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Research Article

Experimental investigation of power losses in PV panels soiling and designing an affordable cleaning solution

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ABSTRACT

This study investigates the impact of soiling on the power output of photovoltaic (PV) panels and presents a cost-effective cleaning solution to mitigate this issue. Conducted in the semi-arid coastal environment of Karachi, Pakistan, the research focuses on both polycrystalline and monocrystalline PV panels. Results indicate that soiling significantly reduces power output, with clean panels generating 7.8% to 15.6% more power than their dirty counterparts. A novel wiper-based cleaning system, designed using locally sourced materials, was tested and proved effective in restoring the panels' efficiency. The economic analysis suggests a payback period of less than two years for this cleaning system. The study provides practical recommendations for PV panel maintenance and highlights potential areas for future research.

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INTRODUCTION

In recent decades, the escalating hazard of climate change has highlighted the urgent need for sustainable energy solutions. With the adverse impacts of climate change becoming increasingly evident, the quest for viable alternatives to traditional fossil fuel-based energy sources has gained unprecedented urgency. Among these alternatives, solar energy stands out as a pivotal player in the transition towards a low-carbon future [1]. As the world faces with the consequences of greenhouse gas emissions and strives to meet the ambitious targets set forth in international agreements such as the Paris Agreement, the significance of harnessing solar power as a clean, renewable energy source cannot be overstated [2]. In this context, exploring the role of solar energy in mitigating climate change emerges as a pressing priority, underscoring the critical nexus between environmental sustainability and energy innovation [3]. The trajectory of solar energy deployment has witnessed a remarkable ascent in recent years, setting its position as a cornerstone of the global energy landscape. Projections indicate a staggering addition of at least 1,177 gigawatts (GW) of solar capacity by the year 2024, underscoring the unprecedented growth and significance of this renewable energy source [4]. This substantial expansion reflects not only the increasing recognition of solar power as a pivotal component in the transition towards sustainable energy systems but also

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its competitive edge over conventional fossil fuel-based alternatives. As nations worldwide commit to ambitious renewable energy targets and capitalize on technological advancements in solar photovoltaic (PV) technology, the forecasted surge in solar capacity heralds a transformative shift towards a cleaner, more resilient energy future [5].

Despite remarkable advancements in PV technology, challenges persist in maximizing efficiency and output, particularly due to soiling, which significantly impedes performance. The electrical efficiency of commercial photovoltaic (PV) modules is restricted to 10% to 25%, despite the growing deployment of PV systems [6]. The overall losses in PV panels are broadly classified into six categories including Bridging, Open Circuit, Soiling or Shading losses, Degradation, Line-to-Line, and Bypass diode [7]. These various types of losses are shown in Figure 1 below.

Soiling, characterized by the accumulation of various contaminants such as dust, dirt, and other particulate matter on solar panels, poses a challenging obstacle to optimal energy generation [8]. The accumulation of these substances diminishes the amount of sunlight reaching the PV cells, thereby compromising their efficiency and overall energy output. As a result, mitigating the impact of soiling emerges as a critical priority in the quest to enhance the performance and viability of solar energy systems. The accumulation of the dust also accelerates the degradation of the panel in some cases [9]. Addressing this challenge necessitates innovative approaches and solutions to minimize the adverse effects of soiling and unlock the full potential of solar power as a clean and sustainable energy source [10].

Soiling, in the context of solar energy, refers to the accumulation of various forms of debris, such as dust, dirt, pollen, and other particulate matter, on the surface of solar panels [11]. This accumulation can obstruct the passage of sunlight to the photovoltaic cells, thereby reducing the efficiency of energy conversion and ultimately diminishing the overall energy output of the solar system. The significance of this problem is underscored by empirical data revealing substantial losses incurred due to soiling. For instance, in the United States, reported annual losses attributable to soiling have exhibited a range from 0% to 6% [12-14]. Moreover, in certain arid dry-regions locations, peak losses resulting from soiling can escalate significantly, ranging from 10% to a staggering 70% [15]. Such findings highlight the considerable impact of soiling on the performance and effectiveness of solar energy systems, emphasizing the

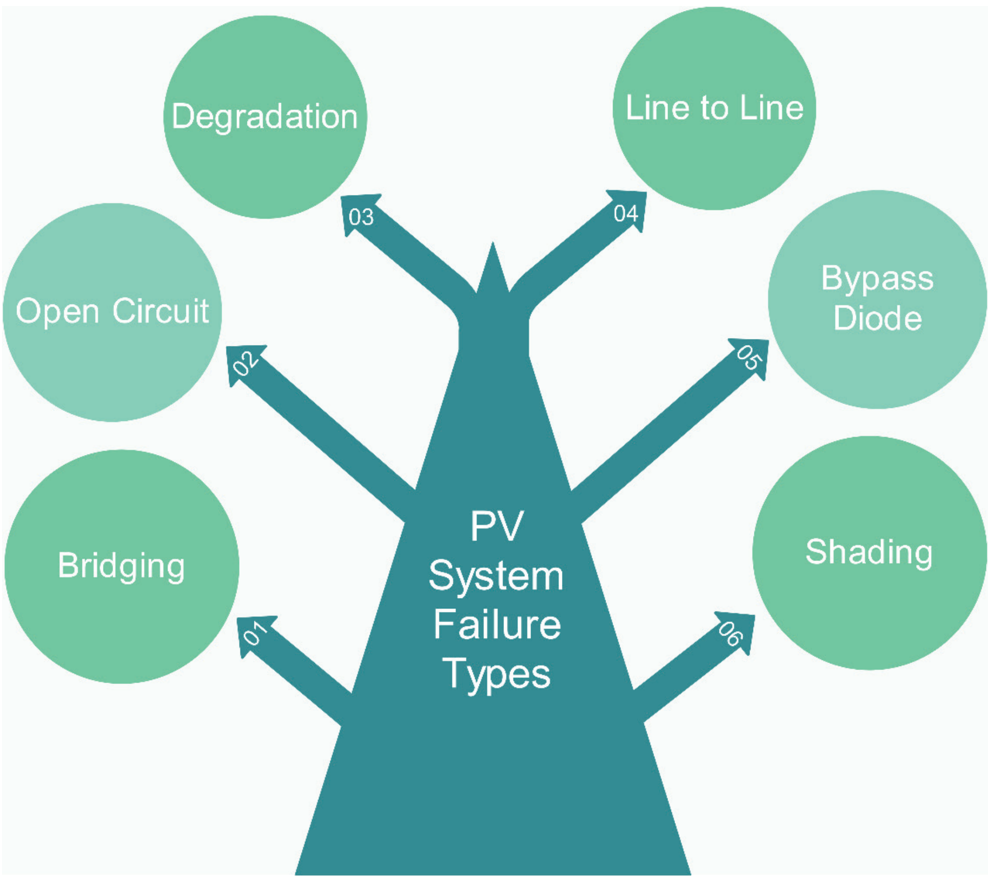


Figure 1. Six general categories of PV panel losses.

critical need to address this challenge effectively to optimize the utilization of solar power resources.

Several parameters influence the extent and impact of soiling on solar panels. These parameters include environmental conditions such as humidity, ambient temperature, wind speed, and direction, which can affect the accumulation rate of dust and debris on the panel surfaces [16, 17]. Additionally, the characteristics of dust particles, such as their size, weight, and shape, play a significant role in determining how effectively they adhere to and accumulate on the solar panels [18]. The tilt angle and orientation of the panels also influence the deposition of soiling, with panels located closer to the equator being more susceptible to dust accumulation [19]. Other factors, such as the presence of nearby vegetation, industrial activities, and geographical location, can further exacerbate soiling issues [20]. Understanding these parameters is essential for developing effective mitigation strategies to minimize the adverse effects of soiling on solar energy systems.

This in perspective, an experimental study was conducted to investigate and prevent the effects of soiling in PV panels in Karachi, Pakistan. This study distinguishes itself from previous research in several key ways. Firstly, while many studies have explored the effects of soiling on solar panels, few have specifically addressed the performance disparities between small and large panels. By comparing the soiling impacts on different panel sizes, this study provides valuable insights into optimizing solar energy production across various panel configurations. Secondly, the research fills a critical gap by focusing on Karachi, a region where soiling studies are scarce. By conducting the study in this location, we offer region-specific insights into the challenges and solutions related to soiling in a unique environmental context.

Moreover, while previous studies often identify the problem of soiling, this research takes a proactive approach by proposing innovative solutions to mitigate its effects. By offering practical strategies for minimizing soiling and maximizing solar panel efficiency, this study provides actionable recommendations for stakeholders in the renewable energy sector. Overall, this study not only contributes new knowledge to the field of solar energy and soiling but also offers tangible solutions that can enhance the performance and reliability of solar energy systems, setting it apart from existing research efforts.

MATERIALS AND METHODS

Soiling Effect Experiment

To assess power losses attributed to soiling, a soiling station was established at Pakistan Navy Engineering College (PNEC) NUST, Karachi, Pakistan. The primary parameters measured over time were the short-circuit current and open-circuit voltage of PV modules. Four PV panels were installed atop a 2-story building without a parapet. PV 1 and PV 2 were polycrystalline panels with 120 watts capacity each, while PV 3 and PV 4 were monocrystalline panels with 30 watts capacity each. All PV panels were affixed at a fixed tilt angle of 24°, corresponding to the latitude of Karachi, and oriented southward (180°). The detailed specifications of the panels 1 & 2 (120 W) and 3 & 4 (30 W) are presented in Tables 1 and 2, respectively.

Panels 1 and 4 were designated as clean panels and were cleaned manually twice a week, specifically on Thursdays and Fridays. Conversely, panels 2 and 3 were categorized as dirty panels and were left uncleaned, thus exposed to environmental dust accumulation for one month. Data recording for both sets of panels began after this period. Data for both sets of PV panels, including open-circuit voltage, short-circuit current, and corresponding Power output, were recorded utilizing a digital multimeter. Measurements were taken randomly between 11:00 AM-1:00 PM (peak sun hours) from April 12, 2023, to May 14, 2023 (23 days). The data for 10 days i.e. 14th to 17th, 21st to 24th, 28th and 30th April was not recorded. The performance parameters of the PV modules were computed employing the following equations [21]:

$$P_{max} = V_{oc} \times I_{sc} \times FF \quad (1)$$

Table 1. Specification of the solar panels

Parameter	Symbol	Panels 1 and 2 (120 watts)	Panels 3 and 4 (30 watts)
Maximum power at STC	P_{max}	120 W	30 W
PV type	-	Polycrystalline	Monocrystalline
Vendor	-	JC solar company	JC solar company
Open circuit voltage	V_{oc}	19.8 V	18.0 V
Optimum operating voltage	V_{mp}	16.0 V	1.667 A
Short circuit current	I_{sc}	8.03 A	22.5 V
Optimum operating current	I_{mp}	7.50 A	1.8 A
Dimensions (mm)	L×W×H	1320 mm×680 mm×35 mm	510 mm×440 mm×25 mm
Weight	M	10.5 kg	2.6 kg

Where V_{oc} and I_{sc} are the open circuit voltage (V) and short circuit current (A) respectively. FF is the fill factor which ranges from 0.70 to 0.75 for crystalline solar cells (both monocrystalline and polycrystalline cells) [22]. A study investigating the fill factor and efficiency of monocrystalline and polycrystalline solar cells installed in another city in Southern Pakistan indicated that fill factors range from 0.74 to 0.76. Therefore, a fill factor of 0.75 was used in this study for both panels. It should be noted that the fill factor does affect the power produced by the PV panels however, it will not affect the percentage difference between the power produced by the clean and dirty panels.

Wiper-Based PV Cleaning Solution

Researchers have actively explored various solutions aimed at preventing, reducing and mitigating the impact of soiling on PV performance. Among these efforts, considerable attention is directed towards the development of Anti-Soiling Coatings (ASC), which hold promise for optimizing performance levels. The research by Jiehong Wang et. Al shows that both the hydrophobic coating and the Super Hydrophobic coating have better anti-soiling and dust removal performances compared with bare glass [23]. Additionally, significant research is being devoted to evaluating various cleaning techniques, encompassing dry, wet, drones retrofitting, Mechanical Vibrator and natural cleaning methods [24-27]. However, previous solutions exhibit certain limitations:

- Costly implementation: Many existing solutions incur significant expenses, rendering them financially impractical for widespread adoption.
- Limited scalability: Some solutions are only feasible for large-scale application, making them unsuitable for smaller installations.
- Lack of readily available equipment: Certain approaches rely on specialized or proprietary equipment, which may not be easily accessible or affordable. In contrast, our approach utilizes commonly available car wipers, which are both inexpensive and widely accessible.

To address the above mentioned limitations, a wiper-based cleaning solution was designed due to its practicality for cleaning glass surfaces, which are typical of PV panels often installed at heights that are not easily accessible. The automotive industry has employed wiper systems for windscreen for over a century, owing to their simplicity in design, cost-effectiveness in manufacturing, robust construction, and smooth operation [28]. Although conventional wipers follow a circular path to clean surfaces, PV panels require cleaning of rectangular glass surfaces. Therefore, a straightforward straight wiper blade was adopted, in contrast to the curved windscreen with claw-type construction commonly found in automobile. The design was created using SolidWorks software, and the necessary components were procured from the local market and subsequently fabricated.

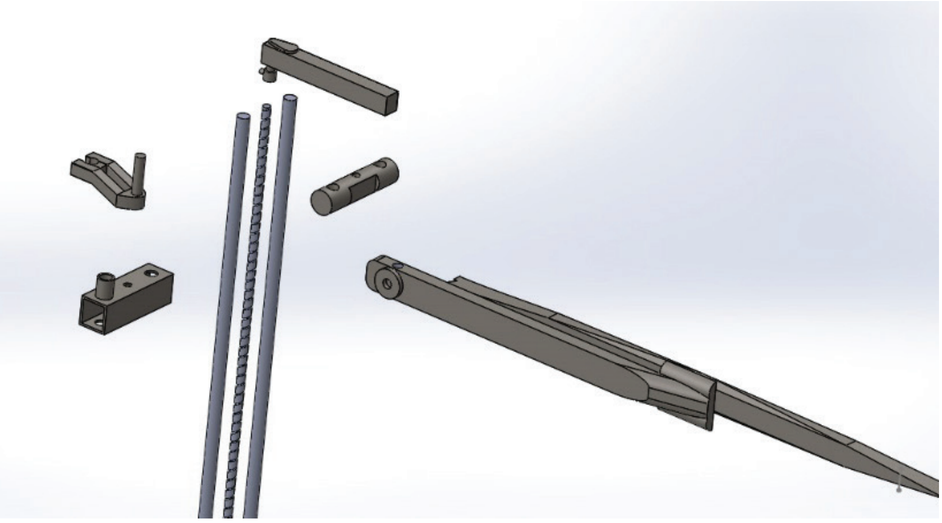
The wiper-based design integrates a 12-volt two-way DC motor with a gearbox to provide the necessary torque for optimal performance. This motor, regulated by limit switches at both ends, facilitates the back-and-forth motion critical for efficient cleaning. To ensure smooth operation, a bush mechanism is utilized, similar to the carriage assembly movement in traditional lathe machines, driven by a lead screw connected to the motor.

The linkage mechanism entails the installation of fixed balance rods made of mild steel along the panel's sides. On one side, a two-way motor is installed, while on the opposite side, a water-supplying pump is mounted. This setup ensures balanced movement and efficient distribution of resources. The lead screw, in conjunction with the motor, converts rotational motion into linear movement through a meticulously crafted bush mechanism, fabricated using traditional lathe machines. Support for the auxiliary components is provided by four brackets, strategically positioned at each corner. Additionally, three limit switches are employed for precise control: two for governing motor motion and one to regulate the water-supplying pump. This comprehensive system ensures effective and reliable cleaning of solar panel surfaces, optimizing their performance and longevity. The model developed in SolidWorks, is presented in Figure 2 (Exploded view and side view).

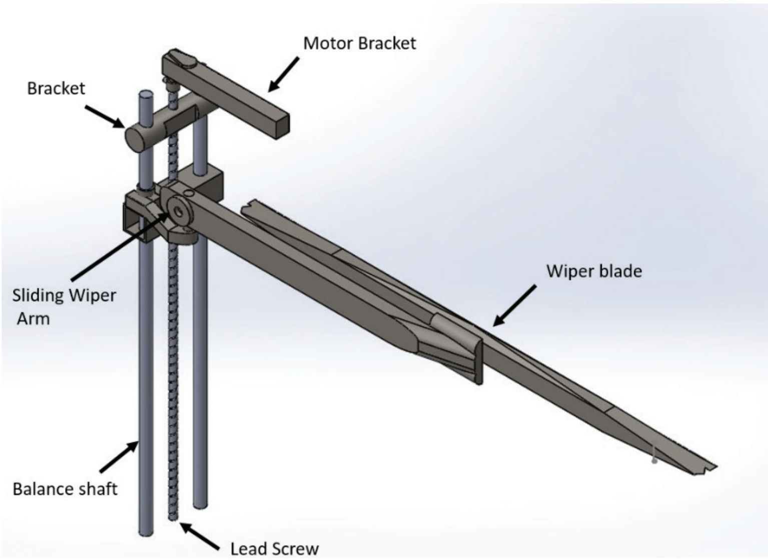
The inclusion of one 2 mm bore water nozzle mounted on the wiper guarantees thorough cleaning in both forward and backward directions. A small yet essential component, a low-input pump similar to those used for automobiles windscreens, draws water from an external tank to supply the nozzle. Control of this pump is facilitated by a discreet limit switch. A single nozzle along with the low-input pump, was found to be sufficient for the width 120W solar panel (0.68 m). It's emphasized that operating the wiper without water is discouraged, as it could potentially damage the glass surface, adversely affecting the panel's output efficiency. A single forward-backward sweep of the wiper on the plate was found sufficient to clean the panel (based on the power output being restored to clean panel levels). The nozzle is mounted on the wiper carriage assembly, allowing it to travel along the lead screw. This design ensures that a single nozzle can effectively cover the entire panel. A cleaning frequency of once every day was found to be sufficient.

The cleaning system does not necessitate high-speed operation of the wiper blades. Operating them at high speeds would result in excessive inertia, increasing driving torque and reducing the system's lifespan. Therefore, the driving shaft speed was set at 5.2 rotations per minute, corresponding to an angular velocity (ω) of 0.5235 rad/s.

The calculations for the length-to-width ratio and the percentage of PV panel area cleaned are presented in Table 2.



(a) Exploded view



(b) Side view

Figure 2. CAD models for wiper-based developed on solid works.

Table 2. Panels 1 & 2 dimensions and length to width ratio

Dimensions of panel (mm)	Total area of glass (mm)	Length to width ratio of panel	Area of glass cleaned	Percentage of area cleaned
1302 x 662	862	1.97	794	93 %

The normal torque, T (N-m) required by the wiper is given by the following equation [28]:

$$T = \mu \times F_N \times L1 \quad (2)$$

Where,
μ is the coefficient of friction (-)
FN is the total normal force exerted on flat wiper blade (N)
L1 is the length of the wiper blade = 0.66 m (Length of the wiper blade is 0.6m which is equal to the width of 120 W panel)

Due to the intricate interaction between the wiper normal load, coefficient of friction, and sliding velocity, a complex correlation exists, primarily influenced by the properties of the rubber blade and its contact with the glass surface. As the interference of the wiper blade increases, the coefficient of friction μ tends to decrease. Empirical observations indicate a coefficient of friction ranging from 0.7 to 2.3 for variations in interference between 0.6 to 2.4 mm in a 4 mm specimen of the wiper blade under dry conditions [28]. For the current design calculations, a conservative estimate of 2 was chosen for the coefficient of friction.

The total normal force FN is as the product of normal force per unit length, fiN (N/m) and the blade length L (m) as given by the following equation.

$$F_N = fiN \times L1 \tag{3}$$

The typical normal force exerted on flat wiper blades in automobiles, as indicated in wiper selection catalogues, ranges between 10 to 15 Newton's per meter (N/m) of blade length. Unlike automotive wiper systems, which encounter shocks and vibrations, wipers on solar panels operate without such disturbances. Therefore, a normal force of 12 N/m is sufficient for adherence to the glass surface. Using fundamental equations, the normal force leads to motor which can provide a torque of 10.45 N-m. A list of components along with specification and cost for each is given in Table 3. The results of the soiling effect experiment and performance of the wiper-based solution is presented in the next section. An economic analysis was conducted to evaluate the performance of the wiper-based solution. This analysis considered the additional power generated from panels cleaned using the wiper-based solution, along with its associated costs, to estimate the break-even point and determine the payback period.

RESULTS AND DISCUSSION

Figure 3 shows photographs of the clean and dirty panels after the end of the trial period. It can be seen that the dirty panels are coated with a fine layer of dust. Streaks of clean lines can also be observed on the dirty panels which are likely traced by water droplets that have condensed from the humid air during the nighttime. There was no rainfall during the trial period. This soiling is expected to cause the PV power output from the dirty panels to be lower than that of the clean panels.

(a) Clean Panels

(b) Dirty Panels

Figure 3. Photographs of front view of (a) clean solar panels (panel 1 and 2) and (b) soiled solar panels (panel 3 and 4).

Maximum power generated by the clean and dirty set of 120 W polycrystalline PV panels for each day and that by the 30 W monocrystalline panels are presented in Figures 4 and 5 respectively. The difference between the power produced by the clean and dirty panels is also plotted on the secondary axis.

Figure 4 shows that the clean 120 W panel consistently produces more power than the dirty one. On average, the clean panel generated 7 W (7.8%) more power than the dirty panel. The total power produced by the panels varies as the it depends on a number of other factors including but not limited to the solar insolation received, cloud cover, and the nominal operating cell temperatures (which depends on the ambient air temperature). These factors were the same for both the clean and dirty panels, however, these were not constant throughout the experiment. Additionally, the loss in the power due to soiling (i.e. the difference in power) is also not constant as the level of sunlight that the accumulated dust on the dirty prevents from reaching the solar cell in turn depends on these factors. It is also interesting to note that the power loss due to soiling does not exhibit a clear increasing or decreasing trend, possibly due to the short-duration of the study. On average the clean panel produces 97.4 W which is 81% of the rated power capacity at standard testing conditions (STC) of 120 W in contrast to the 90.4 W generated by dirty panel (75.3% of 120 W STC capacity). The standard deviation of the power produced is 9.8 W and 11.8 W for the clean and dirty panel respectively. Similar to the previous case, figure 5 shows that the clean 30 W panel consistently produced more power and on average produced 2.6 W (or 15.6%) more than the dirty 30 W panel. As with the previous case, the power produced fluctuates due to the variation in the environmental parameters, and there is not clear increasing or decreasing trend for the soiling loss. On average the clean panel produces 19.5 W which is 64.9% of the rated power capacity at standard testing conditions (STC) of 120 W in contrast to the 16.8 W generated by dirty panel (56.1% of 30 W STC capacity). The standard deviation of the power produced is 4.7 W and 3.8 W for the clean and dirty panel respectively.

Figure 6 shows photograph of the wiper-based cleaning solution installed and operated on 120 W solar panel. The wiper-mechanism discussed earlier was installed, and successfully tested for cleaning the 120 W solar panel. The system effectively restored the panel's output to match that of a clean panel within a cleaning time of 7 minutes. For optimal performance, daily operation at dawn is recommended. Additionally, the system can be integrated with a light detection sensor to enable fully automated cleaning based on ambient light conditions. Although the system was installed and tested on a single panel, it is designed to an entire array of panels, provided they are installed flush against each other. In such cases, the lead screw and shafts will extend across multiple panels, allowing the wiper to

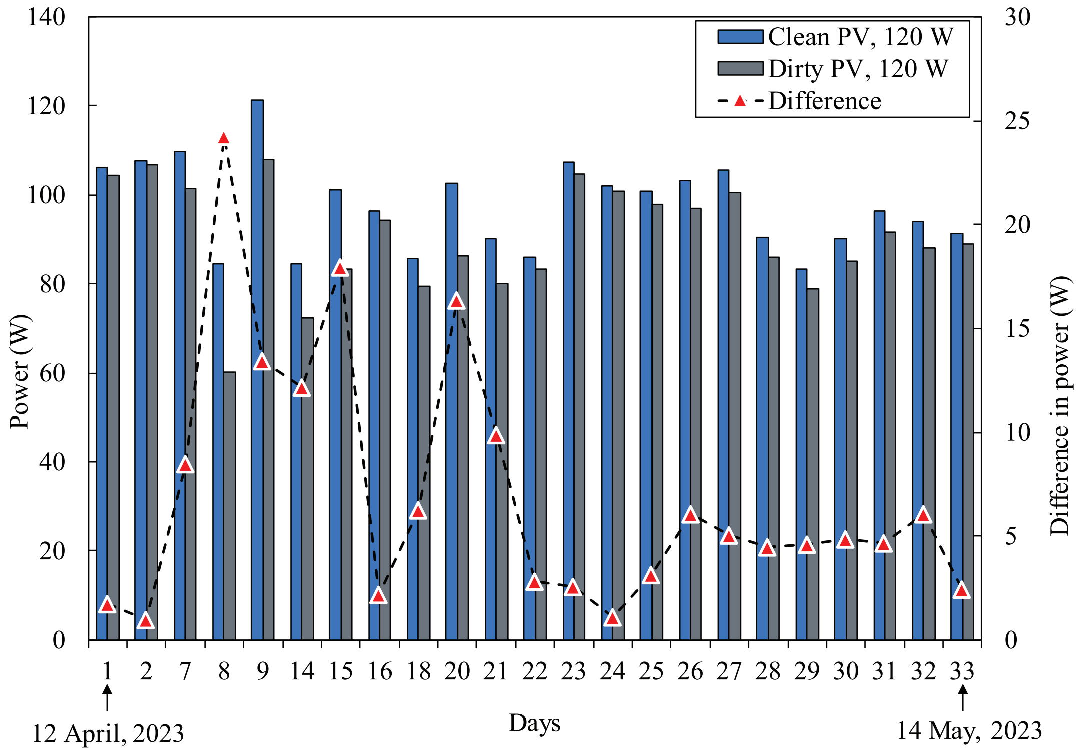


Figure 4. Maximum power generated by clean and dirty 120 W polycrystalline PV panels. The difference between the power output is also plotted on the secondary axis.

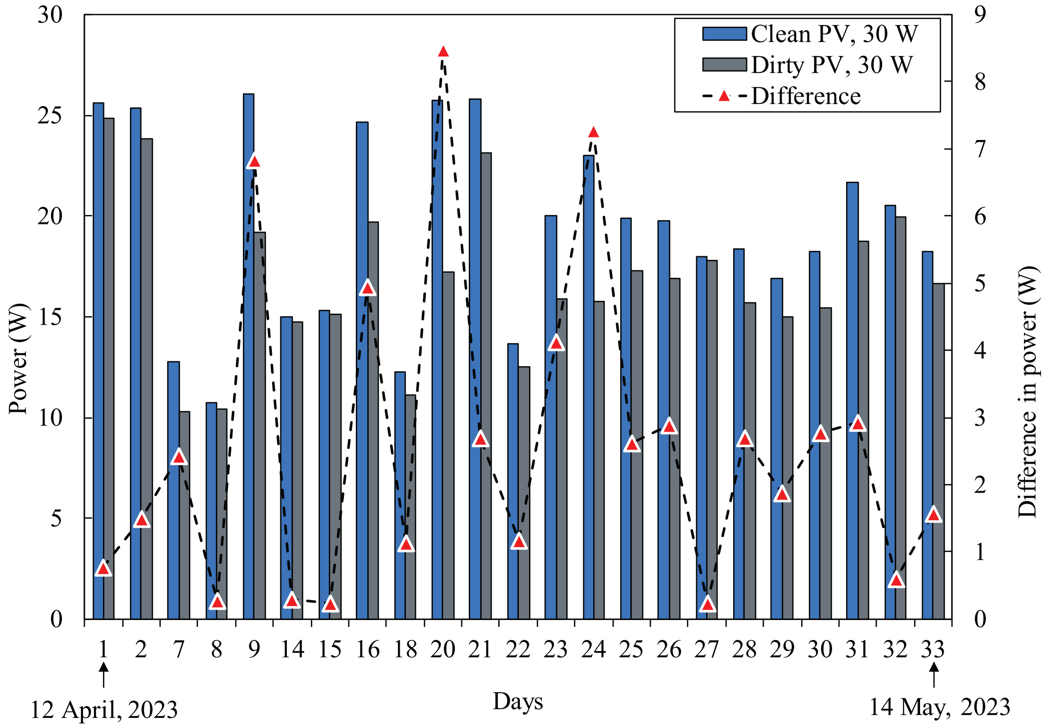


Figure 5. Maximum power generated by clean and dirty 30 W monocrystalline PV panels. The difference between the power output is also plotted on the secondary axis.

Figure 6. Photograph of the wiper-based cleaning solution installed and operated on 120 W solar panel. Cleaning time is under 7 minutes.

Table 3. Cleaning system cost comparison

Cleaning system (with reference)	Module Power	Cost (USD)
Automated system with cleaning bar at the top of the panel with eight openings on which flat-fan nozzles to spray throughout the length of the panel. Water is collected and recycled [31]. System cannot be installed on multiple panels without additional expenditure.	175 W	30.48
Automated system with air jets, water jets and a sponge cleaner moving from one side of the panel. [32]	1000 W	1340.00
Water-free robot with wheels that travels over the panels and removes dust using a rolling brush and negative air pressure. [33]	2×265 W	(Low)
Silicon brush robotic cleaning system that moves from one end to the other [34]	10,000 W	(Low)

clean one panel after another. More than one nozzles may be required based on the overall length of the array. The system is anticipated to require minimal maintenance, primarily limited to seasonal lubrication of its moving parts. However, the design must undergo more rigorous testing to validate this expectation.

Economic Analysis

The total cost of the cleaning system is USD 28 and a single system can clean multiple solar panels. The cost of other cleaning system is presented in the table below. The current analysis indicates that on average, a clean 120 W panel can produce 7.02 W (7.8%) more power than a dirty panel. The difference in power would last throughout the day, however, as a conservative estimate, we can assume this difference for 4 hours a day. This would be especially true for a country like Pakistan which on average has 5.3 peak sun hours per day (5.3 kW/m^2-h) [29]. Thus if the system is installed on ten 120 W panels, the cleaning system would lead to an additional 0.281 kWh (10×7.02 W× 4 h = 281 Wh = 0.281 kWh) generated each day. At an electricity tariff of PKR 39.6/KWh or USD 0.14/kWh (for unprotected residential consumers with 1 to 100 kWh monthly consumption [30]), this would result in a payback period of approximately 1.92 years in Karachi. The comparative economic analysis of few of the other system are as follows.

Implications of This Study

This study highlights the critical role of maintaining clean PV panels for maximized power generation and economic benefit. Soiling significantly reduces efficiency, as evidenced by the increased power output (7.8% and 15.6%) from clean panels compared to dirty ones. Regular cleaning not only mitigates revenue loss but also presents a cost-effective solution through the proposed low-cost wiper system that minimizes downtime. Furthermore, the findings inform decision-making processes for large-scale PV systems, ultimately promoting the advancement of the renewable energy industry. This study contributes to the knowledge base on maximizing solar power generation, a crucial aspect in addressing global energy demands and environmental concerns.

CONCLUSION

This research highlights the detrimental effect of soiling on PV panel efficiency, emphasizing the importance of regular maintenance for optimal performance. Our experimental findings demonstrate that soiling can cause significant power losses, underscoring the need for effective cleaning strategies. The proposed wiper-based cleaning system offers a practical and economical solution, with a payback period of less than two years, making it a viable option for regions with similar environmental conditions as Karachi. Future research should explore the long-term durability of such cleaning systems and their performance under varying climatic conditions, as well as potential automation to further enhance their effectiveness and ease of use.

NOMENCLATURE

Pmax	Maximum power
Pm	Measured Power
Voc	Open Circuit Voltage (V)
Vmp	Optimum Operating Voltage (V)
Isc	Short Circuit Current (A)
Imp	Optimum operating current (A)
L	Length of Panel (m)
W	width of Panel (m)
H	Height of Panel (m)
W	Weight of Panel (kg)
L1	Length of wiper blade
FF	Fill Factor
fiN	Normal Force
T	Torque
μ	coefficient of friction

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AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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