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Technological Advances in Solar Panel Cleaning and their Impact on Photovoltaic Efficiency

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ABSTRACT

As the adoption of solar energy continues to rise, maintaining the efficiency of solar panels is critical, particularly as dust and debris accumulation can substantially hinder their performance and energy output. To address this challenge, we present an advanced solar panel cleaning system that leverages state-of-the-art robotics and intuitive user interfaces. This system features a highly efficient cleaning mechanism, utilizing integrated brushes and a precision water spray, all orchestrated by an Arduino controlled microcontroller to ensure optimal functionality. The robot is seamlessly operated through a mobile application, developed with MIT App Inventor, which enables real-time control via Bluetooth. This application provides users with a streamlined interface to command the robot's movement and initiate cleaning operations, enhancing both convenience and performance. Our work details the robot's hardware design, software architecture, and the algorithms that enable efficient solar panel maintenance, contributing to sustainable energy management.

Keywords: Solar Panel Cleaning Robot, Arduino IDE, MIT App Inventor, Remote Control, Solar Panel Efficiency, Microcontroller, Bluetooth Interface, User-Centered Design, Renewable Energy Systems, Automation in Solar Maintenance

1. Main text

In recent decades, the global demand for energy has grown rapidly and is projected to increase by more than 50% by 2030. Currently, much of this demand is met by conventional sources like coal, oil, and natural gas, which are being consumed at unsustainable levels. This heavy reliance on fossil fuels raises concerns about resource depletion, increasing energy costs, and environmental damage.

To address these issues, renewable energy sources, particularly solar power, are gaining popularity. Solar energy is mainly captured using photovoltaic (PV) cells, which are organized in arrays. For solar photovoltaic (SPV) systems to be economically viable, these PV modules need to deliver reliable performance over 25 to 30 years under real-world conditions. However, broader adoption of PV technology faces challenges, such as high initial costs and relatively low energy conversion efficiency, partly due to heat buildup in the panels. The temperature of PV modules often exceeds ambient temperatures because the glass cover traps infrared radiation, reducing both power output and efficiency. Furthermore, dust accumulation on PV panels can further lower efficiency, and power output is strongly dependent on sunlight levels. Increased solar radiation directly enhances power output.

Dust or debris buildup on a single panel within an array can significantly reduce energy output, underscoring the need for consistent cleaning. Humidity also affects light reception, as water droplets can refract, reflect, or scatter sunlight. High humidity levels may cause water vapor to accumulate around the cells, potentially resulting in failures in crystalline silicon cells or degradation in thin-film modules, particularly at cell connections or scribe lines. Dust accumulation rates vary based on location, wind direction, and dust characteristics, as illustrated in Figures 3–6. Different PV technologies also offer distinct efficiencies, summarized in Table 1.

The orientation and tilt angle of PV modules are essential for maximizing efficiency, as these factors determine how much solar radiation each panel receives. PV modules are typically positioned northward in the southern hemisphere and southward in the northern hemisphere. The ideal tilt angle is site-specific and should be optimized to capture the maximum solar energy on the PV module surface.

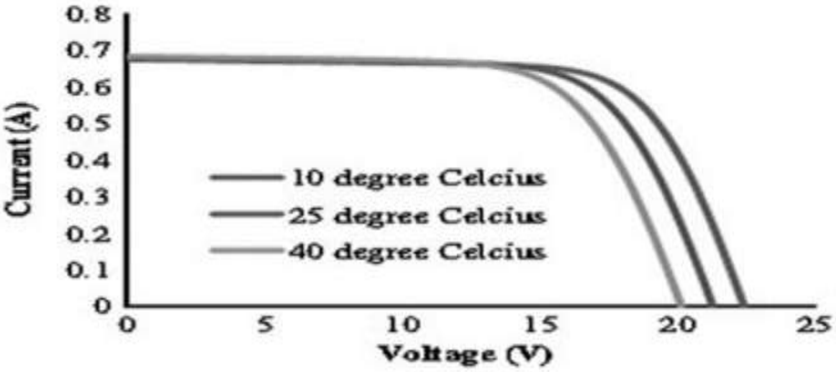

Figure 1. Impact of temperature on the I–V characteristics of the PV module [1].

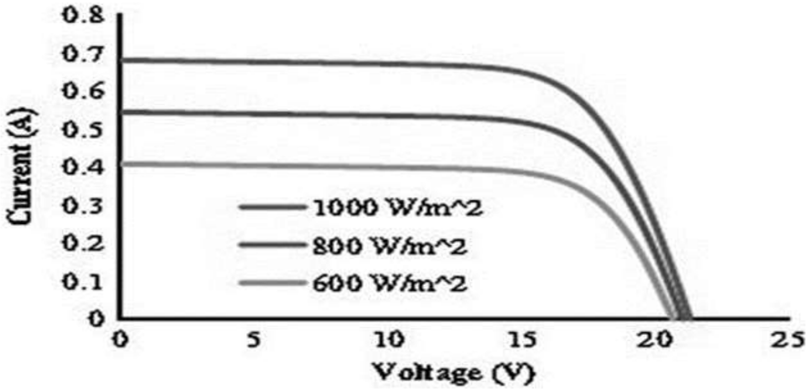

Figure 2. Impact of solar irradiance on the I–V curve of the PV module [1].

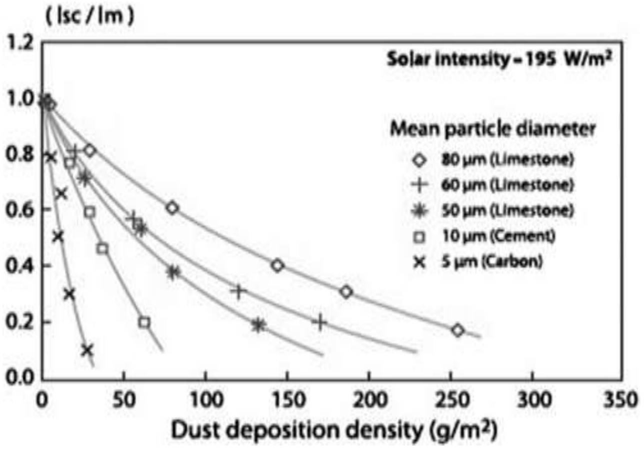

Figure 3. Variation of short-circuit current with dust deposition density for different particle sizes [1].

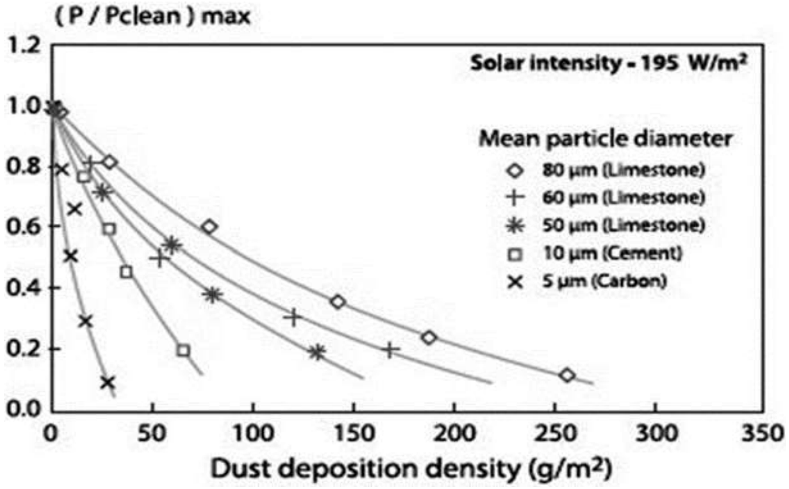

Figure 4. Power output as a function of dust deposition density for different particle sizes [1].

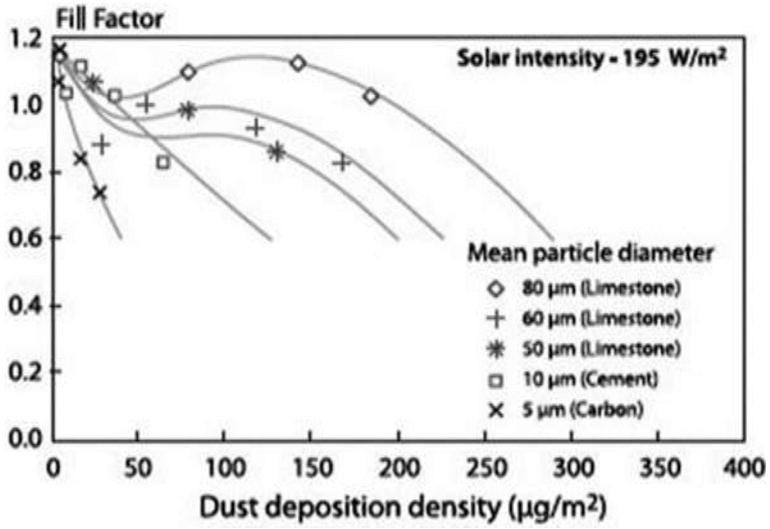

Figure 5. Reduction in solar intensity for various particle sizes as a function of dust deposition density [1].

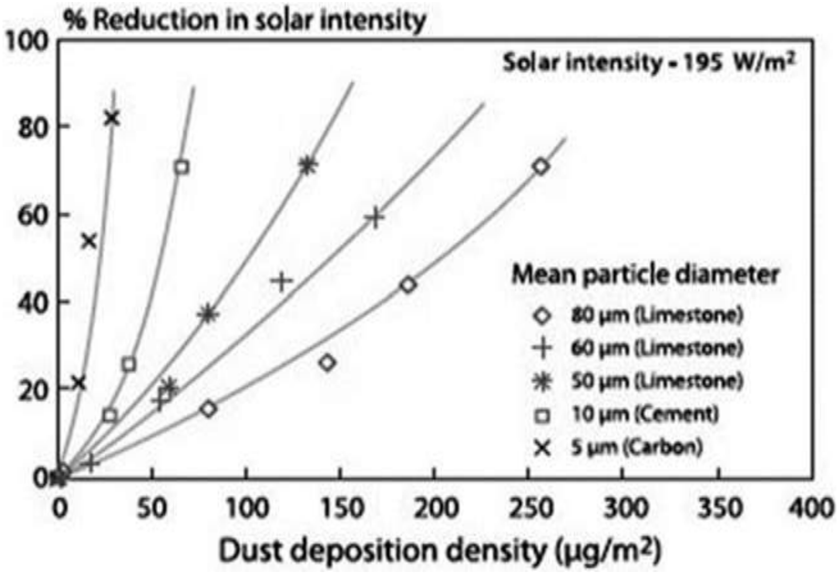

Figure 6. Decrease in fill factor for different particle sizes as a function of dust deposition density [1].

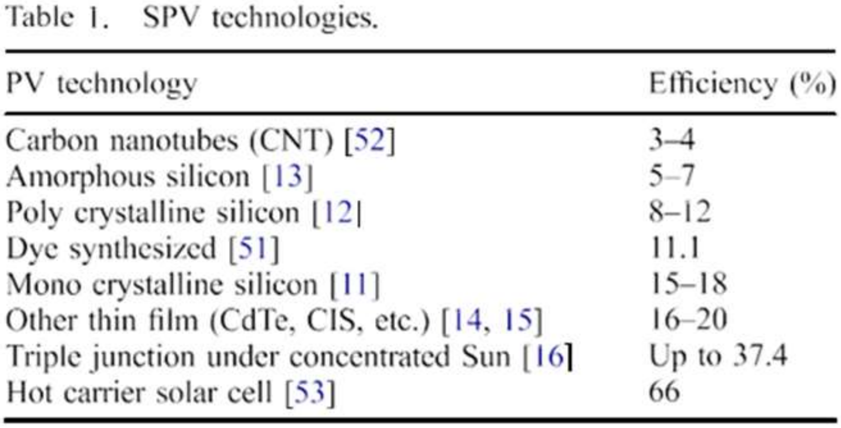

Table 1. SPV technologies.

PV technology	Efficiency (%)
Carbon nanotubes (CNT) [52]	3–4
Amorphous silicon [13]	5–7
Poly crystalline silicon [12]	8–12
Dye synthesized [51]	11.1
Mono crystalline silicon [11]	15–18
Other thin film (CdTe, CIS, etc.) [14, 15]	16–20
Triple junction under concentrated Sun [16]	Up to 37.4
Hot carrier solar cell [53]	66

Automated Cleaning Solutions Advanced Automated Cleaning Technologies for Industrial Applications

Advanced In various industrial settings, including on Earth and Mars, advanced automated cleaning technologies play a crucial role. The choice of cleaning solutions is determined by factors such as geographic terrain and specific area requirements. This approach enables a cost-effective, user-friendly, and efficient assessment of cleaning systems. For instance, solar panel cleaning robots utilize motorized trolleys for horizontal movement, and a vertically operating cleaning head with rotating brushes and scrapers effectively removes dirt from the panels.

Notable robotic cleaning systems include "Gekko Solar" and "Gekko Solar Farm" from Serbot Swiss Innovations. These are specially designed for solar panels, featuring rotating brushes, demineralized water for thorough cleaning, and a mobile movement system. Equipped with vacuum-powered feet and a trapezoidal belt drive, they allow flexible mobility in all directions and can be remotely controlled for large installations.

An advanced model by Wash Panel, an autonomous solar panel cleaning robot, integrates dual functions: activation by rain sensors and water-jet cleaning. Its modular design allows remote control and continuous monitoring through mobile alerts, suitable for installations on various structures

Survey of Cleaning Techniques and Technologies:

Among A popular cleaning method for solar panels uses low-volume spray nozzles controlled by a Programmable Logic Controller (PLC) that also logs operational data. During cleaning, a biodegradable soap is applied, followed by a rinse. For large solar arrays, nozzles are directly mounted to each panel, facilitating effective cleaning. The system operates through a microprocessor and PLC, which can be managed via a web-based interface.

Kawamoto developed a detachable cleaning system that utilizes electro-dynamic force to remove dust from photovoltaic panels. This technology includes screen electrodes that, when charged, apply forces that shift dust downward, ideal for desert conditions. Huang's research highlights the use of fuzzy logic to optimize cleaning schedules based on solar efficiency, employing light sensors and stepper motors to automate the process.

Additionally, a hydrophobic, water-repellent PDMS elastomer coating with a micro-shell array has shown promise in reducing dust accumulation on photovoltaic panels. This super-hydrophobic coating outperforms traditional PDMS and enhances solar panel cleanliness and efficiency.

Efficiency Computation:

To ensure optimal performance, continuous monitoring of solar cell parameters for any drops in efficiency is essential. The efficiency of each panel module is tracked in real-time, and this information is sent to a centralized computer system that oversees all solar cells. Given the variability in environmental conditions, averages over specific periods are considered to account for fluctuations.

The efficiency of a solar cell is defined as the ratio of the energy output from the cell to the energy input from sunlight. Accurate calculations are crucial for evaluating solar cell performance. Solar radiation intensity varies throughout the year and is significantly affected by climatic conditions; for example, solar radiation peaks during summer and decreases in winter, with these patterns also varying by geographic location.

To improve and maintain panel efficiency, an efficiency threshold is set in advance, accounting for expected climate-related variations. This proactive approach ensures that the solar panels operate at their best despite changes in solar radiation intensity.

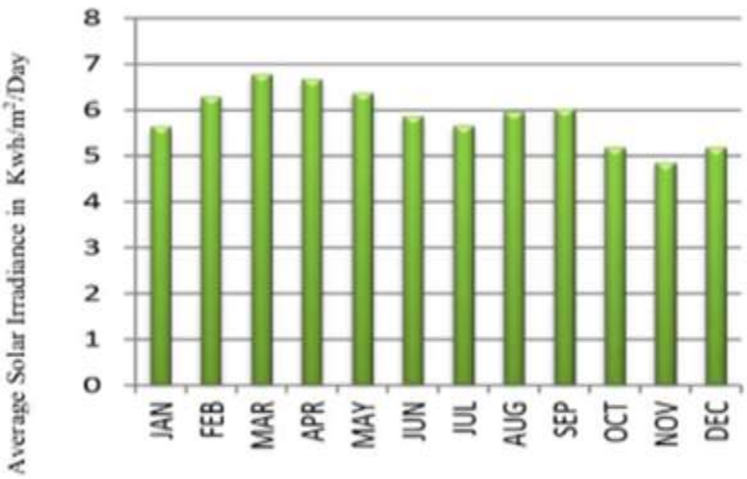

Figure 7. average solar irradance falling on the plane[3]

The efficiency of the solar cell is expressed as follows:

$$\eta = \frac{\text{Voc Isc } FF}{Pin}$$

Where:

- Voc is the open-circuit voltage,
- Isc is the short-circuit current,
- FF is the fill factor, and
- η represents the efficiency.

The system begins by establishing an initial efficiency threshold. If the efficiency of a particular solar cell drops below this threshold, automatic control mechanisms are activated. Additionally, the system compares the efficiency of individual cells to identify any irregularities. The buildup of various particles on the cells gradually reduces their efficiency. If left unaddressed, this accumulation leads to a significant overall decrease in efficiency. Each type of particle affects efficiency differently, with the degree of reduction influenced by factors such as the particle's mass, texture, and color. Figure 8 shows how output power declines as particles accumulate on the panel, while Figure 9 illustrates the efficiency loss resulting from dust buildup on the panel.

Figure 8. Percentage decrease in output power due to soiling.[3]

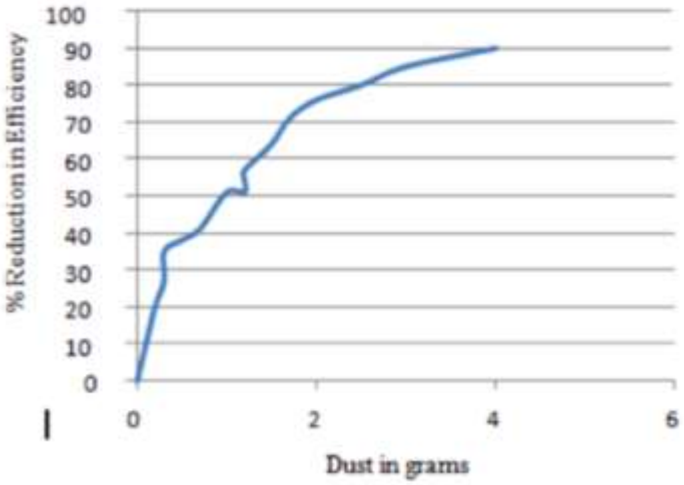

Figure 9. Reduction in panel efficiency due to dust accumulation.[3]

Materials and Methods:

To accurately assess the effect of dust on photovoltaic modules, we conducted an experiment in which dust particles were collected at regular intervals. The power output of the dust-affected modules was then compared to that of clean panels under identical conditions.

1. Dust Measurement System:

We utilized a specialized measurement system to evaluate dust density in an open-air environment. This system includes a dust photometer for continuous monitoring of dust density (measured in mg/m³ with an accuracy of 0.002 mg/m³) and a laser optical particle counter to identify the size and shape of dust particles. Both instruments are controlled by a microprocessor and connected to a computer via an IEEE interface. Additionally, two portable dust photometers and a stationary dust sampler with a programmable filter exchange were used. Filters were dried in an oven and weighed on precise scales to ensure accuracy. The photometer was designed for automatic and continuous dust density monitoring, while the laser photometer could detect particles with a minimum diameter of 0.3 mm.

For this study, three identical photovoltaic solar panels, each tilted at 30°, were installed at the Solar Physics Laboratory in Baghdad, Iraq (latitude: 33.200°N, longitude: 44.220°E, elevation: 41.2 m). Each panel consisted of 33 mono-crystalline silicon cells and was positioned 1.8 meters above the ground to maximize exposure to environmental conditions. The experiment involved daily, weekly, and monthly measurements of dust accumulation. All panels were subjected to the same temperature, spectral distribution, and solar radiation intensity, facilitated by a solar simulator providing constant radiation (750 W/m²) and temperature.

Key measurements included dust density, particle size distribution, voltage, current, and panel efficiency. A Kethly multimeter, with an RMS accuracy of 99%, was used to measure current and voltage, while the module temperature was recorded using additional instrumentation.

Thermocouples were linked to a YSI 74 IC thermometer, which has an accuracy of ±0.2°C. Solar insolation data was obtained using a Kip and Zonen solar integrator, boasting a 99.5% accuracy, with readings printed and recorded by a sensor. The study aimed to establish a correlation between dust density, particle characteristics, and the performance of solar panels over time.

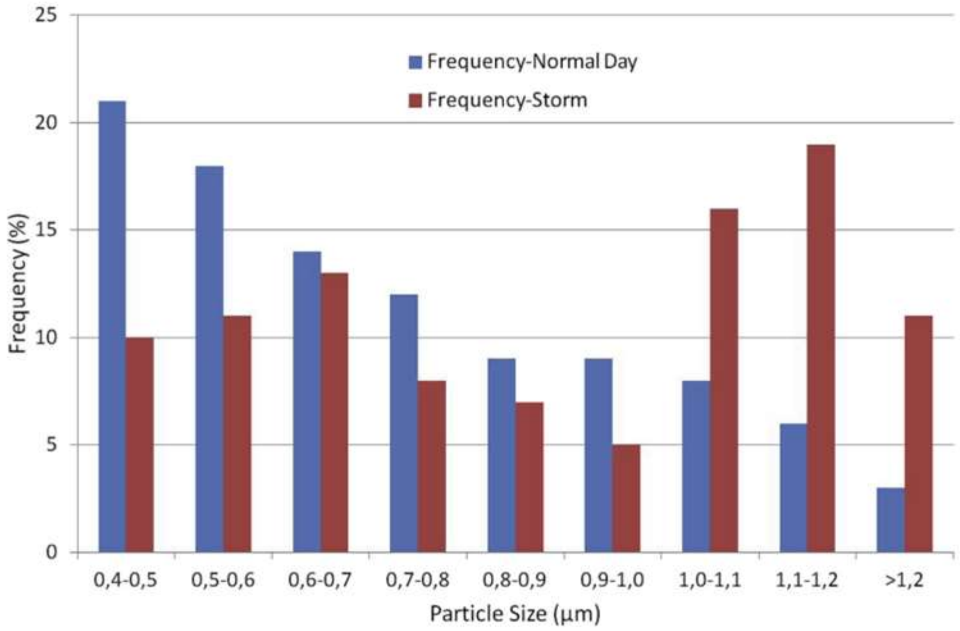

Figure 10. Comparison of dust particle frequency on regular days versus during wind storm events [2].

To examine the impact of dust storms on photovoltaic (PV) panels, the Current-Voltage (I-V) relationship was analyzed for panels operating daily, weekly, and monthly in a dust-affected environment. During these assessments, one module was left exposed to outdoor conditions while another identical, clean module served as a control. Both modules were subsequently tested in a controlled laboratory setting with constant radiation of 750 W/m² and a temperature of 27°C, using the KX-150 solar simulator.

The collected data indicated a significant reduction in current, primarily due to the decreased number of photons reaching the surface of the PV panels as dust accumulates. Performance began to decline at approximately 6%, as dust obstructs sunlight necessary for generating photocurrent.

It is important to note that urban environments, such as Athens, have distinct air compositions, with pollutants like ash and limestone more prevalent alongside red soil, commonly found in Baghdad. This results in a more moderate reduction in energy efficiency in these regions.

To validate the measurements, the experimental data were compared with predictions from a well-established analytical model. This model estimates the efficiency loss, denoted as "$\Delta\eta$," of a dust-covered PV panel relative to a clean one under identical conditions, taking into account both dust concentration and particle characteristics. The efficiency loss "$\Delta\eta$" is determined by the original efficiency of the clean panel "η_0" and the dust mass "DM" (in g/m²) deposited on each panel.

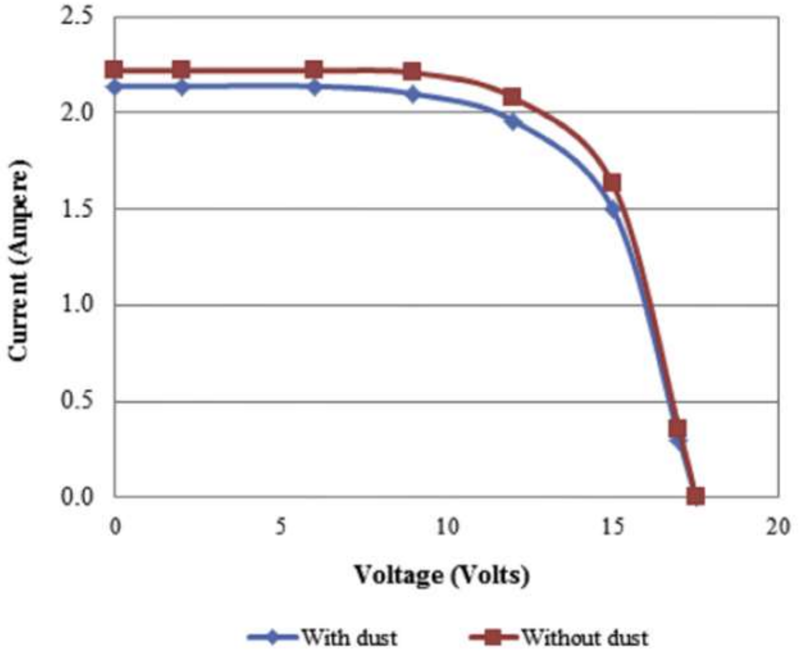

Figure 11. Changes in the Current-Voltage (I-V) characteristics of photovoltaic modules (measured in amperes versus volts) resulting from dust accumulation due to daily exposure[2].

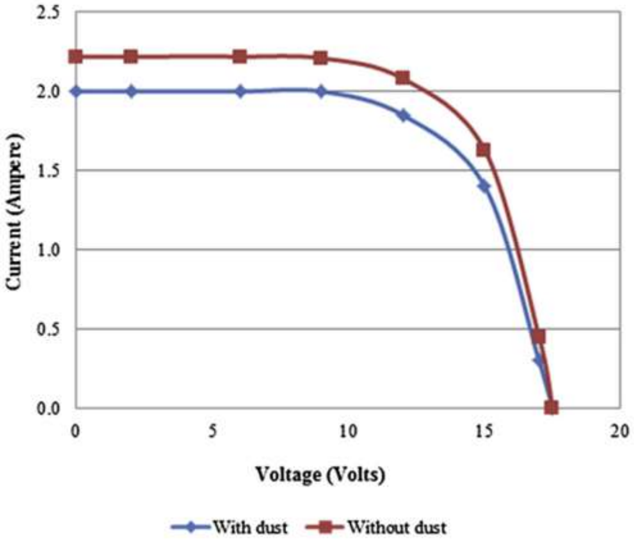

Figure 12. Changes in the Current-Voltage (I-V) characteristics of photovoltaic modules (measured in amps versus volts) resulting from dust accumulation after weekly exposure[2].

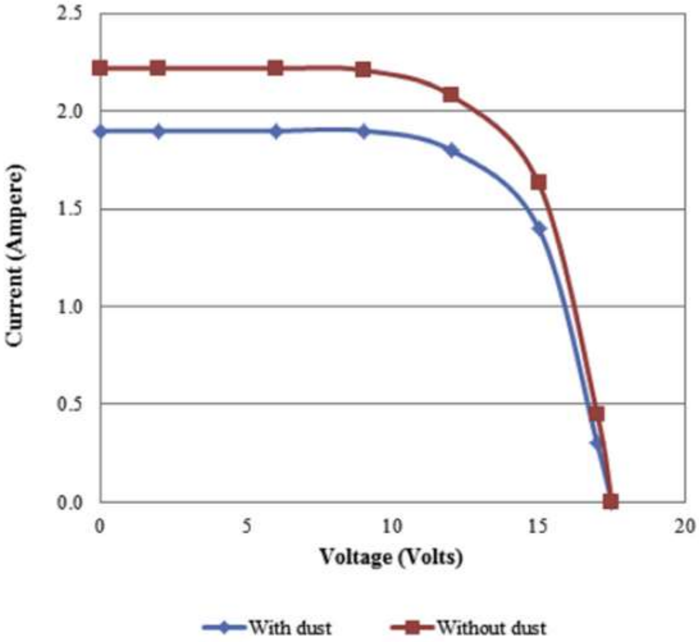

Figure 13. Changes in Current-Voltage (I-V) characteristics (measured in amperes versus volts) of photovoltaic modules subjected to dust accumulation over a month-long exposure period[2].

The dust deposition model includes an empirical coefficient, denoted as "A," which is derived from the characteristics of the dust. In the case study conducted in Baghdad, a semi-empirical coefficient specific to red soil was utilized, with a value A = 0.24 ± 0.085 m^2/g.

$$\Delta\eta = \eta_0 - \eta_0 e^{-A} \cdot \Delta M$$

The analytical model indicates that the efficiency of photovoltaic (PV) panels is slightly underestimated, with a maximum discrepancy of no more than 15%. In Iraq, however, the estimated efficiency reduction for panels affected by dust is significantly greater—more than double—than what is observed in[4]-[20] urban areas like Athens, where natural deposition occurs. This highlights the severe impact of dust on PV installations in near-desert environments. A similar efficiency decline has been observed in Cyprus, where experimental analyses show that PV panels were impacted by dust transported from the Sahara Desert. Specifically, Kalogirou reported that the efficiency reduction of polycrystalline PV panels during dry periods ranged from 10% to 15% after exposure to dust for four to twelve weeks

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