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AUTONOMOUS SOLAR PANEL CLEANING SYSTEM BASED ON RECOVERED THERMAL ENERGY AND AIOT CONTROL

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Abstract

This paper proposes the concept of an autonomous system designed to detect surface contamination on solar panels using sensors, initiate cleaning based on demand, and power the control unit using thermal energy harvested via a Thermoelectric Generator (TEG). Existing approaches regarding AIoT, cleaning technologies, and PV thermal energy harvesting were compared. While the system's operation has not yet been experimentally validated, the paper outlines the measurement plan and principles for safe control.

Keywords: autonomous cleaning, solar panel, dust accumulation, AIoT, TEG, sensor, clean energy, preventive maintenance.

INTRODUCTION

The accumulation of dust and other contaminants on the surface of PV panels can reduce the amount of solar radiation reaching the active layer and lower power generation capacity. Manual cleaning is time-consuming and labor-intensive, while washing with water faces constraints related to water resources and quality. Dry mechanical, robotic, and other automated methods are considered for various conditions [6]. A review of AIoT-based approaches integrates real-time monitoring, automatic cleaning, fault detection, and predictive maintenance within a unified control framework [5]. The distinctive feature of this approach goes beyond merely selecting a cleaning method: before initiating a cleaning cycle, the system must assess surface soiling, calculate the expected energy recovery, check available energy, and verify safety conditions. Since the energy harvested via the TEG may be minimal, it is intended to power the sensor and control node, whereas the power source for the cleaning motor is selected based on a separate energy balance.

II. METHODS

The conceptual system comprises five modules: (1) a soiling and optical condition sensor or camera; (2) a PV power and weather sensor; (3) a TEG-based energy harvesting unit and battery; (4) a cleaning actuator; and (5) an AIoT controller and data logger. The cleaning strategy takes into account the panel surface soiling level, the deviation of PV output from expected values, irradiance, wind, humidity, and energy reserves. If a camera is used, a calibrated dataset is required to distinguish between shading, bird droppings, and dust.

Decision-making sequence: check sensor data; assess the probability of soiling; estimate the expected additional energy gain post-cleaning; verify safety for the actuator and panel; initiate the cleaning cycle if sufficient energy reserves are available; re-measure PV output and surface condition after the cycle. If sensors provide conflicting data or if wind/humidity conditions do not meet safety criteria, the system must postpone cleaning and log a notification.

Net gain is estimated as follows: $\Delta E_{net} = \Delta E_{PV} - E_{clean} - E_{control} - E_{conversion}$, where ΔE_{PV} is the additional energy expected to be generated after cleaning, E_{clean} is the energy consumed for mechanical cleaning, $E_{control}$ is the energy consumed by controls and sensors, and $E_{conversion}$ represents power conversion and storage losses. This formula does not yield a universal result but rather defines the energy balance that must be calculated during prototype testing.

III. RESULTS AND DESIGN SOLUTION

A synthesis of the literature highlights three practical requirements for the system. First, the cleaning frequency should not be strictly calendar-based but rather adapted to measured levels of soiling and power loss. Second, the decision to initiate cleaning should be justified by net energy gain rather than merely technical feasibility. Third, the amount of energy harvested from the TEG depends

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on weather conditions and temperature differentials; Therefore, the load requirement is tested before designing the cleaning actuator to rely solely on TEG power [2,3].

IV. DISCUSSION

The optimal cleaning time depends not only on the amount of dust on the panel surface but also on the weather forecast and the expected solar irradiance for the remainder of the day. For instance, if rain is expected soon, mechanical cleaning might be postponed; however, this decision must be evaluated based on the local dust composition and the rain's actual potential to clean the surface. Dry cleaning can reduce water consumption, but the brush material and pressure must not scratch the glass surface, and mechanical components must not damage the panel frame [6].

Over-reliance on the AI system poses risks. Therefore, safety features such as an emergency stop button, mechanical limit switches, wind speed limits, low-battery shutdown, and a manual control mode are incorporated before actuator operation. If the camera classifier generates a false positive signal, the system can verify power output deviation over time and check a second sensor instead of proceeding with cleaning.

V. TESTING PLAN AND EVALUATION CRITERIA

At least three modes are recommended for testing the prototype: A — standard PV panel without automatic cleaning; B — PV panel with TEG monitoring but manual cleaning; C — TEG monitoring with on-demand automatic cleaning. In each mode, PV energy, panel temperature, TEG energy, cleaning consumption, water usage (if applicable), post-cleaning power recovery, and erroneous commands are recorded. The test must be repeated over several weeks and under various weather conditions.

Key indicators include: the power difference before and after cleaning; energy consumed per cycle; net energy gain; precision and recall metrics of the detection algorithm; frequency of missed cleanings and over-cleaning; mechanical safety; and system operational readiness. These criteria allow for the assessment of the project's practical effectiveness, though the specific values must be determined through experimentation.

5.1. Criteria for selecting cleaning technology

When selecting a cleaning technology, factors such as panel area, dust type, water availability, mechanical robustness, maintenance costs, and energy consumption are evaluated collectively. Liu et al. [7] review soiling accumulation and removal methods in the context of optical, thermal, and electrical effects. A review by Kumar et al. [2] also discusses robotic, dry, and surface-coating-based methods; however, each method requires specific testing tailored to the particular climate and panel design.

Method	Potential benefit	Constraint to be checked
Dry brush/robot	May reduce water consumption	Glass scratching, mechanical pressure, brush wear
Wet cleaning	May remove adhered dirt	Water consumption, water quality, residual spotting, and drying
Surface coating	May extend cleaning intervals	Coating durability, optical loss, and cost
Demand-based AIoT	Potential to reduce unnecessary cleaning	Sensor errors, incorrect commands, model recalibration

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5.2. Net energy criterion and safe state

The benefit of cleaning is evaluated not merely by the visual result of a "cleaned panel," but by the difference in PV energy output measured before and after the cleaning process. Variations in irradiance and temperature must be accounted for in this comparison; if weather conditions change during cleaning, the difference in power output might not be solely attributable to the removal of dust. Whenever possible, a reference panel or standardized measurements taken over a short time interval are used. The net energy calculation excludes the energy consumed by the cleaning actuator, controller, sensors, communication module, and power converter.

Safety protocols must be an integral part of the algorithm: these include mechanical movement limits, emergency stop functions, prevention of operation during low battery levels, postponement of cleaning during high winds, and reversion to a safe state in the event of sensor failure. While an AI model can assess the need for cleaning, protective functions should not rely exclusively on the model's predictions. It is advisable to first test a simple rule-based control system and then compare the results with those of the AI model.

5.3. Experimental design and reproducibility

A minimal test design might encompass three modes: a standard PV panel; monitoring via TEG but with manual cleaning; and demand-based automatic cleaning utilizing TEG and AIoT. For each mode, the panel model, tilt, orientation, measurement time, and weather conditions are recorded. No definitive conclusions regarding cleaning efficiency or energy savings are drawn without conducting at least several repeated cycles. The report also includes all unsuccessful cycles, as selectively reporting only successful instances could lead to an overestimation of the system's benefits.

5.4. Algorithm evaluation and incorrect decisions

Two types of errors are specifically monitored in the cleaning-need detection algorithm: false positives—initiating cleaning when the panel is not sufficiently soiled; and false negatives—failing to initiate cleaning when soiling is present. The former can result in the wasteful consumption of electrical energy, mechanical resources, and brush service life, while the latter can lead to continued production losses. Therefore, in addition to overall accuracy, metrics such as precision, recall, and the false activation rate are reported separately.

For the AI model, the image, panel power output, and weather data must cover various seasons and soiling conditions. If the training dataset consists solely of data from a single day or a single panel, the model may fail when deployed under different conditions. Therefore, the model must be validated against data from different time intervals and, if possible, different panels. In the event of sensor contamination or changes in camera imagery due to lighting conditions, the system should detect low confidence levels and either halt automatic operations or require further verification.

5.5. Recommendations for testing under conditions in Uzbekistan

Dust composition, wind, humidity, and precipitation levels vary across different regions of Uzbekistan; consequently, applying a cleaning schedule calibrated for one region uniformly to all locations is inappropriate. Local testing should document factors such as panel tilt, proximity to roads or construction sites, dust accumulation rates, and water availability. Cleaning thresholds should be adjusted only after analyzing the test results. This approach ensures management based on local data rather than relying on universal figures or estimated savings percentages.

VI. CONCLUSION

Integrating energy harvesting, AIoT monitoring, and on-demand autonomous cleaning offers a conceptual framework for more efficient solar panel maintenance. An important principle is to manage the cleanup based on energy balance and safety, taking into account the potential for low TEG output. The value of the proposed architecture must be validated through a prototype, a control regime, and long-term measurements.

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REFERENCES

[1] Boucif O. H., Lahouaou A. M., Boubiche D. E., Toral-Cruz H. (2025). Artificial Intelligence of Things for Solar Energy Monitoring and Control. Applied Sciences, 15(11), 6019. https://doi.org/10.3390/app15116019

[2] Kumar A., Sable A., Sahare A., Sonune A., Arshad S. (2026). Review of Solar Panel Cleaning Technology. International Journal of Creative and Open Research in Engineering and Management, 2(3). https://doi.org/10.55041/ijcope.v2i3.055

[3] Demir H. (2022). Application of Thermal Energy Harvesting from Photovoltaic Panels. Energies, 15(21), 8211. https://doi.org/10.3390/en15218211

[4] Basem A., Opakhai S., Elbarbary Z. M. S., Atamurotov F., Benti N. E. (2025). A comprehensive analysis of advanced solar panel productivity and efficiency through numerical models and emotional neural networks. Scientific Reports, 15, 259. https://doi.org/10.1038/s41598-024-70682-2

[5] Mitul M. T. R., Mondol N., Reza M. N., Roy,S., Islam M. N. (2025). Enhance the efficiency of solar modules and produce electricity from waste heat using thermoelectric generators (TEGs): A comprehensive practical work. Heliyon, 11, e42869. https://doi.org/10.1016/j.heliyon.2025.e42869

[6] Ekins-Daukes N. J. (2009). Solar energy for heat and electricity: the potential for mitigating climate change. Grantham Institute for Climate Change, Briefing Paper No. 1.

[7] Liu Y., Li H., Li L., Yin X., Wu X., Su Z., Gao F., Cai B., Tang L., Zhou S. (2024). Solar photovoltaic panel soiling accumulation and removal methods: A review. IET Renewable Power Generation. https://doi.org/10.1049/rpg2.12940

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