

Investigating the Effects of Autonomous Dry  
Mechanical Cleaning on Solar Panel Performance

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## Literature Review

Solar panels, or photovoltaic (PV) modules, are a renewable energy source made of silicon semiconductor cells that convert solar energy to electricity. Solar panels have become the preferred source of renewable energy, passing 1046 GW of power capacity in 2022, comprising 31% of the total installed renewable energy capacity, and the cost of installing solar power reduced by 67% from 2014-2022 [1]. Due to their easy installation, easy maintenance, and the abundance of sunlight on Earth, PV panels are a big component in lowering the world's reliance on fossil fuels by 2050. However, a decrease in power output due to soiling or dust has been observed in previous literature and confirmed in different regions and environments in the world whether deserts, arid climates, industrial areas, rural areas, or tropical biomes. As dust accumulates on the surface of the panels, transmittance is reduced, also reducing the power output of the panels.

The infamous obstacle of dust deposition on solar panels occurs at higher rates in places where there is more abundant sunlight year-round, such as in desert regions like Southern California. Dust is a general term for any particulate matter less than 500 micrometers in diameter, and can comprise small amounts of pollen, cells, hair, microfibers, and organic materials from geomorphic fallout. The particle size, constituents, and shape vary through each region, and deposition behavior and accumulation rates can vary drastically in different climates, urbanization, and geography [2].

Southern California consists of the Mojave and Colorado Deserts, San Joaquin Valley, the Mono Lake Region, and the Imperial Valley where dust storms can greatly affect the efficiency of solar panels, and it's expected that the frequency of dust storms will increase as

the temperatures rise. In Southern and Central California, 80% of excess dust over the years has been attributed to fallowed agricultural land due to a long-term drought and the groundwater policy. In this semi-arid climate with several desert or desert-like regions, there are strong winds that mobilize these dust particles and reduce solar panel efficiency [3]. It is important to address this issue to make renewable energy sources more reliable and efficient. The objective of this research paper is to investigate whether cleaning solar panels causes damage that shortens the lifespan of solar panels or decreases power output over time.

The variance of dust particle size, density, shape, and composition has given rise to different methods of cleaning solar panels such as natural environment soiling removal, manual cleaning, air jet spraying, use of smart devices, self-cleaning coatings, and electrostatic removal. The most common mechanism for particle removal is rolling, sliding, or lifting, but natural methods use solar panel inclination to affect the composition and deposition of soiling particles on the surface. In Saudi Arabia it was shown that a week of soiling accumulation caused a 7.34% decrease in PV glass transmittance [4].

There are benefits to using one method over the other depending on the ambient conditions such as temperature, humidity, weather gradients, wind velocity, and time variations. For example, water cleaning methods are unideal for desert climates, but water-free cleaning methods may cause scratches and struggle to remove stubborn debris like bird droppings. A proposed solution is a hybrid robot that uses controlled water cleaning whenever the solar panels reach a certain level of dust accumulation [5]. This study successfully demonstrated a way to clean solar panels and conserve water resources, while addressing the limitations of traditional cleaning methods. It also made some provisions in the design to limit

the chance of damage to solar panels. However, it failed to monitor the possible damage accumulation after many cleaning cycles and operation of the robot, which could affect the sustainability and long-term value of this approach.

Dual-axis solar trackers have been used to keep the sun's rays perpendicular to the solar panels throughout the day to maximize exposure and efficiency. Previous literature utilizes the solar tracking system to track wind and rainfall to dislodge surface debris without adding any additional components to the system. These results were compared with a dual-axis solar tracker without the self-cleaning protocol, and one fixed angle system [6]. The self-cleaning mechanism first checks the wind speed, then the solar panels are tilted parallel to the ground to collect water for five minutes then dump it off at 45 degrees, or it checks for wind direction and adjusts the panel to tilt 45 degrees against the direction of the wind. This system takes advantage of the micro-climate of the solar panels and outperformed the solar tracking panel without the self-cleaning protocol and the fixed angle solar panel. This may be a viable approach for areas that experience frequent rain and wind. However, it is also important to consider the Potential Induced Degradation (PID) from frequent tilting and water exposure. More research is needed to determine the long-term effects of using this method for cleaning solar panels.

The electrostatic cleaning method uses an electrostatic charge from the electric curtain on a solar panel to remove dust [7]. Dust particles are lifted off the panels as the electrodes impart an electrical charge on the particles and are repelled from the charge applied to the panel itself. This method is useful for low humidities and vacuum environments, repelling 90% of the dust off the surface. The advantage of this method is that it reduces the consumption of

water, labor costs, and the scraping and wear of the surface of solar panels [4]. Some disadvantages include water accumulation in the dielectric membrane over time, inefficiency at removing small particles, and high manufacturing costs. Further research can explore more economical, effective, and feasible methods for applying electrostatic removal to solar panels.

There are two methods of mechanical cleaning: dry or wet. Dry cleaning is ideal for regions with limited water access; however, wet cleaning recovers more transmittance and does not cause damage to solar panels [9]. Using water in the cleaning cycle also reduces the temperature of the panels, increasing efficiency, and reducing the probability of hotspots forming at high-density deposition areas. Wet cleaning is a good solution when water is available but does not apply to arid or semi-arid climates.

This research will focus on the waterless mechanical method of brush cleaning, considering the semi-arid climate of Southern California and its frequent droughts. Some concerns about the mechanical cleaning method include damage to the coating and other surface components after long-term use, hurting the lifespan of the panels [4].

It's important to monitor the power output of solar panels to assess whether they are operating efficiently. Previous literature measures the short circuit current and open circuit current of the solar panels before and after accumulating dust. Short circuit current is the amperage a solar module produces when its positive and negative leads are connected, giving the maximum rating for current the module can create. Open circuit current is obtained by measuring the voltage across the positive and negative terminals using a voltmeter, representing the maximum voltage a solar panel can produce under Standard Test Conditions

(STC), and a higher VOC implies greater potential for power generation. However, it's important to remember that STC are rarely met in the field [8].

Solar panel efficiency is measured at STC, including solar irradiation of  $1,000 \text{ W/m}^2$  and cell temperature at  $25 \text{ }^\circ\text{C}$ . Previous papers have suggested that electricity production drops 0.2 – 0.5% for every  $1 \text{ }^\circ\text{C}$  increase in panel surface temperature. A cooling system can help mitigate this but requires the essential resource of water. It has been shown that as cell temperature rises, short circuit current drops slightly and open circuit voltage drops dramatically [8]. Solar panel cleaning and cooling are proven ways to increase efficiency after particle deposition on the surface, given the resources necessary are available.

There are many methods of cleaning dust from solar panels. This research identifies the most popular techniques that have shown promising results for improving the efficiency of solar panels after dust accumulation. Limitations exist surrounding water dependency, long-term maintenance, and potential surface damage with self-cleaning solar panel mechanisms. The goal is always to improve power output without affecting the average 20-year lifespan of solar panels. A previous study has shown how to calculate the 20-year lifespan equivalent for research testing purposes, considering the brush speed, cleaning frequency, and area of contact [10].

This research identifies gaps in the literature surrounding the long-term effects of cleaning solar panels using different brush types and dry cleaning without using water to wash or wipe panels afterwards. Understanding the effects of these variables can further improve solar panel cleaning systems and ensure long-term reliability of renewable energy. Although

previous work has considered the effects of brush-based cleaning over simulated lifetimes, only a few studies investigated the efficiency of continuous autonomous dry-cleaning systems using low-cost equipment and small-scale photovoltaic applications

### Methodology

A linear rail system was constructed using a T2020 aluminum extrusion, T2020 v-wheel gantry plate, NEMA 17 stepper motor, 6mm timing belt, and a belt tensioner. This system automated the continuous cleaning of the solar panel over the duration of each test. A 10W 12V solar panel with a cylindrical microfiber brush to align with previous automated solar panel cleaning experiment setups was used for testing purposes. The microfiber brush was secured to the gantry plate and programmed using an Arduino Uno to pass over the length of the solar panel. One cleaning cycle consisted of the brush passing over the length of the panel and returning to its starting position. The solar panel and linear rail system were mounted on a wooden platform to ensure stability, levelness, and maximum brush contact throughout the experiment, as shown in Figure 1 below.

*Figure 1*



Two sensors were mounted onto the platform. The BH1750 light sensor measured light intensity in lux and was attached at the bottom left edge of the panel. This ensured that none of the cells were blocked during the testing trials and thus, there were no changes to the light readings due to movement. The INA219 sensor was used to measure the current and voltage of the solar panel. The A4988 driver that was used to power and control the motor, SDA/SCL lines for communicating with the sensors, and a 20W 15Ω load resistor to provide a consistent current draw for measurement by the INA219, were housed on a breadboard. The load resistor was chosen to approximate the theoretical optimal resistance of 14.4 Ω under standard test conditions. This was calculated by rearranging Ohm's Law and Watt's Law as shown in Equation 1 below.

***Equation 1***

$$R_{optimal} = \frac{V^2}{P}$$

where  $V$  and  $P$  are the solar panel's rated values of voltage and power, respectively. An external 12-Volt power supply was used to power the motor, and an Arduino Uno was used to control the sensors and send signals to the A4988 driver.

A five-minute cleaning cycle was run before any dirt was added to the panel to establish a baseline for the solar panel performance. Before initiating the cleaning cycles, 15 grams of dirt were evenly spread across the panel as an initial deposit. A 15-minute continuous iteration of cleaning cycles was run to assess whether repeated mechanical cleaning causes measurable degradation to solar panel performance over time. Prior research has examined cumulative cleaning damage over simulated 20-year periods [10], and this test similarly aimed to observe

whether extended brush contact results in measurable performance loss over time. Throughout the 15-minute test, an additional 100 grams of dirt was continuously deposited onto the panel using a sieve to simulate real-world conditions where dust and debris are dynamically redeposited onto panels during operation.

Sensor readings for light intensity, voltage, and current were taken every three seconds and stored in a comma-separated values (.csv) file for analysis in Excel. The light intensity data were used to normalize the power output to account for changes in sunlight during the cleaning cycles. This was calculated using Equation 2 below

**Equation 2**

$$P_{normalized} = \frac{P}{E}$$

Where  $P$  is the power output in milliwatts and  $E$  is the light intensity in kilolux. This allowed for a comparison between the panel's relative performance before, during, and after the tests.

After confirming that the first test logged data correctly, the panel was wiped clean with a microfiber cloth. A second test was completed using the same steps as the first. After the second test finished, the panel was wiped clean with a microfiber cloth, and another five-minute test was run without dirt to establish the post-cleaning baseline. The performance of each test was analyzed using the normalized power output over time.

## Results

A baseline performance was established in a five-minute test before dirt was introduced to the system. Then, two tests were performed, with dirt introduced to each system to compare the baseline performance of the solar panel before and after 15 minutes of

continuous mechanical cleaning. That data was used to evaluate if there was a measurable decrease in power output after the mechanical cleaning. Finally, after the panel was wiped clean with a microfiber cloth, another five-minute test was run to establish the solar panel's performance after mechanical cleaning to analyze if damage accrued as a result of the cleaning. Light intensity was measured in lux, voltage was measured in volts, and current was measured in amperes.

The average baseline performance was measured at  $2.60 \pm 1.70$  mW/klx over the five-minute period. The average performance of the solar panel during test one was  $1.17 \pm 0.80$  mW/klx over the 15-minute period and the power output of the solar panel at its measured baseline and during the first 15-minute test were compared. The average performance of the solar panel during the second test was  $1.15 \pm 0.43$  mW/klx. The power output of the solar panel at its measured baseline and during the second 15-minute test were also compared. The solar panel performance was shown to be consistently lower than the baseline during the first and second test. The average performance of the solar panel after completing both 15-minute tests and being wiped clean with a microfiber cloth was  $1.74 \pm 0.19$  mW/klx over the 5-minute period was investigated. The power output increased from an average performance between test one and two of 1.16 mW/klx to 1.74 mW/klx. This is an increase of about 40%. However, the solar panel still performed about 40% lower than the baseline of 2.60 mW/klx before dirt was introduced.

### Discussion and Conclusion

With the increased use of solar energy, it is important to maintain the cleanliness of solar panels to ensure maximum power output, as dirt and other particulates accumulate on

the panel's surface over time. Research has been conducted on autonomous mechanical cleaning as a solution, since it requires minimal setup, maintenance, and labor costs. However, the presence of particulate matter on solar panels during an autonomous mechanical cleaning cycle may potentially introduce damage as they slide across its surface. Previous research identifies that the friction necessary to remove particles from solar panels may introduce damage since the dust particles themselves are hard and may scratch the surface as they are pushed off [10]. In this study, it was observed that solar panel performance during and after the cleaning cycles was consistently lower than before the system was introduced to dirt. This suggests that damage was introduced during the cleaning cycle itself, effectively lowering the post-test power output.

The decrease in power output could also be due to dirt being continuously deposited on the panel, which blocks the solar cells from sunlight. However, this is unlikely to fully account for the observed decrease, as both baseline and post-test performance were taken using the same procedure and under similar conditions. Since the load resistor was near the theoretical optimal resistance, power loss due to the resistance was negligible relative to the panel's rated output. The low power readings are therefore attributed primarily to overcast conditions during the test, rather than circuit design. The average baseline performance was measured at  $2.60 \pm 1.70$  mW/klx, and the average post-test performance was  $1.74 \pm 0.19$  mW/klx. The observed reduction in normalized power output is consistent with the possibility of surface damage resulting from dry mechanical cleaning; however, additional measurements such as microscopic surface analysis or transmittance testing are needed to confirm this.

Previous research states that the decrease in solar panel performance can be restored when the panels are cleaned with delicate wipes and water after running a dry-cleaning cycle with water serving as a form of transportation for particles off of the panel [10]. This approach could be useful in wet climates, but Southern California and other arid regions that frequently experience drought require different solutions. This study has several limitations, including tests conducted during overcast conditions, the use of one solar panel, and a sample size of four data sets. These limit the applicability of the findings.

These findings suggest that dry autonomous mechanical cleaning does not preserve solar panel performance due to damage introduced during the cleaning process itself. The average post-test performance of the solar panel was lower than the average baseline performance after continuous dry mechanical cleaning, indicating a relationship between mechanical cleaning and reduced power output. Future work could improve upon this research by gathering more data over different sunlight conditions, testing different amounts of initial and continuous addition of dirt, and completing more tests to observe the long-term impact of short intervals of mechanical cleaning. This would help more conclusively determine whether mechanical cleaning cycles introduce damage to solar panels. As solar panel use increases in arid regions like Southern California, where solar energy is abundant but water-assisted cleaning is impractical, future work identifying damage-free dry cleaning methods becomes increasingly critical.

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