The Effect of Soiling on the PV Performance Ratio for Different PV Systems

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ABSTRACT

Soiling is an important and unpredictable factor that affects PV plant performance. Soiling is dependent on so many factors making it hard to quantify and accurately incorporate in PV prediction models and levelized cost of electricity (LCOE). In this experiment, a comparison was done to establish the effect of soiling for 2 different PV plants installed at the Council of Scientific and Industrial Research (CSIR) campus in Pretoria. The soiling rate for the performance ratio (PR) was 1.2 % per week on the 558 kWp DC single-axis tracker system and 0.4 % per week on the 202.3 kWp DC dual-axis plant over the period from June 2017 to August 2017. Soiling has a smaller effect on dual-axis systems as compared to single-axis systems due to the soiling accumulation mechanics and PV system elevation above ground level.

Keywords: Soiling; PV; Performance ratio; Single-axis; dual-axis; GHI and POA

1. INTRODUCTION

In recent years the PV industry has become the leading renewable energy sector with megawatt systems becoming the norm [1]. As more systems become operational and are exposed to the environment, the life time performance and reliability of these systems needs to be accurately determined. Soiling is considered one of the factors that affect the performance the most, and has become a great concern for the PV community as losses can range from 0.1 % to 20 % per day [2,3].

Soiling is the term given to describe the creation of a layer of different natural and artificial particulate matter on the surface of the PV modules. This layer of “dust” reduces the active area by blocking some of the incident light on the module. The dust affects the performance of the PV modules in different ways, from creating hot-spots, to reducing the active cell area resulting in shorting out a fraction of the module, to PV module damage [4]. Soiling is dependent on many environment factors making it challenging to generalize this phenomenon. To understand and accurately determine the effect of soiling; various intensive investigations needs to be done. The primary contributors to soiling are the soil particulate matter in the PV system region, pollution and elevation of the PV systems above ground level [5]. Secondary parameters include PV orientation and design, climate, wind speed, wind direction and rain. This paper determines the effect of soiling on the temperature corrected PR for these different plants for the Southern African region.

Accurately determining the effect of soiling holds many benefits for the PV community. Some of these benefits include reduced risks in PV investment and optimized PV system performance as the Southern African PV industry grows. Achieving a high performance PV system is necessary while reducing the maintenance costs during its lifetime. Previous studies undertaken for the South African region are inconclusive and contradict the findings within this study [5,6]. The purpose of this study is to investigate the effect of soiling on the performance of different PV systems and how the soiling rates differ as a function of seasonal variations in the calendar year. It is envisaged that accurately measuring the soiling rates for different PV systems can lead to design of a optimized PV system and develop cleaning methods and frequency while maintaining high performance ratio (PR).

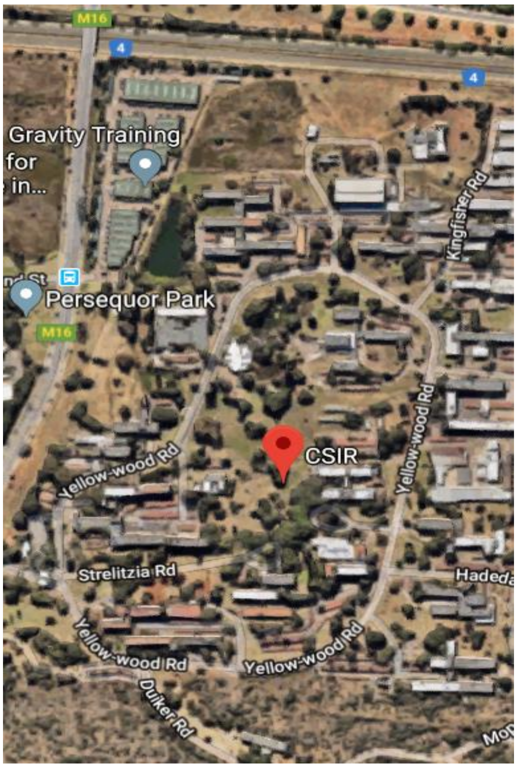
2. EXPERIMENTAL DETAILS

Figure 1 presents the CSIR campus with the locations of building 34 testing facility (green mark), single axis tracker (red mark) and dual axis tracker (blue mark) where experiments were conducted at simultaneously.

2.1 Data collection

For one calendar year Global Horizontal Irradiance (GHI) and Plane of Array irradiance (POA) data was collected from the different PV systems. The single-axis tracker PV plant has 2 pyranometer sensors on the tracking system, giving us accurate POA irradiance. The dual-axis tracker system only has GHI measured irradiance and the outdoor testing facility has multiple GHI, DNI and POA irradiance measuring sensors. The POA for the dual-axis system was estimated using System

Advisor Model (SAM) software by using the measure GHI (Global Horizontal Irradiance) and DNI (Direct Normal Irradiance) and the Perez algorithm within SAM. GHI and POA measurements were collected at a 30 second interval and converted to hourly and daily values for the analysis.



Single-axis system 1800 modules 558 kWh capacity.

Dual-axis system 714 modules 202kWh capacity.

Fig. 1. Google map shot of the CSIR PV testing facility (top) and single (middle) and dual-axis (bottom) PV systems.

The rain data was collected at the CSIR outdoor testing facility and University of Pretoria weather station at 30 second interval and converted to total rain per day in mm.

2.2 PR data analysis

Using the measured power generation and POA irradiance the performance ratio (PR) was calculated and plotted with the rain profile for the same year. The performance ratio is one of the most important parameter for evaluating the performance of the PV plant. It is the ratio between the actual and theoretical energy output of the PV plant [7].

$$PR = \frac{Generated\ energy\ (kWh)}{Name\ Plate\ Power\ (kW)} / \frac{Total\ POA}{Reference\ irradiance} \qquad (1)$$

The *Generated energy (kWh)* is the total AC energy generated by the system. The *Name Plate Power (kW)* is the total DC power the system would provide under STC (Standard Testing Conditions – 1000W/m^2, 25 deg C, AM1.5). The *Total POA* is the total plane of array irradiance incident on the system and is measured by the pyranometer sensors. The *reference irradiance* is the standard test condition irradiance of 1000 W/m^2 [9].

PR is stated as a percentage and describes the relationship between the actual and theoretical energy outputs of a PV system. Taking PR one step further is the temperature corrected PR (PR_{Tcorr}). This correction minimizes the known temperature affect arising from different seasons. The temperature corrected PR normalizes all the known and expected variations in PV output as a result of irradiance and module temperature. This leads to a metric that can be used to monitor for unexpected deviations in plant performance. This allows for more consistent results throughout the year while monitoring actual system yields [8].

The studied systems did not have reliable module temperature measurements; hence equation 2 was used to calculate the module back temperature.

$$T_m = G_{POA}\left(e^{(a+b*WS)}\right) + T_a \qquad (2)$$

Where T_m is the calculated module back-surface temperature [°C]. G_{POA} is the POA irradiance from calibrated reference cells [W/m^2] for the single-axis system.

T_a is the ambient temperature [°C] and *WS* is the measured wind speed from a nearby weather station located at building 34 in [m/s], *a* is the empirical constant reflecting the increase of module temperature with sunlight [a = -3.56], *b* is the empirical constant reflecting the effect of wind speed on the module temperature [b= -0.075 s/m], *e* is the Euler's constant and the base for the natural logarithm [8,9].

Using the module back surface temperature, the cell temperature can be calculated using the following:

$$T_{cell} = T_m + \left({G_{POA}}/{G_{STC}}\right)(\Delta T_{cnd}) \qquad (3)$$

Where ΔT_{cnd} is the conduction temperature drop and is equal to 3 for a glass, cell and polymer sheet module type with an open rack [8]. The Temperature corrected PR value can be calculated using equation (2) and (3) and is then given by the following formula:

$$PR_{Tcorr} = \frac{\sum_i EN_{ACi}}{\sum_i [P_{STC}(\frac{G_{POAi}}{G_{STC}})(1 - \frac{\delta}{100}(T_{cell_{avg}} - T_{cell}))]} \qquad (4)$$

Where EN_{ACi} is the measured AC electrical generation in kW, P_{STC} is the nameplate power of the studied system, G_{POAi} is the POA irradiance, G_{STC} is the standard testing condition irradiance, $T_{cell_{avg}}$ is the average cell temperature for one year and δ is the temperature coefficient for power of the studied module [9].

Now this temperature corrected PR gives us the ability to look past the irradiance and temperature effects on the performance of the system, leaving the secondary affects still at play. The largest of these effects is soiling. During the analyzed period, there were some general grid failures and irradiance measurement errors due to technical issues resulting in some inaccurate measurements. Using an error logbook must of these errors were captured and removed in the data analysis.

2.3 SAM analysis

In addition to analysing the two PV plants performance data, SAM was used to predict the affects the soiling has on the POA irradiance. This was demonstrated using various module types currently installed at the outdoor testing facility. These modules include Panasonic (330 W), LG Neon (360 W), Sunpower (327 W), Jinko (330 W), BYD (315 W) and Yingli (310 W). There are 2 of each module at the testing facility. Understanding how soiling can impact the irradiance plays a huge factor in understanding how soiling affects the final PV system performance.

2.4 Cleaning and Rain analysis

Cleaning of both single and dual axis tracker plants was completed on 26th August 2017 within a duration of 1 week. Comparing the performance ratio with the rain profile and cleaning period, the effect of soiling is analyzed for different seasons in a year. The effect of rain was a focus point in this experiment, as this effect is still under debate in the PV community [6]. The desired question we wanted to help answer is; Does rain incident on the system have a positive or negative impact on soiling?

2.5 DNI sensor comparison

Two DNI sensors are installed on the outdoor testing facility. The first is cleaned by air blown on the sensor constantly and the other is left without cleaning exposed to the outdoor elements. This is another method to see the impact on irradiance by soiling. The irradiance was measured every 5 seconds resolution. The daily total DNI was compared. The determined soiling loss ratios for different seasons allow the cleaning method and frequency to be optimized. This will enhance PV systems to deliver better performance while minimizing cleaning cost.

3. RESULTS AND DISCUSSIONS

First a simulation using SAM was done using the PV modules installed on the roof of Building 34 testing facility. This simulation shows how an average soiling loss of 5 % would directly affect the POA irradiance and indirectly the power output for different modules. In natural environment there are a few occasions where the irradiance is above 1000 W/m^2 and in this period the PV modules will produce higher power than their name plate power. As the irradiance can go past 1000W/m^2 in only clear sky condition, the maximum effect of soiling on PV power can be observed. The number of such occasions (termed as active hours) where excess PV power will be clipped due to 5 % soiling were calculated. Separate modelling with 0 & 5 % soiling losses was done to determine number of active hours lost due to 5 % soiling and observed a reduction of up to 35 % to 43 % instances of active hours depending on the PV module type. This emphasizes the effect of soiling on PV plants performance. Figure 2 presents the effects on PV module power production with 0 % soiling and 5 % modelled soiling losses.

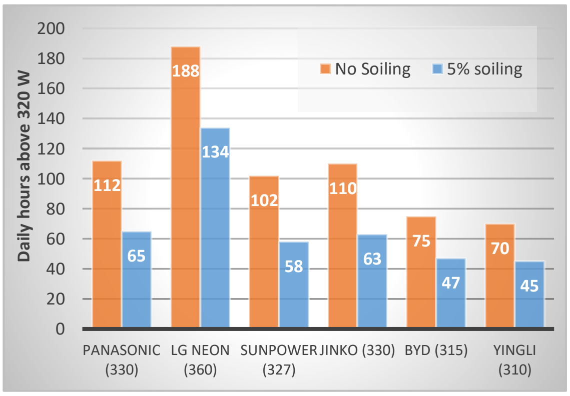
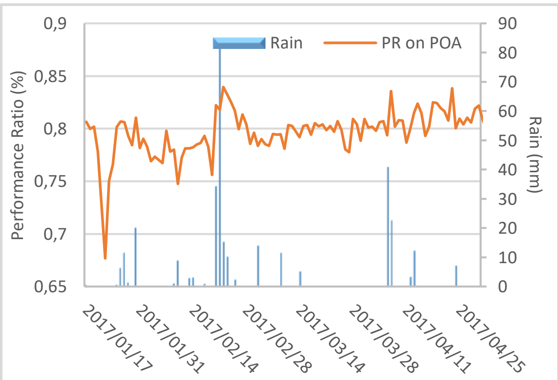
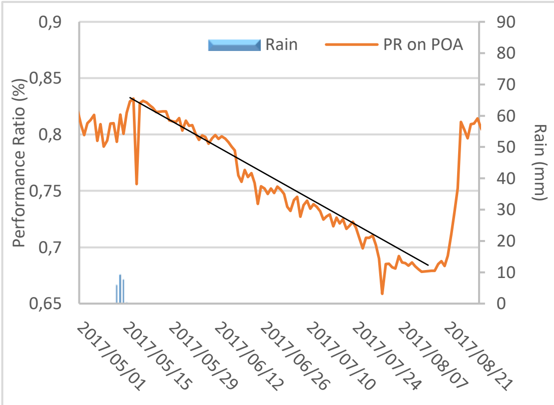


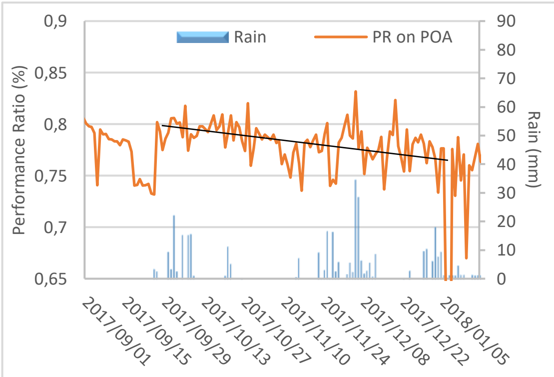
Fig. 2. Daily hours of different PV technologies above 320 W for 0 % and 5 % soiling rates.

Soiling rates for the single axis tracker show different values for the different seasons of the year with winter values between May and August 2017 of approximately 1.2 % reduction in PR per week, from a PR value of 83 % in Mid-May to 67 % by mid-August. An interesting result also indicated that rain does not always “clean” the modules and can, in some cases lead to an increase in soiling. Light rain can lead to a muddy residue forming on the modules and can also, in extreme cases, lead to cementation [3,10]. Nevertheless, heavy rain can also assist in cleaning the modules thus reducing soiling. From the analysis, rain duration has little effect, however rain intensity is the real factor on the soiling caused by rain. Since February 2018, a rain intensity meter is installed at CSIR campus and this will be further investigated in the future. As South Africa experiences dry winters, soiling rates were higher in these periods reaching 1.2 % per week and a total soiling loss of 15 % measured before the cleaning event during this period. While summer periods had average soiling rates of 0.5 % per week and frequently returned to 0 % soiling loss due to high frequency of intensive rain events. Figure 3a, 3b, 3c, 3d presents the real time calculated PR for the period of 1 year and the impact by soiling rate is cleary visible from these graphs.

The figure 3d shows the natural soil period in winter with a soiling loss on PR of 1.2 % per week (solid line) and a clean event from the 21st to 26th August indicated by the green lines. The soiling rate for the month after the clean was approximately 2.1 % per week, as indicated by the dotted line. This is nearly double the soiling rate before the clean event and was observed from the 26th August to 25th September. The PR decreased 5 % absolute from 0.8 to 0.75 between 16 September and 18 September and increased by 7 % absolute again on 25th September. This long dip in performance may be unrelated to soiling but it is impacting the soiling rate estimation for this week ending 25th September. The soiling rate was 1.1 % per week for the three weeks following the clean, but prior to the unexplained drop on 16th September. This soiling rate is consistent with the 1.1 % observed across the three months over winter prior to the first clean. Further investigation is required to determine the cause of drop in PR.







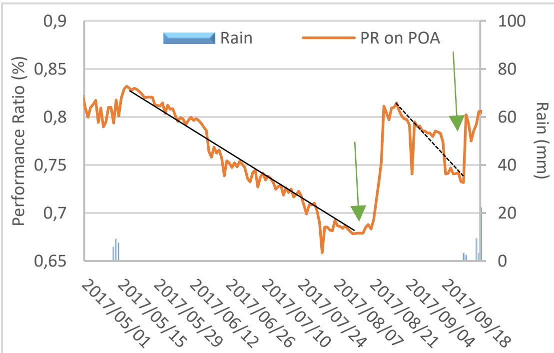


Fig. 3. Temperature corrected PR (orange) and rain (blue) for the single-axis PV system. Summer (3a, 3c) and winter period (3b). Soiling period (3d).

The dual-axis PV system has a similar behaviour yet it has less significant soiling impact on the PV performance. Figure 4a and 4b below depicts the temperature corrected performance ratio from May 2017 to March 2018. During this period, soiling has a much lower impact on the PR of the dual-axis system. For example, in the winter months there is a lower rate of soiling loss as compared to the single-axis tracker system. The PR value of 81 % in Mid-May dropped to 76 % by mid-August. The PR loss rate for the winter period was approximately 0.4 % per week and a total loss of 5 % in the winter period.

The high delta in temperature corrected PR and the values above 100% for the dual-axis system is due to the fact that the POA irradiance was not actually measured but predicted by the SAM software using GHI and DNI data. This can lead to some errors in daily POA values resulting PR above 100 %. This effect however only occurred in the summer months.

After the cleaning event at the end of August, the soiling loss per week is higher than the soiling loss before the cleaning event (indicated by the dotted line). The soiling loss on PR after the clean was 1.5 % per week, which is approximately 4 times larger than the soiling loss per week before the clean event. This is shown in figure 4a.

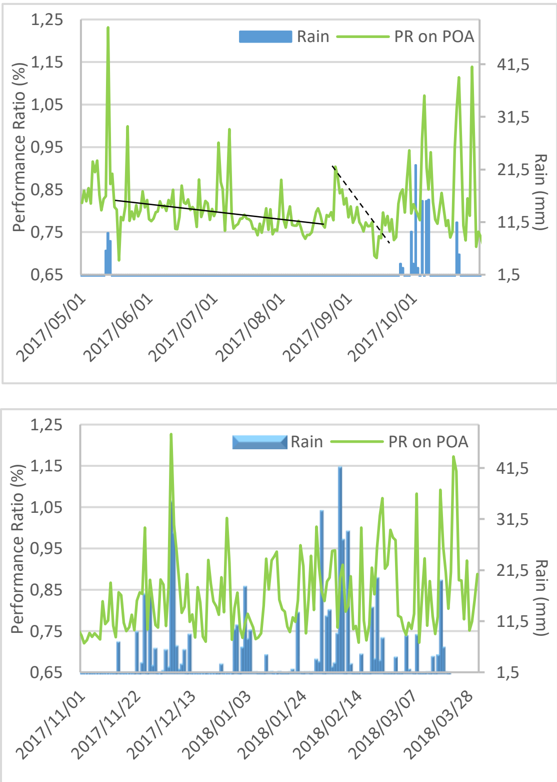


Fig. 4. Temperature corrected PR (green) and rain (blue) for the dual-axis PV system at the CSIR Pretoria campus. Winter period (4a) and summer period (4b).

This is an interesting comparison as these PV plants are adjacent to one another and had same cleaning schedule, weather conditions and irradiance. The single-axis tracker showed a soiling loss on PR of 1.2 % per week as compared to the dual-axis of 0.4 % per week. The factors that are different are the type of tracking system and the elevation. The elevation plays a key role in soiling as most soil is within 5m from the ground surface and this can explain why the single-axis has a higher soiling loss rate [6]. The single-axis modules are approximately 1 m from the ground whereas the dual-axis modules are approximately 5 m from the ground. The orientation of the panels on these systems also play a role in soiling as horizontal surfaces have higher soil accumulation compared to vertical surfaces. The single axis tracker daily spends more time in a horizontal position as compared to the dual-axis tracker.

High level of rains occurred nearly every fortnight and qualifies as a natural clean of the PV systems within the summer period. For the single-axis tracker the each calculated PR value remains within 5 % consistently whereas due to predicted POA values used for PR calculations in dual axis tracker, the delta fluctuates during summer period. Figure 5 shows the single and dual-axis plants PR for the winter period of 2017 from May 17th to August 21st . The dashed line represents the average PR for the dual axis and the solid the single-axis PV plant.

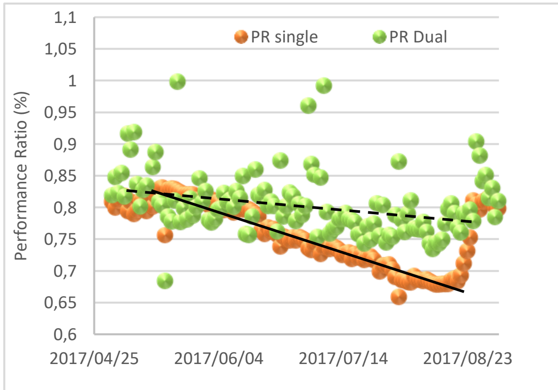


Fig. 5. PR comparison for the single and dual-axis PV plants at the CSIR Pretoria campus.

At building 34 testing facility, DNI sensor 1 is constantly blown by air to prevent dust accumulation settling on the front glass surface were DNI sensor 2 is left uncleaned exposed to outdoor elements. These sensors are on the roof and approximately 10 m above ground level. Figure 6a and 6b shows the irradiance for both sensors throughout 2017 and also the delta in irradiance between the two sensors. There is an increase in the delta for the winter period which corresponds to more soiling on DNI 2. The maximum delta recorded was close to 15 %, increasing at a rate of approximately 0.75 % per week. The increase in soiling reduces the incident irradiance due to dust particles setting on the surface further reducing the active area of the cell. The rain during October 2017 has cleaned the sensors naturally reducing the soiling build up and thus reducing the delta between the DNI measurements. Both the sensors were also physically cleaned on the 2nd October and again on 13th November 2017.

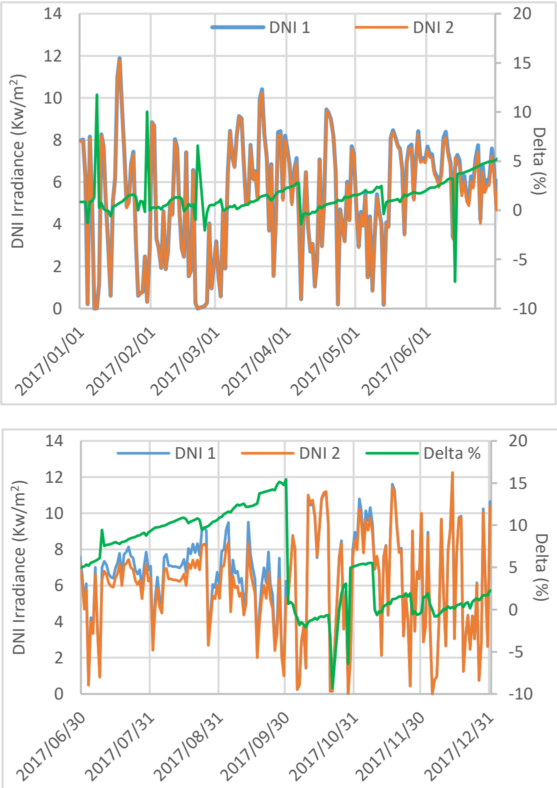


Fig. 6. DNI measurements for both cleaned and non-cleaned DNI sensors at the outdoor testing facility CSIR Pretoria campus. Summer months (6a) and winter months (6b)

4. CONCLUSIONS

This paper presented soiling rates and soiling losses on a 558 kWp single-axis tracker system and a 202.3 kWp dual-axis tracker system located adjacent to one another in Pretoria, South Africa. The analysis was conducted on the temperature corrected performance ratio, which corrects for irradiance and temperature effects and enables an accurate estimation of soiling loss. At the beginning of winter (mid-May) the PR for both plants were around 83 % and 81 % for the single and dual-axis plants respectively. From mid-May up until mid-August there was no rain or cleaning of these plants. Soiling starts to accumulate on the PV modules and the effects on the PV systems can be observed. As time goes, more and more soil accumulates reducing the active cell area; thus reducing the performance of the PV plants. By mid-August the PR for the single and dual-axis systems were 67 % and 76 % respectively. The dual-axis system shows a lower soiling impact on PR compared to single axis tracker system. A soling rate of 0.4 % on PR against 1.2 % on PR per week was observed. This allows us to see the impact of soiling as a function of system design. On August 26 the PV plants were cleaned and the PR value returned to 83 % and 81 % again for the single and dual systems respectively. The soiling loss per week after the clean event was higher for both systems. The single-axis PV plant before and after the clean reported a soiling loss of 1.2 % and 2.1 % respectively; and the dual-axis plant reported a soiling loss per week of 0.4 and 1.5 % respectively. These results indicate a significant difference in soiling rates for a dual-axis and single-axis tracker system under these environmental conditions which will be analyzed in future.

A comparison of co-located DNI sensors indicates soiling losses of 0.75 % per week in winter months. Understanding the effect of soiling can lead to more efficient PV system design depending on location and PV technology type. Understanding how the factors contribute to soiling and how soiling mechanics work in different environments can lead to designing of optimal cleaning methods and techniques. Underestimating the effect of soiling can lead to errors in performance prediction models. Using accurate soiling data in prediction models can reduce PV plant performance uncertainty and reduce investment risk.

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