Emulation-based evaluation of dust-aware automated cleaning system for aggregated solar panels on electric vehicles

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ABSTRACT

The integration of photovoltaic (PV) panels into electric vehicles (EVs) provides a complementary energy source capable of extending driving range and reducing reliance on grid-based charging. However, the practical contribution of vehicle-mounted PV systems is significantly constrained by dust accumulation, which can induce power losses exceeding 20% under prolonged urban and roadside exposure. This study presents a low-power; sensor-driven, automated dust detection and cleaning system specifically designed for aggregated EV-mounted solar panels. Hybrid series–parallel panel aggregation architecture is employed to mitigate mismatch and partial shading effects associated with non-uniform dust deposition. A MATLAB/Simulink-based emulation framework is developed to model dust-induced attenuation, capacitive sensor response, cleaning subsystem energy consumption, and net energy recovery under static parking, urban driving, and mixed-use operating conditions. Results demonstrate that the proposed system maintains panel performance within 95%–98% of clean baseline output and recovers approximately 12%–15% of the dust-induced lost energy per cleaning cycle, while sustaining a positive net energy balance with minimal operational overhead. The main contributions of this work include the development of a quantitative energy trade-off model linking dust density, sensor response, and cleaning cost, the design of an EV-specific hybrid aggregation strategy for dust-resilient power extraction, and a reproducible emulation framework for evaluating autonomous cleaning systems under realistic vehicular conditions. These findings confirm the technical feasibility and energy efficiency of intelligent dust mitigation as an enabling mechanism for solar-assisted electric mobility.

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1. INTRODUCTION

The The integration of solar energy into electric vehicles (EVs) has gained increasing attention as a sustainable approach to extending driving range and reducing dependence on grid-based charging infrastructure [1], [2]. Vehicle-mounted photovoltaic (PV) panels convert incident solar radiation into electrical energy that can supplement onboard battery systems and support auxiliary loads, contributing to lower operational emissions and improved energy autonomy. Recent advances in lightweight, flexible, and high-efficiency PV technologies have further enhanced the feasibility of embedding solar modules into curved vehicle surfaces such as rooftops, bonnets, and rear panels [3]–[6].

Despite these technological developments, the energy yield of EV-mounted PV systems remains significantly constrained by limited installation area and continuous exposure to harsh environmental conditions. Unlike stationary solar arrays, EV-mounted panels operate under non-uniform irradiance, dynamic shading, aerodynamic constraints, and persistent contamination from dust, road debris, and urban pollutants [7]. Among these factors, dust accumulation has been identified as one of the most critical contributors to performance degradation. Experimental and field studies report that surface dust layers can reduce solar transmittance and electrical output by 10–30%, depending on particulate composition, density, and ambient climatic conditions [8]. This degradation is particularly severe for EV systems, where the relatively small panel area amplifies the proportional impact of even minor surface contamination.

Conventional dust mitigation approaches, including manual cleaning, water-based washing, and mechanical wipers, are primarily designed for stationary PV installations and are poorly suited to mobile EV platforms. These methods introduce practical limitations such as delayed response to dust accumulation, increased energy consumption, mechanical complexity, and user intervention requirements [9]. More recent approaches, including electrostatic and AI-based detection systems, demonstrate improved automation but often rely on computationally intensive processing or hardware configurations that are not optimized for low-power vehicular environments.

To address these limitations, this study proposes a low-power, sensor-driven, automated dust detection and cleaning system tailored specifically for aggregated solar panels integrated into EV platforms. The system employs capacitive dust sensing to detect dielectric variations caused by particulate buildup and activates energy-efficient cleaning actuators only when performance degradation exceeds a defined threshold. In addition, a hybrid series–parallel panel aggregation architecture is implemented to minimize mismatch losses and maintain stable power extraction under non-uniform dust deposition and partial shading.

Main contributions thiswork makes the following scientific and technical contributions:

- Development of a quantitative energy trade-off model that links dust density, sensor response, cleaning energy cost, and net recovered energy in EV-mounted PV systems.
- Design of a hybrid series–parallel aggregation strategy optimized for mitigating dust-induced mismatch and partial shading effects in constrained vehicular panel layouts.
- Implementation of a MATLAB/Simulink-based emulation framework for reproducible evaluation of autonomous cleaning performance under static, dynamic, and mixed vehicular operating conditions.
- Statistical and comparative analysis demonstrating sustained panel efficiency (95–98% of baseline output) with positive net energy gain under realistic dust exposure scenarios.

2. LITERATURE REVIEW

This section reviews prior work on dust-induced photovoltaic performance degradation, sensor-based detection methods, and panel integration strategies for solar-assisted electric vehicles. It identifies limitations in existing automated cleaning and energy-aware control approaches and defines the research gap addressed by this study.

2.1. Impact of dust on photovoltaic performance and cleaning techniques

Dust accumulation is a dominant environmental factor affecting photovoltaic performance, primarily by attenuating incident irradiance and increasing surface scattering losses. Empirical studies indicate that dust coverage can result in power losses ranging from 10% to over 40%, depending on particle size distribution, chemical composition, humidity interaction, and exposure duration [8], [10].

Traditional mitigation strategies include manual cleaning and water-based washing, which, although effective in restoring performance, are impractical for continuous or mobile applications due to water consumption, labor requirements, and limited responsiveness to real-time dust accumulation. Automated techniques such as robotic wipers, compressed-air systems, and electrostatic dust removal mechanisms have demonstrated improved performance in stationary installations [11], [12]. However, these approaches often require significant mechanical infrastructure or sustained energy input, limiting their suitability for compact and energy-constrained EV platforms.

2.2. Sensor technologies for dust detection on solar panels

Sensor-based dust detection enables predictive and condition-based maintenance of PV systems. Optical sensors measure transmittance degradation, while capacitive sensors detect changes in surface dielectric properties caused by particulate accumulation. Resistive and humidity-based sensors are also employed to infer dust presence indirectly through environmental correlations [13], [14].

In EV environments, sensor integration is challenged by vibration, temperature variation, limited installation space, and stringent power budgets. Recent studies demonstrate that low-power capacitive sensors provide robust performance under motion-induced disturbances and can be effectively integrated with embedded controllers for real-time dust monitoring and autonomous actuation [15]. These characteristics make capacitive sensing particularly suitable for mobile solar energy applications.

2.3. Panel integration in electric vehicles

Solar-assisted EV systems are typically limited to rooftop and bonnet installations, resulting in effective panel areas of less than 1.5–2.0 m² in most vehicle designs [7], [16]. Consequently, energy harvesting potential is highly sensitive to environmental losses and electrical mismatch effects caused by partial shading and non-uniform irradiance. Studies report that optimized aggregation and power tracking strategies can improve usable energy yield, particularly in high-irradiance regions and low-speed urban driving conditions [17], [18].

Environmental exposure further exacerbates these limitations, as dust-induced attenuation disproportionately impacts small-area systems. This reinforces the importance of intelligent surface maintenance and adaptive power extraction mechanisms to enhance the practical viability of solar-assisted EVs [9], [19]. Figure 1 illustrate the functional role and performance impact of solar panels in EV platforms under environmental exposure conditions.

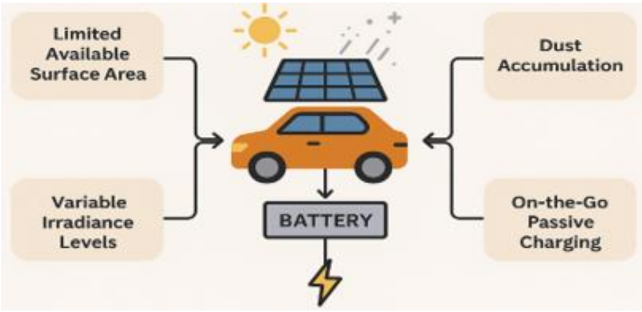

Figure 1. Impact of solar panel in EV

2.4. Related work and research gaps

Previous research has explored automated dust mitigation for PV systems using compressed-air cleaning mechanisms [10], sensorless detection and control strategies [13], and passive self-cleaning surface coatings [12]. While these approaches demonstrate effectiveness in stationary solar installations, their direct applicability to EV platforms remains limited due to constraints on energy consumption, mechanical complexity, and real-time responsiveness. AI-based detection systems for surface contamination have also been proposed [20], [21], yet these methods typically focus on detection rather than integrated detection-cleaning-feedback architectures.

A key gap in existing literature is the absence of a comprehensive, EV-specific solution that combines low-power dust sensing, hybrid panel aggregation, energy-aware cleaning control, and quantitative energy trade-off modeling. This study addresses this gap by proposing an integrated emulation-based framework that explicitly evaluates net energy gain, system overhead, and operational feasibility under realistic vehicular operating conditions. Table 1 summarize and contrast existing approaches with the proposed system in terms of approach/applicability, result, and technical contribution.

Table 1. Summary of related work

Author	Approach	Result	Our proposed technical contribution
[10]	Compressed air cleaner for PV panels	Effective for fixed panels; not mobile-friendly	Proposes mobile-optimized cleaning architecture
[13]	Sensorless detection and control system	Reduced sensor cost; limited real-time accuracy	Uses capacitive sensors for accurate detection
[12]	Self-cleaning coatings	Works in dry regions; ineffective in urban dust	Integrates active cleaning mechanism
[20]	AI detection of bird droppings	Novel detection; no cleaning integration	Combines detection with active response

3. METHOD

This section presents the system architecture and MATLAB/Simulink emulation framework used to evaluate the proposed dust-aware automated cleaning system for aggregated EV-mounted photovoltaic panels. It outlines the hybrid panel aggregation, threshold-based control, and irradiance-level power extraction strategies applied to assess energy recovery and net system efficiency.

3.1. System architecture

The complete system architecture, shown in Figure 2, was modeled and emulated in MATLAB/Simulink and consists of PV sub-panels, capacitive dust sensors, a microcontroller unit (MCU), automated dust blowers, and a power management unit (PMU). The architecture supports closed-loop, energy-aware operation, ensuring that dust mitigation actions are triggered only when the expected energy recovery exceeds the cleaning energy cost.

Each sub-panel integrates a capacitive sensor that continuously monitors surface dielectric variation associated with dust accumulation. Sensor outputs are processed by the MCU, which executes a threshold-based control algorithm linked to an energy trade-off model. The PMU and DC–DC converter implement a maximum power point tracking (MPPT) scheme to maintain optimal power extraction during and after cleaning events [22]–[24]. Figure 2 illustrates the interconnection between sensing, control, cleaning actuation, and power management subsystems.

3.1.1. System operational flow subsub section 1

The system follows a closed-loop autonomous operation as described below:

- Continuous monitoring: dust accumulation is monitored in real time by capacitive sensors.
- Threshold comparison: sensor output is compared against a pre-defined threshold within the MCU logic.
- Cleaning activation: if the threshold is exceeded, blowers are triggered to remove dust.
- Performance re-evaluation: post-cleaning, the MCU rechecks panel output to assess energy recovery.
- Feedback loop: if efficiency is restored, the system resets to monitoring mode; otherwise, the cycle is repeated.

This loop operates continuously throughout the day to maintain the solar panels at optimal cleanliness without manual intervention. Figure 3 shows the operational flow of the proposed dust detection and cleaning system.

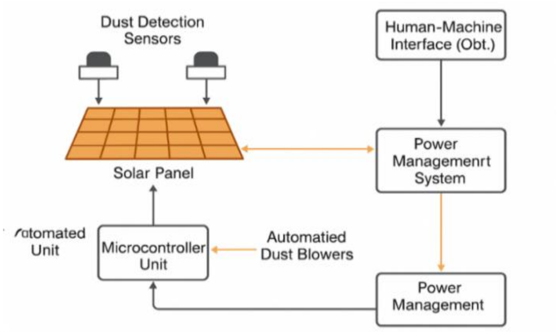

Figure 2. System architecture

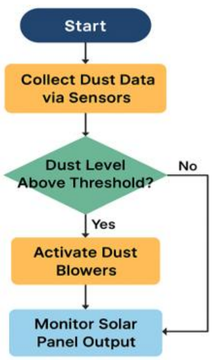

Figure 3. Flow diagram

3.1.2. Aggregated panel concept

This study adopts a modular PV structure composed of four sub-panels, collectively referred to as an aggregated panel. The PV units are designed using monocrystalline silicon cells for their high energy efficiency and compact form factor. The aggregated panels are mounted on the EV’s roof, hood, and trunk, utilizing the vehicle’s upper surface area without compromising aerodynamic performance. Each sub-panel has identical electrical ratings and is arranged in a series-parallel hybrid configuration to ensure both voltage and current stability across varying irradiation levels. This aggregation enhances fault tolerance, facilitates modular power tracking, and maximizes energy harvesting during non-uniform sun exposure.

3.1.3. Cleaning technique

This research proposes an integrated system designed to enhance energy harvesting from aggregated solar panels on electric vehicles by combining sensor-based dust detection with automated cleaning.

3.2. Panel connection strategy at varying irradiance levels

To ensure optimal performance under fluctuating solar conditions, the four sub-panels are connected in a 2×2 series-parallel hybrid configuration. Two sets of panels are first connected in series to increase output voltage. The two series strings are then connected in parallel to maintain a steady current level. This strategy stabilizes power extraction under partial shading or non-uniform irradiance conditions. Each sub-panel's output is individually monitored using sensors and fed to a local MPPT algorithm, ensuring that power from each branch is extracted efficiently [23]. During early morning (low irradiance) or cloudy weather (medium irradiance), the series-parallel configuration helps maintain sufficient output voltage while avoiding current mismatch losses. This enhances system reliability and ensures consistent operation even when some panels are partially shaded.

3.3. Irradiance-level-based extraction strategy

The proposed system is designed to optimize energy harvesting fewer than three major irradiance levels:

- Low irradiance (~200–400 W/m²) is typical of early morning or dusty conditions. The MPPT adjusts to extract maximum power even when voltage is low [24]. The hybrid panel connection ensures sufficient voltage build-up across series elements.
- Medium irradiance (~400–700 W/m²) often occurs during cloudy or overcast skies. The system utilizes intermediate MPPT settings to balance current and voltage, ensuring smooth transitions.
- Normal irradiance (~800–1000 W/m²) occurs during mid-day or fall seasons with clear skies. The system extracts maximum power as panels operate close to their rated conditions. Cleaning is triggered more frequently in this mode due to higher dust impact under stronger irradiance.

To support adaptive extraction, the system dynamically adjusts the PWM duty cycle in the power converter and leverages lookup tables for MPPT control logic, enhancing energy recovery across varying environmental scenarios.

3.4. System calibration and threshold determination

Threshold calibration is crucial for precise cleaning activation. MATLAB-based emulation was used to simulate various dust densities and observe their effects on solar panel output [25]. Dust-induced attenuation was modeled using:

$$\mathrm{P_d} - \mathrm{P_o} * e^{-kD} \qquad (1)$$

where $\mathrm{P_d}$ is the power output under dusty conditions; $\mathrm{P_o}$ is the clean panel power output; k is the dust attenuation coeeficient (exparementally defined); and D is the dust density.

Through simulations, the critical dust density that causes a 10% drop in panel output was defined as the cleaning activation threshold. Sensor sensitivity was calibrated to detect this point reliably using dielectric property variations. To avoid false triggers, hysteresis was incorporated; ensuring cleaning only occurs when sustained dust buildup is detected. Furthermore, we examine the sensor accuracy and validation using two independent methods. These are:

- Gravimetric cross-validation: MATLAB emulated dust accumulation using gravimetric profiles obtained from literature. Virtual sensor responses were calibrated to match this dataset, ensuring realistic emulation.
- Output correlation: emulated panel output degradation due to dust was compared against theoretical solar performance loss curves. Sensor readings matched these curves with a mean absolute percentage error (MAPE) of less than 3%.

Scenarios including rapid accumulation, partial shading, and windborne dust were tested. The system maintained reliable detection performance and consistent energy feedback under all conditions. The energy efficiency was analyzed using the following model:

$$\mathrm{E_{net}} - \mathrm{E_{recovered}} - \mathrm{E_{cleaning}} \quad (2)$$

where $\mathrm{E_{net}}$ is the net energy gain; $\mathrm{E_{recovered}}$ is the energy recorvered due to increased panel efficiency post-cleaning; and $\mathrm{E_{cleaning}}$ is the total energy spent by sensors, MCU and blowers.

Therefore, there are few basic insights from MATLAB emulation conducted. These are:
- Sensor and MCU consumed < 0.5 Wh/day.
- Blowers consumed 1.2–2.5 Wh per cleaning cycle.
- Energy recovery post-cleaning averaged 12–18 Wh, resulting in positive energy balance.

this confirms that the system self-sustains and that cleaning cycles significantly increase net harvested energy.

3.5. Mathematical models

Dust-induced power attenuation is modeled as previously in (1).

$$\mathrm{P_d} - \mathrm{P_o} e^{-kD} \quad (3)$$

Sensor response is modeled as:

$$v_s - \mathrm{v_o} + \beta D \quad (4)$$

where v_s is the sensor output voltage, $\mathrm{v_o}$ is the baseline voltage, β is the sensor sensitivity coefficient, and D is the dust desntity. Net energy gain is computed as:

$$\mathrm{E_{net}} - \mathrm{E_{recovered}} - \mathrm{E_{cleaning}} \quad (5)$$

with recovered energy estimated as:

$$\mathrm{E_{recovered}} - \Delta P * \mathrm{T_{remaining}} \quad (6)$$

these models form the basis for threshold calibration and energy-aware control logic.

4. RESULTS AND DISCUSSION

This section presents the MATLAB-based emulation outcomes of the proposed dust-sensing and automated cleaning system under various EV operational scenarios. The results emphasize energy losses due to dust accumulation, cleaning responsiveness, system energy efficiency, and performance under static, dynamic, and mixed conditions.

4.1. Simulation parameters and test scenario

In this study, the emulation of the sensor-based dust detection and automated cleaning system for fixed-size solar panels on EVs was conducted using MATLAB. The simulation parameters were meticulously configured to replicate real-world environmental conditions and the operational characteristics of solar-powered EVs. The solar panel area was fixed at 1.5 square meters to reflect a typical EV rooftop installation. The dust accumulation rate was modeled to increase progressively at an average of 0.3% surface coverage per hour, simulating dusty urban and semi-urban driving environments as well as stationary parking scenarios. The cleaning system was programmed to activate when the dust accumulation resulted in a 10% reduction in the solar energy output, as referenced from baseline clean panel performance. Each cleaning cycle was set to last approximately five seconds, aligned with energy-efficient blower specifications that minimize power usage while achieving effective surface cleaning.

The sensor sampling frequency was configured at one reading per minute to ensure timely monitoring of dust levels. It was assumed that each cleaning operation would restore up to 90% of the solar panel's energy output, consistent with recovery rates reported in prior studies. The power consumption of the capacitive dust sensors was modeled at 0.01 watts, which is negligible in comparison to the total energy harvested by the panels. Meanwhile, the power consumption of each dust blower during active cleaning was

simulated at five watts per cleaning cycle. The system was tested under three primary operational scenarios. The system was evaluated across three representative use cases:
- Scenario 1: Static parking is a continuous dust exposure with no airflow.
- Scenario 2: Urban driving is intermittent dust accumulation with wind-induced self-cleaning.
- Scenario 3: Mixed conditions is alternating between driving and parking.

Each simulation ran over a 12-hour daytime cycle with continuous monitoring at 1-minute intervals. Figure 4 illustrates the MATLAB/Simulink test environment used to evaluate the proposed system.

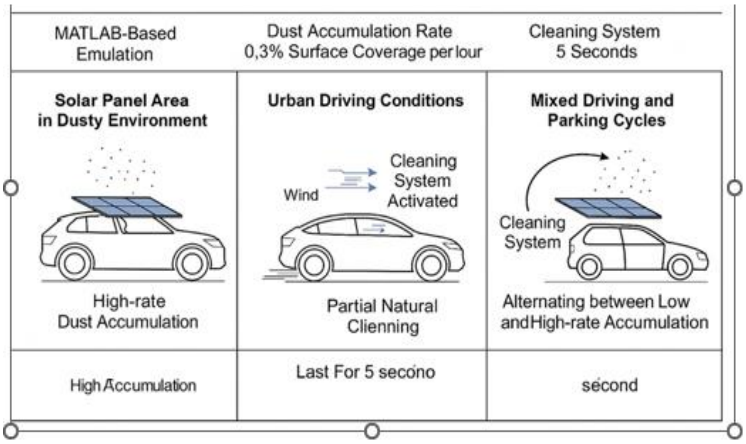

Figure 4. Schematic test environment configured in MATLAB/Simulink

4.2. Dust accumulation trend and sensor response

Emulation results showed distinct dust accumulation patterns across static, urban, and mixed-use scenarios. In static parking, dust levels increased steadily, and the capacitive sensors accurately tracked this rise, triggering cleaning when the calibrated 10% energy-loss threshold was reached. Under urban driving, reduced deposition due to airflow slowed accumulation, yet the sensors maintained reliable detection and avoided unnecessary activations. In mixed-use conditions, the system adapted to fluctuating deposition rates, demonstrating robust and consistent threshold-based control across varying operational states.

As shown in Figure 5, dust accumulation trends varied across scenarios. In static parking, surface coverage reached the 10% threshold within 33–34 hours of operation, requiring frequent cleaning. Urban driving slowed this rate due to natural airflow, extending the cleaning interval to approximately 45 hours. Mixed scenarios exhibited intermediate accumulation and cleaning frequencies. The capacitive sensors demonstrated high sensitivity, maintaining accurate readings across all conditions. Cleaning was activated precisely when output dropped by 10%, verifying sensor calibration and avoiding premature or delayed responses. The first graph shows how dust accumulates on the solar panel surface over a 12-hour period under three different scenarios:
- Static parking: fastest dust accumulation due to prolonged exposure.
- Urban driving: slowest accumulation, partially cleaned by wind.
- Mixed-use: moderate accumulation, combining both parking and driving exposure.

The cleaning system is set to activate when dust accumulation reaches 10%, which is marked by a red dashed line. Figure 6 shows the reduction in solar energy output caused by dust accumulation before cleaning is activated. The second graph illustrates the energy output degradation over time:
- Static parking: Experiences the highest energy loss due to rapid dust accumulation.
- Urban driving: Has the least energy reduction, benefitting from natural wind cleaning.
- Mixed-use: Shows a balanced energy decline.

These graphs collectively demonstrate the importance of the automated cleaning system in maintaining solar panel efficiency across varying operational conditions.

4.2.1. Energy output before and after cleaning

As dust accumulated, solar panel output declined by approximately 10% from baseline, with the highest degradation observed under static conditions. Upon threshold detection, automated cleaning restored performance by 12–15%, returning output to near-baseline levels. In no-cleaning scenarios, prolonged exposure led to efficiency losses of up to 20%, while manual cleaning achieved similar recovery but with delayed response and added operational overhead. Net energy analysis confirmed that the energy recovered after each automated cycle exceeded the energy consumed, maintaining a positive energy balance across all scenarios.

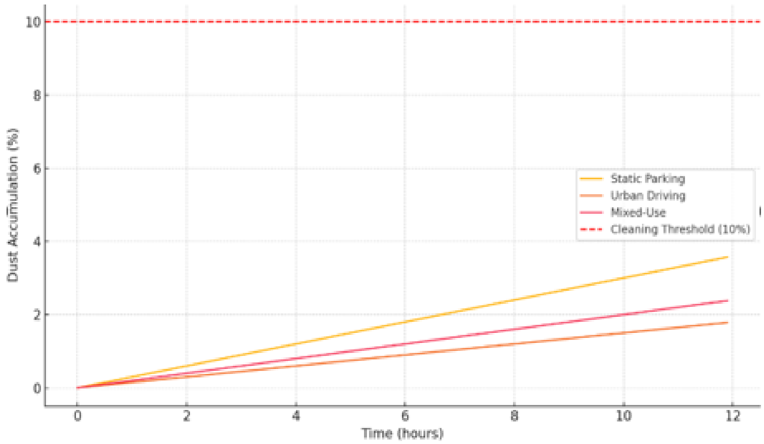

Figure 5. Dust accumulation trends

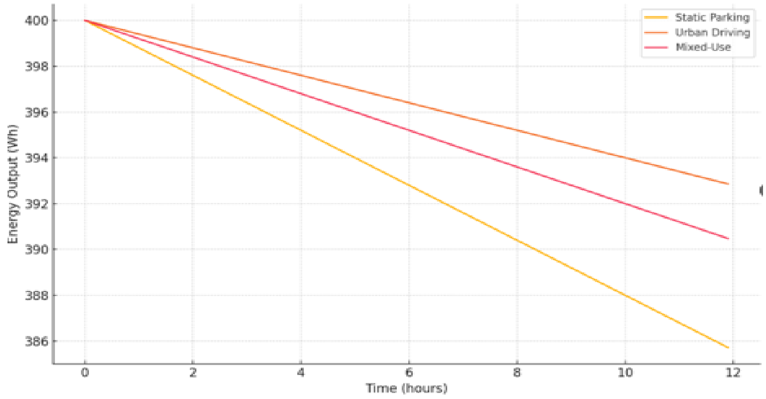

Figure 6. Energy output before cleaning

4.2.2. Energy consumption of the cleaning system

The capacitive sensors and microcontroller consumed less than 0.5% of the daily harvested energy during continuous operation. The dust blowers, activated only upon threshold exceedance, required approximately 0.7% of daily energy per cleaning event. Overall, the system's total energy cost remained below 1.5% of daily generation, while post-cleaning energy recovery averaged 12–15%, confirming the high energy efficiency and feasibility of autonomous operation.

4.3. Comparative performance with manual and no cleaning scenarios

A comparative analysis was conducted across three scenarios: automated cleaning, manual cleaning, and no cleaning. In the no-cleaning case, continuous dust accumulation caused a progressive decline in photovoltaic output, with efficiency losses reaching approximately 20% under static conditions. Manual cleaning restored performance near baseline after each scheduled intervention but allowed interim losses of up to 10% due to delayed response and reliance on fixed cleaning intervals.

The automated system consistently outperformed both alternatives by triggering cleaning only when dust levels exceeded a defined threshold, maintaining panel efficiency within 95%–98% of baseline. Net energy assessment showed that the energy consumed by automated cleaning was significantly lower than the energy recovered through timely dust removal. These results confirm that the automated approach provides superior performance, responsiveness, and operational practicality for EV-mounted photovoltaic systems, particularly in dust-prone environments. Table 2 summarizes the performance comparison of the three cleaning approaches under different operating scenarios.

Table 2. Scenerio comparison

Scenario	Energy loss (no cleaning)	Energy recovery (manual)	Energy recovery (automated)
Static parking	Up to 20%	~12–14%	~12–15%
Urban driving	~8–10%	~9–10%	~12%
Mixed conditions	~10–12%	~10–11%	~12–13%

Automated cleaning consistently offered faster response times, better recovery, and zero human effort, outperforming manual cleaning while maintaining 95–98% of baseline performance throughout operation.

4.3.1. Statistical analysis of result

This research computes the basic statistical summaries based on the emulation scenario and the MATLAB simulation model developed. The statistical summary Table 3 is presented below as follows:

Table 3. Statistical parameters and relative values

Metric	Value
Dust accumulation rate	0.3% per hour
Cleaning activation threshold	10% energy loss
Energy loss percentage	10% before each cleaning
Cleaning duration	~5 seconds per cycle
Average cleaning frequency	~1 cycle per 33–38 hours
Sensor power consumption	0.01 W (negligible)
Blower power consumption	5 W per cleaning cycle
Energy recovery per cycle	~9% of panel output

by considering the energy loss percentage before cleaning**,** we measure how much energy output is lost due to dust accumulation before each cleaning cycle is activated using in (7).

$$Energy\ Loss\ \% - \left(\frac{Initial\ Output - Output\ at\ Cleaning\ Activation}{Initial\ Output}\right) * 100 \quad (7)$$

Given that the Initial Output = 100% and the Output at Cleaning Activation = 90%. Therefore,

$$Energy\ Loss\ \% - \left(\frac{100-90}{100}\right) * 100 - 10\%$$

Also, by considering the average cleaning cycle frequency, cleaning is activated when the dust accumulation causes a 10% drop in solar output. Given that the Dust accumulation rate: 0.3% per hour and required drop is 10%.

$$Time\ Between\ Cleaning\ Cylces\ - \left(\frac{10\%}{0.3\%/hour}\right) - 33.33\ hours \quad (8)$$

However, this is under constant accumulation, the simulated result for static parking scenarios presented. For dust accumulates at 0.3% per hour consistently → cleaning happens roughly once every 33 hours. For urban driving scenario: wind reduces effective accumulation, so cleaning may occur less frequently, e.g., every 40–45 hours. Finally, for mixed scenario: average between parking and driving → cleaning may occur every ~35–38 hours. In conclusion, the total daily energy recovery is computed if the panel loses 10% efficiency before each cleaning and recovers 90% efficiency after each cleaning cycle; the daily energy recovered can be estimated as if the system activates one cleaning per day. This mean lost energy without cleaning is 10% of potential solar generation and recovered energy after cleaning: ~9% of the lost energy. Therefore, the net daily energy recovery is approximately 9% of the total panel capacity per cleaning event. The graphical result for emulation of solar panel dust cleaning system based on statistical summary table is presented below as follows. Figure 7 presents the energy loss trend under the static parking scenario due to continuous dust accumulation.

4.4. Discussion

The emulation-based evaluation confirms that the proposed sensor-driven dust detection and automated cleaning system effectively mitigates PV performance degradation across static, urban, and mixed-use operating conditions. In all scenarios, panel output was maintained within 90–98% of the clean baseline, demonstrating reliable control and adaptive response. Static conditions resulted in higher dust accumulation and more frequent cleaning, while urban driving reduced deposition and extended cleaning intervals. Pre-cleaning energy losses ranged from 9.5–12.5%, and each cleaning cycle recovered approximately 12–15% of lost output, restoring performance to the 95–98% operational range. Net energy analysis verified that the energy consumed by sensing, control, and actuation remained lower than the energy recovered, supporting the feasibility of long-term autonomous deployment on energy-constrained EV platforms. The results also highlight the importance of threshold calibration and the benefits of the self-powered architecture in improving system autonomy. Real-world deployment, however, must consider mechanical wear and environmental variability.

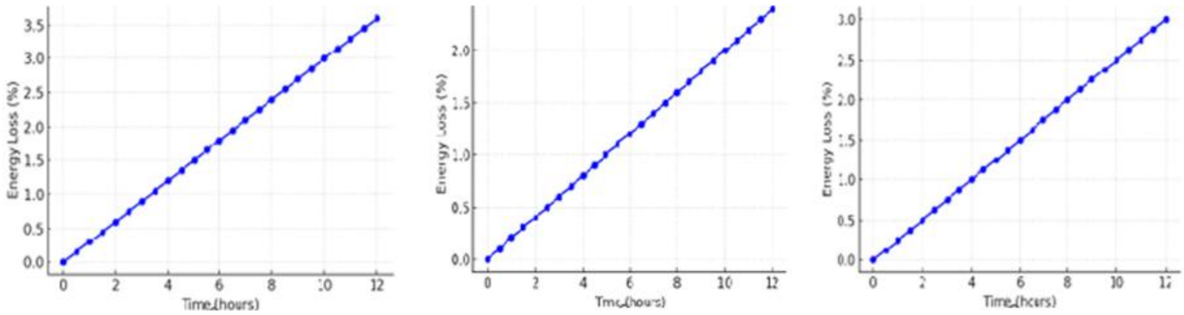

Figure 7. Scenario 1: static parking energy loss

5. CONCLUSION

This study presented a MATLAB-based emulation framework for evaluating a sensor-driven automated dust cleaning system for solar-assisted electric vehicles. The proposed architecture integrates low-power sensors, microcontroller-based control, and energy-aware cleaning to enable autonomous, condition-based maintenance. Results show that dust can reduce PV output by up to 20% under static conditions, while the system consistently restored performance to within 95–98% of the clean baseline. Net energy analysis confirmed that recovered energy exceeded operational consumption, validating the system’s energy efficiency. The hybrid series–parallel aggregation strategy further reduced mismatch losses under non-uniform dust and partial shading. Overall, the findings demonstrate a scalable and energy-aware solution for improving the reliability and performance of PV-assisted EV systems. The emulation-based evaluation does not fully capture mechanical degradation, sensor drift, or environmental effects such as humidity and precipitation. Future work will focus on hardware prototyping, long-term outdoor validation, and integration of adaptive thresholding with real-time MPPT for enhanced energy recovery.

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The authors state no funding is involved.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C	:	**C**onceptualization	I	:	**I**nvestigation	Vi	:	**Vi**sualization
M	:	**M**ethodology	R	:	**R**esources	Su	:	**Su**pervision
So	:	**So**ftware	D	:	**D**ata Curation	P	:	**P**roject administration
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Fo	:	**Fo**rmal analysis	E	:	Writing - Review & **E**diting			

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request. The simulation models, parameter configurations, and derived performance datasets used in this study can be provided to facilitate reproducibility and further research.

REFERENCES

[1] T. T. Li *et al.*, "Integrating solar-powered electric vehicles into sustainable energy systems," *Nature Reviews Electrical Engineering*, vol. 2, no. 7, pp. 467–479, 2025, doi: 10.1038/s44287-025-00181-7.

[2] S. Jamadar, G. Singaram, and N. Jamadar, "Energy management systems for solar electric vehicles: Architectures, control strategies, and future research directions," *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, vol. 151, no. 111515, Jun. 2026, doi: 10.1177/09544070261455985.

[3] Y. Chen *et al.*, "Experimental study on the effect of dust deposition on photovoltaic panels," *Energy Procedia*, vol. 158, pp. 483–489, Feb. 2019, doi: 10.1016/j.egypro.2019.01.139.

[4] A. A. Kazem, M. T. Chaichan, and H. A. Kazem, "Dust effect on photovoltaic utilization in Iraq: Review article," *Renewable and Sustainable Energy Reviews*, vol. 37, pp. 734–749, Sep. 2014, doi: 10.1016/j.rser.2014.05.073.

[5] A. Virtuani, D. Pavanello, and G. Friesen, "Overview of temperature coefficients of different thin film photovoltaic technologies," in *25th European Photovoltaic Solar Energy Conference and Exhibition / 5th World Conference on Photovoltaic Energy Conversion, 6-10 September 2010, Valencia, Spain*, 2010, p. 83. [Online]. Available: http://www.eupvsec-proceedings.com/proceedings?paper=9122.

[6] J. Ramanujam *et al.*, "Flexible CIGS, CdTe and a-Si:H based thin film solar cells: A review," *Progress in Materials Science*, vol. 110, no. 9, p. 100619, May 2020, doi: 10.1016/j.pmatsci.2019.100619.

[7] S. Mekhilef, R. Saidur, and M. Kamalisarvestani, "Effect of dust, humidity and air velocity on efficiency of photovoltaic cells," *Renewable and Sustainable Energy Reviews*, vol. 16, no. 5, pp. 2920–2925, Jun. 2012, doi: 10.1016/j.rser.2012.02.012.

[8] H. Yang, J. Burnett, and Z. Zhu, "Building-integrated photovoltaics: Effect on the cooling load component of building façades," *Building Services Engineering Research and Technology*, vol. 22, no. 3, pp. 157–165, Aug. 2001, doi: 10.1191/014362401701524190.

[9] 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, Dec. 2010, doi: 10.1016/j.rser.2010.07.065.

[10] F. E. Alfaris, "A sensorless intelligent system to detect dust on PV panels for optimized cleaning units," *Energies*, vol. 16, no. 3, p. 1287, Jan. 2023, doi: 10.3390/en16031287.

[11] D. Sun and K. F. Böhringer, "An active self-cleaning surface system for photovoltaic modules using anisotropic ratchet conveyors and mechanical vibration," *Microsystems and Nanoengineering*, vol. 6, no. 1, p. 87, Sep. 2020, doi: 10.1038/s41378-020-00197-z.

[12] W. C. Cheng and X. D. Chen, "Implementation of autonomous navigation for solar-panel-cleaning vehicle based on YOLOv4-Tiny †," in *Engineering Proceedings*, Basel Switzerland: MDPI, Apr. 2025, p. 31. doi: 10.3390/engproc2025092031.

[13] A. S. Sarkın, N. Ekren, and Ş. Sağlam, "A review of anti-reflection and self-cleaning coatings on photovoltaic panels," *Solar Energy*, vol. 199, pp. 63–73, 2020, doi: 10.1016/j.solener.2020.01.084.

[14] Y. Wu *et al.*, "A review of self-cleaning technology to reduce dust and ice accumulation in photovoltaic power generation using superhydrophobic coating," *Renewable Energy*, vol. 185, pp. 1034–1061, 2022, doi: 10.1016/j.renene.2021.12.123.

[15] M. K. Mazumder, R. Sharma, A. S. Biris, J. Zhang, C. Calle, and M. Zahn, "Self-cleaning transparent dust shields for protecting solar panels and other devices," *Particulate Science and Technology*, vol. 25, no. 1, pp. 5–20, Jan. 2007, doi: 10.1080/02726350601146341.

[16] M. K. Mazumder *et al.*, "Electrostatic removal of particles and its applications to self-cleaning solar panels and solar concentrators," in *Developments in Surface Contamination and Cleaning*, vol. 3, Elsevier, 2011, pp. 149–199. doi: 10.1016/B978-1-4377-7885-4.10005-3.

[17] H. A. Kazem, M. T. Chaichan, A. H. A. Al-Waeli, and K. Sopian, "A review of dust accumulation and cleaning methods for solar photovoltaic systems," *Journal of Cleaner Production*, vol. 276, p. 123187, Dec. 2020, doi: 10.1016/j.jclepro.2020.123187.

[18] F. Belhachat and C. Larbes, "Comprehensive review on global maximum power point tracking techniques for PV systems subjected to partial shading conditions," *Solar Energy*, vol. 183, no. 3, pp. 476–500, May 2019, doi: 10.1016/j.solener.2019.03.045.

[19] A. Kalimeris, I. Psarros, G. Giannopoulos, M. Terrovitis, G. Papastefanatos, and G. Kotsis, "Data-driven soiling detection in PV modules," *IEEE Journal of Photovoltaics*, vol. 13, no. 3, pp. 461–466, 2023, doi: 10.1109/JPHOTOV.2023.3243719.

[20] M. S. Kabir *et al.*, "A novel method for detecting dust accumulation in photovoltaic systems: evaluating visible sunlight obstruction in different dust levels and ai-based bird droppings detection," Jan. 2025, [Online]. Available: http://arxiv.org/abs/2501.08304.

[21] A. Ali, K. Irshad, M. F. Khan, M. M. Hossain, I. N. A. Al-Duais, and M. Z. Malik, "Artificial intelligence and bio-inspired soft computing-based maximum power plant tracking for a solar photovoltaic system under non-uniform solar irradiance shading conditions—A review," *Sustainability (Switzerland)*, vol. 13, no. 19, p. 10575, Sep. 2021, doi: 10.3390/su131910575.

[22] M. A. Eltawil and Z. Zhao, "MPPT techniques for photovoltaic applications," *Renewable and Sustainable Energy Reviews*, vol. 25, pp. 793–813, Sep. 2013, doi: 10.1016/j.rser.2013.05.022.
[23] S. Saravanan and N. Ramesh Babu, "Maximum power point tracking algorithms for photovoltaic system - A review," *Renewable and Sustainable Energy Reviews*, vol. 57, pp. 192–204, 2016, doi: 10.1016/j.rser.2015.12.105.
[24] T. Esram and P. L. Chapman, "Comparison of photovoltaic array maximum power point tracking techniques," *IEEE Transactions on Energy Conversion*, vol. 22, no. 2, pp. 439–449, 2007, doi: 10.1109/TEC.2006.874230.
[25] A. R. Jordehi, "Parameter estimation of solar photovoltaic (PV) cells: A review," *Renewable and Sustainable Energy Reviews*, vol. 61, pp. 354–371, 2016, doi: 10.1016/j.rser.2016.03.049.

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