# Direct Monitoring of Energy Lost Due to Soiling on First Solar Modules in California

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***Abstract*—The optical loss caused by the accumulation of dirt and other contaminants on solar collectors is the third most important meteorological input, after insolation and air temperature, that determines energy yield in a photovoltaic power plant. First Solar is monitoring the impact of dust accumulation on solar panels using a methodology similar to that proposed by Ryan and colleagues in a long-term study in Eugene, OR. The method seeks to be a practical and automated technique for measuring the soiling rate, foregoing complex equipment such as $I(V)$ curve tracers, and eliminating other performance-influencing factors. The test setup includes several First Solar plane-of-array modules that are allowed to accumulate natural contaminants, and several controls held clean by regular washing. This study reveals clear region-specific soiling trends as well as insight into the amount of rainfall required for full recovery of module performance. Soiling rates of up to 11.5% per month are observed in heavy agricultural areas. As little as 0.5 mm of rainfall is sufficient to completely clean a dirty frameless module in regions with lighter soiling rates.**

***Index Terms*—CdTe, dust, photovoltaic performance, soiling, solar energy.**

## I. Introduction

PHOTOVOLTAIC power plant performance may be adversely affected by dust accumulation on the arrays. Dust is considered an environmental stimulus, third in importance after irradiance and air temperature. Although it is difficult to quantify the accumulation of dust on a glass panel on a continual basis in terms of deposition rate, particle sizes, types, etc., measuring the drop in performance due to this accumulation is a more approachable method of detection. This study observes the energy lost to the reflected and backscattered light by comparing the energy generated between clean and dirty modules or arrays. This lost energy is defined as "loss due to soiling." Previous studies [2] have empirically characterized the soiling rate in different regions by studying declines in power plant performance. The goal of this study is to further improve techniques for directly measuring and modeling soiling losses in order to more accurately predict plant performance in these regions.

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## II. Station Design

First Solar is monitoring the solar irradiance and weather at various locations in the Desert Southwest for solar resource prospecting and solar power plant performance assessment purposes. The soiling measurement technique is based on a methodology proposed by Ryan *et al*. in a long-term study in Eugene, OR [1]. This method seeks to be a practical and automated technique for measuring the soiling rate, foregoing complex equipment such as $I(V)$ curve tracers. Dust accumulation can be considered a loss in effective irradiance resource available to the solar collector. Since the short-circuit current of a photovoltaic cell (PV) cell is directly proportional to irradiance, this metric is used when comparing the clean and dirty modules. For a given test site, an independent laboratory normalizes and calibrates a pair of First Solar modules. The panels are mounted at a $25^\circ$ fixed tilt and $0^\circ$ azimuth, the same orientation as the proposed power plant at the site. Each module is biased in short circuit, and the short-circuit current measured by means of the voltage drop across a very low-resistance shunt. A datalogger continuously monitors this voltage in 1-min averages. Plane-of-array irradiance is calculated using the unique calibrated sensitivity given in $\mu$V/Wm$^{-2}$. One of these modules, the control, is cleaned periodically.

In addition to the two modules measuring soiling, a standard meteorological measurement stand is installed. This includes a rainfall sensor, pyranometers in horizontal and plane-of-array tilts, ambient temperature sensor, relative humidity sensor, air pressure sensor, and wind speed and direction sensor. The back-of-module surface temperature is also recorded.

Remote soiling monitoring stations reported in this study have been installed in the Carrizo Plain, the southern part of California's Central Valley, the Antelope Valley in the Mojave Desert, and southern California's Colorado Desert. These sites can be categorized into two land-use areas: dry agricultural and undisturbed desert.

## III. Analysis Method

The instantaneous irradiance measurements are summed to yield daily insolation totals, in Watt-hours/m$^2$ for both modules. The ratio of dirty-to-clean insolation is calculated, thereby eliminating common-mode errors such as temperature [3] and spectral response [4]. The close proximity of the control and dirty modules also eliminate any irradiance spatial nonuniformity due to clouds or near-shading objects. Soiling accumulation rate is determined by time trending the ratio of short-circuit currents of dirty-to-clean module pairs. We first plot the daily ratios as a time series. Then, a regression line is fit to each span of data

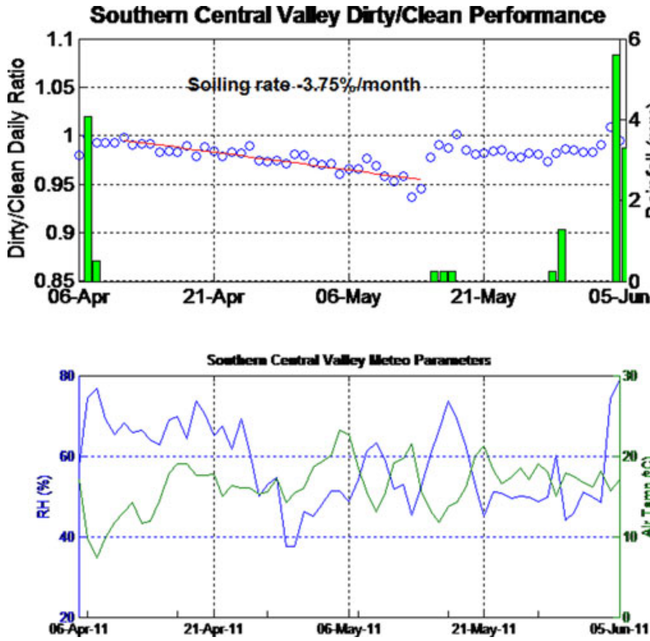


Fig. 1. Southern Central Valley soiling trend in Spring 2011. Blue circles are daily ratios of dirty-to-clean insolation. Green bars are rainfall (right-hand $Y$-axis). The soiling rate of 3.8% per month is determined by the linear fit between rainfall events.

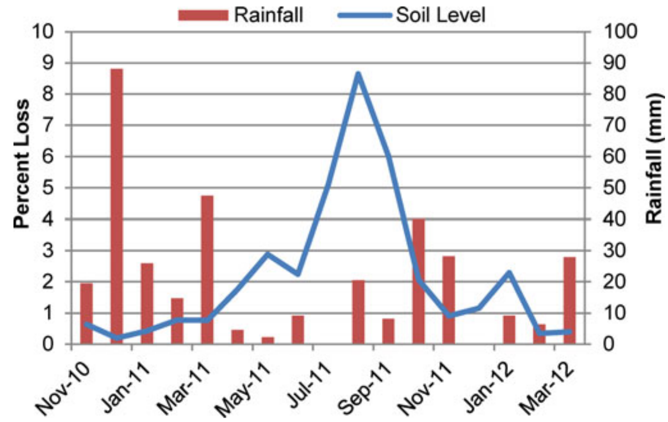


Fig. 2. Southern Central Valley soil level and rainfall from November 2010 to March 2012.

punctuated by cleaning events, as shown in Fig. 1. The slope of a given line corresponds to the rate of soil accumulation in that time period.

During commissioning of the station, the initial daily insolation ratio is established when both the test module and control module are known to be clean. Any return to this initial ratio following a cleaning event signifies a full recovery for soiling. This "clean-clean offset" should be re-established annually by manual module washing and recalibration.

The cumulative soil level over an interval of time can then be determined by integrating the area between the trend line and a horizontal line at the clean–clean offset. The terms "soil rate" and "soil level" are defined as follows. The "soil rate" refers to how quickly contaminants will accumulate on the panels. It does not take cleaning events into account. The "soil level" represents the total decrease in energy production expected from a PV plant over a defined time period. This is affected by the combination of the soil rate and natural cleaning events.

## IV. Dry Agricultural Regions

Soiling in agricultural areas appears to be governed by the seasonal tilling and harvest activity of surrounding farms and the difference in seasonal rainfall patterns. Both of the following stations are surrounded by active farms.

### A. *Southern Central Valley*

In the Central Valley, the soil rates and soil levels between rain events follow one of two patterns. Fig. 2 illustrates the soil levels as a continuous line and monthly rainfall overlaid as bars. This remote station was commissioned in mid-October 2010, when surrounding agricultural activity was heaviest. Through the first week of November, we observed a heavy soiling rate of 10.5% per month. However, the overall soil level held below 1% due to frequent rains. From November 2010 to March 2011, decreased farm activity and plenty of rainfall kept absolute soiling levels very low at an average of 0.8%. Dust from surrounding farms combined with less rainfall in the summer months led to a much increased average soiling level of 4.1% from April 2011 to October 2011, peaking at 8.6% in August 2011.

Between rain events, the soiling rate from April to October gradually increases from 3.8% per month in the spring to 7.9% per month in mid-late summer. With the return of the rains in October, the soil levels drop again to the 1–2% per month range, despite a very steep soiling rate of 11.5%. Seasonal soiling rates are summarized in Table I. As in 2010, frequent rains helped mitigate any effects of local agriculture. There was no rainfall recorded in December 2011, allowing the soil level to climb to a peak of 2.3% in January 2012.

### B. *Carrizo Plain*

The soiling monitoring station on the Carrizo Plain was installed in late April 2011. Rainfall ceased on June 4 and did not return until September 10. This caused the absolute soiling to climb steadily to a maximum of almost 5% energy loss in August before dropping off with the fall rain, as shown in Fig. 3.

Although this site is also surrounded by agriculture, the soil accumulation rates observed at the Carrizo Plain are significantly lower than those seen in the southern Central Valley. They average between 1.7% and 2.2% per month from summer to winter, and increase slightly to 3.6% per month in the spring.

## V. Arid Regions

Observed soiling rates between rain events were fairly constant throughout the year in the low desert regions of southeastern California, fluctuating between 0.9% and 1.2% per month for an average of about 1% per month. As illustrated in Fig. 4, decreased rainfall in the spring of 2011 led to a peak absolute

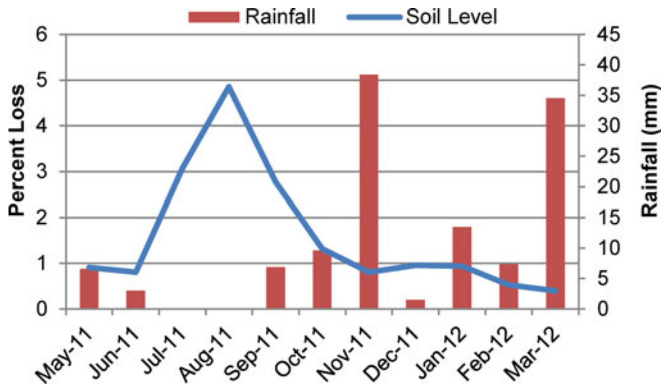


Fig. 3. Carrizo Plain soil level and rainfall from May 2011 to March 2012.

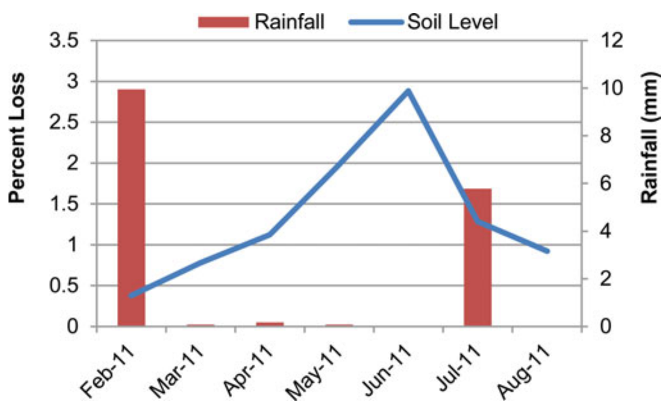


Fig. 4. Colorado Desert soil level and rainfall from February 2011 to August 2011.

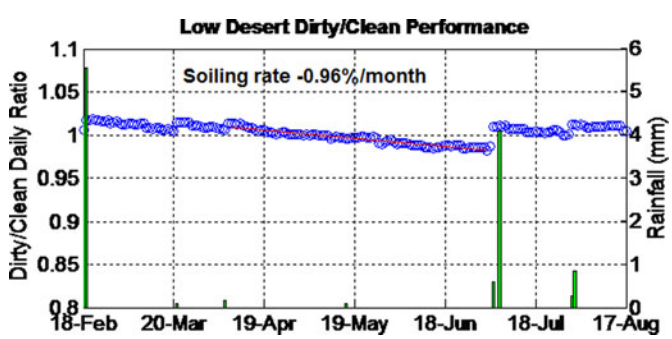


Fig. 5. Soiling rate in a low desert region from February 2011 to August 2011.

TABLE I
SUMMARY OF SOILING RATES (% PER MONTH)

| Region Type | Winter | Spring | Summer | Fall |
|---|---|---|---|---|
| Natural Desert | 0-1.2 | 0.8-2.0 | 0.9-1.1 | 0-1.0 |
| Dry Agricultural | 0.3-3.6 | 1.3-5.5 | 2.2-10.9 | 0-11.5 |

energy loss of 2.8% in June, before a 4-mm rain event on July 6 brought the dirty module back to its initial performance.

The July 6 recovery is illustrated in Fig. 5, but the two rain events on March 21 and April 6 show that even trace amounts of rain can yield essentially complete cleaning events. The soiling levels are much lower in this region; therefore, there is physically less dust to remove.

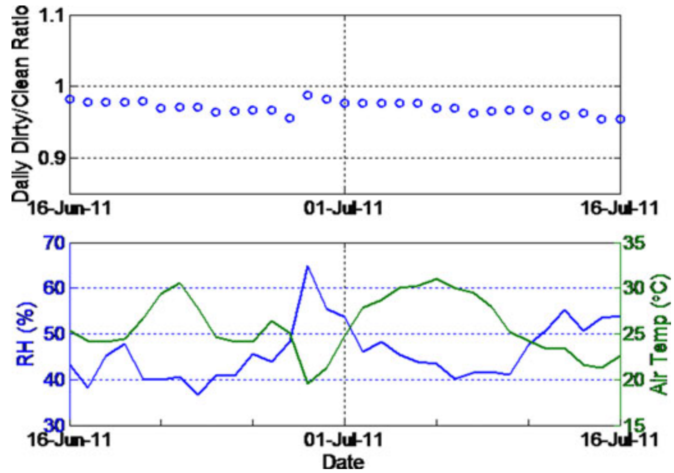


Fig. 6. (Top) Daily dirty/clean ratios from June 16, 2011 to July 16, 2011 at the southern Central Valley soil measurement station. Cleaning event on June 29, 2011 with no recorded rainfall. (Bottom) Relative humidity and air temperature.

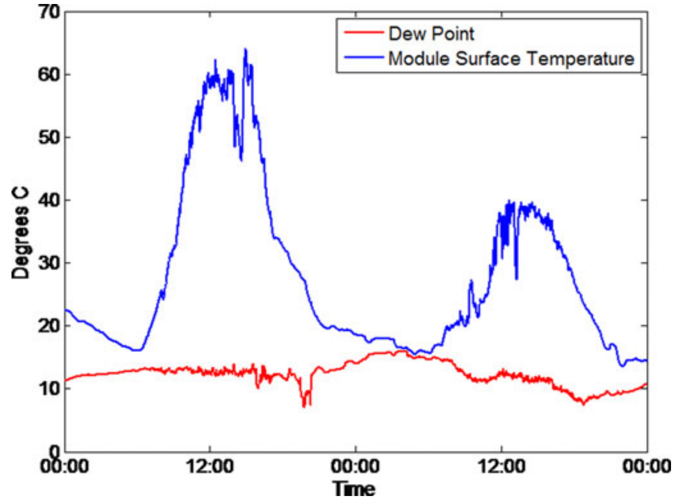


Fig. 7. Approximate dew point and back-of-module surface temperature on June 28, 2011 and June 29, 2011. Possible formation of dew on modules between 04:15 and 04:30 A.M. on June 29, 2011.

## VI. Cleaning Events in the Absence of Rain

There were a number of partial recoveries observed when there was no recorded rainfall. In these cases, we used relative humidity and ambient temperature to calculate the dew point using (1) and (2), shown below, where $a = 17.271$ and $b = 237.7\ ^{\circ}\mathrm{C}$, and compared the back-of-module surface temperature with this metric. If the dew point surpassed module surface temperature, it is possible that dew gets collected on the front side of the modules, causing a partial cleaning event.

Fig. 6 shows an example of a cleaning event with no concurrent rainfall. Relative humidity and ambient temperature are plotted over the same time period. There is a spike in relative humidity during the perceived cleaning event on June 29, 2011. This could indicate a light rain that was not enough to register on the rain gauge; however, concurrent weather data collected 10 km to the east also show no recorded rain.

In Fig. 7, the approximate dew point and module surface temperature are plotted on 1-min intervals. Between 4:15 and

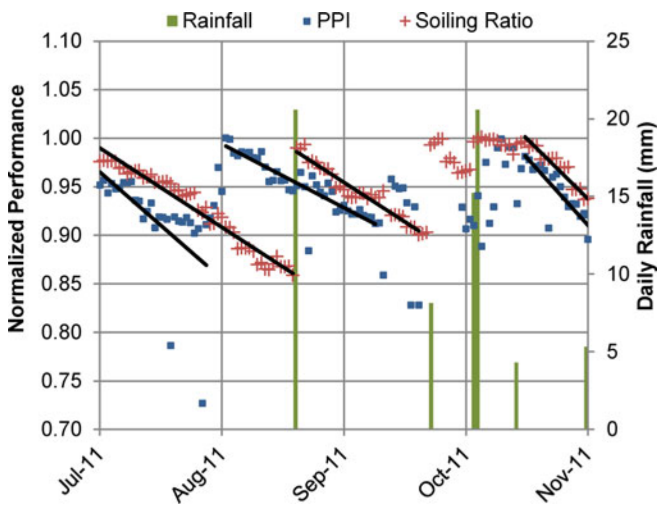


Fig. 8. Normalized PPI of a PV array overlaid on daily ratios from a nearby soiling station. Rainfall measured at the soiling station displayed as bars.

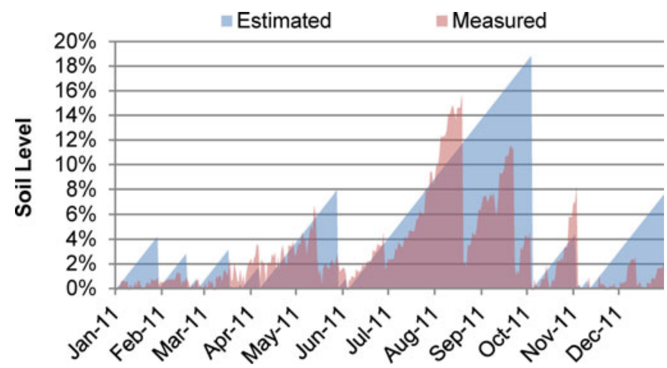


Fig. 9. Estimated soiling levels in the southern Central Valley using average monthly soiling rate and nearby rainfall data plotted against actual measured soiling levels.

4:30 AM on June 29, 2012, the two lines intersect, suggesting formation of dew on the glass. Photgraphs taken on June 27 and June 30 confirm a partial cleaning event. It is possible that the frameless design of First Solar modules helps cleaning in such light precipitation and dew events, where a frame would block beading or sheeting water from transporting dirt off the bottom edge of the glass

$$T_d = \frac{b\gamma(T, RH)}{\alpha - \gamma(T, RH)} \tag{1}$$

$$\gamma(T, RH) = \frac{\alpha T}{b + T} + \ln(RH/100). \tag{2}$$

## VII. Comparison With Plant Performance

A small PV array of First Solar modules is located 35 km northeast of the southern Central Valley soiling measurement station. We compared performance data from this site against soiling levels measured at the station.

The metric that is used to evaluate the performance of the array is called the power performance index (PPI). PPI values, which are calculated daily, represent the power output of a system under standard test conditions, irradiance of 1000 W/m$^2$, module temperature of 25 °C, and ASTM G173 solar spectrum (AM 1.5). This metric is not affected by fluctuations in irradiance and air temperature, allowing us to attribute the bulk of any apparent losses in system performance to soiling. Calculating PPI involves normalizing measured system power to irradiance and module temperature [5].

The PPI for this site has been adjusted for dc losses, normalized to 1 as its maximum value, and overlaid on the daily soil ratios from the nearby soiling station in Fig. 8. The site owners periodically clean the array, which is seen around August 1, 2011 as a gradual recovery of PPI. For the month of July, the soiling station measured a soiling rate of 8.1% per month. The drop in PPI at the nearby PV array was 8.7% per month. The soiling station continued to measure 8.1% per month soiling through September, while the rate at the array slowed to 6.5% per month. In November, the rate at the soiling station measured 12.0% per month and the array measured 13.2% per month.

By using the PPI as a metric, we attempt to account for major performance factors outside soiling losses, such as variable irradiance and air temperature, allowing us to realistically compare the maximum power point performance of the array with our measured soiling rate. The results from the relatively simple measurement system align with actual performance deficits observed at a nearby PV array.

## VIII. Estimating Soiling Losses

Using the soiling rates determined in these analyses along with historical rain data, we can begin to estimate losses due to accumulated soiling. A common method is to create a sawtooth plot of repeating soil rate segments punctuated by rain events [2]. A sample year was created using this method and compared against real soiling rates measured at the Southern Central Valley station. Historical rainfall data were gathered from the CIMIS station in Stratford, CA, which is located 10 km to the east of the soiling measurement station [6]. The sample year of estimated soiling levels is plotted in Fig. 9.

A threshold must be set to establish the minimum amount of rain required for the soiling level to reset back to some level understood as the clean state. The model results are highly dependent on this variable, which is a function of module tilt angle, soil composition, and soil accumulation. Based on measured data for this region, we set a threshold of 1 mm. For this study, we set the clean state to 0, but measured data suggest that the soil level does not fully recover from rain alone. After rain events, some residual soiling remains on the modules. This amount has not been measured in the laboratory but is estimated to be less than 1%.

We used an average monthly soiling rate rather than different rates for each month. This is simply the average of all the monthly soiling rates in the time period studied. We determine a daily soil rate by dividing by 30.5. For every day without rain, the running soil level increases by this daily soiling rate. When rainfall is measured over the set threshold of 1 mm, the running soil level is reset to 0. The mean of these daily soiling levels is compared against the mean soiling level measured at the southern Central Valley soiling measurement station.

When using a rain threshold of 1 mm, a reset soiling level of 0, a monthly soiling rate of 4.8%, and daily rain totals from the CIMIS weather station in Stratford, CA, the estimation method predicts a 4.9% annual average soiling loss. The actual average soiling loss measured was 2.9%. Much of the discrepancy is due to a cleaning event at the soiling station on August 20. Over 20 mm of rain was measured and the soil level recovered from a peak of 15.6–2.0% after the rain event, but the CIMIS station measured no rain on that day. At the CIMIS station, no rain was measured from June 6 to October 5, causing the overprediction of soiling losses that summer.

When we feed the measured rain data from the soiling station to this model, the estimate is exactly 2.9%, matching the measured soil ratio. This suggests the following:

1) the method of determining soiling rates from measured data from this soiling station is sufficient to accurately predict soiling levels using just an annual average rate and historical rain data;
2) averaging the monthly soiling rates allows for simple, reasonably accurate soiling level estimations. Feeding the algorithm individual monthly soiling rates does not necessarily improve accuracy.

The output of the model is a set of monthly soiling levels, which can be entered into PV energy simulation tools such as PVsyst [7], which treat these levels as loss coefficients affecting the available irradiance. For other energy prediction models that accept inputs for rainfall, the soiling rate can be input to build the monthly levels directly.

## IX. Conclusion

With soiling rates of less than 1.0% per month in the low desert and peak rates of 11.5% per month in heavy agricultural regions of the Central Valley, it is clear that soiling trends vary greatly across California. The maximum soiling rates measured in this study are significantly less than rates seen in other studies in other parts of the world. Furthermore, the 20–30% soiling loss levels measured by AlBusairi and Möller are the result of higher average relative humidity and dusty rains [8], conditions not encountered in our region of study. The modules in this study were installed at a 25° module tilt. For other tilt orientations, and especially for tracker systems, further analysis is needed to evaluate losses.

Unlike the studies by Kimber *et al*. [2], we were not able to discern a minimum amount of rain required for cleaning. We saw partial recoveries with as little as a fraction of a millimeter at the low desert site. This is partly because the sites under test in the Powerlight study were flat mounted on rooftops, which can require more rain to clean.

Dust accumulation is a major factor in the performance of solar power plants. Standard industry practice specifies that large utility-scale PV farms be sold with an energy guarantee that spans decades. The ability to properly model expected annual losses due to soiling improves the accuracy of energy predictions and in turn boosts the confidence of potential customers and financiers. Eliminating the precise contribution of dust on the modules on the power plant performance allows subtler effects, such as long-term device degradation, seasonality in spectral response, etc., to be isolated and more accurately characterized. In addition, soiling studies help determine the costs and benefits of periodic cleaning of the modules versus leaving them to the elements. As this study continues and multiple years of data are collected, regional- and weather-specific soiling models will be refined further. Areas of investigation include the seasonality of soiling rates, and an analysis of the distribution of monthly soiling levels and their correlation with long-term rainfall recurrence intervals.

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Authors’ photographs and biographies not available at the time of publication.