An Intelligent Dust Detection and Protection System (DDPS) for Autonomous Management of Photovoltaic Performance

I. A. Suleymanov [1], N. T. Muradova [2]

[1] Baku Engineering University, Department of Cyber Security and Computer Engineering, Baku, Azerbaijan

[2] The Baku Turkish Lyceum of Turkiye Diyanet Foundation, Baku, Azerbaijan

Abstract. Dust accumulation introduces significant performance degradation in photovoltaic (PV) systems operating under uncertain and dynamic environmental conditions, particularly in arid, remote, and infrastructure-limited regions. Traditional maintenance approaches based on periodic manual inspection or fixed cleaning schedules are inefficient, resource-intensive, and poorly suited for environments where access, water, and human intervention are constrained. This paper presents an information-driven Dust Detection and Protection System (DDPS) for the autonomous management of photovoltaic performance. The proposed system integrates sensor-based environmental monitoring with a predictive reflex control architecture implemented on an embedded microcontroller platform. Instead of relying on predefined schedules, the DDPS continuously evaluates real-time sensor data and triggers cleaning actions only when performance degradation is detected, forming a closed-loop cyber-physical control system. A waterless air-fan cleaning mechanism is employed, and all system components are powered directly by the host photovoltaic panel, enabling complete energy autonomy. Experimental evaluation of a functional prototype demonstrates effective restoration of photovoltaic performance following dust-induced degradation, achieving an average power output improvement of 56.055%. The results confirm that event-driven, reflex-based control can significantly enhance system efficiency while minimizing unnecessary actuation, energy consumption, and mechanical wear. Beyond its application to solar panel maintenance, the proposed DDPS illustrates a scalable and low-complexity framework for autonomous performance management in complex physical systems. The architecture is applicable to a wide range of cyber-physical and embedded control problems requiring adaptive, real-time decision-making under environmental uncertainty.

Keywords: Photovoltaic systems, Autonomous system management, Sensor-based control, Waterless solar panel cleaning, Dust accumulation, Efficiency optimization.

1. Introduction

Photovoltaic (PV) systems increasingly operate as distributed energy resources within complex and uncertain environments, where environmental disturbances and limited maintenance access significantly affect system performance. Among these disturbances, dust accumulation on PV surfaces remains one of the most persistent and difficult-to-manage factors, leading to non-linear efficiency degradation and unpredictable power losses. While the physical impact of soiling on photovoltaic output has been extensively studied, the system-level challenge of autonomously managing performance degradation under dynamic environmental conditions remains insufficiently addressed.

Conventional PV maintenance strategies rely primarily on periodic manual inspection or fixed-time cleaning schedules. Such approaches implicitly assume stable environmental behavior and predictable soiling patterns. In practice, however, dust deposition is highly irregular and influenced by site-specific climatic conditions, anthropogenic activity, and sudden environmental events. As a result, schedule-based cleaning often leads to inefficient resource utilization, unnecessary energy consumption, or delayed intervention, during which system performance remains degraded. These limitations highlight the need for adaptive, information-driven control mechanisms capable of responding to real-time environmental changes.

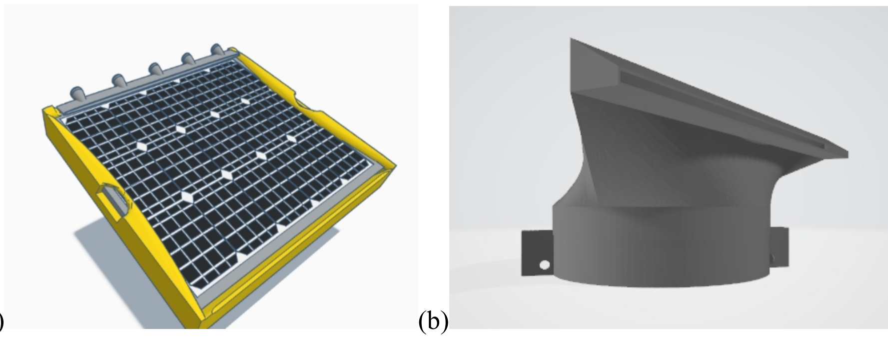
From an information technology perspective, photovoltaic installations can be modeled as cyber-physical systems, where physical energy generation processes are tightly coupled with sensing, data processing, and control layers. In such systems, effective performance management requires continuous monitoring, intelligent decision-making, and autonomous actuation. Rather than treating panel cleaning as a purely mechanical task, it becomes a closed-loop control problem, in which environmental data must be interpreted and acted upon without human intervention.

In this context, this paper proposes an intelligent Dust Detection and Protection System (DDPS) designed for the autonomous management of photovoltaic performance. The DDPS integrates sensor-based environmental monitoring with a predictive reflex control architecture implemented on an embedded microcontroller platform. Unlike conventional approaches based on predefined schedules or manual triggering, the system continuously evaluates real-time sensor data and initiates cleaning actions only when performance degradation is detected. This event-driven operation enables efficient resource utilization while maintaining system responsiveness under uncertain conditions.

A key feature of the proposed system is its complete energy autonomy. All sensing, control, and actuation components are powered directly by the host photovoltaic panel, eliminating the need for external power sources, communication infrastructure, or continuous human supervision. This design enhances system robustness and enables deployment in decentralized, off-grid, and infrastructure-limited environments.

The main contribution of this work lies in demonstrating a low-complexity and scalable autonomous control framework for managing photovoltaic performance, rather than merely introducing a cleaning mechanism. Experimental validation using a functional prototype confirms that the DDPS effectively restores system performance following dust-induced degradation. Beyond solar panel maintenance, the proposed approach illustrates a generalizable architecture for autonomous performance management **a**pplicable to a wide range of cyber-physical and embedded systems operating under environmental uncertainty.

The overall system architecture, illustrated in Fig. 1, reflects a closed-loop cyber-physical control approach in which sensing, decision-making, and actuation are tightly integrated to support adaptive photovoltaic performance management. Detailed hardware design, control logic, and system operation are presented in the following section.



(a) (b)

Fig. 1. (a) Illustration of the cleaning device positioned beside the PV panel (dimensions exaggerated for clarity). (**b)** Cleaning device's head

1.1. Problem Statement

Dust accumulation on photovoltaic (PV) panels leads to a gradual and often non-linear degradation of power output by obstructing incident solar radiation. While the physical mechanisms of soiling-related efficiency loss are well understood, the primary challenge lies in the absence of intelligent, autonomous mechanisms capable of managing performance degradation under dynamic and uncertain environmental conditions. In most existing installations, maintenance actions are triggered manually or based on fixed schedules, without considering real-time system behavior or environmental variability.

Traditional water-based and mechanically intensive cleaning solutions introduce additional constraints, including dependence on external resources, frequent servicing requirements, and vulnerability to harsh outdoor conditions. Many such systems rely on external power supplies, complex mechanical assemblies, or scheduled activation mechanisms, making them unsuitable for decentralized or resource-constrained deployments. Moreover, the absence of adaptive decision-making leads either to unnecessary and frequent cleaning actions, resulting in increased energy consumption and mechanical wear, or to delayed intervention, during which photovoltaic performance remains suboptimal.

Manual cleaning remains the most widely adopted maintenance approach in many regions; however, it is inherently inefficient and prone to human error. The process is labor-intensive, difficult to scale, and often associated with safety risks due to high temperatures, elevated installation locations, and exposure to electrical hazards. From a system management perspective, manual intervention prevents continuous monitoring and timely response to performance degradation, limiting the overall reliability of photovoltaic installations.

Recent advances in automated and dry-cleaning techniques demonstrate the feasibility of reducing water dependency and human involvement. Nevertheless, many existing solutions focus primarily on the mechanical removal of dust**,** while neglecting the information-driven control problem of determining *when* and *why* cleaning should occur. Without real-time sensing, adaptive decision logic, and closed-loop feedback, automated systems remain reactive or schedule-driven rather than truly autonomous.

Consequently, there exists a clear need for an information-centric, autonomous management framework that integrates environmental sensing, performance evaluation, and event-driven control into a unified system. Such a framework must operate with minimal external dependencies, adapt to changing environmental conditions, and maintain photovoltaic performance through intelligent, real-time decision-making. Addressing this gap forms the core problem tackled in this study.

1.2. Aim and objectives

The aim of this study is to design and validate an autonomous, information-driven management system for maintaining photovoltaic (PV) performance under dynamic environmental conditions. Rather than focusing solely on mechanical cleaning, the research emphasizes adaptive sensing, real-time decision-making, and closed-loop control for efficient system operation.

The specific objectives of this research are as follows:

- To develop an intelligent autonomous framework that monitors environmental conditions and photovoltaic performance without continuous human supervision.

- To reduce energy losses caused by dust accumulation through event-driven intervention, ensuring timely and efficient performance recovery.
- To implement a predictive reflex control mechanism that activates maintenance actions only when required, avoiding unnecessary actuation and resource consumption.
- To eliminate dependency on manual maintenance by integrating sensing, decision-making, and actuation into a self-operating cyber-physical system.
- To design a low-complexity, scalable, and energy-autonomous solution suitable for decentralized, off-grid, and resource-constrained photovoltaic installations.

1.3 Related works

Numerous studies have examined the impact of dust accumulation on the operational efficiency of photovoltaic (PV) systems and proposed various mitigation strategies. Early approaches primarily focused on mechanical or water-based cleaning mechanisms aimed at restoring panel efficiency. While these solutions demonstrated measurable performance improvements, they often relied on predefined schedules, manual supervision, or external resources, limiting their adaptability to dynamic environmental conditions.

Several works have explored low-cost automated cleaning systems for small-scale PV installations. Nkinyam et al. proposed a waterless cleaning system integrating an Arduino-based controller with real-time clock scheduling and a combined air-blower and brush mechanism, achieving an efficiency improvement of 26.23%. Although cost-effective, the system remains schedule-driven and does not incorporate adaptive decision-making based on real-time environmental or performance data. Similarly, Maindad et al. developed a microcontroller-controlled cleaning mechanism employing linear actuators, water pumps, and GSM communication. Despite reducing human involvement, the system remains dependent on water and external infrastructure, which constrains deployment in resource-limited environments.

Other studies have investigated automated cleaning solutions for specific applications, such as solar-powered street lighting systems and multifunctional PV maintenance platforms. Dahoud et al. introduced a GSM-enabled cleaning system for solar lighting installations, while Myyas et al. developed an integrated solution combining cleaning, temperature regulation, and water recycling. Although these systems enhance operational efficiency, they typically involve complex architectures and lack lightweight, autonomous control strategies suitable for decentralized PV deployments.

Robotic and mobile cleaning approaches have also gained attention, particularly for large-scale solar farms. Khadka et al. proposed a rail-guided robotic cleaner with cloud-based monitoring, and Makmee et al. introduced a stretch-sling robotic mechanism to improve positioning accuracy. While effective in controlled environments, such robotic systems often require substantial mechanical infrastructure, external power sources, and continuous monitoring, limiting their applicability to small or off-grid installations.

In parallel, non-contact dust removal techniques have been explored to reduce mechanical wear and water dependency. Electrodynamic shields, electrostatic cleaning, and surface acoustic wave-based methods have demonstrated potential for dust detachment with low power consumption. However, these approaches generally focus on the physical removal process and provide limited integration with real-time sensing, adaptive control, or system-level performance management.

More recent research has begun to incorporate sensing and classification mechanisms to trigger cleaning actions. For instance, vision-based and color-analysis techniques have been used to estimate dust levels and initiate cleaning. While these methods represent a step toward automation, they often remain reactive and lack closed-loop control architectures capable of continuously managing performance under uncertainty.

In summary, existing research predominantly addresses the mechanical and physical aspects of dust removal, with limited emphasis on information-driven, autonomous system management. The integration of real-time sensing, adaptive decision logic, and energy-autonomous operation into a unified cyber-physical framework remains an open challenge. The present work addresses this gap by proposing a lightweight, event-driven Dust Detection and Protection System (DDPS) that emphasizes autonomous performance management rather than scheduled or manually supervised cleaning.

2. System Overview

2.1. Hardware Architecture

The hardware architecture of the proposed Dust Detection and Protection System (DDPS) is designed to enable autonomous, real-time decision-making with low complexity and high energy efficiency. The system integrates environmental sensing, embedded control, and actuation into a compact cyber-physical configuration suitable for small- and medium-scale photovoltaic (PV) installations.

Ambient light conditions are monitored using two light-dependent resistor (LDR) sensors, which improve measurement stability and reduce the influence of transient disturbances. Sensor data are processed by an embedded microcontroller to determine the system's operational state. Two potentiometers are used to adjust motor power limits and sensor sensitivity, allowing adaptive operation under varying environmental conditions. A calibration push button enables on-site system tuning by establishing reference light levels.

The control unit is implemented using an Arduino Uno microcontroller, while actuation is performed via a brushless motor controlled through an electronic speed controller (ESC). System feedback is provided through basic visual and audible indicators. Power is supplied by a 12 V (3S, 11.1 V) battery, enabling standalone and energy-autonomous operation. The overall electrical architecture and signal flow of the DDPS are illustrated in Fig. 2.

Key hardware components include: Arduino Uno, LDR sensors, potentiometers, brushless motor with ESC, calibration button, LED, buzzer, battery, and ON/OFF control switch.

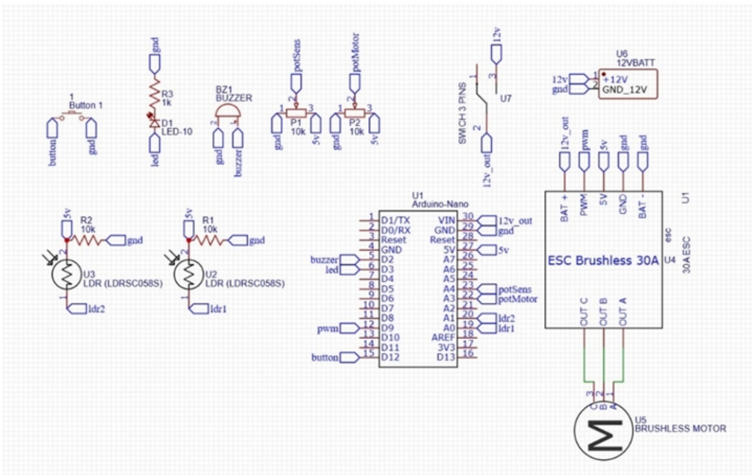


Fig. 2. Electrical schematic and hardware architecture of the proposed DDPS.

2.2. Software and Algorithm

The Dust Detection and Protection System (DDPS) operates based on an autonomous control algorithm implemented on an embedded microcontroller. The system continuously monitors ambient light conditions using LDR sensors to detect potential performance degradation caused by dust accumulation on the photovoltaic surface.

Sensor readings are compared against calibrated threshold values representing normal operating conditions. When the measured light intensity falls below the defined threshold, the control algorithm activates the cleaning mechanism by starting the motor. Once the light level returns to the normal range, the motor is automatically deactivated. This event-driven logic ensures that cleaning actions occur only when required.

The operational sequence includes system initialization, continuous sensor monitoring, conditional motor activation, and automatic return to standby mode. All processes are executed autonomously without the need for continuous user intervention. The sensor configuration used for ambient light monitoring is shown in Fig. 3.

Fig. 3. LDR sensors

2.3. PV module

The photovoltaic (PV) module serves as both the energy generation unit and the physical surface subject to dust accumulation in the proposed system. Variations in incident solar radiation caused by surface soiling directly affect the electrical output of the module, making it a suitable reference element for performance monitoring. In the DDPS framework, changes in illumination and resulting power degradation are used as indirect indicators of dust accumulation, enabling autonomous detection without additional sensing infrastructure. The PV module also supplies electrical energy to the system, supporting energy-autonomous operation.

2.4. Control unit (Arduino Uno)

The control unit of the proposed system is implemented using an Arduino Uno microcontroller, which serves as the central processing and decision-making component of the DDPS. The microcontroller acquires sensor data, executes the control algorithm, and generates actuation commands for the cleaning mechanism. The Arduino Uno was selected due to its low power consumption, ease of integration, and suitability for embedded autonomous control applications. Its use simplifies system implementation while ensuring reliable real-time operation in resource-constrained environments.

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. **Fig.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.

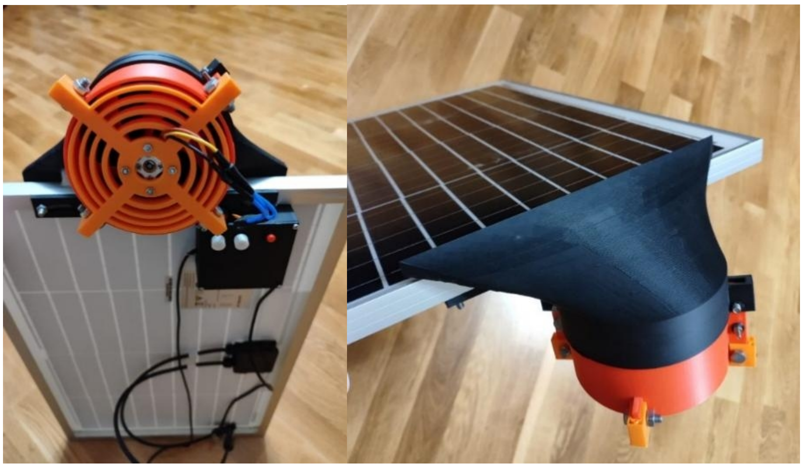


Fig. 4. Prototype of cleaning system for solar panels

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

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 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.

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

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)**.

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

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

The experimental results confirm that dust accumulation has a substantial impact on the electrical performance of photovoltaic modules. Comparative measurements obtained under dusty and clean conditions show a clear reduction in voltage, current, and output power due to surface contamination.

The clean photovoltaic panel consistently delivers higher output power compared to the dusty panel. The observed average power improvement of 56.055% after cleaning highlights the severity of dust-induced performance degradation and confirms the effectiveness of the proposed Dust Detection and Protection System (DDPS).

More importantly, the results validate the event-driven control strategy employed by the DDPS, in which cleaning actions are initiated based on detected performance degradation rather than fixed schedules or manual intervention. This demonstrates that the system functions as an autonomous performance management solution rather than merely a mechanical cleaning device.

From a system-level perspective, the experimental findings indicate that lightweight embedded control combined with simple sensing mechanisms can reliably support autonomous operation under varying environmental conditions, making the proposed approach suitable for small-scale photovoltaic installations.

In addition to performance recovery, the DDPS exhibits several system-level advantages relevant to autonomous photovoltaic operation. The waterless and mechanically simple design eliminates dependence on external water resources and reduces mechanical wear. A brushless or minimal-contact cleaning approach enhances system durability, while the predictive, reflex-based control strategy optimizes cleaning frequency and minimizes unnecessary energy consumption. Furthermore, the low-complexity and energy-autonomous configuration enables deployment in small-scale, rural, off-grid, and infrastructure-limited environments.

3.3. 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.

3.4. 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.

4. Conclusion

This paper presented an intelligent Dust Detection and Protection System (DDPS) as an information-driven autonomous control solution for managing photovoltaic system performance under dynamic environmental conditions. By integrating sensor-based monitoring with a predictive reflex control architecture, the proposed system enables real-time, event-triggered decision-making without reliance on fixed schedules or human supervision.

Experimental results demonstrate that the DDPS effectively detects performance degradation and initiates corrective action, achieving a measurable restoration of photovoltaic output following dust accumulation. These findings validate the effectiveness of reflex-based autonomous control in maintaining system performance while minimizing unnecessary actuation, energy consumption, and mechanical wear. The closed-loop nature of the system ensures adaptive behavior in response to environmental uncertainty, a critical requirement for modern cyber-physical energy systems.

A key advantage of the proposed architecture is its energy-autonomous operation, as all system components draw power directly from the photovoltaic panel itself. This characteristic enhances resilience and enables deployment in off-grid, remote, or high-risk environments where external power supply and maintenance access are limited. Furthermore, the system's modular and low-complexity design supports scalability and integration into small and medium-scale photovoltaic installations.

From an information technology perspective, the DDPS exemplifies how embedded sensing, lightweight control logic, and autonomous decision-making can be combined to manage complex physical processes efficiently. While this study focuses on photovoltaic performance management, the underlying architecture is broadly applicable to other domains requiring autonomous monitoring and control under uncertainty, such as smart infrastructure, environmental monitoring, and distributed energy systems.

Future work will extend the DDPS framework by incorporating distributed communication technologies such as LoRaWAN and Zigbee, enabling cooperative management across multiple photovoltaic units. Additionally, integrating predictive models based on weather data and machine learning techniques for dust accumulation forecasting could further enhance system intelligence and long-term performance optimization.

References

1. Adekanbi, M. L., Alaba, E. S., John, T. J., Tundealao, T. D., & Banji, T. I. (2024). Soiling loss in solar systems: A review of its effect on solar energy efficiency and mitigation techniques. Cleaner Energy Systems, 7, 100094.
2. Al Dahoud, A., Fezari, M., & Al Dahoud, A. (2021, November). Automatic solar panel cleaning system Design. In 2021 29th Telecommunications Forum (TELFOR) (pp. 1–4). IEEE.
3. Alagoz, S., & Apak, Y. (2020). Removal of soiling materials from solar panel surfaces by applying surface acoustic waves. Journal of Cleaner Production, 253, 119992.

4. Al-Housani, M., Bicer, Y., & Koç, M. (2019). Experimental investigations on PV cleaning of large-scale solar power plants in desert climates: Comparison of cleaning techniques for drone retrofitting. Energy Conversion and Management, 185, 800-815.
5. Amin, A., Wang, X., Alroichdi, A., & Ibrahim, A. (2023). Designing and Manufacturing a Robot for Dry-Cleaning PV Solar Panels. International Journal of Energy Research, 2023(1), 7231554.
6. ASEU. (2023, March 4). Ukrainians shift to renewable power for energy security amid war.
7. Badalyan, N. K. (2024). Analysis of Soiling Measurement Systems and Cleaning Methods of Solar Photovoltaic Modules. Proceeding of NPUA: Electrical Engineering, Energetics, 1, 74-83.
8. Bessa, J. G., Micheli, L., Almonacid, F., & Fernández, E. F. (2021). Monitoring photovoltaic soiling: assessment, challenges, and perspectives of current and potential strategies. iScience, 24(3).
9. Boulaid, M., Oaddi, R., Tihane, A., Elfanaoui, A., & Ihlal, A. (2020). Photovoltaic system energy yield monitoring. Materials Today: Proceedings, 24(Part 1), 81–84.
10. Burke, M., Greenough, R., Jensen, D., & Voss, E. (2016). Project SPACE: Solar Panel Automated Cleaning Environment. Mechanical Engineering Senior Theses, 62.
11. Crawford, M. (2022). Water-Free Cleaning of Solar Panels Saves Millions of Gallons of Water. ASME.
12. Ghosh, A. (2020). Soiling losses: A barrier for India's energy security dependency from photovoltaic power. Challenges, 11(1), 9.
13. Hooshyar, P., Moghadasi, H., Moosavi, S. A., Moosavi, A., & Nouri Borujerdi, A. (2025). Recent progress of soiling impact on solar panels and its mitigation strategies: A review. Applied Energy, 379, 124979.
14. Kalaji, A. A., Abbas, A. S., & Magdy, M. (2022). A review of automatic cleaning systems for photovoltaic solar panels. International Advanced Research Journal in Science, Engineering and Technology, 9(1).
15. Kawamoto, H. (2019). Electrostatic cleaning equipment for dust removal from soiled solar panels. Journal of Electrostatics, 98, 11–16.
16. Khadka, N., Bista, A., Adhikari, B., Shrestha, A., & Bista, D. (2020, March). Smart solar photovoltaic panel cleaning system. In IOP Conference Series: Earth and Environmental Science (Vol. 463, No. 1, p. 012121). IOP Publishing.
17. Li, D., King, M., Dooner, M., Guo, S., & Wang, J. (2021). Study on the cleaning and cooling of solar photovoltaic panels using compressed airflow. Solar Energy, 221, 433–444.
18. Maindad, N., Gadhave, A., Satpute, S., & Nanda, B. (2020, April). Automatic solar panel cleaning system. In 2nd International Conference on Communication & Information Processing (ICCIP).
19. Makani, J. M., Patel, V. B., Sharma, A. J., Patel, M. M., & Patel, H. A. (1954). Design of waterless solar panel cleaning system. Int. Res. J. Eng. Technol, 1958.
20. Makmee, T., & Pengwang, E. (2021, April). Design and experiment of four-side stretch sling-based solar cleaning robot. In 2021 7th International Conference on Engineering, Applied Sciences and Technology (ICEAST) (pp. 182–189). IEEE.
21. Mekonnen, M. M., Gerbens-Leenes, P. W., & Hoekstra, A. Y. (2015). The consumptive water footprint of electricity and heat: a global assessment. Environmental Science: Water Research & Technology, 1, 285–297.
22. Min, R. (2024, February 13). Palestinians rely on solar panels amid electricity cuts to talk to friends and family. Euronews.

23. Myyas, R. E. N., Al-Dabbasa, M., Tostado-Véliz, M., & Jurado, F. (2022). A novel solar panel cleaning mechanism to improve performance and harvesting rainwater. Solar Energy, 237, 19–28.
24. Nahar Myyas, R., Al-Dabbasa, M., Tostado-Véliz, M., & Jurado, F. (2022). A novel solar panel cleaning mechanism to improve performance and harvesting rainwater. Solar Energy, 237, 19–28.
25. Nkinyam, C. M., Ujah, C. O., Nnakwo, K. C., Ezeudu, O., Kallon, D. V. V., Ike-Eze, I., & Ezema, C. (2025). Design and implementation of a waterless solar panel cleaning system. Unconventional Resources, 5, 100131.
26. Otter, P., Sattler, W., Grischek, T., Jaskolski, M., Mey, E., Ulmer, N., Grossmann, P., Matthias, F., Malakar, P., Goldmaier, A., Benz, F., & Ndumwa, C. (2020). Economic evaluation of water supply systems operated with solar-driven electro-chlorination in rural regions in Nepal, Egypt and Tanzania. Water Research, 187, 116384.
27. Patel, S., Veerasamy, V. S., John, J. S., & Orlov, A. (2023). A comprehensive review on dust removal using electrodynamic shield: Mechanism, influencing factors, performance, and progress. Renewable and Sustainable Energy Reviews, 183, 113471.
28. Topaloglou, L., & Nikolaidou, K. (2025). Exploring Climate, Energy, and Environmental Justice in Climate Change, SDGs, and Transition Contexts.
29. White, W. J., O'Connor, A. C., & Rowe, B. R. (2004). Economic Impact of Inadequate Infrastructure for Supply Chain Integration. National Institute of Standards and Technology Planning Report 04-2. Research Triangle Park: RTI International.