Comparing PV Power Plant Soiling Measurements Extracted from PV Module Irradiance and Power Measurements

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***Abstract* — The accumulation of dust and other environmental contaminants on PV modules, also known as PV module soiling, is a significant source of lost potential power generation for PV installations. Designers and operators of utility-scale solar power plants are increasingly seeking methods to quantify soiling-related losses, in order to improve performance modeling and verification or to optimize washing schedules. Recently, soiling measurement equipment has been introduced based on the measurement of two co-planar PV modules, one of which is regularly cleaned, and the other of which naturally accumulates environmental contaminants. These measurements are used to determine a soiling ratio (*SR*), which may be applied as a derate factor in analysis of the PV system performance. In this work, we examine the difference between a soiling ratio metric calculated from measured temperature-corrected short-circuit current values (SR^{Isc}), which represents the fraction of irradiance reaching the soiled modules, versus a soiling ratio calculated from measured temperature-corrected PV module maximum power values (SR^{Pmax}), which represents the fraction of power produced by the soiled modules compared to clean modules. We examine both techniques for CdTe and c-Si module technologies. This study is motivated by the fact that variations in module efficiency versus irradiance, as well as any non-uniformity of soiling, may introduce differences between the power losses estimated from short-circuit current values versus actual soiling-induced power losses. For CdTe, the SR^{Isc} method is found to be a good proxy for the SR^{Pmax} method for non-uniform soiling levels up to 11%.**

***Index Terms* — measurement uncertainty, performance analysis, photovoltaic systems, solar power generation, dust, module soiling.**

I. Introduction

The accumulation of dust, dirt, pollen and other environmental contaminants on PV modules, also known as PV module soiling, results in a reduction in solar irradiance reaching the semiconductor junctions of the module and therefore reduced power generation. Following irradiance and air temperature, soiling is the third most important environmental factor determining the output of a PV power plant. Average annual energy losses due to soiling are typically in the range 3-6% [1], [2]. However, studies have shown annual soiling losses as high as ~14% [2], monthly soiling losses as high as 20% [3], and short-term soiling losses as high as 30% [4].

Estimates of power losses due to soiling are often simply extracted from measured power plant performance data, as illustrated in [1]. However, more recently, soiling measurement systems have been introduced which provide specific data used to quantify soiling power losses. Such systems, now manufactured by Atonometrics, are in use at First Solar power plants. The systems use a method which to our knowledge was first introduced by Ryan *et al.* in 1989 [5], and has also been used in more recent studies [6],[7]. The method uses the side-by-side comparison of the measured output of two co-planar, calibrated PV modules, the first of which is kept clean and the second of which naturally accumulates soiling. The temperature-corrected short-circuit current (*Isc*) of each PV module is used to extract irradiance measurements, which in turn are used to calculate a Soiling Ratio (*SR*). Soiling ratios calculated in this way have been shown to be correlated with PV power plant energy production [6].

However, variations in module efficiency with irradiance and any non-uniformity of soiling may both introduce differences between the power losses estimated from short-circuit current values and actual soiling-induced power losses. In this paper, we examine the potential magnitude of these differences compared to an alternative metric based on module power measurements.

II. Soiling Ratio Metrics

We begin by defining terminology for PV soiling and soiling measurement.

We define the *soiling level* as the average percent reduction in irradiance perceived by a PV cell or module due to accumulated soiling, while the *soiling power loss* is the percent reduction in output power of the module due to soiling. To enable measurements of soiling on actual modules, we will define two *soiling ratio* metrics, SR^{Isc} and SR^{Pmax}. Each soiling ratio is based on comparing measurements from a soiled module to a clean module.

The SR^{Isc} metric follows previous work and is defined as follows:

$$SR^{Isc} = \frac{G_2}{G_1} = \frac{C_2^{Isc} \cdot \left(1 - \alpha \cdot \left(T_2 - T_{ref}\right)\right) \cdot Isc_2}{C_1^{Isc} \cdot \left(1 - \alpha \cdot \left(T_1 - T_{ref}\right)\right) \cdot Isc_1} \qquad (1)$$

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Here the subscript "1" refers to the clean module and the subscript "2" refers to the dirty module. The denominator in this equation represents the perceived irradiance G_1 received by the clean module, while the numerator represents the perceived irradiance G_2 received by the dirty module, where $G_2 < G_1$ when soiling is present. Isc_i and T_i are the short-circuit current and temperature of module i (i=1 or 2) at the time of measurement. T_{ref} is the temperature at a reference condition and α is the temperature coefficient of the short-circuit current. C_1^{Isc} and C_2^{Isc} are calibration constants that relate the short-circuit current of each module (when both are clean during an initial calibration step) to the irradiance at the reference condition. Details on the factors contributing to the calibration constants can be found in Ref. [8] and references therein, but are omitted here for simplicity. SR^{Isc} = 1 in the absence of soiling and is reduced as soiling increases.

We now define a new soiling ratio metric based on measurements of the dirty and clean modules' maximum powers, as follows:

$$SR^{Pmax} = \frac{C_2^{Pmax} \cdot \left(1 - \gamma \cdot \left(T_2 - T_{ref}\right)\right) \cdot Pmax_2}{C_1^{Pmax} \cdot \left(1 - \gamma \cdot \left(T_1 - T_{ref}\right)\right) \cdot Pmax_1} \quad (2)$$

As before the subscript "1" refers to the clean module and the subscript "2" refers to the dirty module. $Pmax_i$ and T_i are the maximum output power and temperature of module i (i=1 or 2) at time of measurement. T_{ref} is the temperature at a reference condition and γ is the temperature coefficient of the maximum power. C_1^{Pmax} and C_2^{Pmax} are calibration constants which serve to normalize the results. The calibration constants could be independently determined, for example, as the inverse of the maximum power of each module at the reference condition, such that the numerator and denominator of Eq. (2) both equal 1 in the absence of soiling. Alternatively the ratio of the two constants can be replaced with a single constant that also ensures SR^{Pmax} = 1 in the absence of soiling.

In practice the metric SR^{Isc} is more easily measured than the metric SR^{Pmax}, which requires more sophisticated equipment capable of I-V curve tracing or maximum power point tracking. However, SR^{Pmax} more directly correlates to actual soiling power loss in the PV array to be monitored. Soiling measurement equipment with *Pmax* determination capability is now becoming commercially available.

In this paper we examine the differences between the SR^{Isc} and SR^{Pmax} metrics for both uniform and non-uniform soiling examples, in order to explore the potential benefits of using SR^{Pmax} in a power plant soiling monitoring system.

III. Effects of Efficiency Variations with Irradiance

One effect leading to a discrepancy between SR^{Isc} and SR^{Pmax} is the variation of PV module efficiency with irradiance. Typical PV modules have somewhat smaller efficiencies at low irradiances compared to their Standard Test Condition (STC) values. Thus, while for typical outdoor irradiance values of 100 to 1100 W/m^2 the short-circuit current of a PV module is proportional to irradiance (at a given temperature), the maximum power of a PV module is not. Instead, as irradiance is reduced below a typical value of 1000 W/m^2, the maximum power of a PV module declines somewhat faster than the reduction in irradiance. Since soiling represents a reduction in irradiance received by a module, this results in a difference between SR^{Isc} and SR^{Pmax}.

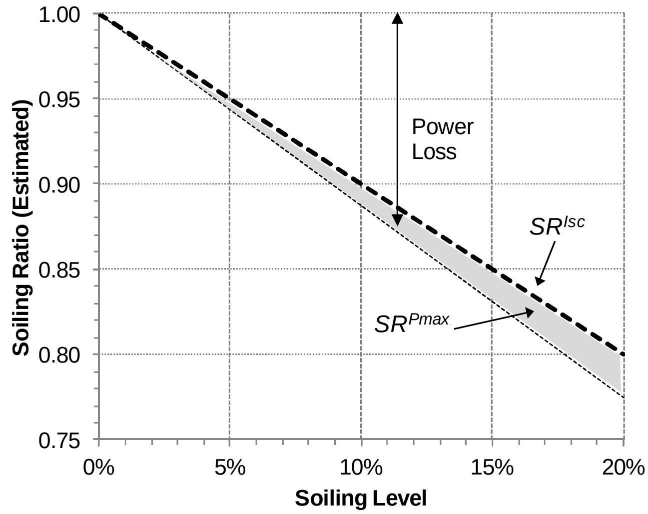

Fig. 1: Comparison of estimated *Isc* and *Pmax* soiling ratios as a function of soiling level for a range of typical PV modules, based on datasheet values. The soiling power loss determined by 1 - SR^{Pmax} may be up to 10% larger than the value of 1 - SR^{Isc}, depending on module parameters.

To illustrate the potential magnitude of this effect, we have examined datasheets from leading PV module manufacturers, representing both thin film and crystalline silicon technologies. Using datasheet values for module performance at STC (1000 W/m^2, 25 °C), performance at Normal Operating Cell Temperature (NOCT) (800 W/m^2, 45 °C), and temperature coefficients of *Isc* and *Pmax*, we have determined estimated values for the SR^{Isc} and SR^{Pmax} values that would be measured as a function of soiling level up to 20%. These results are shown in Fig. 1, where a range of values is indicated for SR^{Pmax} corresponding to different PV module types from different manufacturers. The graph was constructed by using NOCT values to set the endpoints at the 20% soiling level and assuming that the quantities trend linearly towards the 0% soiling level endpoints. Based on these results, for example, at a soiling level of 10%, SR^{Isc} may equal 0.90 while SR^{Pmax} could be as low as ~0.89. Therefore 1 - SR^{Isc} may tend to underestimate the actual soiling power loss by up to 10% (on a relative basis), compared to 1 - SR^{Pmax}, depending on PV module parameters.

The significance of this effect depends on how the measured soiling ratio is to be used for performance analysis. If the measured soiling ratio is to be used simply as a derate factor applied to the expected PV array power output, then the SR^{Pmax} metric is more strictly correct and SR^{Isc} is an approximation. However, if the soiling ratio is to be used as derate factor on the measured irradiance, within the context of a performance model which includes the effect of the module's efficiency dependence on irradiance, then the SR^{Isc} metric is the correct one.

IV. Effects of Soiling Nonuniformity

A. Background

A more significant effect leading to potential differences between SR^{Isc} and SR^{Pmax} is non-uniformity of soiling across a PV module, which can result in a greater power loss than would be indicated by the average soiling level alone, *i.e.* the same amount of dust distributed uniformly over the module.

The pattern of accumulation of dust and other contaminants on PV module surfaces depends on many factors, including characteristics of the dust particles and contaminants, wind, rain and other precipitation, and module mounting mechanisms and orientation. The use of tracking systems can also contribute to non-uniform soiling accumulation patterns depending on the night-time stowage position of the modules.

One characteristic type of soiling non-uniformity is the accumulation of dust and dirt at the edges of framed modules. This is illustrated in several photographs in [9]. Soiling is particularly likely to accumulate at the bottom edges of the modules, since precipitation carries particles downward. The effect may be stronger for modules mounted at lower tilt angles [10].

However, besides accumulating at the bottom of framed modules, soiling may also accumulate along the sides or tops of framed modules, as shown in photographs in [9] and [11]. Interestingly, the photograph in [11], from a utility-scale solar plant in Arizona, shows a group of modules with a thick band of soiling accumulated along the bottom edge of the modules, covering at least one row of silicon cells, next to another group of modules where the soiling has accumulated in a thin band across the tops of the modules, rather than at the bottom. The two groups are only a few meters apart, yet display very different patterns of soiling accumulation.

Frameless modules exhibit different soiling accumulation patterns than framed modules. However, while trapping of dust by frames is not an issue, frameless modules may still show a vertically graded pattern of soiling, due to precipitation and gravity effects. In Ref. [12], the authors characterized dust accumulation on frameless glass samples, representing frameless modules, installed outdoors at varying tilt angles for 3 months in Kuwait. They found that dust accumulated in a vertically graded pattern, with more dust deposited towards the bottom of the samples. In addition, they also found and quantified characteristic non-uniformities within the graded dust deposition, speculating that such non-uniformities were introduced by light rain causing redistribution of accumulated dust without cleaning the modules. The authors used SPICE simulation to simulate I-V curves of CdTe modules with soiling uniformity patterns matching those measured on the glass. These showed that for a representative non-uniform dust distribution the maximum power was reduced by 19.4% compared to a reduction of only 14.8% for the same overall dust concentration applied in a uniform graded distribution. These results indicate the potential impact of the soiling uniformity pattern.

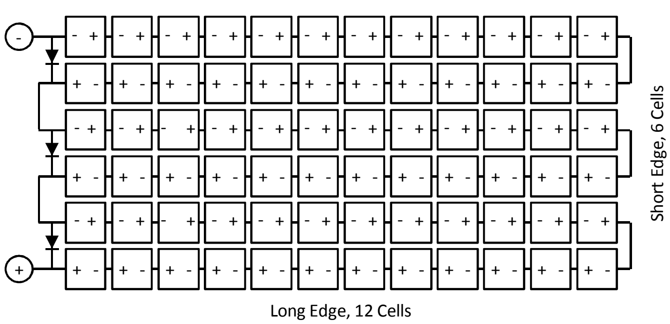

Fig. 2: Electrical diagram of 72-cell crystalline silicon module used for experiment. Cells are arranged in 3 groups of 24, with 3 bypass diodes between groups, and the short and long edges of the module have 6 and 12 cells, respectively.

B. Experimental Results

In order to demonstrate the effects of soiling non-uniformity on soiling ratio measurements, we performed experimental measurements of simulated soiling on two PV modules, including a framed crystalline silicon module and a frameless CdTe module. The crystalline silicon module consists of 72 square cells (each 125 × 125 mm) with 3 bypass diodes, arranged as shown in Fig. 2. The CdTe module consists of 154 narrow rectangular-shaped cells (each approximately 600 mm × 7 mm) arranged in two parallel groups of 77 series-connected cells, with no bypass diodes. Rather than using a pair of modules of each type, one clean and one dirty, as in a field-installed soiling measurement system, we used one module of each type, comparing measurements before and after simulated soiling.

For each module, we simulated the effects of soiling by selectively covering some of the cells with a filter, and measuring I-V curves of the modules outdoors before and after application of the filter. Short-circuit current (*Isc*) and maximum power (*Pmax*) were extracted from the I-V curves and used to calculate soiling ratios per Eqs. (1) and (2), where the I-V curves measured before and after application of the filter were designated as the "clean" and "dirty" module states, respectively.

Two types of filters were used to simulate different levels of soiling. Clear plastic sheets were used to simulate a moderate soiling level of approximately 11%, while a porous foam sheet was used to simulate a heavy soiling level of 24-27%. The light transmission of each filter was calibrated for each module by uniformly covering the module with the filter material and measuring the reduction in module short-circuit current.

All measurements were performed on a clear day with irradiance within 5% of 1000 W/m^2 in the plane of the modules, as measured with a calibrated reference cell. Module temperatures were in the range 35-55 °C as measured with a resistance temperature detector (RTD) applied to the backs of the modules. Prior to analysis, each I-V curve was translated to an irradiance of 1000 W/m^2 and approximately 40 °C using translation methods outlined in IEC 60891 [13], in order to allow all extracted parameters to be directly compared.

We also constructed a SPICE model of each PV module using individual cell models. As shown below, the modeled I-V curves fit the measured curves well. The models were used only to guide the selection of experimental conditions and to interpret the data; results of soiling metrics presented below are from the experimental measurements only.

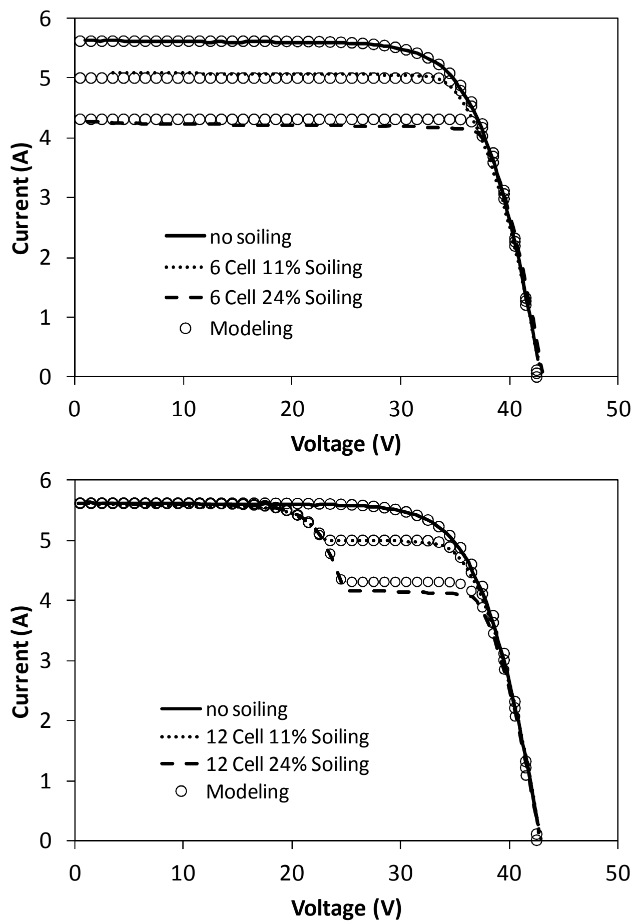

Fig. 3: Measured I-V curves of crystalline silicon module with simulated soiling on 6 cells across the short edge of the module (top figure) and 12 cells across the long edge of the module (bottom figure). Open symbols indicate SPICE model simulation of the measured I-V curve.

Crystalline Silicon Module

Fig. 3 shows measured I-V curves for the crystalline silicon module under various simulated non-uniform soiling conditions. We examined the effect of soiling along either the short (6 cell) or the long (12 cell) edge of the module, which would be similar to the types of patterns observed in [9] and [11]. Note that silicon modules may be installed in either landscape (long edge down) or portrait (short edge down) configurations; thus, even neglecting potential preferential soiling at the tops or sides of modules, and considering only preferential soiling at the bottom edges, the soiling may be along either the short or long edges of the modules, depending on mounting configuration.

The top portion of Fig. 3 shows results for simulated soiling across the short (6 cell) edge. In this case, the short-circuit current of the module is dominated by the shaded cells, which are distributed equally among the 3 groups of 24 cells shown in Fig. 2, and the short-circuit current decreases rapidly with additional shading from the simulated soiling. In contrast, the bottom portion of Fig. 3 shows results for simulated soiling across the long (12 cell) edge of the module. In this case, the shaded cells are all within one group. At short-circuit, the bypass diode for this group is activated such that the module short-circuit current is not affected by the shaded cells.

Fig. 4 shows the soiling ratio metrics calculated from the *Isc*

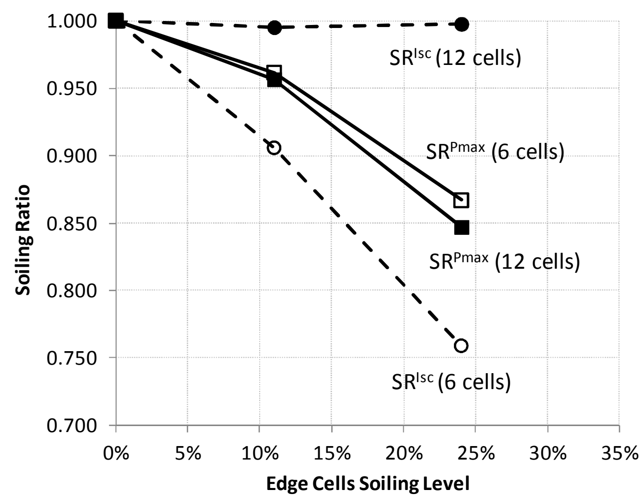

Fig. 4: Soiling ratio metrics (SR^{Isc} and SR^{Pmax}) measured for simulated soiling of the crystalline silicon module, with preferential soiling on either the short (6 cell) or long (12 cell) edge of the module. For these conditions, SR^{Isc} either over- or under-represents the actual soiling power loss.

and *Pmax* values extracted from the translated I-V curves, as a function of the soiling level of the edge cells. Note that, depending on which cells are preferentially soiled, the value $1 - SR^{Isc}$ either greatly over- or under-estimates the actual soiling power loss, which is equal to $1 - SR^{Pmax}$. Also note that the maximum spatial average soiling level shown in these results is only 4% (24% × 12/72), yet the power loss corresponding to this condition is ~15%.

<u>CdTe Module</u>

For the CdTe module, to simplify the interpretation, we tested a simulated soiling pattern involving 20 shaded cells, 10 from each of the two parallel groups. This represents an extreme example of the type of non-uniform soiling observed in [12], but allows identification of the important trends. Fig. 5 shows measured I-V curves for the CdTe module with the simulated soiling. The results for this test are qualitatively similar to those shown in the bottom portion of Fig. 3 for soiling along the long (12 cell) edge of the crystalline silicon module. Even though no bypass diodes are present, the module short-circuit current is not greatly reduced by the shading of the selected cells, because these cells become reverse-biased by the remaining cells. However, the maximum power is significantly reduced with increasing shading.

Fig. 6 shows the soiling ratio metrics calculated from the *Isc* and *Pmax* values extracted from the translated I-V curves, as a function of the soiling level of the 20 selected cells. The results are again qualitatively similar to those obtained for soiling along the long edge (12 cell) of the crystalline silicon module, in that the SR^{Isc} metric under-represents the soiling power loss, although the discrepancy is only significant once the soiling exceeds a threshold of ~11%. Note that the maximum spatial average soiling level shown in these results is only 3.5% (27% × 20/154), yet the power loss corresponding to this condition is ~15%. The measurements were repeated with only 10 cells from one parallel group shaded by the filters instead of 20, with qualitatively similar results, including a maximum power reduction of ~10% at the 27% soiling condition.

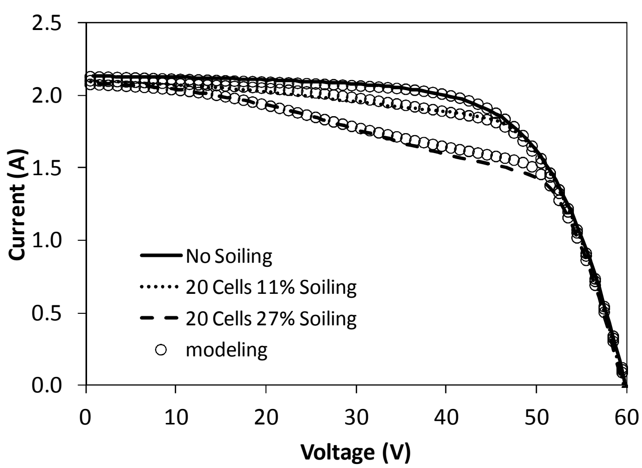

Fig. 5: Measured I-V curves of the CdTe module with simulated soiling on 20 cells comprising two groups of 10 cells from each parallel group. Open symbols indicate SPICE model simulation of the measured I-V curve.

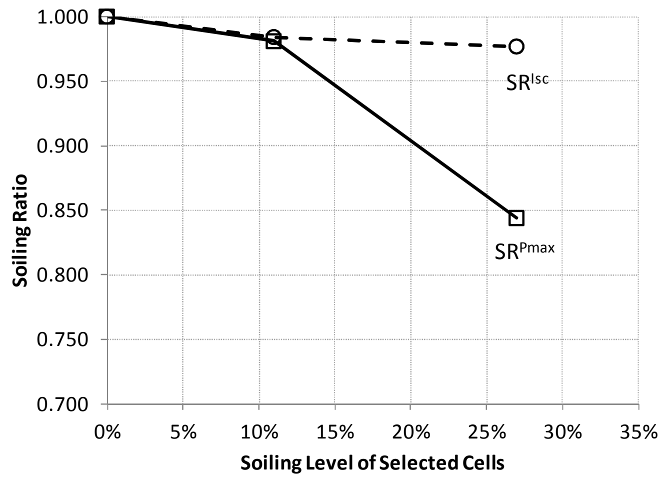

Fig. 6: Soiling ratio metrics (SR^{Isc} and SR^{Pmax}) measured for simulated soiling of the CdTe module, with preferential soiling on 20 selected cells, comprising 10 cells from each of the two parallel groups. For these conditions, $1 - SR^{Isc}$ under-represents the actual soiling power loss when the soiling level of the selected cells exceeds a threshold of ~11%.

V. CONCLUSIONS

Soiling measurement systems based on measuring the ratio of temperature-corrected short-circuit currents from a “dirty” to a “clean” module have recently been introduced, and soiling ratios calculated in this way have been shown to be correlated with PV power plant energy production [6]. For the case of uniform soiling, short-circuit-current-based measurements of effective irradiance are a good proxy for the soiling-induced power loss. However, measuring the ratio of temperature-corrected maximum powers offers an improved measurement under certain conditions. Even for uniform soiling, the variation of efficiency with irradiance may lead to an under-estimate of soiling-induced losses by up to 10% on a relative basis, depending on module parameters, when using current-based measurements in the absence of a performance model which accounts for the relation between power and irradiance. When potential non-uniform soiling accumulation patterns are considered – which are very specific to local site conditions – power-based measurements may yield much more accurate results in certain cases, particularly for c-Si modules. For the CdTe case, use of SR^{Isc} shows a close alignment with SR^{Pmax} as long as the non-uniformity in soiling does not exceed about 11%. Understanding the potential benefits will require a greater understanding of the typical uniformity patterns of soiling accumulation on PV modules in different environments and under different conditions. However, a newer generation of soiling measurement equipment is now becoming available with the capability to quantify both short-circuit current and power reductions due to soiling, allowing for the possibility of more detailed characterization.

REFERENCES

[1] A. Kimber, L. Mitchell, S. Nogradi, and H. Wenger, “The Effect of Soiling on Large Grid-Connected Photovoltaic Systems in California and the Southwest Region of the United States,” in *Conference Record of the 2006 IEEE 4th World Conference on Photovoltaic Energy Conversion*, Waikoloa, HI, 2006.

[2] S. Canada, “Quality Assurance: Impacts of Soiling on Utility-Scale PV System Performance,” *SolarPro Magazine*, no. 6.3, pp. 14–20, May-2013.

[3] T. U. Townsend and P. A. Hutchinson, “Soiling Analysis at PVUSA,” in *Proceedings of ASES-2000*, Madison, WI, 2000.

[4] J. Zorrilla-Casanova, M. Piliougine, J. Carretero, P. Bernaola, P. Carpena, L. Mora-López, and M. Sidrach-de-Cardona, “Analysis of Dust Losses in Photovoltaic Modules,” in *Proceedings of the World Renewable Energy Congress 2011*, Linköping, Sweden, 2011.

[5] C. P. Ryan, F. Vignola, and D. K. McDaniels, “Solar Cell Arrays: Degradation Due to Dirt,” in *Proceedings of the American Section of the International Solar Energy Society*, Denver, CO, 1989, pp. 234–237.

[6] J. R. Caron and B. Littmann, “Direct Monitoring of Energy Lost Due to Soiling on First Solar Modules in California,” *IEEE Journal of Photovoltaics*, vol. 3, no. 1, pp. 336–340, 2013.

[7] J. Zorrilla-Casanova, M. Piliougine, J. Carretero, P. Bernaola-Galván, P. Carpena, L. Mora-López, and M. Sidrach-de-Cardona, “Losses produced by soiling in the incoming radiation to photovoltaic modules,” *Progress in Photovoltaics: Research and Applications*, pp. 790–796, Feb. 2012.

[8] K. Emery, “Radiometry in photovoltaics: calibration of reference solar cells and evaluation of reference values,” in *Handbook of Photovoltaic Science and Engineering*, 1st ed., Wiley, 2003, pp. 701–752.

[9] E. Lorenzo, R. Moretón, and I. Luque, “Dust effects on PV array performance: in-field observations with non-uniform patterns,” *Progress in Photovoltaics: Research and Applications*, p. n/a–n/a, 2013.

[10] J. Cano, “Photovoltaic Modules: Effect of Tilt Angle on Soiling,” Master’s Thesis, Arizona State University, Phoenix, AZ, 2011.

[11] F. Brill, “EnviroPolitics Blog: PSEG building solar farms--and not just in New Jersey,” 16-Nov-2012. [Online]. Available: http://enviropoliticsblog.blogspot.com/2012/11/pseg-building-solar-farms-and-not-just.html#.UagS95xXqdI. [Accessed: 31-May-2013].

[12] H. Qasem, T. R. Betts, and R. Gottschalg, “Spatially-resolved modelling of dust effect on cadmium telluride photovoltaic modules,” *Solar Energy*, vol. 90, pp. 154–163, Apr. 2013.

[13] “IEC 60891 ed2.0 - Photovoltaic devices - Procedures for temperature and irradiance corrections to measured I-V characteristics.” IEC, 2008.