Prototype Wi-fi Enabled Energy Efficient Solar Panel Surface Cleaning System

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***Abstract*—** Solar cells are not very efficient when dirty or polluted. Manual cleaning is labour-intensive and dangerous for large- or roof-mounted systems, and most of the automated systems are not able to be controlled remotely. This paper discusses the construction and testing of a Wi-Fi controlled Solar Panel Cleaner prototype, made up from readily available simple components. Featuring a motorized cleaning mechanism and wireless control, the system removes dust without even water. The experimental results demonstrate that increasing in panel output due to the cleaning effect is significant. The prototype is robust, cost-effective and ideal for small-scale deployment with the potential to scale up into a full system.

Keywords— Solar dust cleaning, PV automation system, enhancing panel efficiency.

1. Introduction

Contrary to finite and environmentally harmful hydrocarbon fuels, solar energy is unlimited, clean and renewable [1]. Increasing energy demand worldwide is leading to the quick deployment of photovoltaic (PV) systems for cost-effective electricity and reduction in greenhouse gas emissions [2]. But, the effectiveness of PV panels gets greatly influenced due to dust and dirt build-up. Reported power losses from [3],[4] when panels are not cleaned routinely can range up to 15% for low-dust locations and up to 35% in harsh or arid environments.

Conventional cleaning techniques such as manual scrubbing, water-based rinsing and chemical washing are time consuming, work-intensive, water-intensive and not applicable to large or inaccessible facilities like desert regions receiving scant rainfall [5].

This article describes a prototype solar panel cleaning machine controlled via an Arduino-compatible microcontroller had that is powered by a DC motor-driven arm (that is accompanied with a spindle mechanism) either manually or using sensors/program texts. The designed system facilitates automatic, non-water cleaning process and it is capable of wireless communication for connection to IoT platforms, as well as smart grids [6], [7]. Applicable to residential, commercial, and industrial level are found the PV performance near the best efficient and enhance total cost-effectiveness [8]

2. Literature Review

Solar photovoltaic (PV) plants are one of the main sources for generating electricity from renewable power generation technology, however effectiveness of solar cells decreases if surface of panel is covered by dust. The magnitudes of power reduction between 15% and 35% are reported by researchers in different environmental conditions and cleaning intervals [1], [2]. In arid and dust prone areas, this rate can be even larger if panels are not cleaned frequently [3].

The traditional cleaning process is primarily based on artificial labour and water flushing, which is not adapted to such huge solar installations because of security risk and high cost for operation [4]. Researcher have suggested mechanical cleaning apparatus using motors, brushers and microcontroller-based control units to solve this problems [5].

M. Kaushik et al. (eds.), *Proceedings of the International Conference on Responsible, Risk-aware, and Regulated AI (RRRAI 2026)*, Advances in Intelligent Systems Research 210,
https://doi.org/10.2991/978-94-6239-723-1_7

Recent advances have involved in incorporating Wi-Fi and IoT devices that allow cleaning systems work to be monitored and operated remotely. Arduino and ESP based controllers are typical due to their low cost and programmability [6]-[7]. These systems permit cleaning to be initiated from a remote location and monitor system operations for better maintenance practices. However, a majority of the developed devices continue to display insufficient long-term stability and mechanical robustness under outdoor conditions [8]. Accordingly, it is desirable to provide a simple, durable, and cost-effective system for cleaning that can be used over long periods in the field.

3. Problem Identification

The generation of a solar control reduces the efficiency of Photovoltaic (PV) system. In photovoltaics, encumbered irradiance is needed to avoid damage caused by pollutants (dust, dirt, and atmospheric pollution), but it reduces the efficiency of PV systems [1]. Several researches demonstrate a loss in power generation between 20 % and 40% due to soiling, for dry and dusty places, whilst continuing non cleansing of the panels can cause 60% power generation loss over time [2], [3].

Traditional wet-cleaning means, mainly including artificial washing and regular machine swiping, consume a large amount of water and are not applicable to ceiling or high surface contaminated for the safety hazard caused by altitude operation ,as well as the trouble of costly personnel [4]. Since many of these mining processes require large amounts of water, they are ethically inviable in water impoverished areas. In addition, lack of maintenance leads to cumulative deterioration in the performance and a higher operational cost along with shortening module life span [5].

Although, automated cleaning systems have been presented in literature; however configuration with intelligent pollution detection, real-time performance monitoring and condition-based activation (based on solar panel gradient), secure wireless link to monitor the cleanliness status of modules and field trial for long duration is still not known [6]. Although some of these Wi-Fi-connected systems allow for an on-demand actuation, they generally lack autonomy of control and predictive performance analysis, which highlights the need for holistic internet-of-things (IoT)-based frameworks suitable for flexible and robust PV maintenance [7], [8].

A. Dust Accumulation on solar panel

General dust deposition cause overwhelming decrease of PV (Photovoltaic) systems performance by shading blocking the incident solar radiation and escalating optical losses [1]. Laboratory and field measurements have recorded degradation in power output of around 20%–40% in dust-moderate environments and to as high as 60% with long-term exposure in an arid area if the panels are not piled regularly cleaned [2], [3]. PM2.5 (fine particulate matter) from construction work, vehicle exhaust emission and dry weather lead to homogeneous scattering on the module surface results in declining short circuit current, open-circuit voltage as well as power output [4]. Moreover, nonuniform soiling can result in local shading that addressees thermal stress and high potential for hot spots due to long term degradation of the solar cell causing irreversible damages [5].

B. Manual Cleaning is Inefficient & Unsafe

Despite their inefficiency and associated safety issues [1], so far hand cleaning is still the most widely used maintenance method for photovoltaic (PV) plants. The work is very laborious, especially for rooftop and utility-scale solar farms where the working-at-height increases risks of falling down as well as occupational injury vicissitudes [2]. In addition, the cleaning efficiency is greatly influenced by operator training and frequency of maintenance, thus leading to non-uniform removal of contamination and prolonged low energy output when surface fouling is not rapidly detected or removed [3], [4].

C. High Water Usage in Traditional Cleaning

Conventional wet scrubbers exacerbate resource issues in arid and semi-arid climates by using significant amounts of water for each wet-scrubbing cycle. In field, water consumption varies between 20 and 100 liters per panel per week in very dusty environments quickly exhausting the scarce water in the territories with highest solar incidence [1], [2]. These actions can considerably increase the operation costs and the eco friendliness of photovoltaic (PV) power station [3].

These semi-automated existing cleaning systems aren't really autonomous and rely on a human to turn them on and off, not based on the condition [4]. Consequently, the cleaning process may take place when there is little soiling or it may take longer to initiate in the wake of intense soil events and this could cause inappropriate energy spending, as well as a boosted mechanical wear out and life degradation [5], [6]. These constraints suggest the requirement for a smart sensor-based adaptive cleaning system, which adjusts to dynamic environmental conditions.

D. Lack of Automation in Existing Systems

There are several automated solar panel cleaning systems, however most of these systems are operated using fixed or conditional based operation strategies without incorporating intelligent sensing of soiling levels which leads to inefficient operations [1], [2]. This can lead to cleaning cycles being initiated even on relatively clean panel surfaces and that a substantial amount of dust passes undetected upon long idle times [3]. This lack of adaptive control causes the cleaning frequency and timing to be nonoptimal, leads to increased wastage of energy and system wear, and compromises the overall system reliability [4]. These limitations however underscore a requirement for sensorinformed, condition aware cleaning systems that are able to adapt dynamically to the environment and the state of surfaces in real-time [5].

4. Methodology

The system is comprised by three main subsystems (a mechanical cleaning system, a sensor based controller and a wireless communication interface) programmed by central microcontroller [1]. The mechanical system consists in a light structure installed on top of the PV panel, and guidance elements (guide rails, timing belts, or lead screw mechanisms) to provide proper driving linear motion for uniform coverage of the whole panel area [2], together with a motor-driven brush or wiper mechanism used as sweeping attachment, which purpose is removing dust from the surface. These are arrangements for ensuring stability in operation with minimal vibration and sound emissions.

The electronic control system consists of a Wi-Fi-enabled microcontroller board such as ESP32, which encompasses a multi-core processor with peripheral controls and integrated communication modules [3]. Motor driver circuits and power management ICs are used to control actuator operation and maintain consistent power supply. A number of sensors are used to support smart, condition-dependent operation including voltage and current sensors for monitoring the real-time PV output, irradiance sensor is used for controlling the environmental conditions, camera may be utilized to detect visually surface soiling by using image-based analysis methods [4], [5].

Wireless communication is realized by means of Wi-Fi, and lightweight application-layer protocols like MQTT or HTTP are employed, to allow the cleaning unit to exchange data with a cloud or an edge server in both directions [6]. The user-interface of the system is based on a mobile or web-dashboard which provides an interface for operators to schedule cleanings, and observe performance in real-time, as well as keep record logs for historical performance analysis and preventative maintenance scheduling [7]. This unified IoT architecture allows easy installation and operation at scale and provides the potential for smart-grid integration with emerging energy management applications.

A. **Design of the Automatic Cleaning System**

The proposed mechanical architecture employs a compact composite rail system in which a carriage carrying a brush–wipe cleaning assembly travels along an overhead guide rail mounted on a pivoted support frame [1]. A motor and transmission mechanism drive the carriage across the photovoltaic (PV) panel surface to remove accumulated dust and debris. The carriage integrates both power and control electronics responsible for scheduled or sensortriggered motor activation, safety interlock enforcement, and system status reporting via Wi-Fi communication [2]. To prevent surface abrasion and mechanical stress on the panels, the carriage operates at low linear velocity while maintaining sufficient contact force for effective dust removal [3]. The system is designed to be compatible with standard PV module dimensions and emphasizes gentle cleaning, energy efficiency, weather resistance, and ease of installation.

For structural support and mounting, lightweight rectangular frames such as aluminum extrusion profiles are used due to their high stiffness-to-weight ratio and modularity [4]. The frame is pivot-mounted at the upper edge of the panel array, providing both rigid support and sufficient clearance for carriage travel. This configuration also allows integration of end-of-travel limit switches for positional safety and motion control. Linear guidance is achieved using paired parallel rails fabricated from anodized aluminum or hardened steel with bronze or polymer sliding elements [5]. The carriage employs low-friction bushings or slider bearings to minimize wear and vibration, ensuring stable motion and preventing over-travel. Mechanical end stops and electronic limit switches are implemented to provide redundant safety and precise travel termination. As shown in figure 1.

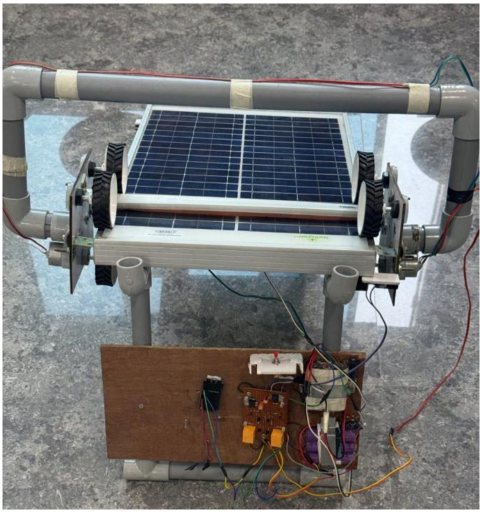


Fig 1 System Model

1) Theorical impact of soiling on Soar Panels

Dust accumulation on photovoltaic (PV) modules forms a semi-transparent layer that scatters and absorbs incident solar radiation, thereby reducing the photon flux reaching the semiconductor junctions [1]. Experimental studies show that even thin dust layers in the range of approximately 0.1–1 mm can reduce optical transmittance by 20%–40%, leading to proportional reductions in short-circuit current and overall output power, along with measurable degradation in open-circuit voltage and fill factor [2], [3].

With prolonged exposure, deposited particles may become cemented to the glass surface due to humidity and temperature cycling, increasing surface adhesion and electrical series resistance [4]. Non-uniform dust distribution also introduces partial shading, which causes current mismatch between cells and results in localized hot spots where temperatures may exceed 80 °C, accelerating cell degradation and increasing the risk of bypass diode failure [5]. In addition, sustained thermal stress and surface charge accumulation contribute to potential-induced degradation (PID), further reducing module lifespan and long-term energy yield [6].

2) Post Cleaning Efficiency Restoration

Effective cleaning of photovoltaic (PV) module surfaces restores optical transmittance to above 95%, thereby realigning operating conditions closer to Standard Test Conditions (STC: 1000 W/m² irradiance, 25 °C cell temperature) and enabling immediate recovery of approximately 15%–35% of lost power output in previously soiled modules [1], [2]. From an optical standpoint, removal of diffuse scattering particles minimizes reflection and absorption losses, allowing anti-reflective (AR) coatings to regain their intended effectiveness in maximizing photon transmission into the semiconductor layers [3].

Empirical performance models, including the soiling ratio framework proposed by Mani and Pillai, report recovery from degraded ratios of approximately 0.6–0.8 to values exceeding 0.98 after effective cleaning [1], [4]. Thermally, uniform irradiance distribution following cleaning reduces localized hot spots and improves heat dissipation through natural convection, lowering operating cell temperatures by approximately 5–10 °C [5]. Given typical PV temperature coefficients of approximately −0.3% to −0.45% per °C, this thermal reduction further contributes to measurable gains in electrical efficiency and long-term module reliability [6].

A. **Conditions taken into Account** Problem with lux-only logic

Clouds + rain → low lux

Panel may already be clean (rain cleans it)

System may clean unnecessarily

Wastes power, water, and motor life

Weather Condition	Action by Control System
High Lux (Illumination)	No Cleaning
Low Lux + No Rain	Cleaning Start
Low Lux + Raining	Skip Cleaning
Night time	Skip Cleaning
Rain detected earlier	Skip Cleaning for few hours

Logic of Control System Sensor Based Control System for Operation of Cleaner

Best Solution: Sensor Fusion (Lux + Rain + Time logic) We have used:

Lux sensor → dust detection (Level of Illumination)

Rain sensor → skip cleaning during rain

Time window (time-of-day) → avoid night/cloud confusion

Fig.2 Panel without cleaning

Fig.3 Panel after cleaning

5. Result and Discussion

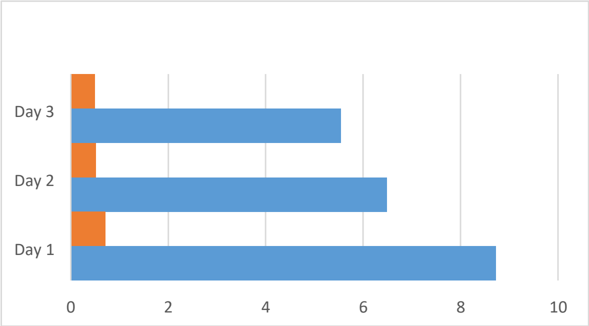
The dataset analyses the behavior of PV panel performance under clean day, dusty day and dirty (second and third days) conditions in a sequence after verification for the configurations shown in fig 1 and fig 2 respectively with corresponding static bar chart showing the reduction in the parameters with dusty condition and increased value under cleaned condition. For the clean state, panel voltage is relatively unchanged and slightly reduced from 12.31 to 11.64 V, while the output current maintains almost unchanged at about 1.7 A, leading the output power stable around 20–21 W all along observing time under unobstructed irradiance (i.e., power generation stability).

Dusty panels on the other hand, suffer fast performance degradation. The output voltage decreases ~36% from day 1 to day 3, and the output current decreases in the range of 29%–41% during that same time. These overlapping effects lead to a pronounced power loss, more than 85% after the third day depositing from about 6.2 W to 2.8 W and reveal the strong association between soiling and electrical degradation due to mainly reduced photon flux as well as increased series resistance caused by non-uniform dust layers in particular.

These findings confirm the need for timely and automatic cleaning systems in order to avoid prolonged exposure to soiling conditions, that would produce direct energy loss and long-term reliability issues on PV plant resources.

With Dust Reading:

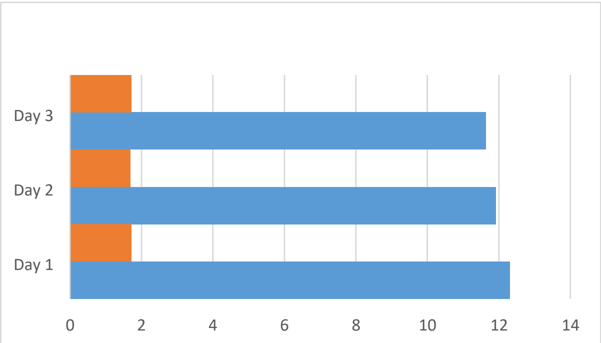
Data taken	**Voltage (v)**	**Current (A)**
Day 1	**8.73**	**0.71**
Day 2	**6.49**	**0.52**
Day 3	**5.55**	**0.50**



The above bar chart representation is showing the parameters of panel without cleaning. As shown in fig 2.

Without Dust Reading:

Data taken	Voltage (v)	Current (A)
Day 1	12.31	1.71
Day 2	11.91	1.69
Day 3	11.64	1.71



The above bar chart representation is showing the parameters of panel after cleaning. As shown in fig 3.

6. Conclusion

A working prototype of the Wi-Fi-controlled solar panel cleaning robot was successfully developed, constructed and tested. It is replete with basic mechanical components and inexpensive electronic control, which allows it to be easily integrated within residential or small commercial environments. The wireless functioning makes it possible to remotely done cleaning cycles and the mechanical construction can be easily adapted for panels of various sizes.

Experimental results demonstrate a remarkable enhancement in the photovoltaic (PV) output due to cleaning and pave way for verifying its efficacy of brushing. Not relying on sophisticated AI algorithms means the system is simple and inexpensive to maintain yet still delivers dependable automation. In conclusion, the proposed scheme provides a simple and scalable way to mitigate energy loss from dust deposition on solar cells.

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