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The Impact of Dust on the Performance and Efficiency of Solar Panels

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ABSTRACT

Dust accumulation on solar panels, commonly referred to as soiling, significantly reduces the energy conversion performance of Photo Voltaic (PV) systems. Dust deposition on the panel surface obstructs sunlight from reaching the cells, and combined with elevated panel temperatures and deterioration of glass optical properties, this results in substantial efficiency losses. Previous studies have reported efficiency reductions ranging from 5% to 40%, depending on dust characteristics, particle size, and environmental conditions. Such losses not only reduce total energy output but also cause considerable economic impact, particularly for large-scale solar power plants. To mitigate these effects, the scientific community has actively developed various cleaning strategies, including manual cleaning, Automatic Cleaning Systems (ACSs), surface coatings, and design optimizations. This study reviews these approaches and highlights their effectiveness in sustaining PV performance.

Keywords: Solar panels, Dust contamination, Soiling effect, Photovoltaic performance, Efficiency degradation, cleaning methods

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1. Introduction

Solar energy is a rapidly growing renewable energy source, offering a clean and sustainable alternative to conventional electricity generation. Among renewable technologies, photovoltaic (PV) systems are particularly attractive due to their low maintenance requirements and capability to generate electricity directly from sunlight [1], [9]. However, a major challenge affecting PV system performance is dust accumulation on the panel surface, commonly referred to as soiling. Soiling reduces the amount of solar radiation reaching the PV cells, while increased panel temperatures and the degradation of the glass cover's optical properties further diminish energy output [2], [10**].**

Empirical studies indicate that efficiency losses due to dust contamination can range between 5% and 40%, depending on dust type, particle size, and ambient environmental conditions [3], [4], [11]. The severity of soiling is influenced by factors such as local climate, humidity, wind speed, and proximity to industrial or agricultural dust sources. Arid and semi-arid regions tend to experience higher dust deposition rates, resulting in more frequent performance degradation [12], [13]. These losses not only compromise overall energy production but also impose significant economic penalties, especially in large-scale solar installations, where even minor efficiency reductions can lead to substantial financial losses over the operational lifetime of a plant [14].

To mitigate the effects of dust accumulation, various countermeasures have been explored. Manual cleaning is a traditional method that is cost-effective for small installations but is labor-intensive and inefficient for large-scale systems [5], [15]. Automatic Cleaning Systems (ACSs), including robotic cleaners and water-free brushing mechanisms, provide more consistent cleaning but require higher initial investment [6], [16]. Additionally, surface coatings, such as hydrophobic or self-cleaning layers, can reduce dust adhesion and facilitate passive cleaning during rainfall [7], [17]. Design optimization of PV modules, including tilting angles and spacing, can also minimize dust accumulation by exploiting natural gravitational or wind-based cleaning effects [8], [18].

2. Literature Review

Despite these interventions, the optimal cleaning strategy depends on multiple factors, including environmental conditions, economic feasibility, and energy efficiency goals. Consequently, ongoing research focuses on developing innovative, cost-effective, and energy-efficient cleaning technologies that maintain PV performance while reducing operational expenses. Understanding the mechanisms of soiling and evaluating the effectiveness of different mitigation strategies is essential to ensure the long-term sustainability and reliability of solar power systems worldwide [19], [20].

Several studies have reported significant efficiency losses in PV modules due to dust accumulation. El-Shobokshy and Hussein [1] demonstrated that dust deposition on solar panels can reduce performance by up to 40%. Goossens and Van Kerschaever [2] highlighted that dust type and particle size significantly influence efficiency loss rates. Javed et al. [3] observed that regions frequently affected by dust storms experience rapid PV performance degradation. Economic analyses by Mani and Pillai [4] further indicate that soiling can impose substantial financial losses on large-scale solar power plants.

To mitigate these effects, strategies proposed in the literature include automated cleaning systems (ACSs), anti-dust coatings, and PV design optimization [5 - 8]. These approaches aim to reduce dust accumulation and maintain the energy conversion efficiency of PV systems, ensuring reliable and sustainable electricity generation. Additional research emphasizes the role of robotic cleaners in both efficiency restoration and operational cost reduction [16 - 20].

3. Methodology

In this study, a prototype robotic solar panel cleaner was developed to investigate effective dust mitigation techniques. The robot features a box-type chassis and is equipped with five IBT-2 BTS7960B motor drivers for locomotion and cleaning operations [21 - 23]. Following are the System Components

3.1 Wheel motors: Four motors drive the wheels, allowing the robot to move across the solar panel surface. Each motor is equipped with encoders to record pulse counts, enabling accurate motion tracking and synchronized wheel control.

3.2 Brush motor: A fifth motor powers a rotating brush to mechanically remove dust.

3.3 Water pump: A pump assists the brush by spraying water, enhancing dust removal efficiency.

3.4 ESP32 microcontroller: Provides real-time monitoring and operational control for all actuators and sensors.

The entire system is controlled by an ESP32 microcontroller, which provides real-time monitoring and operational control. The prototype, shown in Figure. 2, was tested under standard conditions. Both the brush motor and water pump demonstrated effectiveness in restoring panel efficiency.

4. Results and Discussion

The prototype solar panel cleaning robot was successfully tested. The brush motor and water pump effectively removed accumulated dust, restoring panel efficiency. Encoder data confirmed proper wheel synchronization, ensuring stable robot movement.

4.1 *Sample Data for PV Output Before and After Cleaning*

A 100 W solar panel was tested under standard sunlight conditions (irradiance of 1000 W/m²). Dust accumulation caused approximately 18% efficiency loss.

Table 1. PV Panel Performance Before and After Cleaning

TEST DAY	CONDITION	VOLTAGE (V)	CURRENT (A)	POWER (W)
DAY 1	Dusty Panel	15.2	1.05	15.96
	Cleaned Panel	18.1	1.20	21.72
DAY 2	Dusty Panel	14.9	1.10	16.39
	Cleaned Panel	18.4	1.21	22.26
DAY 3	Dusty Panel	15.0	1.08	16.20
	Cleaned Panel	18.2	1.19	21.66

Following are the listed Components of Prototype Solar Panel Cleaning Robot

- 5 IBT2BTS7960b Motor Drivers
- ESP32 Wroom 38pins
- Buck Converter
- 5 DC motors 12v with Encoders
- Water Pump Motor
- Battery 12v 4 Amp

Efficiency Gain Calculation:

$$\text{Efficiency Gain (\%)} = \frac{P_{\text{clean}} - P_{\text{dusty}}}{P_{\text{dusty}}} \times 100$$

Day 1:

$$P_{\text{dusty}} = 15.96\ \text{W}, P_{\text{clean}} = 21.72\ \text{W}, \text{Efficiency Gain} \approx 36.1\%$$

Similarly, the results for Day 2 and Day 3 would be 35.8% and 33.7%.

The slight reduction in efficiency gain may be attributed to incomplete cleaning, micro-scratches, or environmental variations as shown in Figure 1.

Figure. 1(a) Dust accumulation on the surface of a solar panel

Figure. 1b) Cleaned solar panel after robotic cleaning.

Figure. 1(c) Fig. 3. Prototype solar panel cleaning robot.

The results of Comparison of power output before and after cleaning over three test days and Decline in PV output due to extended cleaning intervals. Silver color bar represents the situation before the cleaning and green color bar show after the cleaning. Green bar is most effective and supportive for solar plats as shown in Figure 2.

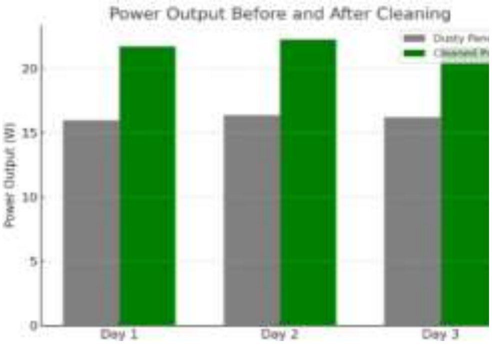

Figure. 2(a) Comparison of power output before and after cleaning over three test

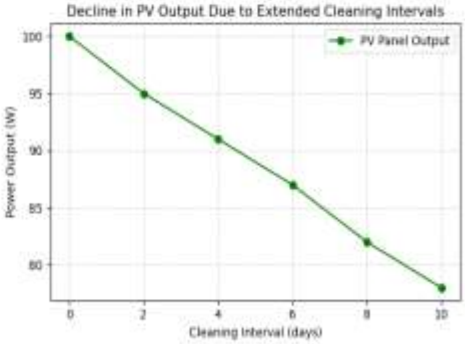

Figure. 2(b) Decline in PV output due to extended cleaning intervals

Additionally, Figure 3 illustrates the block diagram of applicable system, which helps in implementation and proper usage.

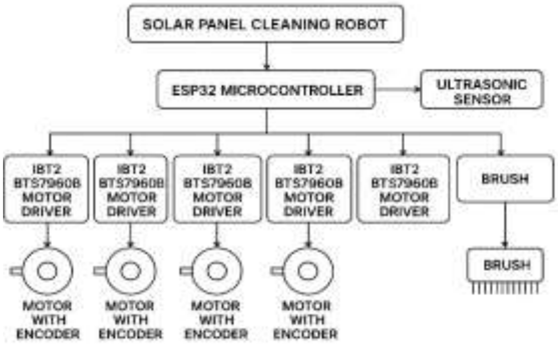

Figure. 3. System Block Diagram

5. CONCLUSION

This research shows the impact of dust build up on solar panel productivity and how well a prototype solar panel cleaning robot works. By putting together brush cleaning, water spraying, and auto control, the system was able to bring the panels back to full working order. Next steps include adding edge detection sensors to the system so it can find its own way, and testing in different weather conditions. The paper ends by showing that robotic cleaning is an affordable and environmentally friendly way to make sure photovoltaic panels work efficiently in dusty areas.

DECLARATIONS

Competing Interests

The authors declare that they have no competing interests

Authors Contribution

All authors have contributed in the paper

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