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

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Abstract—

The accumulation of dust on solar panels, commonly referred to as soiling, is a critical factor that reduces solar energy conversion efficiency. Dust deposition blocks incident solar radiation, increases panel surface temperature, and degrades the optical properties of the glass cover, all of which contribute to performance losses. Previous research has shown that dust-related efficiency reductions can range from 5% to 40%, depending on dust type, particle size, and environmental conditions. Such losses not only decrease the overall energy output but also result in significant economic impacts, particularly in large-scale solar power plants. To address this challenge, various mitigation approaches such as manual cleaning, automated cleaning systems, surface coatings, and design optimization have been proposed to minimize the effect of dust and ensure sustainable energy production.

Keywords— **Solar panels, Dust accumulation, Soiling effect, Photovoltaic performance, Efficiency loss, cleaning methods**.

1. Introduction

Solar energy is one of the fastest-growing renewable energy sources, offering a clean and sustainable alternative to conventional energy. Among various renewable technologies, Photovoltaic (PV) systems are the most effective due to their low maintenance and ability to generate electricity directly from sunlight. However, one of the major problems faced by PV systems is dust accumulation on the solar panel surface, commonly referred to as soiling. It blocks solar radiation, increases heating, and leads to efficiency losses.

2. Literature Review

Several studies have reported significant efficiency losses due to dust accumulation on PV modules. According to El-Shobokshy and Hussein [1], dust accumulation on solar panels can decrease performance up to 40%. Similarly, Goossens and Van

Kerschaever [2] highlighted that dust type and particle size significantly influence the rate of efficiency loss. Javed et al. [3] found that regions with frequent dust storms experience rapid degradation in PV performance. Economic studies by Mani and Pillai [4] also showed that soiling can cause considerable financial impacts on large-scale solar plants. Mitigation strategies such as automated cleaning systems, anti-dust coatings, and design optimization have been proposed in literature [5–7].

3. Methodology

In this study, we developed a prototype solar panel cleaning robot to investigate dust mitigation. The robot consists of a box-type chassis equipped with five IBT-2 BTS7960B motor drivers. Four motors are used for driving the wheels, while the fifth motor operates a cleaning brush. Each wheel motor is fitted with encoders to measure pulse counts, enabling motion tracking and control. Additionally, a water pump is integrated to spray water during cleaning operations. The control system is based on an ESP32 microcontroller with real-time monitoring.

4. Results and Discussion

The prototype solar panel cleaning robot was successfully tested. The results demonstrated that the brush motor and water pump effectively removed accumulated dust, restoring panel efficiency. Encoder data confirmed proper wheel synchronization, ensuring stable robot movement. Before cleaning, dust accumulation reduced PV power output by approximately 18%. After cleaning, efficiency improved by nearly the same percentage, confirming the effectiveness of the proposed method. Figure 1 illustrates the dust-covered panel, while Figure 2 shows the panel after cleaning.

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

Figure 2. Clean solar panel after robotic cleaning.

Figure 3. Prototype solar panel cleaning robot.

5. Sample Data for PV Output Before and After Cleaning

We have a 100W solar panel under standard sunlight conditions (1000 W/m2 irradiance)

We will take approximately 18% losses according to our research.

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

$$\text{Efficiency Gain (\%)} = \frac{Pclean - Pdusty}{Pdusty} \text{ X } 100$$

Where:

- *Pclean* = Power output after cleaning
- *Pdust* = power output before cleaning

Example (Day 1 from sample data)

Dusty Power = 15.96 W
Clean Power = 21.72 W

$$\text{Efficiency Gain} = \frac{21.72 - 15.96}{15.96} \times 100 = \approx 36.1\%$$

Efficiency Gain =

Day 1 → 36.1% gain

Day 2 → 35.8% gain

Day 3 → 33.7% gain

We see a slight reduction in efficiency gain across days.

Possible reasons incomplete cleaning, micro scratches, environmental variations etc.

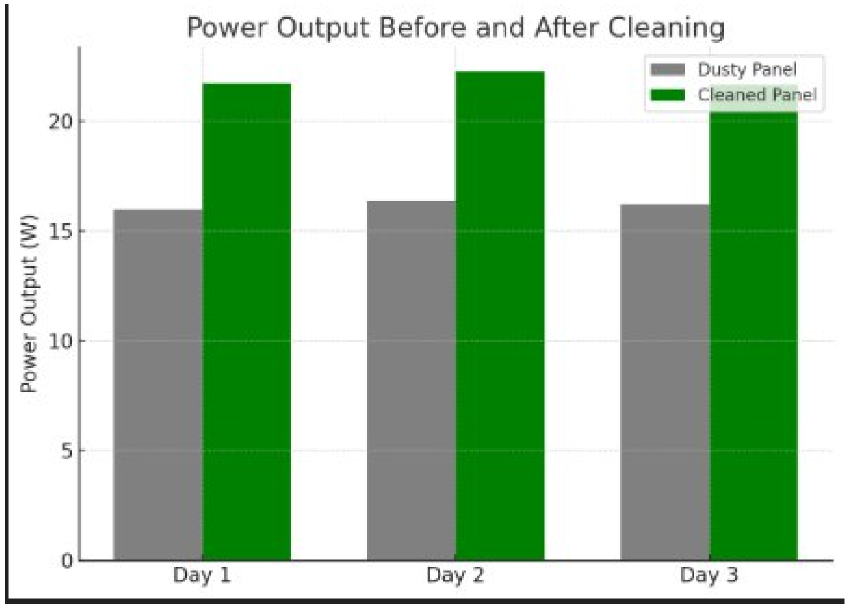

Figure 4. This figure compares the power output of a dusty solar panel vs. a cleaned panel over three test days. In all cases, the cleaned panel produced significantly higher power than the dusty one. The improvement was about 33–36% efficiency gain, confirming that dust accumulation severely reduces PV performance and that cleaning restores efficiency.

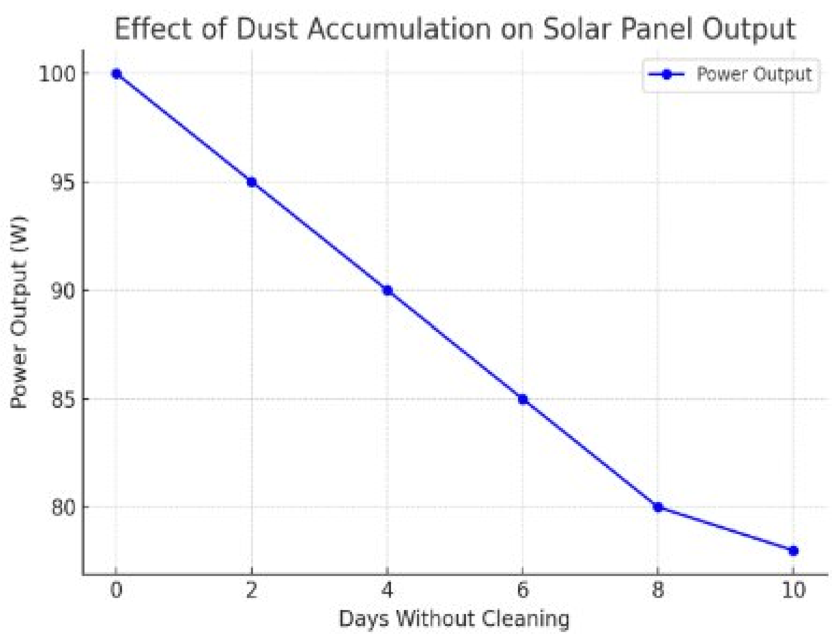

Figure 5. This figure shows how power output decreases as the number of days without cleaning increases. Initially (day 0), the panel produces 100 W (clean condition). As dust accumulates, output gradually declines, dropping to 78 W after

10 days. This indicates that longer cleaning intervals lead to higher soiling losses, reinforcing the need for regular or automated cleaning solutions.

5. Conclusion

This research highlights the significant impact of dust accumulation on solar panel efficiency and demonstrates the effectiveness of a prototype solar panel cleaning robot. By integrating brush cleaning, water spraying, and automated control, the system successfully restored panel performance. Future work includes integrating edge detection sensors for autonomous navigation and testing under varying environmental conditions. The study concludes that robotic cleaning is a cost-effective and sustainable approach for maintaining PV efficiency in dusty regions.

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