefficient for widespread deployment (White *et al*., 2004).

The most widely used method for cleaning photovoltaic (PV) panels is manual labor, where workers are often assigned multiple tasks simultaneously. However, manual cleaning is time-consuming and introduces significant risks. Untrained or unqualified laborers may cause severe damage to costly PV modules during the cleaning process. In addition, many solar farms are located in extremely hot environments, exposing workers to heat stress, heatstroke and other safety hazards. Manual cleaning also frequently requires working at elevated heights, increasing the risk of falls. The need for supervised teams further raises maintenance costs, while human error reduces cleaning effectiveness and can lead to losses in power output (Kalaji *et al*., 2022).

Recently, the high cost and limited availability of water in certain regions have restricted the widespread use of electrostatic and aqueous solar panel cleaning systems**.** In contrast, dry cleaning techniques provide a low-cost, water-independent solution, making them suitable for areas with scarce rainfall. Methods such as applying surface acoustic waves have shown promise in effectively removing soiling materials from solar panels while minimizing water usage (Alagoz & Apak, 2020).

To address the need for an effective cleaning mechanism, automated solar panel cleaning systems have been proposed and developed to improve operational efficiency. Such systems enhance energy output by removing dust and debris in a quick and cost-effective manner while minimizing human intervention. Automation also significantly reduces safety risks by limiting operator exposure to high-voltage environments and hazardous working conditions (Burke *et al*., 2016).

1.2. Aim and objectives

The study aimed to design and implement an automated cleaning system for solar PV panels. The objective of this research is to achieve the following:

- Replace conventional manual solar panel cleaning methods with an automated cleaning system.
- Reduce energy losses in photovoltaic panels caused by dust accumulation on the surface.
- Design a simple and reliable cleaning mechanism that operates automatically only when required.
- Eliminate labor dependency and significantly reduce the time required for panel cleaning.
- Lower overall maintenance and operational costs while maintaining long-term system efficiency.

1.3. Related works

Numerous studies have investigated the influence of dust accumulation on the operational efficiency of photovoltaic (PV) solar panels. Nkinyam et al. (2025) proposes a waterless and cost-effective automatic cleaning system specifically designed for small-scale photovoltaic installations. The system integrates an Arduino-based control unit with real-time clock scheduling to enable adaptive and timely cleaning operations. A two-stage cleaning mechanism combining an ejector air blower and a flexible brush is employed to remove both loose dust and adhesive contaminants. The total estimated cost of a single system, including materials and research expenses, is $72.60 and this cost increases only slightly when scaled up, as one control system can manage multiple solar panels. Experimental results show that the system provides an efficiency gain of 26.23% by effectively removing dust and surface contaminants from the panels.

Similarly, Maindad et al. (2020) presented a microcontroller-driven cleaning mechanism using linear actuators, brushes, water pumps and GSM communication. While the system improved operational efficiency and reduced human involvement, it remained dependent on water-based cleaning. The cleaning system achieves a final efficiency gain of 17.34% in photovoltaic output following the cleaning process.

Al Dahoud et al. (2021) proposed an automated cleaning solution designed for solar-powered street lighting systems, incorporating GSM-based real-time monitoring. Although the system reduced manual labor, it relied heavily on water usage and required frequent servicing.

Myyas et al. (2022) developed a multifunctional intelligent system that integrates self-cleaning, temperature regulation, water recycling and rainwater harvesting to improve PV performance. Experimental results indicated enhanced energy efficiency and reduced maintenance complexity, supporting sustainable energy generation and carbon reduction efforts.

Robotic cleaning approaches have also been explored. Khadka et al. (2020) developed a mobile robotic cleaner integrated with a cloud-based monitoring interface and sensing units for remote operation. The prototype successfully removed dry dust from PV modules and demonstrated potential scalability for large solar farms when deployed along rail-guided structures.

Makmee and Pengwang (2021) further enhanced robotic cleaning technology by introducing a four-sided stretch-sling mechanism that enables accurate positioning, flexible configuration and reduced labor requirements for large-scale installations.

Non-contact dust removal methods have gained attention as alternative solutions. Patel et al. (2023) investigated electrodynamic shield technology combined with self-cleaning coatings applied to glass surfaces. Although the system exhibited suitable optical transmission and electrical properties, its dust removal effectiveness showed limited sensitivity to particle removal rates.

Kawamoto (2019) proposed an electrostatic dust removal technique that applies alternating high voltage across parallel electrodes, generating electrostatic forces that dislodge dust particles. This approach achieved effective cleaning with low power consumption, thereby improving PV efficiency.

In addition, Ahmed et al. (2023) developed an automated inspection and cleaning robot capable of detecting dust levels by analyzing changes in panel surface color. The system successfully distinguished between lightly, moderately and heavily contaminated panels and activated cleaning accordingly.

Alagoz and Apak (2020) conducted theoretical and experimental analyses on dust detachment using surface acoustic waves, demonstrating that acoustic interference can effectively remove dust from inclined PV surfaces under appropriate conditions.

2. System overview

2.1. Hardware architecture

Two light sensors are used in the project. Their main function is to measure the ambient light intensity. Using two sensors ensures more stable and reliable measurements. The Arduino compares the data received from both sensors to make accurate control decisions. The system includes two potentiometers. Motor Power Potentiometer adjusts the maximum operating power of the motor. For safety reasons, this level is limited by the software. Sensitivity Potentiometer adjusts the sensors' sensitivity to light. It allows the system to operate correctly under different lighting conditions. A button is used for system calibration. During calibration, the system is taught which light levels are considered "high" and which are considered "low". This process adapts the sensors to the environment and helps ensure accurate and error-free operation. Figure 2 outlines the workflow of the solar panel cleaning system.

Key components:

- Arduino UNO;
- 2 × Potentiometers (10kΩ);
- 2 × LDR sensors;
- Push button;
- LED + resistor;
- Buzzer;
- 1400kv Brushless Motor;

- ESC (30A);
- 12V battery (3s, 11.1V);
- ON/OFF switch.

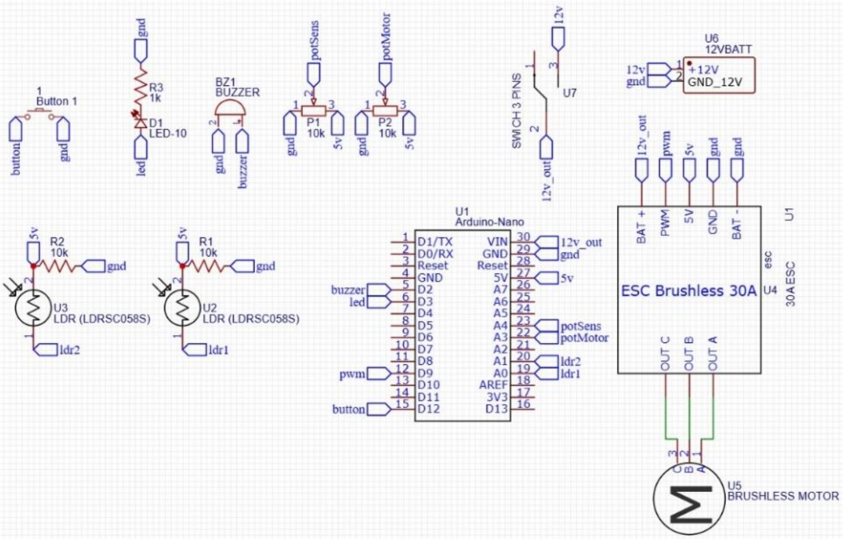


Figure 2. Electrical schematic description

2.2. Software and algorithm

This project is designed for the automatic control of a motor based on light intensity.

The system monitors changes in ambient light using sensors as shown in Figure 3 and the Arduino decides whether the motor should run or stop according to the received data. If the light level drops below a predefined threshold, the motor is activated. When the light level returns to normal, the motor automatically stops.

Figure 3. LDR sensors

Operating Sequence

- The system starts and performs a self-check;
- Light data is read from the sensors;

- The Arduino evaluates the data;
- The motor is activated when necessary;
- The motor stops when conditions change.

The entire process is fully automatic and does not require continuous user intervention.

2.3. PV module

As illustrated in figure, PV (Photovoltaic) modules, sometimes called PV or solar panels, are an integral part of a solar power system. A PV module captures light energy from the sun and converts it into electrical energy. Each module is made up of a grid of small solar cells. The cells are made of a semi conductive material, typically silicon. This material is sensitive to light and uses the photovoltaic effect to convert light energy into electricity. The PV effect is a chemical and physical phenomenon that allows certain materials to change sunlight into electricity.

2.4. Control unit (Arduino Uno)

An Arduino Uno is a small board with programmable electronics. With an Arduino you can control various electrical components. It is an open-source microcontroller board built around the microcontroller and provides a set of digital and analog input/output pins that allow direct connection to external circuits and expansion shields. Owing to its compact size, affordability and ease of integration, the Arduino Uno is widely used in low-cost robotic systems and compact electronic applications. Employing the Arduino Uno as the core of the control unit simplifies the overall system architecture while reducing implementation costs. In the automated cleaning system, the control unit is the programmable unit controlling the operation and monitoring of the entire system. It conveys input from the dusting and measuring devices and sends output to the cleaning devices.

2.5. Cleaning unit

This unit is responsible for removing dust and debris off the surface of the solar panel. The requirement entails cleaning an entire row of solar panels in a PV array efficiently utilizing low energy without water. This unit performs its cleaning operation at all times. The cleaning method finally chosen contains both a motor and fan. Figure 4 shows the system responsible for removing dust and debris off the surface of the solar panel. The requirement entails effectively cleaning an entire row of solar panels in a PV array using solar energy without water.

In this system, the fans serve to generate directed airflows during the cleaning process, dislodging loose sand and dust particles from the surface of the solar panel. The need for solar panel cleaning is highly site-specific and depends on the installation environment, requiring tailored decisions for each photovoltaic system. Several key factors must be considered when selecting appropriate cleaning components, including:

- Annual climatic conditions at the site, such as rainfall, humidity, dew formation, wind patterns and ambient temperature
- The type and characteristics of surface soiling
- Anthropogenic pollution sources, where high traffic density, urban environments or industrial activities can significantly increase contamination levels; agricultural and

farming activities may also contribute to dust accumulation, with seasonal variations influenced by cultivation and harvesting cycles

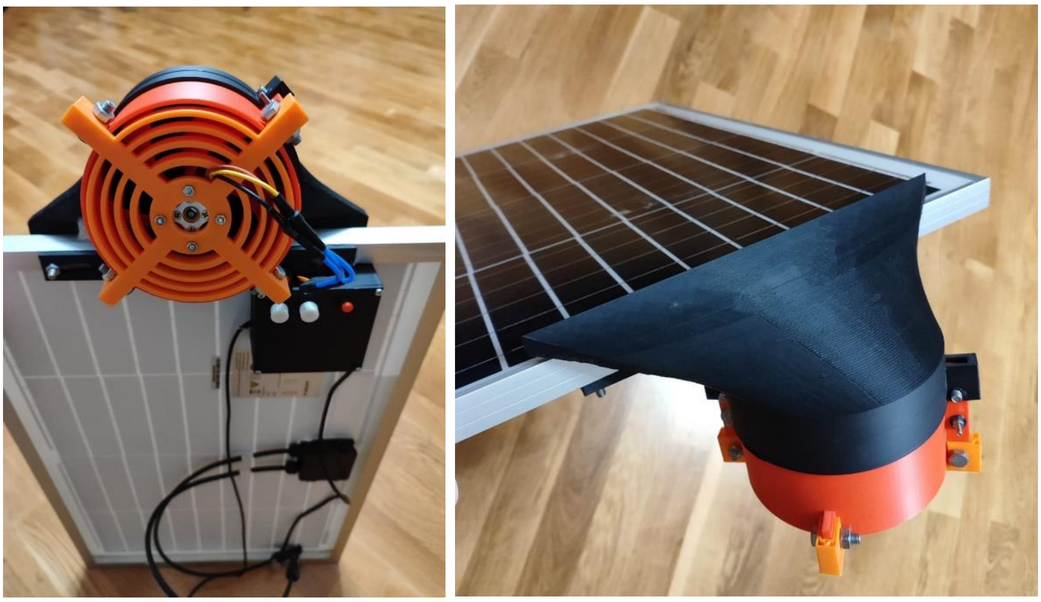


Figure 4. Prototype of cleaning system for solar panels

3. Experiment results

3.1. Results

The efficiency of the automatic solar panel cleaning system was assessed under two conditions by comparing the electrical performance of the panels before and after cleaning using a multimeter. Measurements of voltage, current and power were conducted on both dusty and cleaned panels over a daytime period between 15:00 and 16:30. All measurements were performed with the solar panel fixed at an inclination angle of 20 degrees to ensure consistent irradiation conditions.

3.1.1. Measurements on the dusty solar panel

Current and voltage measurements were carried out on the dusty solar panel to determine the voltage and current of the solar panel, applying 120 g of dust on the surface of the panel and measurement are taken at 30 min interval to have several readings.

Table 1. Measurements on the dusty solar panel

Measurement time	Voltage (V)	Current (A)	Power (W)
15:00	22.6	0.20	4.52
15:30	21.2	0.13	2.756
16:00	20.0	0.07	1.4
16:30	19.1	0.01	1.91

Table 1 shows measurements for a dusty solar panel, we observe a general downward trend in voltage, current and power over time, with each parameter gradually decreasing from 15:00 to 16:30 p.m. The voltage starts at 22.6 V and falls to 21.2 V, while the current drops from 0.20 A to 0.13 A, leading to a decrease in power from

4.52 W to 2.756 W. This decrease corresponds to the reduction in sunlight intensity, which provides less energy for the panel to convert into electrical power.

3.1.2. Measurements on the clean solar panel

Table 2 reflects measurements from a clean solar panel, showing a higher overall performance compared to the dusty panel: The voltage starts at 23.1 V at 15:00 and falls to 21.8 V at 15:30, while the current drops from 0.29 A to 0.22 A, leading to a decrease in power from 6.699 W to 4.796 W. The trends mirror those of the dusty panel but at significantly higher values. The absence of dust allows the panel to harness more solar energy, leading to enhanced performance. The current values show a significant increase, reflecting better electron movement within the photovoltaic cells when sunlight is unblocked.

Table 2. Measurements on a clean solar panel

Measurement time	Voltage (V)	Current (A)	Power (W)
15:00	23.1	0.29	6.699
15:30	21.8	0.22	4.796
16:00	20.5	0.15	3.075
16:30	19.5	0.10	1.950

Table 3 illustrates the average increase in output power between the dusty and clean panels. The results showed an increase in the output power of the clean solar panels using our prototype.

We calculate the average increase in output power using Equation 1.

$$Q = \frac{c-d}{d} \times 100\% \qquad (1)$$

Where Q = average increase of output power, c = daily power of cleaned solar panel, d = daily power of dirty solar panel.

Table 3. Measurements of the average increase of output power

Measurement time	Power from dirty panel (W)	Power from Clean panel (W)	Average increase of output power (Q)
15:00	4.52	6.699	
15:30	2.756	4.796	
16:00	1.4	3.075	
16:30	1.91	1.950	
daily panel power	10.586	16.52	56.055%

3.2. Discussion

Analysis of experiments clearly demonstrates a consistent increase in the power output of the solar panel system following each cleaning cycle, indicating a direct positive impact of panel cleaning on overall efficiency. The removal of these contaminants restores the panel’s capacity to capture sunlight more effectively, highlighting the critical importance of regular maintenance for sustained photovoltaic performance.

The performance evaluation of the proposed automatic waterless solar panel cleaning system provides valuable insights into the strong dependence of photovoltaic efficiency on surface cleanliness. A comparative assessment between dusty and cleaned PV modules reveals the detrimental influence of environmental contaminants on energy generation. Measurements of voltage, current and power before and after cleaning were systematically conducted to quantify this effect.

The clean panel consistently delivers higher power across the entire voltage range. In contrast, the dusty panel exhibits a slower decrease in power and fails to reach the output levels achieved by the cleaned panel, primarily due to dust obstructing incident sunlight. The comparative results reveal that the clean panel produces approximately 56.055% more power than the dusty panel, underscoring the severe impact of surface contamination on photovoltaic performance.

Dust accumulation on the panel surface reduces solar irradiance absorption and consequently lowers power output. If left unaddressed over extended periods, this degradation becomes increasingly pronounced. These findings justify the need for the proposed waterless cleaning system, particularly in arid regions where water availability is limited. The upward performance trend observed for the cleaned panel highlights the advantages of frequent cleaning in maximizing daily energy yield.

Conventional solar panel cleaning methods impose varying economic burdens. Natural cleaning has no direct cost but often results in prolonged efficiency losses, leading to indirect revenue reduction. Manual cleaning involves high recurring labor costs and safety expenses, while water-based cleaning adds further operational costs related to water sourcing, pumping and disposal, particularly problematic in water-scarce regions. Automated and robotic systems reduce labor costs but require high upfront investment, frequent maintenance and external power supply, making them economically unsuitable for small or decentralized PV installations (Badalyan, 2024).

In contrast, the proposed DDPS-based solar panel cleaning system offers a low-cost and environmentally sustainable alternative. By operating in a fully waterless manner, the system eliminates water procurement costs and associated environmental externalities. Its brushless or minimal-contact design reduces mechanical wear and maintenance expenses compared to systems relying on physical brushes or moving arms. Unlike fixed-schedule or reactive cleaning approaches, the predictive, reflex-based control optimizes cleaning frequency, minimizing unnecessary energy consumption and component degradation while maximizing energy yield. Furthermore, the DDPS system is designed for affordability and simplicity, making it accessible to small-scale, rural and off-grid installations where high-cost robotic systems are impractical. Its complete energy autonomy (drawing power exclusively from the host PV panel) removes dependence on external electricity sources, further lowering operating costs and enhancing suitability for remote or conflict-affected regions.

Experimental research by Al-Housani et al. (2019) on various solar panel cleaning methods in arid environments demonstrated that panels cleaned regularly with mechanical systems performed better than those cleaned manually or infrequently, reinforcing the advantages of automated waterless mechanical cleaning. The cleaning process in our system is automated, taking into account factors such as installation location and seasonal climatic variations, thereby reducing the need for human intervention.

Key advantages of the DDPS-Based Solar Panel Cleaning System:

1. **Fully Waterless and Mechanically Simple** - The DDPS cleaning system relies on air to remove, eliminating the need for water. Unlike some prior systems that depend heavily on water-based cleaning - which is impractical in arid regions - this approach is completely water-free, sustainable and low-cost.
2. **Brushless or Minimal-Contact Potential -** Many existing systems still rely on physical brushes or moving arms that wear out and risk scratching panels. A brushless DDPS system reduces mechanical complexity while maintaining effective dust removal.
3. **Predictive and Reflex-Based Cleaning -** While most prior works use fixed schedules, timers or reactive, this system proactively adapts cleaning intervals. This optimization increases energy gain while reducing unnecessary cleaning cycles and mechanical wear.
4. **Cost-Effectiveness and Accessibility -** Many robotic systems are expensive, complex and scaled for large installations, making them less accessible for small-scale or rural setups. The DDPS system is affordable, easy to implement and simple to maintain.
5. **Complete Energy Autonomy -** A distinguishing feature of the DDPS system is that all components - including sensors, control units and motor-driven air blowers - are powered solely by the host photovoltaic panel. No external grid connection or auxiliary power is needed, ensuring continuous operation in off-grid, remote or conflict-affected regions where electrical infrastructure may be unreliable or unavailable.

4. Cost estimation analysis

Table 4. Cost estimation of the proposed system

Components	Cost (dollar)
Arduino Uno	4.27
ESC	5.0
1400kv Brushless Motor	6.0
Potentiometer 2×	0.29+0.29
Button	0.29
Switch	0.29
LDR sensor 2×	1.18+1.18
Cables	2.35
Wire Connectors	2.35
Fan (air blower)	1.79
Frame (enclosure + supporters)	17.0
System construction	10.0
Total	**$52.28**

The cost of maintaining photovoltaic (PV) systems is largely determined by how frequently and how easily dust can be removed from the panel surfaces. In this study, the associated expenses are assessed across the research, design and construction stages. The research phase comprises an extensive review of existing literature and the identification of suitable system components. The design phase includes system conceptualization, development of electrical and mechanical schematics and integration of the Arduino-based control unit. The construction phase involves component procurement, system assembly and prototype testing. Table 4 summarizes the estimated costs related to the system’s design and fabrication. The total expenditure for a single unit, encompassing both material and research costs, is calculated to be $52.28 based on prevailing market prices at the time of development. Furthermore, scaling the system for larger photovoltaic installations is expected to result in only a marginal increase in overall cost, since a single control unit can operate multiple panels.

4.1. Cost-benefit analysis over the system's lifetime

In addition to the initial costs outlined in Table 4, evaluating the long-term economic advantages of the automated waterless solar panel cleaning system is essential. This assessment considers both installation and operational expenses over the system's lifespan, along with the energy efficiency gains achieved through regular automated cleaning.

The initial installation cost of the proposed automated system is $52.28 per panel. By comparison, manual cleaning services typically cost between €21 and €26 per panel per year (Myyas *et al*., 2022). Assuming a conservative 10-year lifespan, the total operational cost would be roughly $100 per panel, while manual cleaning over the same period would amount to approximately €210-€260 per panel.

Dust accumulation on solar panels can reduce energy output by 6-45%, with losses reaching up to 70% in regions like the Middle East (Ghosh, 2020). The automated cleaning system enhances panel performance by an average of 56.055% per cleaning. According to the U.S. Energy Information Administration (EIA) as shown in Table 5, the average residential electricity price in the United States reached 17.27 cents/kWh in 2025, highlighting the increasing cost of grid-supplied electricity. Measured performance analyses of photovoltaic systems indicate that annual energy production typically lies in the range of ~1674-1874 kWh per installed kWp. Based on these values, a 400 W panel (0.4 kWp) would be expected to produce roughly 740-750 kWh per year under similar irradiance and operating conditions (Boulaid *et al*., 2020).

Table 5. U.S. Energy Information Administration (EIA) Electric Power Monthly Table 5.03, the electricity price in the USA in 2025 (Cents per Kilowatthour)

Period	Residential	Commercial	Industrial	Transportation	All Sectors
January	15.94	12.90	8.32	12.13	13.10
February	16.44	13.07	8.21	13.58	13.20
March	17.10	13.25	8.23	14.10	13.25
April	17.55	12.96	8.16	13.62	13.10
May	17.37	13.01	8.26	13.62	13.14
June	17.47	13.62	8.87	13.46	13.88
July	17.47	14.15	9.31	14.27	14.39
August	17.62	14.04	9.06	14.86	14.26
Sept	18.07	14.06	9.02	15.26	14.23
October	17.98	13.41	8.65	13.57	13.63

Considering a 40% soiling rate, the proposed DDPS device is projected to yield a profit of approximately $1,502.02 per unit over its lifespan, based on its cost, the average U.S. residential electricity price and the annual energy production of the associated solar panels.

Furthermore, the system eliminates the need for human labor, lowering associated costs and mitigating safety risks, particularly in high-voltage environments. Unlike conventional cleaning methods, which often consume large quantities of water (especially in arid regions) this solution is entirely water-free, promoting environmental sustainability.

4.2. Product environmental assessment

According to Better World Solar Energy, an utility-scale 1 MW solar farm typically produces on the order of 1,800,000 to 2,000,000 kWh of electrical energy per year under average sunlight conditions, although actual output varies with site-specific factors such as irradiance, panel efficiency and capacity factor. According to typical estimates for coal-dominated electricity grids, the grid emission factor is around 0.65 kg CO_2/kWh (or 650 g CO_2/kWh), meaning that each kilowatt-hour of electricity produced from such a grid emits approximately 0.65 kg of CO_2. The water intensity of displaced fossil fuel electricity is approximately 3 L/kWh when solar PV displaces conventional fossil-fuel-based electricity (Mekonnen *et al*., 2015).

Considering an annual clean generation of 2,000,000 kWh and assuming a 30% soiling loss due to dust accumulation, the total recovered energy after cleaning is estimated to be approximately 600,000 kWh per year. By generating 600,000 kWh of electricity per year, the PV system prevents approximately 390,000 kg of CO_2 emissions annually, considering a grid emission factor of 0.65 kg CO_2/kWh. Additionaly, the PV system saves approximately 1.8 million liters of water annually through the displacement of fossil fuel-based electricity. The water saved per year (~1.8 million liters) is equivalent to the annual drinking water needs of approximately 2,470 people and translates to an economic saving of approximately 2,400 €/year in arid regions like Nepal, Egypt and Tanzania (Otter *et al*., 2020). The system features a 10-year lifespan and a modular design, making it durable, easy to repair and helping to minimize electronic waste.

4.3. Anticipated maintenance requirements and technical considerations

The proposed waterless solar panel cleaning system requires periodic maintenance to ensure sustained operational efficiency. Prolonged mechanical operation can also contribute to wear in moving components, potentially decreasing cleaning effectiveness over time. To mitigate premature component degradation, routine lubrication of mechanical elements such as DC motor shafts is advised. Moreover, electronic components may be prone to calibration drift or connectivity issues. Implementing scheduled system diagnostics can help detect and resolve such faults early, thereby minimizing the risk of unexpected system interruptions.

4.4. System limitations and operational challenges

In regions experiencing extreme weather events, such as heavy snowfall or elevated humidity levels, the air blower mechanism may be less effective. In such environments, supplementary solutions may be required to maintain cleaning efficiency. While the system demonstrates strong performance in removing dry dust, its effectiveness may be reduced when encountering sticky or oily deposits commonly found in industrial zones or coastal regions. Furthermore, although the current configuration is well suited for small-scale photovoltaic installations, expanding the system to larger PV arrays may necessitate structural reinforcement and increased power capacity to ensure uniform cleaning coverage.

5. Conclusion

The DDPS prototype successfully demonstrates autonomous dust detection and cleaning for solar panels. Its sensor-based decision-making, air-fan-driven cleaning mechanism, reflex control algorithm and ability to draw power directly from the host photovoltaic (PV) panels make it well suited for deployment in environments with high soiling rates, such as Gaza. Experimental results indicate a significant enhancement in solar panel performance, with an average power output increase of 56.055% following the cleaning process.

By maintaining dust-free panel surfaces, the system improves both the efficiency and operational lifespan of solar installations. This substantial performance gain underscores the effectiveness of the proposed approach, demonstrating that automated dry-cleaning methods can deliver notable results without reliance on water-based techniques. Moreover, the system's cost-effectiveness and adaptability allow it to be applied to various types of solar panels, addressing a critical challenge in solar energy maintenance.

By integrating innovative engineering with practical implementation, this project not only enhances photovoltaic performance but also contributes to environmental sustainability by eliminating water consumption for panel cleaning. This feature is particularly valuable in water-scarce and conflict-affected regions, where access to maintenance resources is limited. Overall, the developed automated cleaning system represents a meaningful advancement in maximizing solar energy output while minimizing operational costs. Future work may include the integration of LoRaWAN and Zigbee modules for distributed communication, predictive maintenance using weather data and the development of AI-based dust accumulation forecasting models.

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