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POWER LOSS MONITORING OF SOLAR PHOTOVOLTAIC MODULES AT QUAID-E-AZAM SOLAR POWER PARK BY OUTDOOR SOILING STATION

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Abstract
The accumulation of dust on the glass surfaces and frames of photovoltaic (PV) modules in arid and semi-arid regions significantly reduces their efficiency, leading to considerable power losses. This study evaluates the impact of soiling on PV modules using an outdoor soiling station at Quaid-e-Azam Solar Power Park in Pakistan. Over a one-month period, the power output of regularly cleaned and naturally soiled modules was continuously monitored, revealing power losses of up to 17% due to dust accumulation. To mitigate these losses, bi-weekly cleaning schedules were implemented, restoring energy generation efficiency. Additionally, optimizing tilt angles reduced soiling-related losses by approximately 50% for non-horizontal panels, demonstrating the importance of module positioning in minimizing dust accumulation. The research further highlights automated cleaning systems as a scalable and efficient alternative to manual cleaning, ensuring consistent performance and long-term reliability in dust-prone environments. These findings offer practical insights for optimizing solar PV performance, developing cost-effective maintenance strategies, and enhancing the sustainability of solar power systems in arid regions.

INTRODUCTION

Global pressures to move towards clean and renewable energy sources have led to the dramatic increase in use and development of solar photovoltaic (PV) technology. In many regions, solar energy generation can be a brilliant solution, especially in countries like Pakistan which has high amount of solar irradiations available. But one of the problems with solar modules is the loss of efficiency due to environmental conditions like dust accumulation on the surface of the solar panel. This problem mostly occurs in aried and semi-aried areas where water to naturally clean them is scarce.

In the photovoltaic literature, soiling refers to dust and other particles that can accumulate on solar PV modules which reduce the amount of sunlight that reaches a cell, leading it to generate less power. The extent of these losses depends on environmental conditions related to the kind of dust, wind and rain.

The photovoltaic (PV) modules are the primary building block of any solar energy system as they convert sunlight into electricity. The ability of a Panel is highly dependent on the environment it works in, soiling being one primary consideration especially for falling dust and winds due to sandstorms and rainfall regions. PV module power loss is a significant problem because it influences the total energy delivered by solar PV plants. To

maintain optimal performance, regular cleaning and monitoring of PV modules are essential. Soiling effects should be recognized & steps shall be taken to avoid such losses (especially in dry counties like Pakistan with high solar potential)
This research aimed to investigate the effect of power losses caused by soiling on PV modules under dusty conditions. The study focused on measuring power output by comparing the performance of cleaned and soiled modules over a one-month period.

The following are the major contributions of the study:

a. Quantified the impact of dust accumulation on the performance of photovoltaic (PV) modules in semi-arid environmental conditions, demonstrating how soiling affects energy yield.
b. Demonstrated that soiling can reduce power production by up to 17%, with losses increasing as dust accumulation intensifies over time.
c. Conducted a comparative analysis of power output from regularly cleaned versus naturally soiled PV modules over multiple observation periods, providing practical insights into cleaning frequency.
d. Calculated the rate of dust accumulation and its direct impact on energy production, introducing the Soiling Loss Factor (SLF) as a key metric for assessing performance degradation.
e. Highlighted the critical role of periodic cleaning in maintaining the optimal efficiency of solar modules in dust-prone environments and provided recommendations on cleaning intervals.
f. Developed a remote monitoring system for tracking PV soiling effects, reducing the need for manual inspections and improving maintenance planning through automated data acquisition.
g. Identified the impact of non-uniform soiling, showing that dust accumulation does not occur evenly and can create additional efficiency losses beyond simple attenuation.
h. Proposed practical mitigation strategies, including optimized cleaning schedules and monitoring approaches, to enhance PV performance and extend module lifespan.

The structure of the paper is section II presents a comprehensive literature review, summarizing existing research on PV soiling, its impact on energy yield, and mitigation strategies. Section III describes the research methodology, including the experimental setup, data acquisition system, and monitoring techniques used to assess soiling losses. Section IV discusses the results and analysis, highlighting key findings related to soiling loss factors, power degradation, and the effectiveness of proposed mitigation strategies. Finally, Section V provides the conclusions drawn from the study and suggests future research directions for optimizing PV performance in dust-prone environments.

2. Literature Review

The impact of soiling on the performance of a PV module has been studied in detail in locations where environmental parameters like dust and humidity are major contributors to power degradation [1].Soiling refers to the dirt, dust or bird droppings and anything which gets on to the surface of solar panels will soil that area preventing sunlight from reaching PV cells so its generate less power output [2]. Soiling is one of the major challenges for solar energy systems in arid and semi-arid regions, where soiled modules can lose up to 1–6% annually **[3]** energy measurements.
Several elements contribute to the severity of soiling [4]. The kind of dust and also its composition directly affect the rate at which it collects as well as ultimately just how much power is lost [5]. As an example, a study found that the dust in Malaysia is acidic and has abrasive property which can abrade PV module surface [6]. In arid regions, lack of regular rainfall to clean the panels exacerbates soiling-related losses, making manual or mechanized cleaning necessary for maintaining optimal performance [7].
The efficiency of PV module also depends on temperature and irradiance. Studies shows that increased temperature decreases the voltage output of PV modules, despite a slight rise in current [8]. As a result, the overall power output is significantly diminished. To mitigate soiling effects, various cleaning methods have been proposed. Manual cleaning employs specialized brushes to remove dust while minimizing scratches [9], whereas mechanized systems utilize water or air to clean the surface more efficiently [10].
The soiling rate is typically measured by comparing the performance of clean and soiled PV modules

[11], as several research studies have shown that energy losses may fall down remarkably through a periodic cleaning regime **[12]**.

Solar power plants in Pakistan are highly susceptible to the Soiling issues [12] Additionally, research indicates that soiling can reduce solar energy production by approximately 3-5% globally, resulting in revenue losses of €3-5 billion (US$3.3-5.5 billion) in 2018. The study emphasizes that cleaning in arid regions is unavoidable to achieve energy yield targets[13]. Outdoor soiling stations have also been established to conduct experiments, to evaluate the impact of dust accumulation on solar panel efficiency, providing valuable insights into optimal cleaning schedules and soiling trends over time For instance, a study conducted at a 50 MW modular solar tower project in Mount Isa, Australia, utilized field measurements to predict soiling rates and optimize cleaning resources. The findings indicated that the mean predicted soiling rate for horizontally fixed mirrors was 0.12 percentage points per day during low dust seasons and 0.22 percentage points per day during high dust seasons. This data enabled the development of cleaning strategies that balanced resource costs against expected energy losses, thereby enhancing overall plant efficiency [14].

To offset soiling losses, numerous self-cleaning technologies and automated systems have been developed [15]. One such innovation is Electrostatic Cleaning Systems, which use electrostatic forces to remove dust particles from solar panel surfaces without requiring water or mechanical contact. By applying an electric field, these systems repel dust, ensuring panel efficiency while preventing physical abrasion [16]. Similarly, sensors in automated cleaning systems will identify a level of soiling and trigger clean cycles to ensure performance is maintained [17]. In a context like Pakistan where frequent manual cleaning is not practically possible given water scarcity and high maintenance costs, such innovations are much needed [18].

3. Methodology

The methodology of this study outlines the experimental procedures used to evaluate the impact of soiling on photovoltaic (PV) module performance. It details the research site, the setup of the soiling station, and the data acquisition process. The study systematically compares the performance of cleaned and naturally soiled PV modules over a one-month period, monitoring voltage, current, power output, and environmental factors to assess soiling-induced losses. The following subsections describe the experimental setup and data collection procedures in detail.

3.1. Experimental Setup

The Experiments were conducted at an outdoor soiling station located in the southern region of Pakistan, within Quaid-e-Azam Solar Power Park set up under a semi-arid climatic condition. The soiling station contained photovoltaic (PV) modules into two sets, where one set was periodically cleaned and maintained while the second was exposed to outdoor natural soil deposition. The primary objective was to quantify power losses due to dust deposition and environmental factors.

The station was set to analyze several environmental parameters such as dust deposition, temperature and irradiance which affect the efficiency of PV modules. A pair of PV modules was installed in which one was regularly cleaned while one was left untouched for soiling in natural conditions. This was done to compare the results. The study utilized JA Solar JAM6-60-255/3BB monocrystalline silicon PV modules installed at Quid-e-Azam solar park Bahawalpur. Each module has a power output of 255 Wp with an efficiency of up to 15.7%. The dimensions of the module are 1650 mm × 991 mm × 40 mm, with a weight of 18.5 kg. It features 3.2 mm tempered front glass for enhanced durability and an anodized aluminium alloy frame for corrosion resistance. The IP67-rated junction box provides protection against dust and water ingress, while MC4-compatible connectors ensure reliable electrical connections. The module operates within a temperature range of -40°C to +85°C and has a maximum system voltage of 1000 V DC, with a power tolerance of 0 to +5.

Moreover, the setup also consisted of a Soiling Measurement Apparatus equipped with PV modules positioned at different tilt angles (0° to 40°), and a Monitoring Equipment The station was equipped with sensors to measure voltage, current, and meteorological parameters such as temperature, humidity, and solar irradiance.

3.2. Data Collection

Data collection process was done during a one month period. The power outcome of both the modules was recorded daily, several readings for each cleaning pattern were taken to obtain power variation versus daylight hours. Following variables were monitored:

- Short-circuit current (I_{sc}): for cleaned and soiled modules.
- Open-circuit voltage (V_{oc}): Measured for both sets of modules
- Power output (P_{mpp}): Recorded consistently with data acquisition systems.
- Environmental factors: Solar irradiance, Temperature, Humidity and Wind speed.

The soiled module was left untouched in natural soiling conditions while the clean module was cleaned for every two weeks to ensure accurate results

3.3. Data Analysis

The outdoor soiling station measurements were analyzed to determine the impact of soiling over time and on PV (photovoltaic) module power output. This process requires estimating the rate and impact of soiling loss over time. The soiling ratio was estimated as a function of the short-circuit current from the module after and before cleaning.

$$\text{Soiling Ratio} = \frac{I_{SC}\,Soiled}{I_{SC}\,(Cleared)}$$

To quantify power loss, the following formula was used:

$$\text{Power Loss (\%)} = \frac{P_{mpp}\ (Cleaned) - P_{mpp}\ (Soiled)}{P_{mpp}\ (Cleaned)}\ x\ 100$$

This allowed for a direct measurement of the reduction in power output due to dust accumulation. The power loss data was plotted over time to observe how the performance of the soiled modules degraded compared to the cleaned modules. Statistical tool, "SPSS" wss used to analyze the relationship between environmental conditions (such as wind speed, humidity, and irradiance) and the soiling rate. Regression analysis was employed to predict future soiling trends based on environmental factors. The effectiveness of the bi-weekly cleaning schedule was also assessed by comparing the power output before and after cleaning.

4. Results and Discussion

This section presents the findings of the study, focusing on the impact of soiling on PV module performance. The results highlight trends in power loss, voltage degradation, and environmental influences on soiling accumulation. Each subsection explores specific aspects of the analysis, supported by recorded data and graphical representations.

4.1. Impact of Soiling on Power Output

Soiling is recognized as one of the key factors responsible for reducing the power output of a photovoltaic energy system. The ongoing decline in the performance of solar modules is a result of the reduced solar radiation reaching the surface of the panels [27].

This effect is likely caused by the absorption and scattering of sunlight hitting the panel, which becomes dispersed due to the presence of dust particles or soil build-up on the panel's optical surface [10]

4.1.1. Voltage Measurements: November 1 - November 7, 2018

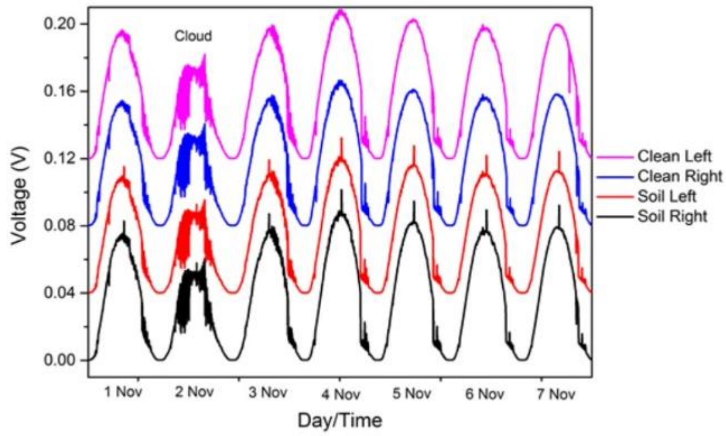

Fig 3.1.1 Recorded Voltage values for the study period (01 Nov-07 Nov 2018)

The voltage data collected from November 1 to November 7 revealed noticeable drops in power output, particularly in the soiled modules, as dust accumulation increased. The clean modules consistently exhibited higher voltage levels, while the soiled modules showed reduced efficiency. Figure 3.1.1 presents the recorded voltage data for this period, capturing the baseline before significant soiling effects became evident. The graph illustrates a wave-like pattern in the voltage values, where the clean modules (represented by the magenta and blue lines) maintained higher voltages with peak values reaching approximately 0.20 V, in contrast to the soiled modules (shown as the red and black lines) which peaked around 0.08 V. This early-stage efficiency loss, attributed to initial dust accumulation, is expected to worsen over time without proper intervention. Additionally, the graph marks cloud cover events—most notably around November 2—which caused a momentary reduction in voltage across all modules. Although the clean modules demonstrated a faster recovery from these events, the soiled modules experienced a delayed restoration, further emphasizing the negative impact of dust buildup on power generation. While the differences between the clean and soiled modules are not as extreme during this initial period compared to later weeks, this phase serves as an essential baseline for future comparisons, highlighting the need for regular cleaning and maintenance strategies as dust continues to accumulate.

4.1.2. Voltage Measurements: November 8 - November 14, 2018

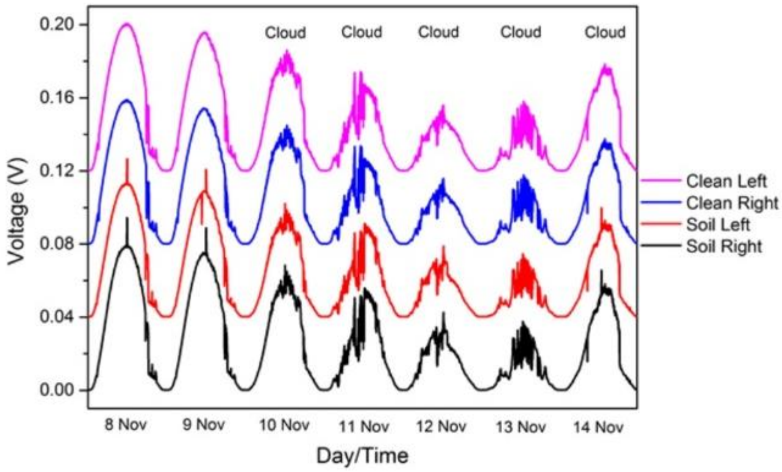

Fig 3.1.2: Recorded Voltage values for the study period (08 Nov - 14 Nov 2018)

Figure 3.1.2 shows the recorded Voltage values from November 8 to November 14. This period shows a gradual decrease in voltage, likely due to the accumulation of dust, leading to reduce efficiency. The graph clearly illustrate that clean modules consistently generate higher voltage, with peak values around 0.20V, whereas soiled modules experience a significant reduction, reaching maximum values near 0.08V. This indicates an efficiency drop of approximately 50% due to dust accumulation, reinforcing the necessity of regular cleaning to maintain optimal performance.

Additionally, cloud cover events are marked on the graph, showing temporary reductions in voltage across all modules. However, clean modules recover more efficiently, while soiled modules exhibit prolonged dips in output. This suggests that soiling not only reduces efficiency under normal conditions but also exacerbates the impact of environmental fluctuations.

4.1.3. Voltage Measurements: November 15 - November 21, 2018

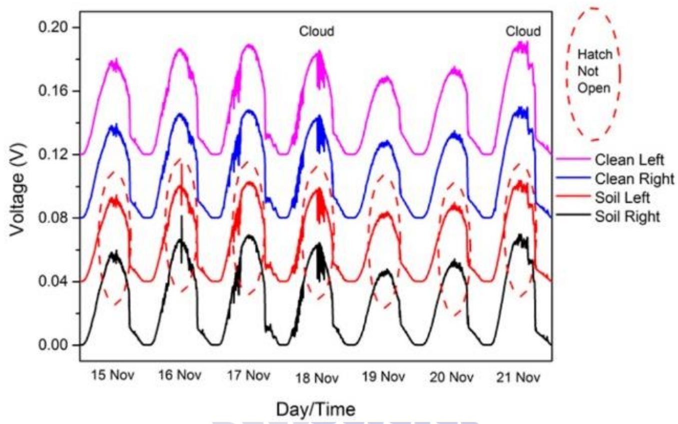

Fig 3.1.3: Recorded Voltage values (Hatch not open) for the study period (15 Nov - 21 Nov 2018)

During the period from November 15 to November 21, 2018, Figure 3.1.3 illustrates voltage values recorded when the hatch was not open, highlighting the impact of accumulated soiling on power output. The absence of hatch opening likely led to reduced cleaning or ventilation, thereby exacerbating the decline in voltage. During this period the efficiency gap between clean and soiled modules widened, indicating progressive performance degradation due to prolonged soiling. The voltage difference became more pronounced, reinforcing the impact of dust accumulation on power output. Cloud events recorded on multiple days temporarily reduced voltage across all modules, but the effects were more severe on soiled photovoltaic (PV) modules, which exhibited slower recovery. The overall peak voltage values showed a downward trend, highlighting the cumulative effect of dust buildup on energy generation.

4.1.4. Voltage Measurements: November 21 - November 28, 2018

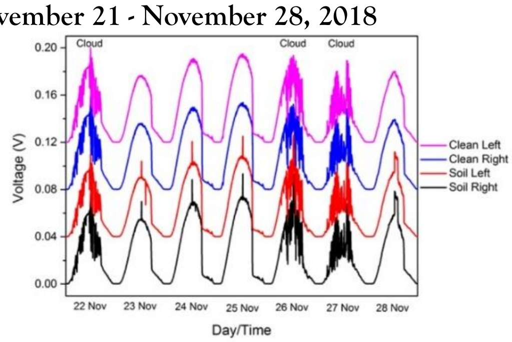

Fig: 3.1.4: Recorded Voltage values for the study period (22 Nov - 28 Nov 2018)

The figure above shows the recorded Voltage values from November 22 to November 28, 2018. The data demonstrates fluctuations due to intermittent cloud cover and soiling. The graph from November 22 to 28, 2018, demonstrates a continued decline in voltage output for soiled modules, reinforcing the long-term impact of dust accumulation on PV performance. The performance gap between clean and soiled modules widened further, indicating that prolonged soiling leads to cumulative energy losses over time. Clean modules consistently maintained higher voltage levels, with peak values around **0.20V**, whereas soiled modules exhibited a significant drop in efficiency. This trend highlights the effectiveness of regular cleaning in sustaining optimal power generation.

Cloud cover events, particularly on November 26 and 27, caused noticeable voltage drops across all modules. However, the recovery time was significantly slower for soiled modules, suggesting that dust accumulation not only reduces efficiency but also delays performance restoration after environmental disturbances. The inability of soiled modules to recover quickly after cloud cover further emphasizes the adverse effects of prolonged soiling.

These findings suggest that if cleaning were performed biweekly, the efficiency of soiled modules could have been restored periodically. However, the continued decline observed in this period indicates that longer cleaning intervals lead to substantial performance degradation. The data reinforces the necessity of routine maintenance, particularly in dust-prone environments, and suggests that a biweekly cleaning schedule may be required to sustain energy yield. Further analysis is needed to confirm the optimal cleaning interval for minimizing soiling-induced power losses.

4.1.5. Voltage Measurements: November 29- November 30, 2018

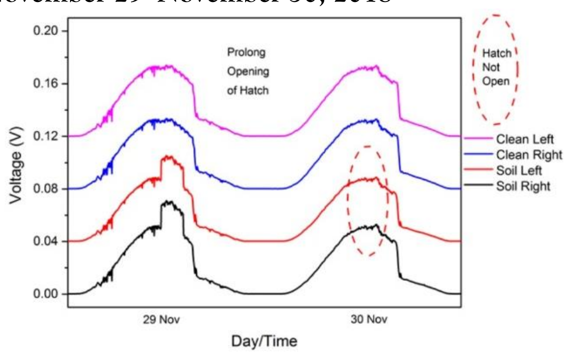

Fig: 3.1.5: Recorded Voltage values for the study period (29 Nov – 30 Nov 2018)

Fig 3.1.5 shows the **r**ecorded Voltage values with hatch open from November 29 to November 30, 2018. This period shows the effect of cleaning on restoring voltage levels. The graph shows a noticeable increase in voltage output on November 29, likely due to the prolonged hatch opening, which allowed more direct sunlight to reach the PV modules. This temporarily improved the performance of both clean and soiled modules, reducing the impact of soiling. However, when the hatch was closed on November 30, a sharp voltage drop was observed, particularly in the soiled modules, highlighting the influence of restricted exposure on power generation. Despite this fluctuation, clean modules consistently maintained higher voltage levels than soiled ones. The findings suggest that while improved sunlight exposure can temporarily enhance performance, soiling remains a major limiting factor, reinforcing the need for regular cleaning and optimal system positioning to sustain PV efficiency.

Discussion

The voltage data recorded over the five-week period illustrates the progressive impact of soiling on photovoltaic (PV) module efficiency. In the initial phase (November 1–7), the differences between clean and soiled modules were relatively small, but as dust accumulated over the following weeks, a consistent decline in the performance of soiled modules was observed. By November 22–28, the efficiency gap had widened significantly, with soiled modules experiencing up to 50% voltage reduction compared to clean ones, emphasizing the cumulative nature of soiling losses.

Cloud cover events throughout the study period further impacted power output, temporarily reducing voltage levels across all modules. However, clean modules consistently recovered faster, while soiled modules exhibited delayed restoration, indicating that dust buildup exacerbates the effects of environmental fluctuations.

The impact of hatch opening and closing, particularly on November 29–30, highlighted the role of external factors in influencing module efficiency. When the hatch was open, voltage levels improved across all modules, temporarily offsetting soiling effects. However, once the hatch remained closed, voltage dropped again, reinforcing the conclusion that restricted sunlight exposure, combined with dust accumulation, significantly reduces PV performance.

Overall, the findings suggest that soiling-induced efficiency losses intensify over time, **and** longer cleaning intervals lead to substantial performance degradation. While improved sunlight exposure can temporarily enhance efficiency, regular cleaning remains essential for maintaining optimal power output. The data strongly supports the hypothesis that biweekly cleaning may be necessary in dust-prone environments, though further analysis could refine the optimal maintenance schedule.

4.2. Soiling Loss Factor (SLF)

The Soiling Loss Factor (SLF) is a crucial metric for understanding the impact of soiling on PV module performance. It represents the efficiency loss due to accumulated dirt, dust, and other contaminants.

Soiling Loss Factor (SLF) is calculated using the formula:

SLF = 1- Soiling Ratio

$$SLF = 1 - \frac{I_{SC}\,(\text{Soiled})}{I_{SC}(\text{Cleaned})}$$

Where;

I_{SC} (Soiled) is the short circuit current of the soiled module and

I_{SC} (Cleaned) is the short circuit current of the cleaned module.

Based on the data collected, the Soiling Loss Factor (SLF) starts close to 1 and gradually decreases, representing increased soiling losses. The maximum soiling loss is about 17%, meaning the SLF drops to 0.83 by the end of November, which reflects a 17% loss in power output. The data in the tabular structure is as follows:

Table 3.2.1 showing the variation of the Soiling Loss Factor (SLF) and corresponding soiling losses over the study period from October 31 to November 30, 2018.

Date	SLF Value	Soiling Loss (%)	Artefact
31-Oct	1	0%	-
1-Nov	0.98	2%	-
3-Nov	0.97	3%	-
5-Nov	0.96	4%	-
7-Nov	0.95	5%	-
9-Nov	0.9 4	6%	-
11-Nov	0.93	7%	-
13-Nov	0.92	8%	-
15-Nov	0.91	9%	-
17-Nov	0.9	10%	-
19-Nov	0.89	11%	~1.02
20-Nov	0.88	12%	~1.04
21-Nov	0.87	13%	~1.06
22-Nov	0.86	14%	~1.07

23-Nov	0.85	15%	~1.10
24-Nov	0.85	15%	~1.08
25-Nov	0.84	16%	~1.06
26-Nov	0.83	17%	~1.03
27-Nov	0.83	17%	-
28-Nov	0.83	17%	-
29-Nov	0.83	17%	-
30-Nov	0.83	17%	-

In the above table the SLF values indicate the ratio of available power after soiling, with 1.00 representing no soiling loss, while the soiling loss percentage shows the corresponding power loss due to soiling. Additionally, the artefact refers to the anomalies—marked by red dots observed between November 19 and 26—with values exceeding 1.00.

Although the losses in photovoltaic modules caused by soiling are influenced by climatic conditions, they can account for 1% to 6% of energy loss annually [9]. Figure 3.2.1 shows the SLF Variation for the study period (October 31 – November 30, 2018). This figure shows the progression of soiling losses over time. As observed, SLF increased from 0 (no soiling) to approximately 0.17, indicating a 17% loss in power output due to soiling.

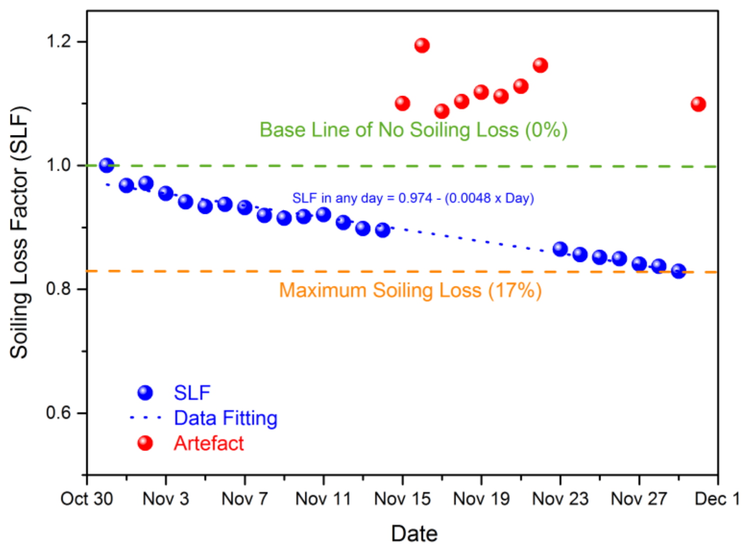

Fig 3.2.1 SLF variation of the whole study period (31 Oct – 30 Nov)

The figure presents the variation of the Soiling Loss Factor (SLF) over time, starting from late October to late November. Initially, the SLF is close to the baseline of 1.0, indicating minimal soiling loss. However, as days progress, a consistent downward trend is observed in the SLF, as captured by the data fitting line: SLF in any day = 0.974 - (0.0048 × Day). This shows a gradual increase in soiling loss with time. Notably, most data points remain above the critical threshold of 0.83, which corresponds to a maximum soiling loss of 17%. However, some data points marked in red are identified as artefacts, showing unusually high values exceeding 1.2, which deviate from the expected trend.

The observed decline in SLF implies that soiling accumulation on the solar panel surface steadily worsens performance over time, with approximately 0.48% loss per day. While the system remains within acceptable performance limits during the monitoring period, the trajectory suggests that regular cleaning or preventive measures will be necessary to maintain efficiency as soiling progresses. Furthermore, the presence of artefacts indicates possible anomalies in measurement or environmental conditions that need to be addressed to avoid data distortion in future assessments. This highlights the importance of both maintenance and data validation in ensuring reliable solar energy output.

4.3. Cleaning Mechanisms and Recommendations

Cleaning methods or liquids are crucial due to their chemical composition. However, sometimes when the cleaning liquid dries, it can leave behind deposits on the surface, which again obstructs solar irradiation and reduces light transmission through the glass, as illustrated in the figure. [5]

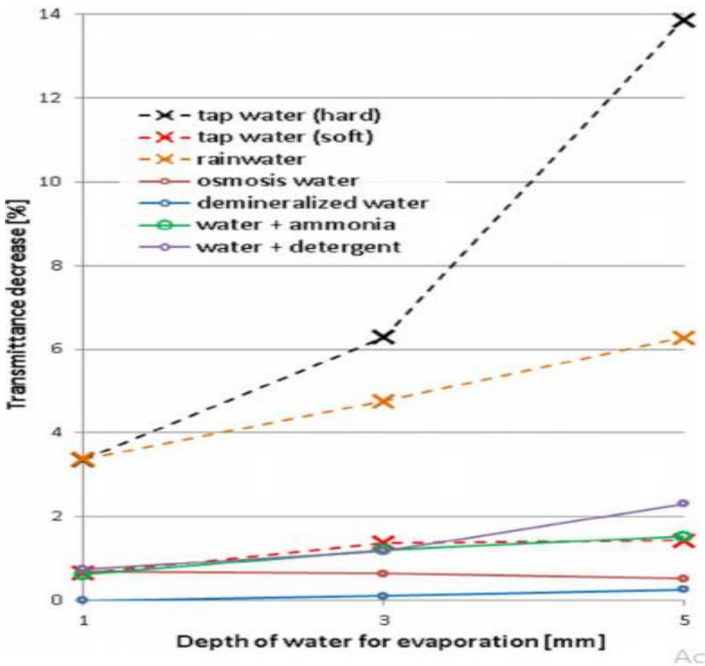

Figure: 3.3.1 Impact on the reduction in transmittance [1].

The study highlights the importance of cleaning frequency in mitigating power losses. The study observed that cleaning frequency plays a crucial role in mitigating power losses. For regions like Pakistan, characterized by arid conditions and limited water resources, bi-weekly or monthly cleaning is recommended. Additionally, the implementation of self-cleaning mechanisms or automated hatch systems can further optimize performance and reduce maintenance costs. Recommendations include:

- Regular Cleaning: Implementing a routine cleaning schedule to remove accumulated dust and debris.
- Self-Cleaning Mechanisms: Exploring technologies such as automated cleaning systems or self-cleaning coatings to reduce maintenance efforts.
- Automated Hatch Systems: Installing hatches that can be opened or closed automatically based on environmental conditions to prevent dust accumulation.

4.4. Discussion

4.4.1. Effects of Soiling

Soiling significantly affects the power output of PV modules. Dust accumulation reduces the amount of sunlight reaching the modules, thereby decreasing their efficiency. The study illustrated that soiling losses can differ based on environmental conditions and cleaning methods.

4.4.2. Cleaning Frequency

The research determines the importance of consistent cleaning to minimize power loss. In arid regions, which have water shortage, alternative cleaning methods or less frequent cleaning schedules may be more practical.

4.4.3. Impact of Module Tilt Angle

Soiling rates depend on the tilt angle of PV modules. There were some soiling losses reductions found in modules at 20° and 33.5° compared to the horizontal. The result shows that performance can be improved by optimizing the tilt angle.

5. Benefit and Advancement in State-Of-The-Art

The results of this study provide important insights for the implementation and operation of photovoltaic (PV) systems in particular as well as advances in state-of-the-art methods to overcome power reduction by soiling.

5.1. Benefit of the Research

One of the key advantages of this study is it leads to a better understanding about how soiling based efficiency loss in PV modules can be hindered, which particularly holds importance for arid and semiarid regions like Pakistan. It is a crucial problem in such environments where dust storms are very common with minimal rainfall, and the soiling to be due to accumulation of modestly hygroscopic fine particulates over surfaces being dry most days. It also reveals illuminating data regarding the scale of energy loss, estimating a 17% decrease in power generation within just one month. This in turn provides solar power plant operators with important data to help them better predict maintenance schedules and lower operational costs.

Furthermore, the research provides real-world answers for reducing power losses with guidelines suggesting intervals of cleaning be kept routine. The research additionally indicates that one effective strategy is to do bi-weekly cleaning of the modules, which helps protect PV efficiency so they can continue maximizing energy generation. Suggestions offered in this context could be most beneficial for underdeveloped countries, such as Pakistan where there is a lot of potential and need available to harvest the solar energy. It is hoped that the findings of this study would brighten plant operators and policy makers to wisely choose management strategies for a better performance of solar power plants (SPPs) operating in dusty conditions.

5.2. Advancement in State-Of-The-Art

This study also makes several advancements in the current state-of-the-art knowledge on soiling impacts and PV system performance:

1. By employing an advanced outdoor soiling station that continuously monitors both cleaned and soiled PV modules, this study adopts an innovative approach to evaluating soiling impacts under real-world conditions. This continuous monitoring provides precise, location-specific data on soiling patterns and environmental factors, significantly enhancing the reliability of the findings compared to studies restricted to controlled laboratory settings.
2. The study offers a comprehensive evaluation of environmental variables such as dust accumulation, temperature, humidity, and solar irradiance, providing a more holistic understanding of their combined influence on photovoltaic performance. This multi-factor analysis distinguishes the research from earlier works that typically focused on individual parameters in isolation.
3. Through the assessment of both technical losses and economic impacts, the research bridges a critical gap by translating performance degradation into financial terms. This dual focus enables practical recommendations for optimal cleaning schedules, balancing energy recovery against maintenance costs.
4. By extending the analysis to evaluate module performance over different tilt angles and environmental conditions, the study enhances its applicability to a broader range of operational scenarios. This ensures the findings are not only relevant to the specific location studied but can also inform PV system design and maintenance strategies in similarly challenging environments worldwide.

6. COMPARISON WITH RECENT STUDIES

The study "Power Loss Monitoring of Solar Photovoltaic Modules at Quaid-e-Azam Solar Power Park by Outdoor Soiling Station" presents several novel contributions that distinguish it from recent research in the field. Unlike many studies that rely on laboratory experiments or intermittent field measurements, this work employs an outdoor soiling station to continuously monitor photovoltaic (PV) module performance under real-world conditions. This real-time approach captures daily fluctuations in environmental factors, providing a dynamic dataset that surpasses static or simulated analyses.

While global reports, such as the IEA-PVPS (2022), estimate soiling losses on a worldwide scale at typically 3–5% annual energy loss, this study focuses on the specific conditions at Quaid-e-Azam Solar Power Park in Pakistan. This localized approach offers insights tailored to semi-arid regions, where the intensity and frequency of dust events can differ markedly from global averages.

A key novelty of this research is the combined analysis of technical performance degradation with its economic implications. By quantifying power losses and translating them into economic terms, the study proposes empirically derived cleaning schedules—information often missing in recent technical studies. This integration of performance data with maintenance recommendations adds a practical dimension to the findings.

Furthermore, this work incorporates a broad range of environmental parameters—including dust accumulation, temperature, irradiance, and humidity—to assess their collective impact on PV performance. In contrast, some recent studies focus narrowly on data-driven soiling detection using minimal inputs. This multi-parameter approach yields a holistic view of soiling effects, supporting more robust, region-specific mitigation strategies.

7. Conclusion and Future Work

This study comprehensively examined the impact of soiling on photovoltaic (PV) module performance at Quaid-e-Azam Solar Power Park, utilizing an outdoor soiling station for real-time monitoring of environmental and electrical parameters. The findings clearly demonstrated that dust accumulation significantly reduces the efficiency of PV modules. During the initial observation period (November 1–7, 2018), the clean modules maintained peak voltage values around 0.20 V, whereas the soiled modules showed lower peaks near 0.08 V, indicating early-stage efficiency loss due to initial dust accumulation. As the monitoring continued, the soiling loss factor (SLF) showed a progressive decline, with the SLF value decreasing from approximately 1.00 at the start of November to 0.83 by the end of the month, corresponding to a peak power loss of about 17%. Cloud cover events further influenced the voltage levels, but clean modules consistently exhibited faster recovery compared to soiled modules. These results highlight the cumulative and detrimental effect of dust deposition, emphasizing the necessity for timely maintenance and cleaning to prevent substantial energy losses in solar installations.

Future research should focus on extending the monitoring period to capture seasonal variations in soiling rates, as well as to quantify long-term performance impacts. Exploring automated and passive cleaning technologies, such as hydrophobic coatings, electrostatic dust removal, or robotic cleaning systems, could offer sustainable solutions, especially in regions like Pakistan where water scarcity poses additional challenges. Integration of machine learning algorithms with real-time monitoring data could further refine predictive maintenance schedules, enhancing operational efficiency. Furthermore, a detailed study on the composition and particle size of locally accumulated dust could lead to optimized cleaning protocols tailored to the specific environmental conditions of the region. Implementing these strategies will be crucial for improving the reliability and economic viability of solar PV systems operating in dusty environments.

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