

Evaluating The Influence Of Soiling Mitigation On Enhancing The Solar Panel Power Production Efficiency

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Abstract

Soiling is a pivotal element that can considerably affect the performance ratio of photovoltaic (PV) systems. The deposition of airborne particles, including dust, pollen, and bird droppings, on solar module surfaces impedes solar irradiation and diminishes energy conversion efficiency. Therefore, it is essential to enhance traditional cleaning procedures due to the related expenses and possible delays that could further reduce generation efficiency. Field evaluation report on customized cleaning tool deployment at Satna, Madhya Pradesh solar plant (March–Aug 2024). The tool was operationally tested from March to Aug 2024 and was specifically designed to match the installed solar modules' size. Through stated outputs of March 2024 to Aug 2024 were 1934775 kWh, 2013083 kWh, 1986539 kWh, 1737500 kWh, 1464900 kWh, and 1343085 kWh respectively. The plant's monthly energy generation demonstrated a steady increasing month of March to May then decreasing the remaining period.

Keywords: Solar Photovoltaic, Soiling, Energy, Sustainability.

1. Introduction

As a renewable energy technology, photovoltaics (PV) has been acknowledged as having the ability to lower carbon emissions and make a substantial contribution to the future energy supply. The use of solar energy has therefore grown dramatically on a global scale. Growing energy demands, technology developments, lower energy prices, and increasing usage are all factors contributing to the surge in SPV power plant installations worldwide, in addition to concerned about GHG emissions [1].

Dust and other particle matter buildup on photovoltaic (PV) modules, known as soiling, acts as an optical barrier to solar irradiance, reducing the quantity of sunlight that reaches the solar cells and, consequently, power generation. A vast array of particle sizes, compositions, and environmental factors that operate over different time periods all have an impact on this deposition process, which is a complex physicochemical phenomenon [2-3].

According to research, soiling can lower solar PV plant efficiency by 10% to 30% annually in areas with moderate dust levels; in arid and desert environments, losses of over 30% are frequently documented [4-5].

For solar photovoltaic (SPV) plant investors, soiling of solar panels creates a double financial burden since it lowers revenue from lower energy output and increases costs for cleaning and maintenance. Furthermore, high solar panel operating temperatures decrease system performance. Standard Test Conditions (STC) contain an air mass of 1.5 (AM1.5), solar irradiation of 1000 W/m², wind speed of 1 m/s, and cell temperature of 25 °C. These conditions are commonly used to grade the performance characteristics of solar modules.

However, solar modules function in a variety of climatic conditions that differ greatly from STC in real-world applications, which results in decreased output and efficiency [6].

Solar photovoltaic (SPV) systems can perform much worse when soiling and high module temperatures are coupled. Although dust-covered panels are thought to receive less solar irradiation and, as a result, have lower temperatures than clean panels, the truth is more nuanced. Higher thermal resistance in dust layers may prevent heat from dissipating and raise the temperature of the module. The thermal effects of dust deposition on PV modules have been the subject of numerous studies. Abderrezek and Fathi [7], for example, investigated how several forms of artificial dust, such as ash, cement, sand, and salt, affected glass surfaces. Since salt has a comparatively better thermal conductivity than the other dust samples and the glass substrate, their data indicated that the surface temperature of all dust types increased, with the exception of salt. Andrea et al. (2018) [8] investigated how industrial dust affected polycrystalline silicon (Si) solar modules' performance. Dust samples gathered from mining and manufacturing facilities were purposefully applied to the panel surfaces for their investigation. The temperature rose by 1 to 9 degrees Celsius when dust was present, showing a direct link between dust buildup and higher module temperatures. Although these studies indicate that dust-covered panels normally function at greater temperatures than clean ones, the majority have used artificially produced dust and recorded temperature changes over brief periods of time, usually one day. The long-term thermal impacts of natural, field-based soiling on SPV system performance are therefore poorly understood.

Particles of soil, which range in size from 1 to 500 μm , originate from both natural and man-made sources, such as organic matter, minerals, and air pollution. Climate, wind, and urbanization are among of the environmental elements that affect their size, form, content, and deposition behavior. Even with increased study, little is known about how dust affects solar panel performance, particularly after cleaning. The effects of dust on power conversion rate and the long-term behavior of cleansed and soiled glass surfaces under actual settings are still poorly understood [9].

The main cause of soiling on solar energy systems is the dry deposition of dust and particles that absorb light. The deposition velocity, which is dependent on the physical properties of the particles and the surface they settle on as well as air conditions, affects the dry deposition flux. Deposition velocity as a function of particle size has been described by a number of models. Important climatic elements like relative humidity and wind speed also have a big impact. greater humidity results in hygroscopic particle development, which raises the deposition rate, while greater wind speeds increase friction velocity, which facilitates particle transport [10].

Soiling, whether caused by natural elements such as dust, mud, and snow, or by man-made obstructions, poses a significant challenge to the energy generation efficiency of solar photovoltaic (SPV) systems. Minimizing energy losses due to soiling and shading is critical for maximizing the output and reliability of solar power installations. Although certain environmental losses are inevitable, soiling can be effectively controlled through appropriate maintenance practices. A wide range of cleaning methods exists, generally categorized into natural mechanisms (such as rainfall or wind) and manual or automated interventions designed by humans. Ensuring the use of suitable cleaning tools and establishing optimal maintenance intervals are essential for sustaining peak system performance. Strategic planning and efficient resource allocation for cleaning activities not only improve actual energy yields but also reduce the return on investment (ROI) time for

solar projects. This study aims to assess the impact of various cleaning methods and maintenance schedules on plant performance, with the goal of identifying practical, cost-effective solutions to mitigate soiling losses. Ultimately, these insights are intended to contribute to enhancing the operational efficiency of SPV systems and supporting the broader adoption of clean energy technologies.

2. Experimental Procedures

The experimental work performed 10 MW ground-mounted solar power plants located in Satna, Madhya Pradesh, India. The plant benefits from high solar irradiance and is directly connected to the TANGEDCO grid. It uses Longi 335 Wp high-efficiency solar panels and 1,000 kW inverters to convert DC to AC power, maintaining an optimal AC-to-DC ratio of 1:1. The system includes ten central inverters connected via string combiner boxes and feeds into the grid through 1,000 kVA transformers (360 V/11 kV), ensuring efficient power transmission and minimal losses.

An average, the performance ratio (PR) of the solar plant declines every 15 days due to dirt accumulation on the modules. The conventional cleaning approach is water-intensive, time-consuming, and heavily reliant on manual labor, highlighting the need for a more efficient solution. In collaboration with Inspire Clean Energy Pvt. Ltd., newly developed tool to enhance the soiling removal process, as shown in Fig. 1. Traditionally, cleaning required six workers per day to wash approximately 2,000 modules, using about 2 liters of water per module.

To evaluate the effectiveness of the newly developed cleaning tools, a six -month experimental study was conducted at the solar power plant from March to Aug 2024. The tools were strategically deployed and monitored daily to assess their performance and the impact of various cleaning methods on energy generation. Three cleaning methods were tested: wet cleaning, dry cleaning, and a combination of both. The tools operated predominantly using the wet method, which accounted for 91.4% of cleaning activities. The dry method and the combined method were used for 1.7% and 6.9%, respectively, indicating a clear preference for wet cleaning during this period.





a. b.



c.

Fig 1. a.Cobot tool b. Mounted on solar panel c. cleaning brush

Wet cleaning made up 80% of operations, while dry cleaning accounted for 20%. This change likely reflected varying environmental conditions and operational insights gained over the previous months. Throughout the study, both tools were closely monitored, and daily performance metrics were recorded. The effectiveness of these tools in maintaining clean solar panels directly influenced the plant's energy output. Therefore, the data collected during this period was critical in evaluating the efficiency of each cleaning method and its impact on daily power generation.

3. The Solar plant's performance

The solar plant's performance is rigorously tracked daily, focusing on the amount of energy produced each day. Energy generation is influenced by several environmental factors such as solar irradiance, wind speed, temperature variations, and other atmospheric conditions. To gain a comprehensive understanding of the plant's output, daily energy production is carefully recorded, facilitating continuous monitoring, detailed analysis, and informed operational decisions. The plant's efficiency is evaluated using the Performance Ratio (PR), (Eqn -1) which is supported by a weather monitoring system that provides accurate, real-

time data on climatic conditions. This integration allows for a precise assessment of how environmental variables impact the plant's performance.

$$PR = \frac{\text{Energy generated (kwh)} \times 100}{\text{Irradiation (kwh/m}^2\text{)} \times \text{total area of solar modules (m}^2\text{)} \times \text{module efficiency}} \quad (1)$$

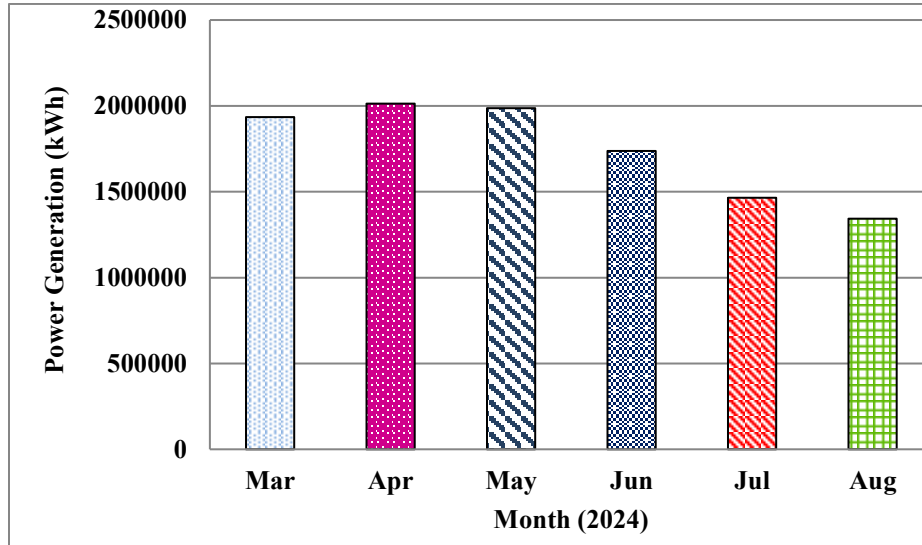


Fig 2. Plant's performance power generation for six months

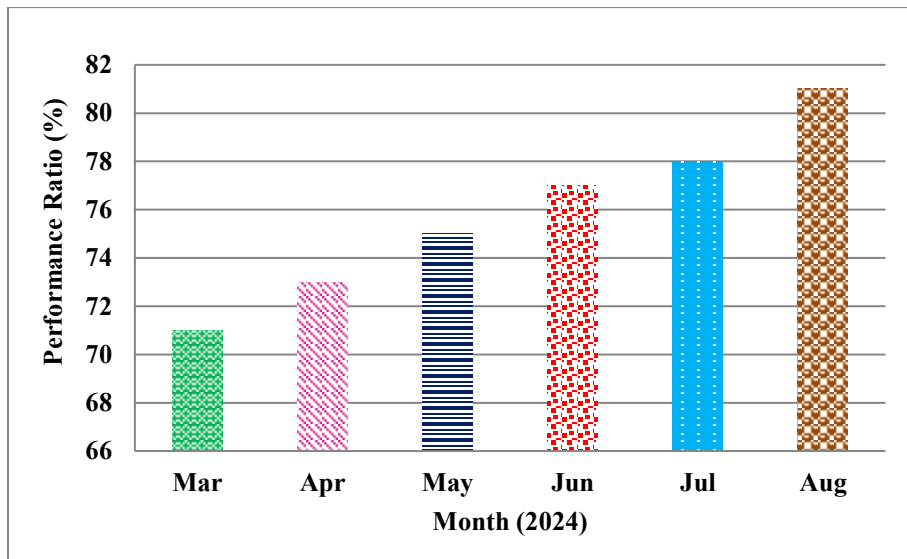


Fig 3. Plant's performance ratio for six months

From the Figure 2, the average energy generation in April increased to approximately 78,446.13 kWh, representing a notable improvement compared to March. This rise in

output is attributed to improved soiling conditions characterized by reduced accumulation of dirt and debris on the solar panels and the implementation of strategic operational efficiencies aimed at optimizing performance. In May, as shown in Figure 3, total energy generation reached 1986539 kWh. This represents a significant increase and highlights the growing operational capacity and efficiency of the plant as the year progresses. A month-by-month analysis reveals a consistent trend of increased productivity and performance shown in Figure 3. Each subsequent month builds upon the improvements of the previous, demonstrating the plant's resilience and its capacity for continuous enhancement. These findings provide valuable insights for optimizing future operations and guiding long-term strategic planning.

4. Results and Discussion

From March to August 2024, two customized cleaning tools were extensively tested at a solar power plant in Satna, Madhya Pradesh. Designed to improve module cleaning efficiency and boost energy generation, the tools were evaluated based on their daily cleaning performance and overall impact on plant operations. The average monthly coverage of 169920 modules was cleaned using Tool 1 and Tool 2. Both tools underwent varied testing methodologies to assess durability, adaptability, and operational efficiency under real-world conditions.

The testing phase also included detailed performance monitoring of the plant, enabling calculation of the Specific Yield—a critical metric indicating how effectively solar energy is converted into electricity. Higher Specific Yield values signify improved operational efficiency and directly contribute to increased returns for the asset owner. The specific yield can be obtained using Eqn 2.

$$\text{Specific Yield} = \frac{\text{Daily Energy}}{\text{Plant Dc Capacity}} \quad \text{-----} \quad 2$$

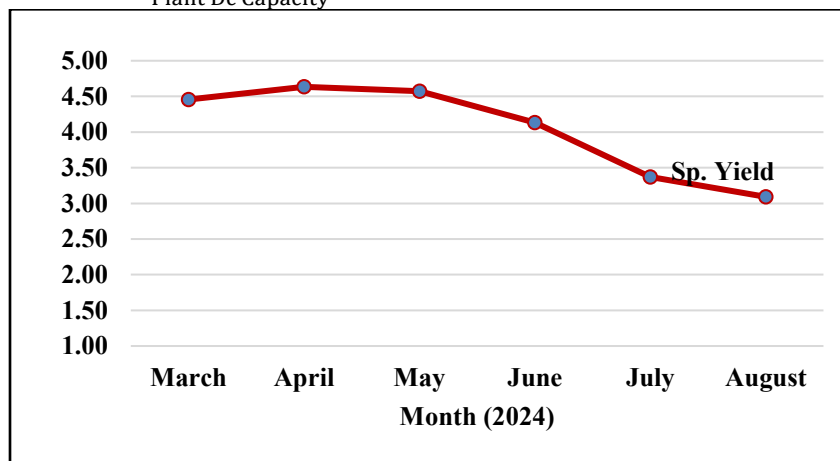


Fig 4. Monthly Specific Yield for March to August

In March, the plant recorded a Specific Yield of 4.45, indicating suboptimal performance despite favorable sunlight conditions shown in Figure 4. This lower-than-expected figure suggests possible inefficiencies in plant operations, such as equipment underperformance, dust accumulation, or inadequate cleaning cycles. These issues warrant further investigation to identify and address the root causes of reduced efficiency. A noticeable improvement was observed in April, as shown in Figure 4, with the average Specific Yield

increasing to 4.63. This upward trend points to better operational management and potentially more stable weather conditions. The gains may also be attributed to adjustments made to the cleaning process and tool utilization during the testing phase. The month of May the specific yield has 4.57. This remarkable improvement is likely due to the implementation of wet cleaning methods and fine-tuning of operational practices, which together contributed to enhanced energy conversion efficiency. The month of June to Aug the specific yield was reduced to 4.13, 3.37 and 3.09 respectively.

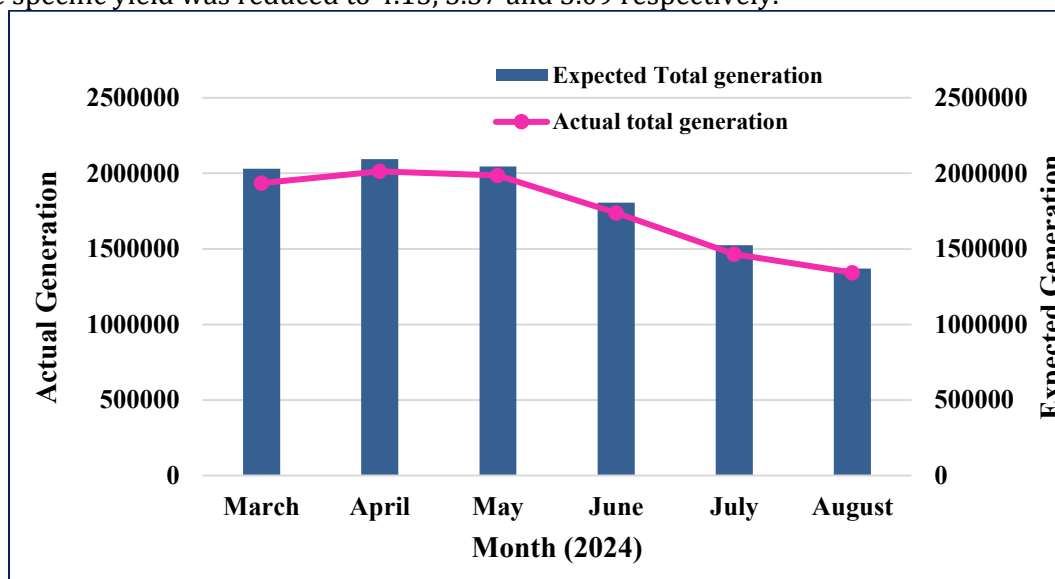


Fig 5. Expected Generation Vs Actual Generation

Further insights are provided in Figure 5, which compares expected versus actual energy generation for the months of March to August. In March, the plant reached 95% of its expected generation. However, April, June and July showed a positive shift, with generation levels increasing to 96% of the target, following the deployment of customized tools and optimized cleaning strategies. By August, the plant's performance reached 98% of the expected generation, indicating near-maximum operational efficiency. The expected generation figures were derived using PvSyst, widely recognized software for simulating and evaluating photovoltaic system performance. This month-by-month analysis highlights the critical importance of consistent monitoring, timely maintenance, and strategic interventions to enhance yield and align actual output with projected targets.

5. Conclusion

The accumulation of dirt, dust, and debris collectively known as soiling on solar panels significantly reduces the efficiency of solar power plants by blocking sunlight from reaching the photovoltaic cells. This results in a noticeable drop in energy generation, making regular cleaning an essential part of plant maintenance. An effective cleaning program not only removes surface contaminants but also carefully balances the use of resources such as water and labor. Excessive consumption of these resources can lead to increased operational costs and environmental impact. Therefore, optimizing cleaning techniques is crucial for maximizing energy output while maintaining sustainability. A prime example of this optimization can be seen at the 10 MW solar power plant Satna, Madhya Pradesh. Here,

a specially designed cleaning tool was introduced to improve cleaning efficiency. After implementation, the plant's performance ratio has improved dramatically from 71% to 81%.

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