Measuring Soiling Losses at Utility-scale PV Power Plants

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***Abstract* — The effect of dust, dirt, and other contaminant accumulation on PV modules, commonly referred to as soiling, is an important environmental factor that causes reduced PV power plant energy generation. Accurate monitoring of soiling losses has become increasingly important, especially for utility-scale PV power plants, and soiling measurement systems are now widely deployed at First Solar power plants. In this work we show how soiling monitoring data are indicative of actual power plant performance and we outline how such data should be collected and analyzed. We study soiling levels and rates alongside PV plant performance in the desert southwest of the United States, the Arabian Peninsula, and Western Australia. We demonstrate that soiling loss measurements correlate with actual power plant performance. In addition, we address measurement methodology questions, including measurement precision, site-wide spatial non-uniformity in soiling, and the amount of rainfall required for a full recovery in soiling losses.**

***Index Terms* — photovoltaic systems, performance analysis, solar power generation, solar energy.**

I. INTRODUCTION

The effect of dust, dirt, pollen, and other contaminant accumulation on PV modules, commonly referred to as soiling, is an important environmental factor that causes reduced PV power plant energy generation. Average annual energy losses due to soiling are typically in the range 1-6% [1],[2],[3] but strongly depend on conditions at the site, with higher annual, short-term, or monthly losses found in some cases [2],[4],[5]. Therefore, accurate monitoring of soiling losses has become increasingly important, especially for utility-scale PV power plants, which might be subject to performance guarantees that mandate a limit on loss generation due to soiling.

Soiling measurement systems are now widely deployed at First Solar power plants. The systems use a simple and reliable method for measuring soiling losses that has been described in previous works [3],[6],[7],[8]. The method uses the side-by-side comparison of the measured output of two co-planar, normalized PV reference modules, the first of which is kept clean as a control and the second of which naturally accumulates soiling at the same rate as the power-producing modules of the plant. The control module is kept clean through manual washing or with an automated washing system.

This simple approach to measuring soiling loss is a good proxy for the soiling-induced power loss of a PV power plant [3]. In previous work we quantified the typical uncertainty of these measurements [7] and examined the effect of within-module soiling non-uniformities [8] on the measured power losses.

In this work we aim to show how soiling measurement system data are indicative of the true effect of soiling on a utility-scale power plant and we outline how such data should be collected and analyzed. Using a large volume of soiling monitoring data from five First Solar power plants in the desert southwest of the United States, the Arabian Peninsula, and Western Australia, we study soiling levels and rates alongside PV plant performance. The five power plants, which we anonymously label A, B, C, D, and E, range in size from 10 to more than 200 MW_{ac} and also cover a wide range of soiling conditions. We show how instantaneous as-measured soiling data may be integrated to provide daily, weekly, or monthly loss estimates, and we demonstrate that these loss estimates correlate with actual measured power plant performance. In addition, we explore key questions regarding the optimization of soiling monitoring, including the number and within-plant spatial distribution of soiling monitors, optimal cleaning frequencies for the control modules, and the amount of rainfall necessary to completely clean dirty modules.

II. SOILING MEASUREMENT METHODOLOGY

A. Measurements

As described above, soiling loss is measured by comparing the output of a dirty reference module to that from a clean control module. The comparison may be made either on the basis of the measured short-circuit currents, which serve as a proxy for the effective irradiance received by the soiled versus the clean module, or on the basis of the measured maximum powers, which represent actual power production of soiled versus clean modules. In both cases the measurements are temperature-corrected and normalized. Previous work [8] showed that for crystalline silicon modules the power-based method should be used, in order to capture the effects of potential within-module non-uniform distribution of soiling, while for First Solar CdTe modules short-circuit current based measurements are sufficient, because the module geometry minimizes the effect of shading non-uniformity on power output. Commercial soiling monitoring equipment supporting both methods is available.

B. Terminology

We begin by defining different metrics used in describing soiling losses. The soiling ratio *SR* is the instantaneously measured ratio of dirty-to-clean (test-to-control) module

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outputs at any given point in time. In this work we focus on CdTe power plants and accordingly we define the ratio in terms of effective irradiance received by each module:

$$SR = \frac{G_{\text{dirty}}}{G_{\text{clean}}} \qquad (1)$$

where G_{dirty} and G_{clean} are determined from the temperature-corrected and normalized short-circuit current measurements of each module. Following the conventions outlined in the International Guidelines of Uncertainty in Measurement (GUM), we found *SR* measurements can be performed with uncertainties on the order of ~±1% or better on an absolute basis, depending on calibration conditions, operating temperatures, angular alignments, and other factors [7].

We derive daily average soiling ratio SR_D by filtering, normalizing and averaging the *SR* data over the desired time period, as described below. In performance models, these daily soiling ratios can be applied directly as loss derate factors for effective irradiance available to the PV plant, in a manner similar to shading factors, incidence angle factors, etc.

We define the daily soiling loss SL_D as 1 - SR_D, and the monthly soiling loss SL_M as the monthly irradiation-weighted average of SL_D.

We define a soiling accumulation rate S_{rate} by measuring the slope of the time series of daily soil ratio SR_D. S_{rate} can be expressed as a daily or monthly value, i.e. 0.1% per day would be equivalent to 3% per month in a 30-day month.

C. Time-of-Day Dependence

It is important to note that instantaneously measured *SR* typically shows a dependence on time of day. Fig. 1 illustrates factors contributing to this dependence.

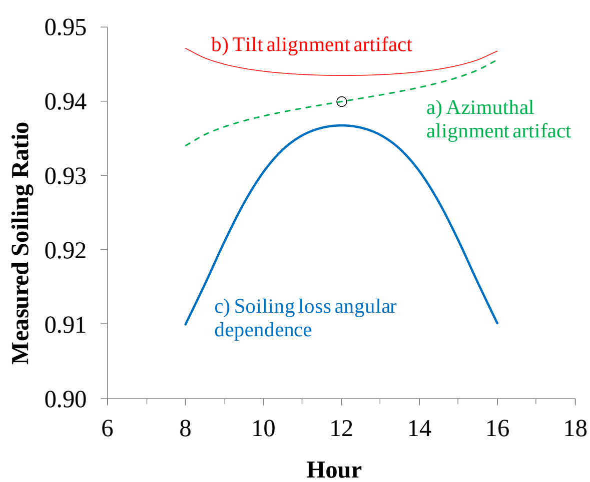

Fig. 1. Examples of time-of-day dependence of instantaneous soiling ratio measurements. a) Measurement artifact due to 0.5° azimuthal angle misalignment of the dirty and clean reference devices. b) Measurement artifact due to 0.5° tilt angle misalignment. c) Representative variation in actual soiling loss due to angle of incidence, assuming loss model similar to that used in [5]. All three curves were calculated for 6% loss at normal incidence (indicated by open circle symbol), for site A coordinates on January 1, 2014.

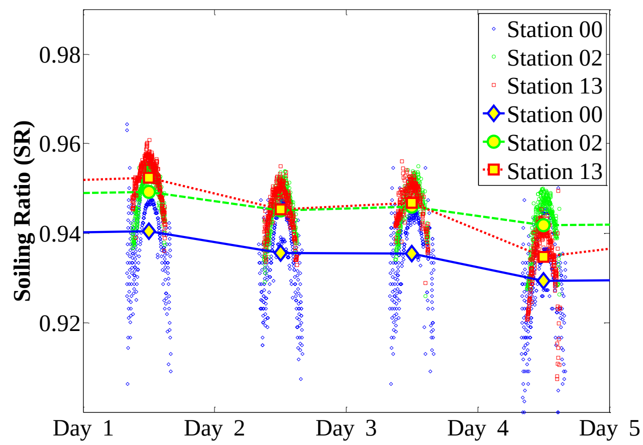

Fig. 2. Soiling ratio measurements from three measurement stations at site A over a four day period. Small symbols show instantaneous readings, taken once per minute, which vary throughout the day due as discussed in the text. Large symbols show daily averaged values.

One factor is any residual differences in the tilt or azimuthal angles of the dirty and clean modules, which causes a difference in the in-plane irradiance received by each module throughout the day and results in measurement artifacts not representative of actual losses. To minimize these artifacts, tilt and azimuthal differences should typically be kept to <0.5°.

Another factor is the variation in actual soiling related losses as a function of angle of incidence (AOI), which arises from the details of light scattering from accumulated soil particles. Such variations were observed in a study by Zorrilla-Casanova [5], which also included a theoretical model of the light scattering versus AOI. We depict this effect in Fig. 1 as profile (c), using a normalized version of the model in [5] as representative.

All three curves in Fig. 1 were calculated for 6% loss at normal incidence (indicated by open circle symbol), for site A coordinates (see below) on January 1, 2014.

Fig. 2 shows an example of actual *SR* measurements, taken once per minute over a four day period at a First Solar utility-scale power plant. The data show a time-of-day dependence similar to that depicted in Fig. 1(c) for AOI effects; we confirmed that the data represent actual AOI dependent losses, rather than artifacts from angular offsets between the dirty and clean modules, by noting that the curved profiles disappear for days when both modules in the pair were clean.

D. Filtering and Averaging

For data analysis, instantaneously measured *SR* values are first filtered to remove points corresponding to low or quickly changing irradiance, during which measurements are likely to be invalid. An irradiance-weighted average is then computed from the remaining points over a daily period, in order to

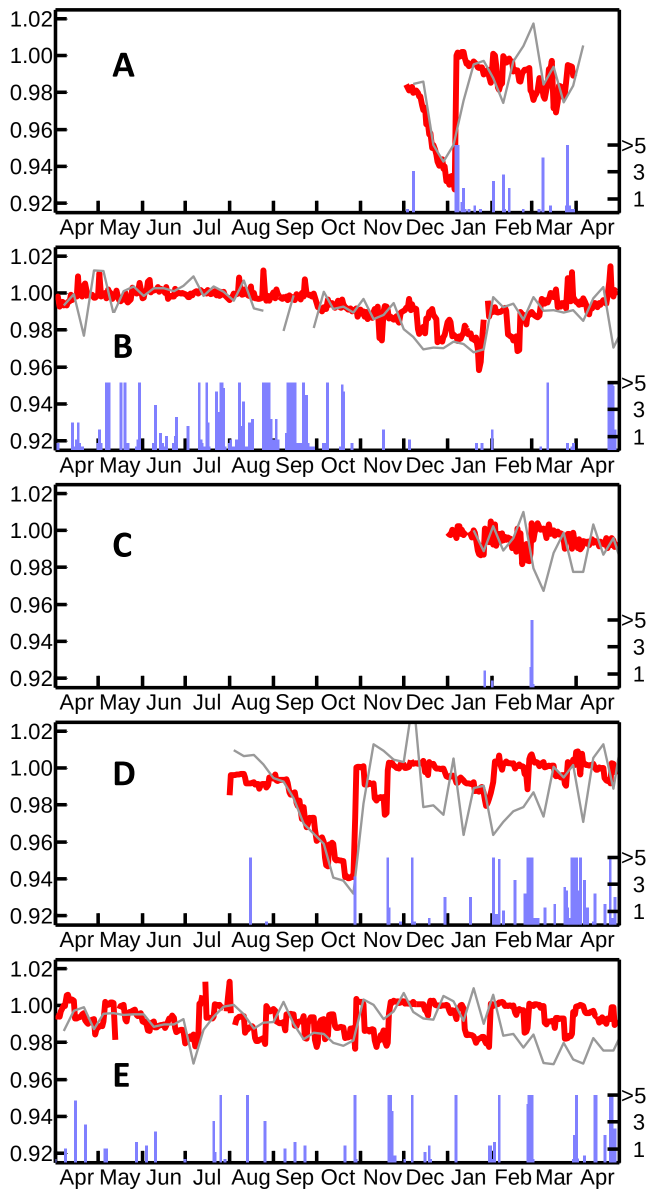

Fig. 3. Time-series plots of daily soiling ratio (thick line) and normalized weekly PPI (thin line) for the five PV power plants from April 2013 through April 2014. Bars show rainfall in mm (right axes).

obtain SL_D. The irradiance-weighted averaging minimizes the contribution of artifacts arising from angular alignment offsets and also provides data most closely representative of lost energy production over the respective period. The solid symbols in Fig. 2 show examples of the reduction of instantaneous SR to daily averaged values.

III. Power Plant Performance Measurement

To correlate soiling measurement with plant performance, we use the Power Performance Index (*PPI*) metric. PPI values, calculated daily, represent the power output of a system normalized to standard test conditions (STC) (irradiance of

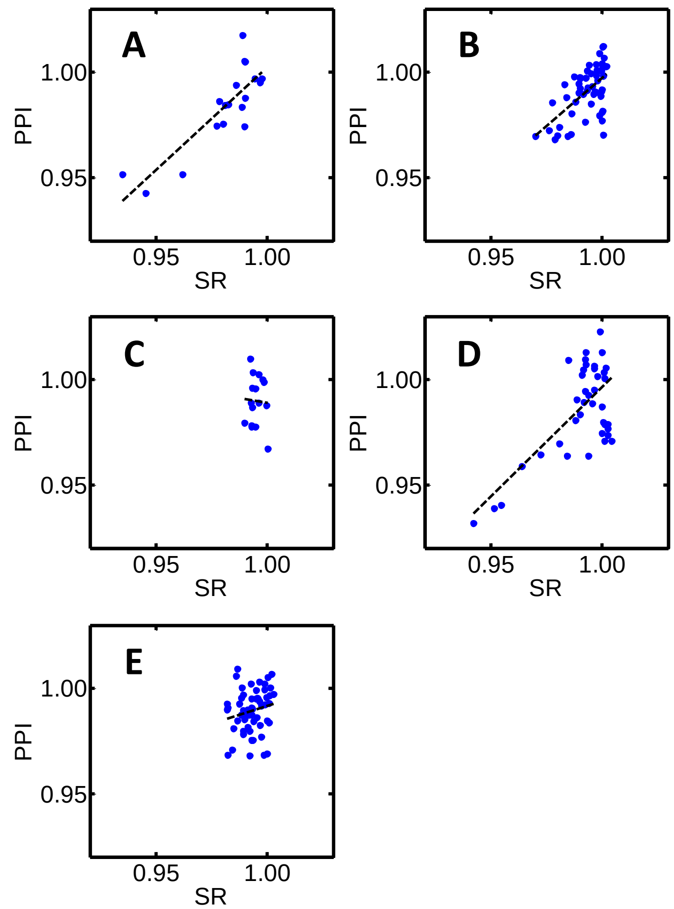

Fig. 4. Measured weekly average power plant performance (PPI axes) versus measured weekly average soiling ratio (SR axes) for the five PV power plants.

1000 W/m^2, module temperature of 25 °C, and ASTM G173 solar spectrum (AM 1.5)). Calculating PPI involves normalizing measured system power by irradiance and module temperature using a linear regression [9]. We also spectrally correct the results to account for differences in spectral sensitivity between reference irradiance measurement devices and CdTe modules [10]. Over medium term time periods, the PPI metric is not affected by fluctuations in irradiance and air temperature, allowing us to compare the bulk of any apparent remaining losses in system performance to soiling. On some days the variability of weather conditions results in a low confidence in the normalized PPI result; we filter out these days based on the coefficient of determination (R^2) of the linear regression between temperature-corrected power and irradiance.

III. Results

A. Measurements

The five power plants each included multiple soiling measurement stations distributed throughout the site, with more stations at larger sites. Each plant also included multiple meteorological stations, from which irradiance and rainfall data were collected. Data from all stations were averaged together, except where noted. Data shown were collected from April 2013 through April 2014, with data for each plant becoming available as the plant was commissioned.

B. Time Series Plots

Fig. 3 shows time series results of measurements at the five PV power plants. The thick line shows the daily average soiling ratio SR_D, while the thin line shows the weekly average PPI representing plant performance. The bars show daily rainfall in millimeters, clipped to 5 mm in order to clearly show small rainfall events.

The soiling ratio values decrease steadily on days between rainfalls, reflecting the accumulation of soiling. Note that the soiling rate – the slope of the soiling ratio line – at each site is relatively constant throughout the time period, although the minimum value of the soiling ratio varies according to rainfall frequency. Soiling rates range from ~0.5% per month (site E) to ~5% per month (site A).

The downward stepped appearance of some of the soiling ratio curves (e.g. site D in September and October) reflects the cleaning frequency of the clean control module in the soiling ratio measurement pair. At some sites the control module was cleaned only weekly, and in this case the measured soiling ratio shows a sharp drop following each weekly cleaning.

C. Correlation with PV Plant Performance

Fig. 3 shows weekly PPI values for each site overlaid on the measured daily soiling ratio. Comparisons of the time series results indicate a good correlation between measured soiling loss and actual plant performance, although in some cases the

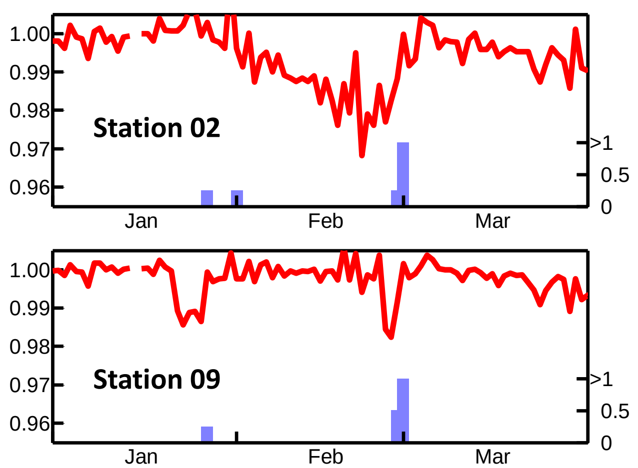

Fig. 5. Example of spatial variation in measured soiling ratio. Top and bottom graphs show soiling ratio results (left axes) from two measurement stations on east (station 02) and west (station 09) sides of power plant C. Results from each station correlated with those from nearby stations, indicating an east-west variation in soiling during January and February. Bars show rainfall in mm (right axes).

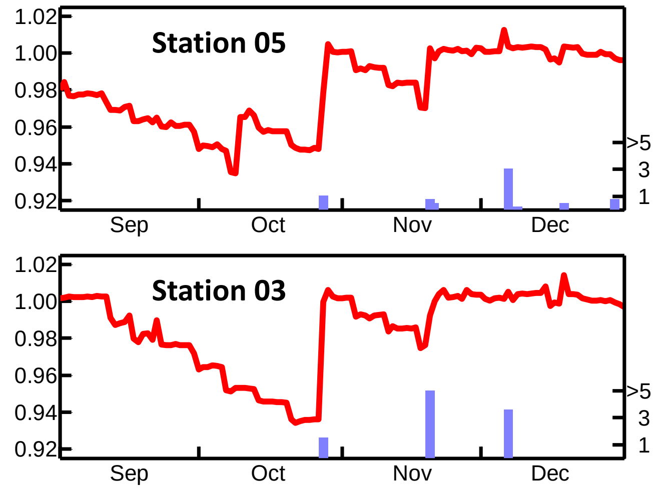

Fig. 6. Example of spatial variation in measured soiling ratio (left axes) at power plant D. Top: station 05. Bottom: station 03. Station 05 shows a recovery event in mid-October that is not apparent at Station 03. Bars show rainfall in mm (right axes).

PPI shows performance deviations that cannot be attributed to soiling.

Fig. 4 presents the same data in the form of correlation plots, where each point pairs the weekly average soiling ratio with the weekly PPI. The plots again indicate the influence of soiling on power plant performance.

D. Spatial Variability of Soiling

In order to understand how many soiling monitoring stations might be needed for a given site, we examined the within-site variation of soiling at a number of the power plants. For the five power plants, soiling generally showed similar trends throughout the site when comparing multiple soiling monitoring stations. However, there were some notable exceptions.

Fig. 5 shows one such example of spatial variation in measured soiling ratio. The top and bottom graphs show results from soiling measurement stations on east and west sides, respectively, of power plant C. These two stations were

Fig. 7. Map of relative PPI at power plant D in late Oct., showing spatial variation in plant performance by inverter and confirming the trend shown by soiling measurement stations in Fig. 6.

separated by ~2 km. It is clear that the two stations measured different soiling patterns during the time period shown. Results from each station correlated with those from nearby stations, indicating an east-west variation in soiling during January and February. However, all stations showed a similar gradual accumulation of soiling in March and April.

Fig. 6 shows results from power plant D, in which there was a notable difference in soiling recovery in a corner of the site – represented by station 05 – in mid-October. This recovery occurred despite there being no measureable rain. It is possible that the recovery resulted from self-cleaning from condensed dew, since the temperatures at the site were regularly very close to the dew point. Some areas of the site may have been just above and others just below the dew point.

This hypothesis appears to be confirmed by examining the PPI by inverter at this site, as shown by the map in Fig. 7. The map shows average PPI values measured for each inverter on 3 days in late October (during the peak soiling) normalized by values for 3 days immediately following rainfall on Oct. 28 These relative PPI values vary across the site. Higher-performing (presumably cleaner) sections are found near the location of soiling measurement station 05 which shows the partial recovery event in Fig. 6. The map may indicate a difference of 3% in performance across the site.

Although the details of within-site spatial uniformity of soiling require more study, and are likely to be site-specific, these examples do illustrate the potential importance of using multiple soiling measurement stations in order to fully capture the impact of soiling, particularly at large sites.

E. Precision of Soiling Measurement

In a previous work [7], the authors examined the uncertainty of soiling measurement based on a detailed uncertainty analysis. This yielded an uncertainty of ~±1%.

Here we wished to compare the theoretical uncertainty analysis with experimental results.

We used data from two soiling measurement stations at power plant D for this analysis. We selected days when the site was known to be clean, due to rain events on the preceding day, and quantified the repeatability of the measured soiling ratio. This yielded a value of ~0.6%.

The repeatability value, as well as a qualitative examination of the measured data e.g. as shown in Fig. 3, including drops in the soiling ratio and rain-induced recoveries, suggests that soiling losses are detectable at a threshold better than ~1.0%. This is consistent with, and more favorable than, the uncertainty analysis performed previously. However, achieving this precision requires properly designed and calibrated equipment.

F. Soiling Pair Cleaning Frequency

The data indicate that cleaning of the control module should be performed at least once per week. In regions with particularly high soiling accumulation rates, weekly cleaning may allow for a step signal to emerge, artificially lowering the average soiling level over a month. The daily *SR* will typically hold at a given value until the next control cleaning where it will step down to the true soiling level on that day. Depending on the difference between this step signal and the true soiling level, it may be beneficial to clean the control modules two to three times per week.

It is possible for the plant to experience a sudden soiling event such as a dust storm, followed by a rainfall. If these events fall between control cleaning days it is possible that they will not be captured in the measured daily *SR*. If it is in the operator's interest to capture these standalone soiling and cleaning events, they should clean the control modules at a higher frequency, but for the purpose of producing monthly average soiling levels, these types of events, with recoveries, generally will have little influence on the monthly result.

G. Performance Recovery Following Rain

It is often necessary to predict soiling losses in a location where soiling measurement has not yet been deployed. In this case, historical rainfall can be used alongside predicted soiling accumulation rates to build an estimated monthly soiling profile [3]. We examined the measured soiling data and tabulated the rainfall levels that produced each significant plant performance recovery event at all five sites. Fig 8 shows the cumulative probability of rain events by rainfall quantity in millimeters, comparing the probability for all rain events with that for events producing recoveries in the soiling loss. From the recovery curve, we estimate a rainfall threshold of ~3.5 mm required to produce soiling recovery with 50% probability, for this aggregation of sites. Specific rainfall thresholds may vary by site due to the type of contaminants accumulated at each site as well as the overall soiling level that

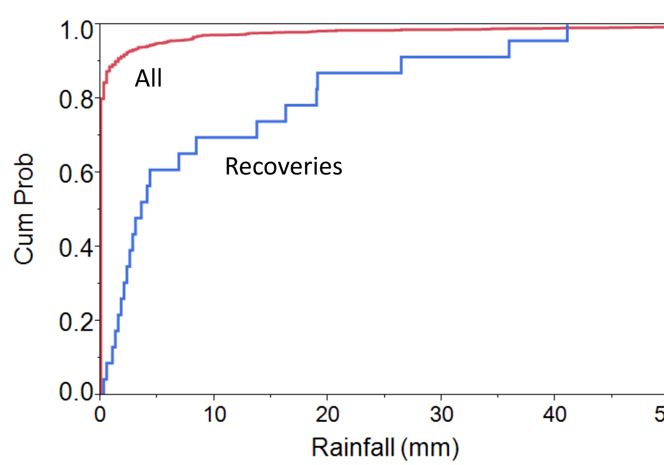

Fig. 8. Cumulative probability (left axis) of rainfall events by rainfall quantity in millimeters (bottom axis), shown for all rainfall events and for rainfall events that produced recoveries in the soiling ratio. From the recovery curve we estimate a rainfall threshold of ~3.5 mm required to produce soiling recovery with 50% probability.

accumulates on the panels, and therefore additional work is needed on this point. Furthermore, we did not observe daily soiling levels above 8%, and high soiling levels may require higher rainfall thresholds for recovery.

IV. Discussion and Conclusions

Quantifying soiling loss is of paramount importance when analyzing performance of a PV power plant, especially in regions with high soiling rates. Accurate measurements of soiling are therefore important for both performance prediction and monitoring. We recommend soiling monitoring be deployed as standard instrumentation at PV power plants.

When deployed in a pre-construction prospecting fashion, soiling measurement systems can help to estimate the frequency of cleaning and thus the cost of cleaning that will be required to maintain a desired average annual soiling level in high soiling locations. For this reason First Solar has deployed soiling measurement systems in many regions.

At operational power plants, ongoing measurement of soiling loss is an important component of performance monitoring, especially at utility-scale facilities. While deviations in plant performance metrics are often attributed to soiling, independent measurement of soiling loss provides verification and allows other potential sources of deviations to be discriminated. Independent measurement of soiling also permits more accurate determination of soiling losses than do estimates based on plant performance metrics alone, since soiling measurements have lower uncertainty and greater resolution than typical plant performance metrics, which are affected by many factors. In addition, independent soiling measurements are especially beneficial at power plants with high DC-AC ratio, especially those employing trackers, since for these plants frequent times of inverter clipping complicate the discrimination of individual loss sources from performance data alone.

For the five First Solar utility-scale PV power plants presented here, soiling rates varied from 0.5% per month to 5% per month. Soiling measurements were found to correlate with plant performance while providing better resolution and independent verification of soiling losses. Each site employed multiple soiling measurement stations, allowing instances of within-site soiling non-uniformity to be detected. The aggregated data for the five sites permits an estimate of the rain threshold required for cleaning, which, together with regional soiling rates, is an important parameter for predicting future plant performance. Further work is anticipated to refine the soiling measurement methodology, investigate within-site soiling non-uniformity in more detail, and better determine rain thresholds which may be regionally dependent.

Since soiling losses are the third-most significant environmental factor affecting PV power plant performance, following irradiance and temperature, they should be quantified with the same care taken to monitor other performance factors. Furthermore, many performance guarantees are now requiring limits on soiling losses during the life of the power plant, resulting in site-specific cleaning regimens. This study has demonstrated the ability to accurately measure and discriminate soiling losses at utility-scale PV power plants using independent soiling measurement systems.

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