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Impact of Soiling on Performance and Cleaning Optimization of a 2.5 MWp Solar PV Plant in Pune, India.

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ABSTRACT

The soiling pattern of PV plants needs to be studied for the proper utilization of solar energy as it creates a partial blockage of radiation and hence reduces power generation. The pattern of soil deposition varies from one location to another location. A large number of studies were carried out for a dry season to measure per day soiling rate. This research article investigates soiling pattern of a varied weather location i.e., Pune, India. Ambient temperature is less with high chances of precipitation and wind speed as compared with other locations of India.

To measure the change in performance of PV plant around the year, a 2.5-MWp grid-tied PV plant having the location coordinates 18.52°N 73.85 °E was investigated. Various performance parameters i.e., Voc and Isc change with temperature, performance ratio, soiling ratio, and soiling loss percentage are evaluated. The results indicate that prediction of the exact value of the soiling rate is not possible due to seasonal variation. An average monthly soiling rate of 10.28 % is estimated based on observed data for the dry season. The cleaning activity is suggested on and after the 8th or 18th day with water or mechanical cleaning with water for avoiding financial losses to the college. Further, a micro-texture sheet can be laminated over the PV module with proper earthing to minimize the static charge formation for reducing the collection of dust.

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تأثير التلوث على الأداء و تحسين التنظيف لمحطة الطاقة الشمسية الكهروضوئية بقدرة 2.5 ميجاوات في بوني، الهند.

كارتيك كابور ، إسوارامورثي موتوسامي ، نيخيل بي جي ، رافي كومار جويل.

ملخص: يحتاج نمط الاتساخ للمحطات الكهروضوئية إلى الدراسة من أجل الاستخدام السليم للطاقة الشمسية لأنه يخلق انسدادا جزئيا للإشعاع وبالتالي يقلل من توليد الطاقة. يختلف نمط ترسب التربة من موقع إلى آخر. تبحث هذه المقالة البحثية في نمط الاتساخ لموقع طقس متنوع ، مثل بيون ، الهند. درجة الحرارة المحيطة أقل مع فرص عالية لهطول الأمطار وسرعة الرياح مقارنة بالمواقع الأخرى في الهند. لقياس التغيير في أداء المحطة الكهروضوئية على مدار العام ، تم فحص محطة كهروضوئية مرتبطة بشبكة بقدرة 2.5 ميجاوات بإحداثيات الموقع 18.52 درجة شمالا 73.85 درجة شرقا. يتم تقييم معلمات الأداء المختلفة ، مثل جهد الدائرة المفتوحة (Voc) وتيار الدائرة القصيرة (Isc) يتغير مع درجة الحرارة ونسبة الأداء ونسبة الاتساخ ونسبة فقدان الاتساخ. تشير النتائج إلى أن التنبؤ بالقيمة الدقيقة لمعدل الاتساخ غير ممكن بسبب التباين الموسمي. يقدر متوسط معدل التلوث الشهري بنسبة 10.28٪ بناء على البيانات المرصودة لموسم الجفاف. يقترح نشاط التنظيف في اليوم الثامن أو الثامن عشر وبعده بالماء أو التنظيف الميكانيكي بالماء لتجنب الخسائر المالية. علاوة على ذلك ، يمكن تصفيح لوح نسيج دقيق فوق الوحدة الكهروضوئية مع التأريض المناسب لتقليل تكوين الشحنة الساكنة لتقليل تجمع الغبار.

الكلمات المفتاحية – نسبة الأداء ، نسبة الاتساخ ، نسبة فقدان الطاقة ، تردد التنظيف ، تكلفة تنظيف الطاقة الشمسية الكهروضوئية.

1. INTRODUCTION

The adoption of solar photovoltaic (PV) technology is pivotal for sustainable development and achieving carbon neutrality. Maharashtra, India, ranks third in land availability for PV installations. Pune's climatic conditions of moderate temperatures and high precipitation make it unique for studying soiling patterns.

The variability of weather, including high humidity and wind speeds, influences the soiling ratio of PV panels. In Pune, Maharashtra, the area is relatively less heated in comparison with other locations in different states as indicated in Figure 1. The chances of a clear sky from May to October are less in Pune in comparison with other areas. Figure 2 indicates the chances of precipitation are high during the same period which results in the sticking of soil over the PV surface. The available hours of solar radiation are less which reduces the solar capturing time. The rates of electricity tariffs are increasing as the power supplied by the grid is generated from conventional resources. The burden on natural resources is increasing with increasing population and the future sustainability of humans demands clean environmental conditions. The Maharashtra government has set a target of 12,000 MW plant installations that will generated power by Solar PV in the year 2022 [2]. Government subsidies are also promoting the installation of solar PV plant throughout India [3].

In the installation of solar PV, the alignment of the panels depends upon several parameters, i.e., declination angle(β), azimuth angle(γ) and latitude (φ) of the location (refer to Figure 3 (a)). To get the maximum output of solar radiation, a solar PV is assumed to align with $\gamma=0°$, $\beta=\varphi$. Several industries are installing the PV panel at different azimuth angles (γ) as per their space available to maximize the power output from limited space.

These panels are fixed with different types of sensors which includes (refer to Figure 3(b)) temperature sensor, pyranometer for solar radiation measurement, rain gauge, humidity sensor, pressure sensor, and anemometer, and all data are recorded with the help of data loggers or SCADA system.

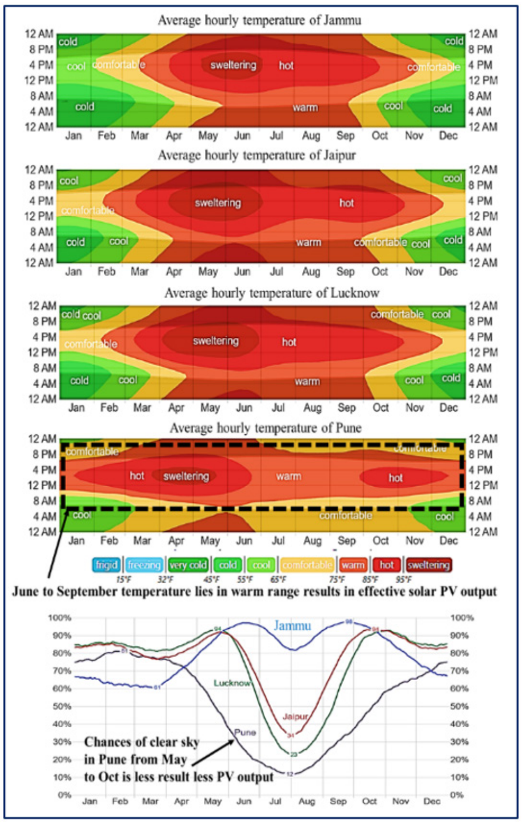

Figure 1. Comparative analysis of Pune's weather conditions with other regions in India Part 1 [1].

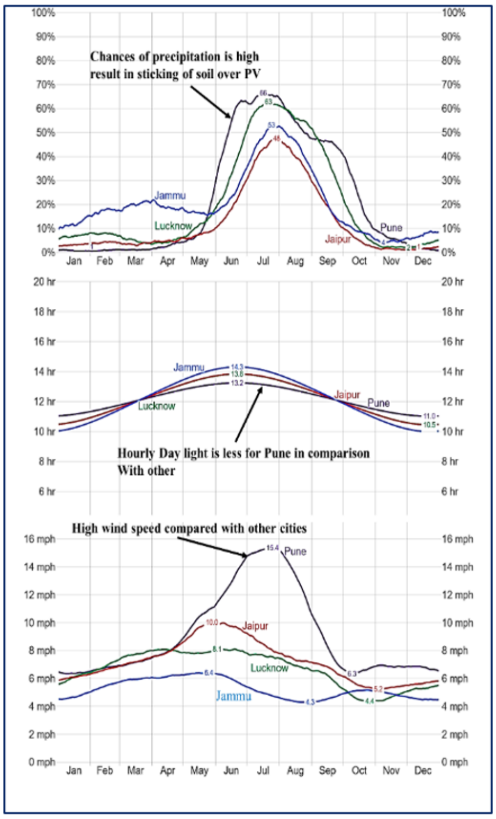

Figure 2. Comparative analysis of Pune's weather conditions with other regions in India Part 2 [1].

The loss of power output measured by the sensors can be of any type mentioned in Table 1. It is generally observed that loss in electrical power output due to less maintenance is mainly caused by soiling, shading, and mismatch losses. As the dust deposited over PV is a common phenomenon. Hence, the maintenance of a photovoltaic plant is critically important to increasing energy yield and the plant's operational life [4].

Table 1. Major Losses in PV Plants [5], [6].

Type of Loss	Catered By		
	Manufacturer	**Design**	**Maintenance**
Incident Angle Modifier	-	Yes	-
Soiling	-	-	Yes
Shading	-	Yes	Yes
Light-Induced Degradation (LID)	Yes	-	-
Potential Induced Degradation (PID)	Yes	-	Yes
Module Quality Loss	Yes	-	-
Module Degradation	Yes	-	-
Ohmic Wiring loss (DC and AC)	-	Yes	-
Connection Loss	-	-	Yes
Inverter Loss	-	Yes	Yes
Irradiance and Temperature	-	Yes	-
System Availability		Yes	-
Mismatch Loss	-	Yes	Yes

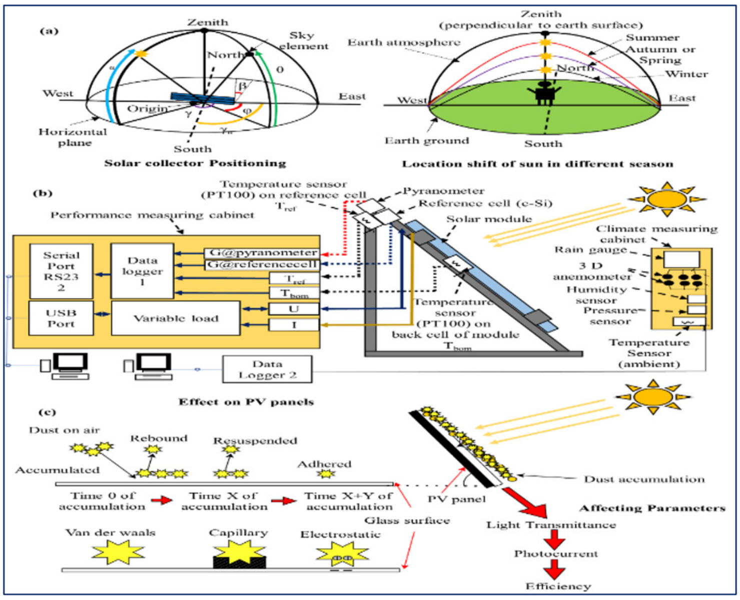

Figure 3. (a) Solar PV panel positioning at various angles with seasonal variations (b) weather moniotoing system along with SCADA/ data loggers for measurement of various weather and operational parameters in PV plant (c) the impact of dust accumulation on panel performance.

The dust deposited on the surface of the PV module is due to the particulate matter present in the air. This dust particle size varies in a range from 1 µm to 500 µm depending on the source of dust formation. The particles outsourced from concrete, carbon fibers, fiberglass, and brick are generally of size 10 µm [7]. In case of humidity is present in the environment, these dust particles start sticking to the surface. The process of dust accumulation is shown in Figure 3(c). The dust particles also stick due to the smooth texture of the panel, or static charge present on the surface of the PV module. Few particles rebound or are resuspended due to the presence of wind but complete cleaning with the wind is not possible which results in the formation of a dust layer over the panel and blocks the solar radiation [8]. The effect of soil deposition can easily be understood on the power plant installed in Pune, India, as shown in Figure 4. Soiling affects solar PV modules, increasing their temperature up to 55°C in dust deposition regions, compared to 28°C for cleaned panels. This does not cause module failure but reduces power output.

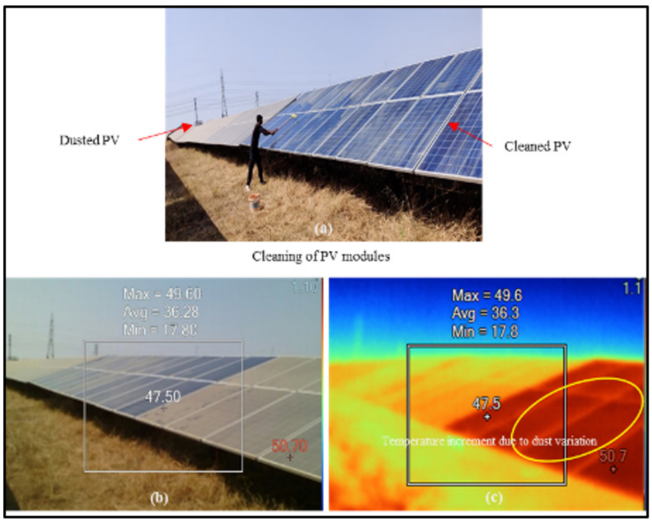

Figure 4. (a) Cleaning process of PV modules (b) and (c) temperature profile of dusted solar PV in Pune, India in a normal and IR image.

Generally, the deposited particle is water soluble and does not require mechanical brushing for complete cleaning. In the case of desert areas, the cleaning activity is executed with chemicals and water to get the desired cleaning of modules [9]. The effectiveness of cleaning modules by rain depends on the humidity present in the atmosphere and quantum of rainfall received in the area. A large number of research and review articles are published that studied the soiling effect of solar PV. Raina and Sinha [10] investigated the effect of soiling on bifacial PV panels. The results observed a soiling rate of 0.328 % /day on the front side of the module and 0.031 %/day on the rear side of the PV module. The reduction of soling losses occurs when a bifacial panel is arranged in the vertical position only (~2%). Po-Ching Hwang et al.[11] primarily focuses on the cleaning pattern of PV modules to generate maximum revenue from Solar PV and proposed an intelligent method to measure the soiling losses with a statistical approach, machine learning and image processing scheme. On validation with experimental data, the accuracy of results is found to be 98.39 %. The results generated through the intelligent method are helpful for the community. Lopez-Lorente et al.[12] study the fundamental challenges in the dry region affected by soiling by both physical and machine learning approaches located in Cyprus. The results obtained indicate the soiling of 0.039 %/day to 0.535 %/day depending on the external environmental conditions. The monthly soiling loss of 2.4 % was reported for 2 years. They also suggested a few limitations of different soiling models for PV modules located in a dry zone. Cavieres et al. [13] developed a new algorithm for measuring the power losses in PV panels affected by natural soiling. The algorithm uses different colours with the measurement of average colour intensity and deviation. Based on the results, inputs are given to artificial neural networks. The results generated show the instantaneous performance of the PV module and the results are compared with the clean module. The method is efficient in image capturing in the radiation from 700 W/m2 to 1000 W/m2 with a high R2 value and RMSE of 0.74 % for loss in power, ranging from 0-20 % caused due to natural soiling. Siyabi et al. [14] study the performance of 2 MWp on the soling rate and tilt of a PV module in the location of Oman. The result observed that after one week of operation of the PV plant. The power generation is reduced from 1460 kW to 1390 kW under the same irradiance level. Further reduction is also observed in the 3rd and 4th week. A reduction of 5.6 % of electrical output is observed when a soiling is 7.5 %. The increase in tilt angle to obviate this is not suggested due to the canopy effect. Álvaro Fernández-Solas et al. [15] emphasize the reduction of operation and maintenance costs of solar PV. They also find soiling as the major issue that affects the cost. Experimental data is collected from the PV plant located in southern Spain and these results are used as an input for the analytical studies and these methods are used for estimating the soiling losses.

Ribeiro et al. [16] performed statistical methodology to estimate the loss of energy due to soiling over the PV for the northeast region of Brazil. The measured results show the loss in daily energy generation from 2.20 % to 12.31 %. Ferrada et al. [17] focus on the characterization of soiling to implement suitable cleaning techniques for the desert located in Atacama. The study found that small dust particle is generally circular, while the large size is prismatic and deposited over the photovoltaic panel for the desert location. Urrejola et al. [7] studied the performance of solar PV based on annual yield for the location of Santiago, the capital of Chile. The findings show that the daily degradation in the performance of PV is 0.13% to 0.56 %, and the yearly degradation of polycrystalline is 1.29 %. Conceição et al.[18] studied the soiling effect of solar PV for the location in Spain. The results indicate that the soiling ratio is between 0.07 % to 0.14 % per day. Conceição et al.[19] developed a model for measuring the optimum tilt angle of solar PV for southern Portugal. Further, an economic analysis is performed to balance the increase in power output and the cost of tilt angle variation over an interval. Javed et al. [20] performed a multi-year study on PV soiling patterns for Qatar in different seasons and storms, which attenuated the solar radiation and soiling rate. Abraim et al. [21] studied the soiling effect of concentrating

PV plants located in an arid region of Morocco in terms of technical and economic aspects. The results indicate a soiling loss of 0.24 % per day for the PV plant. Yazdani and Yaghoubi [22] propose the study of measuring the soiling losses and optimization of the cleaning schedule for the utility-scale solar power plant located in a semi-arid region. The results indicate the soiling rate evaluated in the first week was 0.27 %/day. The optimal cleaning frequency is 17.50 and 6.39 days for manual and machine washing. Fares et al. [23] review the critical issue of soiling of PV for the region of the Gulf cooperation council. They suggested the use of an anti-soil coating. After reviewing the literature, it is highlighted that study of soiling is generally carried out in dry or arid regions, however, no study is performed for mixed weather i.e., dry and rainy weather which leads to sticking of dust over the solar PV and reduces the power generation with much greater impact. Hence the experimental study is carried out for the location of Pune, India. The low-intensity rain does not clean panels but causes cementing of dust particles and increases the temperature of the module causing a decrease in the power extracted from the PV panel. Studies carried out in the literature [24], [25] emphasized that soiling is the leading cause of power loss in a well-designed PV plant which further causes soft shading and then leads to hard shading due to cementing of dust particles. This study focuses on the maximum power output from the available resources. Soiling, shading, and maintenance are the most important factors that affect PV performance. Dust accumulation, exacerbated by environmental conditions, can raise module temperature and lower power output. The present study tries to fill the gap in the literature on mixed weather conditions by analyzing the soiling effect in Pune and optimizing cleaning strategies.

2. METHODOLOGY

2.1. Plant specification and instrumentation

The 2.5 MWp grid-tied PV plant located at Pune (18.52°N, 73.85°E) comprises 7385 modules in 370 strings, with a DC-to-AC ratio of 1.25. Each module has a peak wattage of 325 Wp with 20 modules in one string. There are 10 string combiner boxes (SCBs) input for each inverter, and two inverters are installed in the plant, each with a capacity of 1000 kVA. Detailed specifications of the modules and instruments are in Tables 2 and 3. The I-V characteristics of the module and the technical instruments used in the study are depicted in Figure 5 and 6.

Table 2. Specifications of PV Module and single string [26].

Rating of one Module		Rating of one String
Model	**ADANI**	
Peak Wattage	325Wp	6.5 kWp
V_{oc}	45.26 V	905.2 V
I_{sc}	9.21 A	9.21 A
Vmp	37.29 V	745.8 V
Imp	8.54 A	8.54A
L	1.96 m	
B	0.992 m	
Power/Vmp(Temperature Coefficient)	-0.4 %	
Isc (Temperature Coefficient)	0.069 %	
V_{oc} (Temperature Coefficient)	-0.31%/°C	

Table 3. Technical specifications of instruments.

Measuring Instruments	Operating Parameter	Range	Least count
SS200R	Irradiance	100-1500 W/m^2	1 W/m^2
	Temperature	-30 °C- 150 °C	1° C
	Tilt	0° to 90°	1°
Clamp meter	Load voltage and current	0.5- 40 A	0.1 A
PV 150 Analyser	V_{oc} and I_{sc}	5-1000 V	0.1 V

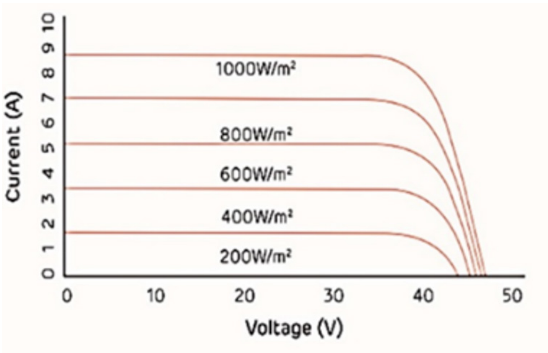

Figure 5. Current and Voltage (IV) curve of the module studied [26].

Figure 6. Instruments used for data record.

SS200R is used for the measurement of solar radiation, module and ambient temperature, and the tilt of the module. The clamp meter is used for measuring load current voltage and power, and Seaward PV 150 Analyser is used to measure Voc and Isc. All these instruments can be synchronized with PV 150 analyser for collection of data. This data is used as an input for measuring the various performance parameters that measure the losses in power generation, soiling ratio, and performance ratio.

2.2. Data collection intervals

Data is collected at intervals synchronized with the PV plant's cleaning schedule to capture the effects of soiling and cleaning under different weather conditions. Observations were made on specific dates throughout 2022, including January 10th and 13th, February 17th and 22nd, May 5th and 10th, August 12th and 17th and October 2nd and 7th at the College of military engineering, Pune (coordinates 18.5204 °N, 73.8567 °E). The only controlled parameter available for increasing the power output is the cleaning activity. Hence, the time gap of data collection is matched with opted cleaning frequency of the college. The tilt angle of all solar panels is 18°, with an azimuth angle variation of -10° to +10° to the south direction. The panels are cleaned with brushes and water just before and after the data collection. The effect of the soiling rate is studied during the complete year.

2.3. Sources of error

Potential error sources included are as follows:

• Environmental fluctuations: Unexpected precipitation or wind variations during data collection lead to errors.

• Instrumentation limitations: Least count and range of devices of SS200R and PV150 analyzer

affects the data.
• Manual errors: Variations in cleaning methods and data recording.
To mitigate these, instruments were calibrated regularly, and data was cross-verified.

2.4. Variation of V_{oc} and I_{sc} and Power output with temperature rise

The open circuit voltage (V_{oc}) and short circuit current (I_{sc}) of PV modules is tested in the standard conditions (i.e., Tamb 25°C and Irad 1000 W/m^2). The actual output varies with the surrounding temperature and solar radiation. With the increase in temperature of the PV module, the bandgap energy level of the semiconductor material decreases which results in less open circuit voltage across the terminal. The change in V_{oc} under elevated temperature is measured with the following expressions:

$$(\Delta V_{oc})_{Tp} = \beta.(\Delta T)_{above\ STC} \quad (1)$$

The temperature coefficient values used in the study is taken from Table 2. The expected V_{oc} of the module under cleaned condition is measured with the following expressions:

$$(\Delta V_{oc})_{expected} = (V_{oc})_{STC} + (\Delta V_{oc})_{Tp} \quad (2)$$

With the rise in temperature of the PV module, the concentration of charge carriers starts increasing which results in increasing the charge carrier availability at the terminal resulting in increasing short circuit current. The change in I_{sc} generation with rising temperature is measured by the following expressions:

$$(\Delta I_{sc})_{Tp} = \alpha.(\Delta T)_{above\ STC} \quad (3)$$

The expected I_{sc} of the module under cleaned conditions at elevated temperature is measured with the following expression:

$$(I_{sc})_{expected} = (I_{sc})_{STC} + (\Delta I_{sc})_{Tp} \quad (4)$$

Expected power output under standard solar radiation is calculated by the expression:

$$P_{expected} = (V_{oc})_{expected}.(I_{sc})_{expected} \quad (5)$$

The reduction of power generation with the rising cell temperature can also be evaluated by the loss coefficient of temperature (η_T) [14].

$$\eta_T = 1 + \beta(T_c - 25) \quad (6)$$

$$T_c = T_a + \frac{1}{A}(T_{STC} - 20) \quad (7)$$

The power loss that occurred due to temperature rise is estimated with the following expression:

$$P_{loss} = P_{STC}.\eta_T.(\Delta T) \quad (8)$$

The power produced by the solar PV plant in a day is evaluated by:

$$P_d = \sum_1^{24} P_{d,h} \quad (9)$$

The power produced in a month is evaluated as:

$$P_m = \sum_1^{K} P_{m,d} \quad (10)$$

K is the number of days in a month taken into consideration. The yield of the plant is the ratio of the total power produced to the rated power of the PV plant. It is given by the expression [14]:

$$Y_{PV} = \frac{P_{out}}{P_{rated}} \quad (11)$$

The daily and monthly plant yield is calculated by the expression [14]:

$$Y_{PV} = \frac{P_{out,d}}{P_{rated,d}} \quad (12)$$

$$Y_{PV} = \frac{1}{K}\sum_{1}^{K} Y_{PV,d} \tag{13}$$

The reference yield of the PV plant is the ratio of global solar irradiance to the solar radiation striking over the installed area of the PV plant. It is evaluated by the expression [7], [14]:

$$Y_{PV} = \frac{H_{PA}}{H_{STC}} \tag{14}$$

Although, the change in V_{oc} and I_{sc} with a rise in the temperature of the module excludes the soil deposition over the PV panel. The above values of V_{oc} and I_{sc} can only be a part of measuring the performance parameter. It is inefficient in defining the performance parameter completely. The performance ratio is used to compare the data of net power output to the expected power output in the tilt condition of the PV panel with reference to solar radiation.

2.5. Performance ratio

The performance ratio estimates the effectiveness in generating electrical output from the solar PV modules when placed in real environmental conditions at a suitable tilt angle to the power generated in standard temperature conditions (I_{rad} 1000 W/m^2 at T_{amb} 25 °C). The value of reference radiation I_{rad} changes as per the tilt of the solar PV module. The performance ratio depends on several parameters, i.e., the temperature of a module, errors in measuring instruments, power dissipation, shadowing, yearly module degradation, electrical installation losses, dust deposition, which is known as soiling and losses due to spectral and angular reflectance. It also depends on operational parameters, i.e., electrical connections efficiency, power generated and yearly degradation of the PV module. It is evaluated by the following expression [7]:

$$PR = \frac{(Power\ \ generated)_{PV}}{(Power\ \ generated)_{PV-STC}} = \frac{P}{P_{STC}\cdot\frac{H_{PA}}{H_{STC}}} \tag{15}$$

Where H_{PA} represents the solar radiation falling perpendicular to the tilted array of PV panels, H_{STC} represents the normalization of reference solar radiation at STC, P is the power generated in real environmental conditions, and P_{STC} is the standard power generation in STC. The normalized value of solar radiation used in the measurement of performance ratio is less affected by weather change but supports weather variability with temperature or wind. The measurement of performance ratio gives an idea for the power generation under different scenarios, i.e., soiled panel and cleaned panel, but it lacks in measuring the actual percentage of soiling losses that occur only due to dust deposition.

2.6. Soiling ratio and soiling losses

The soiling ratio (SR) defines the soil deposition level on the surface of the solar panel. It is the ratio of actual power production under real environmental conditions to the expected power output in the cleaned conditions, and it is defined in standard guidelines given by IEC 67124-1 [27]:

$$Soiling\ \ Ratio\ \ (SR) = \frac{P_{out}}{P_{expected}} \tag{16}$$

The following expression defines the percentage of loss of power due to soiling:

$$(\%)\ loss\ \ of\ \ power = \frac{P_{expected} - P_{out}}{P_{expected}} \times 100 \tag{17}$$

Different performance parameters are analyzed from the recorded data and results are presented in the following section.

3. RESULTS AND DISCUSSION

3.1. Conditions of PV panel

In Figure 7, the first set of readings was taken on 10 January 2022 at 11:30 am for the soiled PV module, the solar radiation recorded at tilted PV panel was 914 W/m2, the average temperature of the modules recorded in the soiled condition was 46°C, and the ambient temperature was 28°C, the expected V_{oc} and I_{sc} of the module were 36.83 V and 10.5 A by considering the module temperature and solar radiation but the recorded output of V_{oc} and I_{sc} during the soiled state of PV module was 33.2 V and 6.73 A. Further, the cleaning activity is performed over the PV module and data is recorded again on 13 January 2022 at 12:15 pm. The recorded solar radiation was 920 W/m2, the ambient temperature was 31 °C, and the temperature of the module was 48 °C. The expected V_{oc} and I_{sc} were 36.21 V and 10.64 A. This change in expected V_{oc} and I_{sc} under soiled and cleaned conditions is observed due to changes in temperature and solar radiation reaching the module. The V_{oc} and I_{sc} output in cleaned condition recorded were 35.1 V and 7.5 A. The cleaning activity increases the power output from 223.43 W to 263.25 W of the PV module. In a similar pattern, similar sets of data were recorded around the year.

3.2. Performance Ratio of PV plant

The power output is measured from the inverter 1 end attached to the SCB and the expected power output is calculated based on the temperature of the module and instantaneous solar radiation. Figure 8 shows the power output pattern based on the seasonal variation. The power output expected on 10 Jan 2022 was 1.119 MW but the inverter is receiving a total output of 0.735 MW. The value of the performance ratio is 0.66 which results in high power losses due to soiling. After cleaning the PV plant, the data is recorded on 13 January 2022. The power output is increased to 0.840 MW at a similar radiation level. The performance ratio is increased to 0.75. As the next cleaning activity (17 February 2022) is performed in a short interval, the effect of soiling is less. The weather in between the duration is dry with clear days. The power expected under received solar radiation was 1.068 MW and the power output is 0.795 MW in soiled condition, the performance ratio reaches 0.74 and after completing the cleaning activity, the power output reaches 0.822 MW with the performance ratio of 0.75 for received solar radiation. Further, the cleaning activity is performed in May 2022, the weather start gaining humidity with the less clear sky as per weather pattern shown in Figure 1. The power output drops to 0.630 MW but the expected power output is 1.104 MW under the received solar radiation. The performance ratio measured was 0.57. This is a major recorded drop in the performance ratio. Further cleaning activity is performed and power is increased to 0.860 MW. The new performance ratio recorded was 0.80. Further, the power output is recorded on 12 August 2022, the period receives heavy rainfall, and hence the dust deposition rate is decreased. The power output before the cleaning is 0.795 MW with expected power of 1.112 MW under solar radiation, the performance ratio under the soiled condition is 0.71. As most of the cleaning activity is accomplished by the rainfall. When the cleaning activity is completed manually, the power output is increased to 0.85 MW from the expected power output of 1.082 MW. The performance ratio is increased to 0.79.

The last data recorded for cleaning activity is proposed in October 2022, the rainfall season ends in September start, the condition of the panel is almost cleaned due to rain wash, the power output is 0.810 MW while the power expected is 1.119 MW under the solar radiation of 910 W/m2. After cleaning, the net power output is increased to 0.830 MW under the expected output of 1.137 MW in the solar radiation of 925 W/m2. The performance ratio shows a slight increment from 0.72 to 0.73 as panels are in a cleaned state.

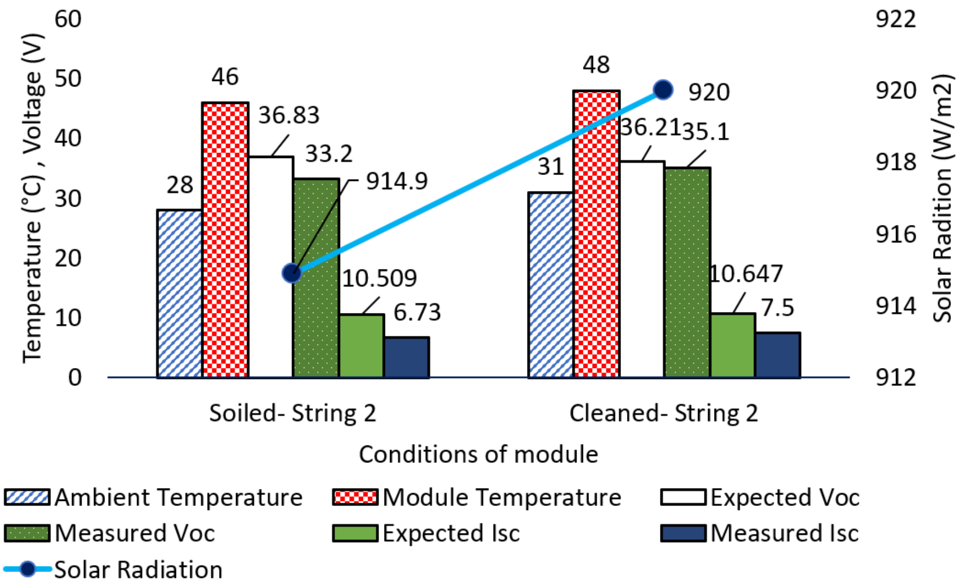

Figure 7. The temperature of a single PV module in different soiling and clean conditions.

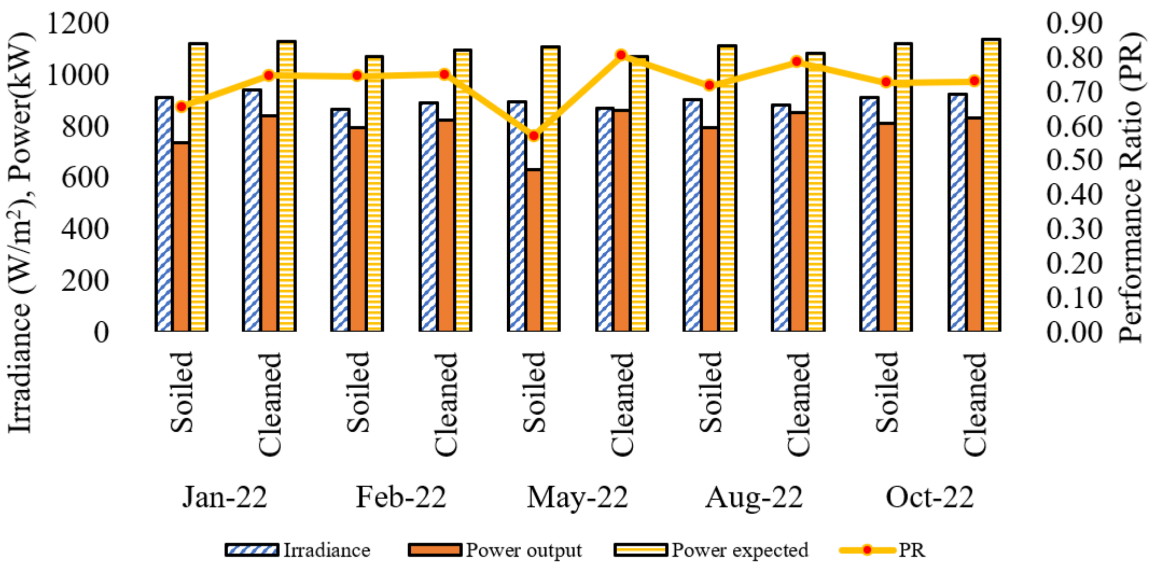

Figure 8. Performance Ratio of the PV plant.

3.3. Soiling losses

The soiling loss is measured as the ratio of actual power to the power output in a cleaned condition. From Figure 9, the soiling ratio measured for January 2022 was 0.87 and the loss in power output due to soiling was 12.5 %. For February 2022, the soiling ratio recorded was 0.92 with a loss in power output of 7.54 %. The power loss decreases as the weather is cleaned and dry in between the cleaning activity of January and February 2022 and this period is short. The next cleaning activity is proposed in May 2022, the soiling ratio recorded was 0.73 with a power loss of 26.74 %. This is the major loss that occurred due to the humid climate with less rainfall. The dust particle starts sticking to the surface of the PV module as cleaning activity is not performed for 3 months. Further, the cleaning is proposed in August 2022, this season received high rainfall which results in partial or complete cleaning. The soiling ratio evaluated for the same time is 0.9353 and power loss was 6.47 %. The last data recorded in October 2022, the soiling ratio is 0.97, and the power loss percentage is 2.41 % as the rainy season end at the start of October.

3.4. Optimization of cleaning activity with the cost of cleaning

The cost of electricity supplied to commercial units in Pune lies in the range of Rs. 7.92 to 9.48 /KW [28]. We considered Rs 8/- per electricity unit for the evaluation. The per-day power loss cost to the college is Rs. 7915/- based on the data shown in Figure 9. It is estimated that average monthly soiling losses of 10.28 % and solar radiation collection of 5.5 hr. The labourer can be hired on a contract basis for performing the cleaning activity with a unit manpower cost of Rs 600/- per day. One labourer can clean 30 modules from the soiled stage daily by with a brush and water spray. A total of 247 labourers are required to perform cleaning in a day, and it can be simplified as 36 labourers for 7 days.

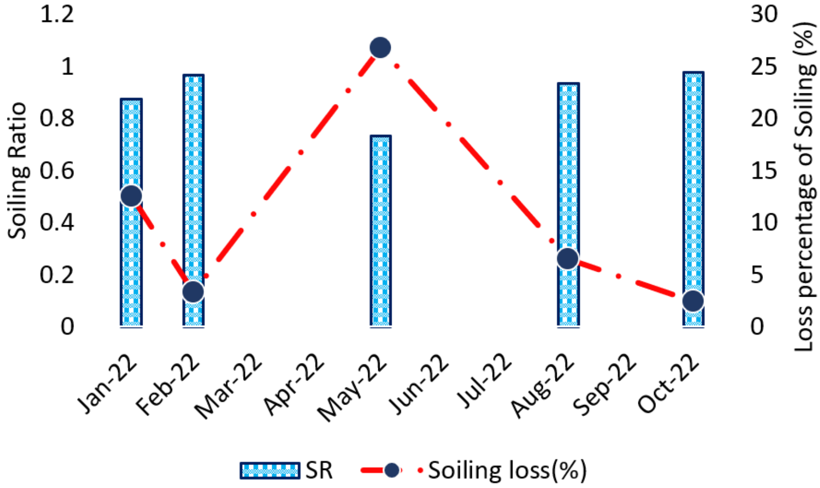

Figure 9. Relationship between soiling ratio and power loss percentage across seasons.

The total cost incurred to the college is Rs 1,48,200/- and the red dotted line shown in Figure 10 crosses the blue marker line when the cost of power loss increases from cleaning cost. Similarly, for cleaning with water spraying, 1 labourer can clean 80 modules per day. For cleaning the complete plant, the required labourer is 93, and the total cost of cleaning to the college is Rs 55387. The break- even point for water spraying is shown as the overlap of black and blue lines in Figure 10.

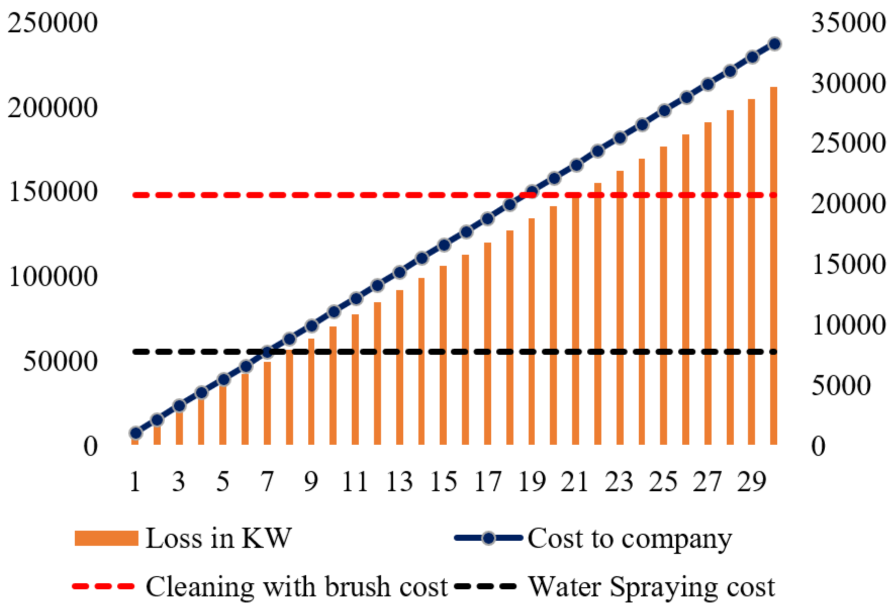

Figure 10. Break-even analysis of cleaning costs versus financial losses due to soiling.

The overlap of the blue line with the black line indicates the cleaning of a panel with water can be performed every 8th day. In case the college delayed the cleaning, the cost to the college increases. While the complete cleaning with water and brushes can be done after the 18th day to minimize the financial losses. This cleaning activity is not required during the rainy season. The cleaning frequency may increase in cases of dust storms.

Cost analysis showed that manual cleaning with water is economically viable every 8th day during the dry season. Cleaning frequency can be reduced during the monsoon.

3.5. Seasonal soiling patterns

Data showed a significant seasonal variation in soiling rates:

- Dry Season: with an average monthly soiling rate of 10.28%, cleaning every 8th or 18th day is advisable to minimize losses.
- Monsoon Season: Less soiling because of natural cleaning by rain.
- Post-Monsoon Season: Minimal soiling with high performance ratios observed.

3.6. Limitations of the study

Findings are most applicable to regions with mixed climatic conditions. Limitations include:

- Present study is focussed on polycrystalline modules, which may differ from other PV technologies.
- The study excludes automated cleaning systems and advanced coatings to minimize soiling.
- Long-term degradation analysis is limited for one year data.

4. CONCLUSION

A 2.5-Megawatt peak grid-tied solar PV power plant located in Pune is investigated in different month intervals to maximize the power output. The controlling parameter available to us is the frequency of cleaning the PV panel. There are other reasons like moisture, static charge formation and texture of the panel which is responsible for the soiling of the PV module. As the plant is already installed with a polycrystalline module. Hence, the chances of removing the static charge or changing the texture of the panel are not possible. Also, the plant is installed in an outdoor environment. Hence, the moisture content of the environment can not be controlled.

A year-long analysis of soiling patterns in Pune's mixed climatic conditions revealed that cleaning intervals significantly impact PV performance and financial viability. From the study, the following points are concluded: -

- The surface of the PV module can be coated with an anti-static coating to reduce the static charge formation on the surface of a module which resists the sticking of dust over the surface.
- To minimize the surface charge formation, a transparent micro-texture sheet can be added as lamination to avoid protruding dust particles.
- Improper grounding of the PV module also affects the soiling rate on the PV module.
- The estimation of the daily soiling rate is difficult due to variable weather conditions. Based on the data recorded, 10.28 % monthly can be considered as an average soiling rate in the dry season.
- The performance drop of PV plants depends upon the weather condition and cleaning frequency.
- The soiling ratio of summer is less as compared with the rainy and winter season.
- The PV plant located in Pune needs the cleaning on 8th or 18th day by water or brushing with water to avoid financial losses.

5. RECOMMENDATIONS

- Cleaning of panels every 8th or 18th day during dry seasons.

• Applying anti-static coatings or micro-textured sheets to minimize dust accumulation.
• Improving grounding to reduce the effects of static charges
These findings aid as a reference for PV plants in similar regions and encourage further research into advanced cleaning and mitigation technologies.

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NOTATION:

H_{PA}	Global solar irradiance striking over the installed area of the PV plant
H_{STC}	Solar radiation under standard test condition
$(\Delta I_{SC})_{Tp}$	Change in ISC under elevated temperature (V)
I	Instantaneous solar radiation measured in ambient conditions, (W/m2)
A	Irradiance at standard test conditions, (W/m2)
$I_{SC\ STC}$	Short circuit current of module at standard test condition, (A)
$I_{SC\ expected}$	Expected Isc of module under cleaned conditions at elevated temperature, (A)
P	Power generated in PV plant in real environmental conditions
P_d	Power produced by a PV plant in a day
$P_{expected}$	Power generation expected
P_h	Power produced by a PV plant in a hour
P_m	Power produced by a PV plant in a month
$P_{out,d}$	Total power produced daily in PV plant, (W)
P_{out}	Total power produced in PV plant, (W)
$P_{rated,d}$	Rated power of the PV plant, (W)
P_{STC}	Power output at standard test conditions, (W)
Ploss	Power loss occurred due to temperature rise, (W)
PR	Performance Ratio
(Power Generation) PV	Power generated by a PV plant
% Loss of powe	Percentage loss of power
SR	Soiling Ratio
STC	Standard Test Conditions (solar irradiance of 1000 W/m2 , a cell temperature of 25°C, and an air mass index of 1.5)
$(\Delta T)_{(above\ STC)}$	Change in temperature above STC
T_{STC}	Cell temperature at STC, (°C)
T_a	Ambient temperature, (°C)
T_c	Temperature of the PV module, (°C)
$(\Delta V_{oc})_{Tp}$	Change in Voc under elevated temperature (V)
$V_{OC\ expected}$	Expected Voc of the module under cleaned condition, (V)
$V_{OC\ STC}$	Module open circuit voltage at STC, (V)
Y_{PV}	Reference yield of the PV plant
	Symbols
α	Temperature coefficient of short circuit current, (% per °C)
β	Temperature coefficient of open circuit voltage, (% per °C)
γ	Temperature coefficient of maximum power of module, (% per °C)
η_T	Loss coefficient of temperature