MEASUREMENT STATION TO EVALUATE ANTI-SOILING PROPERTIES OF PV MODULE COATINGS

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ABSTRACT: Soiling can be a significant loss factor for PV systems, accounting for >5% annual energy loss in locations without frequent rainfall. Therefore, many manufacturers are investigating the potential benefits of incorporating anti-soiling or self-cleaning properties into PV module coatings. In order to study the potential anti-soiling behavior of various surface treatments, we have deployed a test station with custom-made PV modules having coatings with both hydrophilic and hydrophobic properties that may inhibit soiling and/or induce self-cleaning. The soiling of each sample is determined by comparison to an automatically washed reference cell in the station. We present the motivations for and design of the station, along with preliminary results regarding the impact of the coatings on soiling.
Keywords: photovoltaic systems, coatings, soiling

1. INTRODUCTION

Soiling, the accumulation of dust and dirt on PV modules, can be a significant loss factor in PV power plants, accounting for >5% annual reduction in PV system energy output in locations without frequent rainfall. Therefore, many manufacturers are investigating the potential benefits of incorporating anti-soiling or self-cleaning properties into PV module coatings, particularly when such properties can be directly integrated into anti-reflective coatings. Reducing the average annual energy loss due to soiling by even a small amount could have tremendous value in terms of increased energy production, especially for utility-scale projects.

One approach to achieving anti-soiling behavior is to alter the surface energy and water contact angle of the exposed surface. For example, studies have shown that both hydrophilic and hydrophobic surfaces can exhibit anti-soiling and/or self-cleaning effects on solar modules [1]-[5].

In order to further study the potential anti-soiling behavior of various surface treatments, we have deployed a test station in southern California to compare modules with several commercially available anti-reflective coatings having both hydrophilic and hydrophobic properties. The soiling measurement station is designed to make high-resolution measurements of the soiling-related power loss of each of the side-by-side samples.

2. EXPERIMENTAL

Four 60-cell multi-crystalline photovoltaic modules were custom assembled in the same batch from matching PV cells. The only significant difference between the four modules is the anti-reflective (AR) coating on the front side of the cover glass. As listed in Table I, one module uses uncoated glass, one has a hydrophilic pre-tempered coating typical of coatings used on the majority of PV modules currently produced, and the final two have hydrophobic post-temper coatings with similar surface energy but slightly different optical properties. The cover glass was coated at a commercial PV glass manufacturer and the modules were assembled in a production module assembly facility. Table I lists the water contact angle of each of the samples, illustrating the different surface properties.



Figure 1: Station for testing impact of module coatings on soiling.

The test station, depicted in Fig. 1, is installed outdoors near the University of California Riverside campus, and follows a previously described concept [6][7] in which the electrical outputs of the naturally soiled test modules are compared to the output of a reference device which is routinely cleaned. In this station the clean reference device, visible in the left side of the figure, is a crystalline silicon reference cell. The reference cell and the four modules are installed south-facing at a 35 degree tilt. A measurement and control system (Atonometrics RDE300) measures irradiance, via the reference cell, and I-V curves and back surface

Table I: Module descriptions

Module	Surface Treatment	Water Contact Angle
1	Uncoated	37°
2	Hydrophobic 1	90°
3	Hydrophobic 2	90°
4	Hydrophilic	30°

temperature of each of the four modules. From the I-V curves the control unit calculates the short circuit current I_{sc} and the maximum power P_{max} of each module. In addition the control unit operates an automated washing system which cleans the reference cell daily with a pressurized water spray. Measured data are recorded once per minute and logged at a remote server for later analysis.

3. ANALYSIS METHODOLOGY

As described in [7], a soiling ratio metric *SR* is calculated for each module for each minute in the data set by dividing the module's measured maximum power by its expected maximum power if it were clean and free of soiling. Thus, at each minute, for each module,

$$SR = \frac{P_{max}}{P_{max,0} \cdot \left(1 + \gamma \cdot (T - T_0)\right) \cdot (G/G_0)} \quad (1)$$

where P_{max} is the measured maximum power of the module in its soiled state, $P_{max,0}$ is a calibration value for the module's maximum power when clean and at a reference condition (e.g. STC), γ is the temperature coefficient of maximum power, T is the measured module temperature, T_0 is the module temperature at the reference condition (e.g. 25° C at STC), G is the measured plane-of-array irradiance determined from the clean reference cell, and G_0 is the irradiance at the reference condition (e.g. 1000 W/m^2 at STC).

To compute the average impact of soiling for a given day, which we denote $\langle SR \rangle_d$, an irradiance-weighted average of the instantaneously measured values of *SR* is calculated as discussed in [6] and [7]:

$$\langle SR \rangle_d = \frac{\sum SR \cdot G}{\sum G} \quad (2)$$

Note that $\langle SR \rangle_d$ is equivalent to the ratio of the actual measured energy to the expected energy over the summation period.

In using (2) we exclude from the summation the minutes during which any of the modules was shaded by nearby structures. This condition typically occurred only early in the morning. We also exclude any minutes during which data were missing for any of the modules, in order to ensure all modules are treated equally.

The $P_{max,0}$ value of each module was determined from a regression of the measured temperature-corrected P_{max} of each module versus the irradiance G from the reference cell, using data from selected clear-sky days following rain events when all the modules were known to be clean. This self-calibration method ensures that the $\langle SR \rangle_d$ values equal 1.0 for the selected clear-sky clean days. The resulting $P_{max,0}$ values also compared favorably with flash test results for each module determined prior to installation at the site.

4. RESULTS

The station was brought online in August 2015. Data collection is ongoing as of June 2016 and is expected to continue throughout 2016 in order to capture results from the dry summer months.

Results to date are shown in Fig. 2. The top panel shows daily average soiling ratio $\langle SR \rangle_d$ for each module versus time, while the bottom panel shows daily rainfall up to 20 mm. Rainfall data were taken from a nearby meteorological station available via the Weather Underground website. In mid-October and early December the soiling measurement station was offline for maintenance.

The data in Fig. 2 show several examples of the progressive accumulation of soiling followed by cleaning due to rainfall. For example, in the period from August to early September the measured soiling ratios fall gradually,

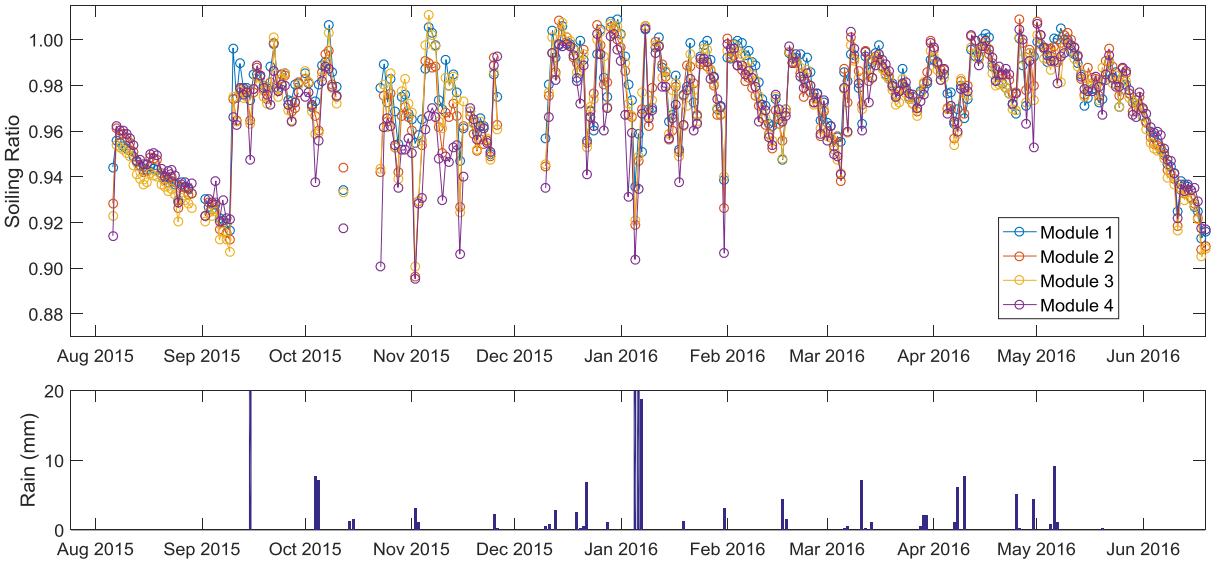


Figure 2: Daily average soiling ratio measured by soiling station (top) and rain at the site (bottom).

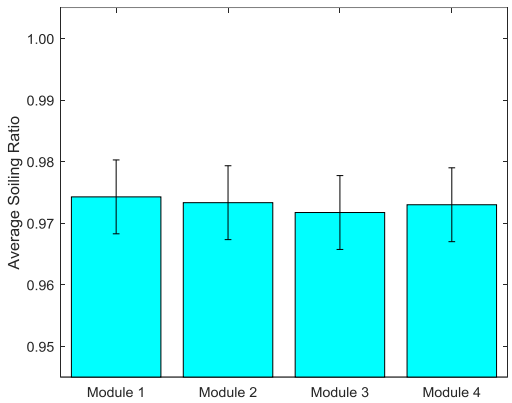


Figure 3: Average soiling ratio for each module over the entire 10-month measurement period to date.

reaching a low point of about 0.92. Following the rain event in mid-September, the ratios recover to values near 1.00 indicating that the modules are clean. This characteristic sawtooth pattern is also visible in the period from February through June. Note that the soiling rates during these periods range from 4-10 % per month, or 0.1-0.3 % per day, which is comparable to published results for the region [8]. Note also that rain events of only a few millimeters, such as in mid-February, were sufficient to clean the modules. In some cases it appears that rain events are not synchronized with the module cleaning; this is likely due to the weather station being located some distance from the soiling station site.

In contrast to the pattern just described, from November through January the upper panel of Fig. 2 is more irregular, which is due to low irradiance and frequent rain conditions.

To assess the overall impact of soiling on the four modules, we take the average of the soiling ratios for the entire period from August 2015 through June 2016. These results are plotted in Fig. 3. All four modules show a soiling ratio of approximately 0.973, indicating approximately 2.7% energy loss over the measurement period. The error bars in Fig. 3 are based on an uncertainty analysis which takes into account the effects of uncertainty in the module calibration constants (the $P_{max,0}$ values used in (2)) and temperature non-uniformities. Within the uncertainties, there was no discernible difference in the average impact of soiling on the performance of the four modules over the current test period.

5. DISCUSSION

The potential anti-soiling behavior of various coatings depends on the characteristics of soiling at the site, because the adhesion of dust particles to hydrophobic or hydrophilic surfaces depends on particle composition as well as meteorological conditions. In particular, hydrophilic versus hydrophobic surface treatments have been found to respond differently to organic particles such as soots versus inorganic particles such as soil minerals. Previous studies [9] have shown different soiling responses to hydrophobic and hydrophilic coatings at different locations.

For the present study the soiling performance of all four modules so far appears equivalent at the test site, within the resolution of the measurement station. These results differ from those recently found in [5], where a hydrophilic surface treatment was found to give a noticeable reduction in soiling. However, the site locations in [5] were characterized primarily by desert conditions, while in the present study the site location is urban and is situated near both a highway and an agricultural area, which together may provide both organic and inorganic soil particles. The soiling behavior at the site is therefore more complex. Furthermore, the data collection so far was concentrated mostly in the rainy season, during which the average soiling loss was small. Data collection is ongoing and we will continue to evaluate the soiling behavior of the modules through a greater range of seasonal conditions, including the dry summer months, to determine how the coatings respond.

6. REFERENCES

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