Evaluating the Accuracy of Various Irradiance Models in Detecting Soiling of Irradiance Sensors

Preprint

Zoe DeFreitas[1], Anthony Ramirez[2], Brian Huang[2], Sarah Kurtz[2], Matthew Muller[3], and Michael Deceglie[3]

1 Envision Digital
2 University of California, Merced
3 National Renewable Energy Laboratory

Presented at the 46th IEEE Photovoltaic Specialists Conference (PVSC 46)
Chicago, Illinois
June 16–21, 2019

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

Conference Paper
NREL/CP-5K00-75156
October 2019

Evaluating the Accuracy of Various Irradiance Models in Detecting Soiling of Irradiance Sensors

Preprint

Zoe DeFreitas[1], Anthony Ramirez[2], Brian Huang[2], Sarah Kurtz[2], Matthew Muller[3], and Michael Deceglie[3]

1 Envision Digital
2 University of California, Merced
3 National Renewable Energy Laboratory

Suggested Citation
DeFreitas, Zoe, Anthony Ramirez, Brian Huang, Sarah Kurtz, Matthew Muller, and Michael Deceglie. 2019. *Evaluating the Accuracy of Various Irradiance Models in Detecting Soiling of Irradiance Sensors: Preprint*. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5K00-75156. https://www.nrel.gov/docs/fy20osti/75156.pdf.

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

Conference Paper
NREL/CP-5K00-75156
October 2019

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

NOTICE

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

Evaluating the Accuracy of Various Irradiance Models in Detecting Soiling of Irradiance Sensors

Zoe DeFreitas[1], Anthony Ramirez[2], Brian Huang[2], Sarah Kurtz[2], Matthew Muller[3], and Michael Deceglie[3]

[1]Envision Digital, Redwood City, CA, 94065, USA
[2]University of California Merced, Merced, CA, 95340, USA
[3]National Renewable Energy Laboratory, Golden, Colorado, 80401, USA

***Abstract* — We evaluate the feasibility of using various clear-sky models or purchased satellite data for estimating the soiling of a reference cell irradiance sensor. We find results to be more accurate for models that consider local meteorological conditions. We conclude that given the data sets considered, and depending on the requirements of the data analyst, choosing to use purchased satellite irradiance data from Solargis to estimate the soiling of a reference cell sensor tends to yield more accurate results, although there are instances where a clear-sky model performs better. The SOLIS clear-sky model in PVLIB with variable P_{wat} provided useful soiling results, implying that the general method of using a clear-sky model with local meteorological data may provide a low-cost tool for detecting soiling of irradiance sensors.**

Index Terms — soiling, photovoltaic performance, soiling losses, irradiance, clear-sky, aerosol optical depth, precipitable water.

I. Introduction

Irradiance sensor readings provide the basis for performance assessment of PV plants. If these sensors are not measuring the true irradiance at the site, for example because they are soiled, then underperforming issues at a PV power plant can potentially be masked.

Soiling is one of the largest loss categories in PV plant performance for sites in dry climates, which are often the same locations with the highest solar insolation. However, analyses aiming to quantify the impact of the soiling at a site usually depend on reference irradiance sensors, which also suffer from soiling. Daily cleaning of irradiance sensors can be very expensive, especially for remote plants with no on-site O&M. Sensors are available to quantify soiling of a PV plant. However, it would be preferable to estimate the soiling level from readily available irradiance sensor data rather than relying on additional hardware. Furthermore, some irradiance sensors have been shown to soil at different rates than a PV array [1], so sensors designed to detect PV array soiling can not necessarily be used to correct for soiling of irradiance sensors.

This paper assesses the feasibility of using clear-sky irradiance models or satellite irradiance data to determine the soiling of irradiance sensors. This is done by comparing measured reference cell data against clear-sky data calculated using various models available in PVLIB [2] and against Solargis satellite irradiance data. Additionally, the spectral sensitivity to unquantified humidity and turbidity variations are assessed with SMARTS2, modeling for both broadband irradiance expected from a thermopile and the photonic irradiance measured with a silicon reference cell.

II. Methods

A. Ground-based measured data collection

Soiling measurement data were collected from two IMT reference cell sensors, shown in Fig. 1, during the summer of 2018 at the University of California, Merced (UC Merced). The sensors were mounted on a single-axis tracking system with a 20-degree south facing tilt.

One of these sensors, referred to as "clean" throughout this paper, was cleaned on a variable schedule. The other sensor, referred to as "dirty", was left to soil unless cleaned by natural precipitation during this period or when the PV system was cleaned. The data from these measurements were used to calculate the true soiling of the dirty reference cell. This setup was also repeated at the University of California, Riverside (UC Riverside) for a fixed tilt system with tilt of 26 degrees and an azimuth of 153 degrees.

Fig. 1. Example of uncleaned (left) and cleaned (right) sensors used to quantify accuracy of soiling determination.

B. Irradiance modeling and satellite data

At both locations the clear sky data were calculated using three readily available models in PVLIB: the Iniechen-Perez [3] model that used fixed monthly Linke-Turbidity [4] values, the Haurwitz model, and the simplified SOLIS [5] models. The SOLIS clear sky was calculated in the case with a fixed P_{wat} of 2.5cm and 1.0cm at UC Merced and UC Riverside based on some research about what is typical at each location, and again with variable P_{wat}, and variable AOD. P_{wat} was derived from ambient temperature and relative humidity data taken from the nearby Municipal weather stations using the equation described by Gueymard [6]. AOD data was taken from the nearest Aeronet locations to each of the sites, Modesto for UC Merced, and Caltech for UC Riverside, each of which were 40-60km away. Satellite irradiance data purchased from Solargis were also included in this study.

In order to compare the irradiance data from the clear sky models to the measured irradiance and satellite data, the modeled clear sky global horizontal irradiance (GHI) was transposed to plane of array irradiance (POA) using PVLIB. The various measurements and models of POA are shown in Fig. 2., below, for UC Merced using normalization for days when both sensors were known to be clean.

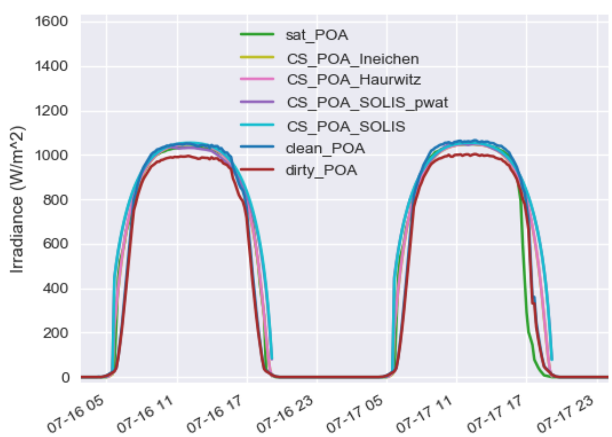

Fig. 2. Multiple irradiance measurements and models shown. The lower irradiance was measured by the soiled "dirty" reference cell 6 weeks after it was last cleaned is clearly visible.

C. Data wrangling

Next, the hourly satellite data and other local weather data were up-sampled using interpolated values to match the 10-minute frequency of the measured on-site data. These 10-minute interval datasets were then filtered using the clear-sky interval filter within PVLIB [7]. Further filtering of data to only include data one hour around solar noon was applied to minimize angle of incidence effects. A final smoothing of the data came from taking a daily mean of the filtered data.

Simple Irradiance Soiling Ratios were then calculated as:

$$Soiling\ Ratio_{POA} = \frac{POA\ Irradiance_{MEAS\_DIRTY}}{POA\ Irradiance_{REFERENCE*}}$$

**Where the "REFERENCE" is either the clean measured irradiance, one of the clear sky modeled irradiances, or the satellite irradiance.*

Fig. 3. illustrates distinct soiling periods punctuated by events where the dirty sensor was cleaned, and in one instance where

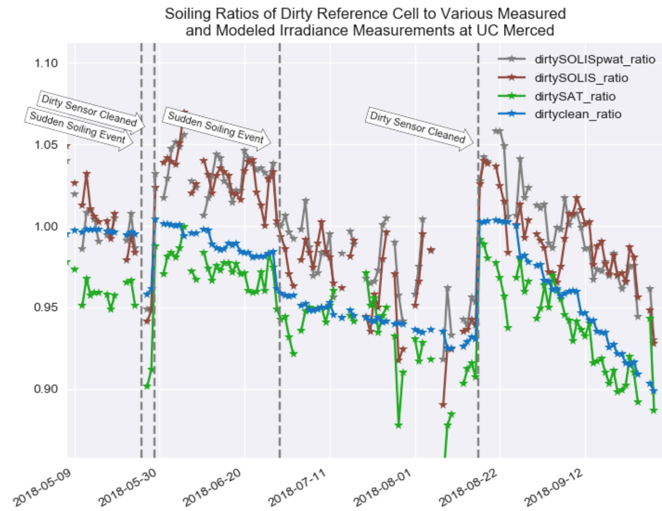

Fig. 3. Variation with time of ratios of the dirty reference cell at UC Merced to the clean sensor, satellite irradiance data, and two clear sky models in 2018.

there was a sudden soiling event that affected the dirty sensor alone. These periods in between cleaning or sudden soiling events were selected according to logs maintained by the students as well as precipitation data from nearby weather stations pulled from the Global Surface Summary of Day (GSOD) database. Detecting periods for estimating soiling can also be automated using algorithms for change detection [8].

Finally, Figure 4 shows how the Theil-Sen method was used to estimate soiling as described in 2016, M. Deceglie et al [9].

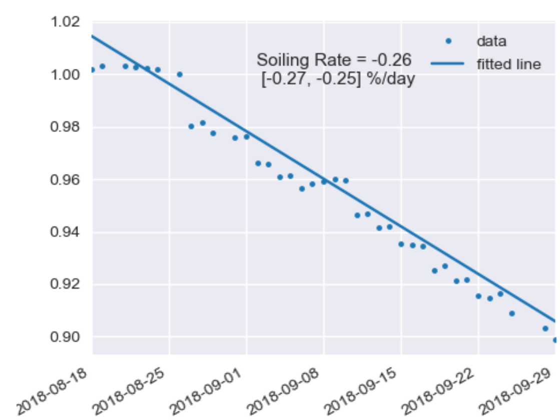

Fig. 4. Method for calculating soiling rate using Theil-Sen for the soiling ratio of the clean to dirty reference cell. Some variability is observed when the sensor was not cleaned for a few days.

C. Sensitivity of Irradiance modeling to AOD and P_{wat}

One important consideration made was the uncertainty introduced by any unmodeled variations in turbidity and P_{wat}. To assess the importance of using local meteorological data, the SOLIS clear-sky model was also calculated using variable P_{wat} and variable AOD as described in II-B, above, and the results were compared to the model using fixed values for both, as shown in Fig. 5.

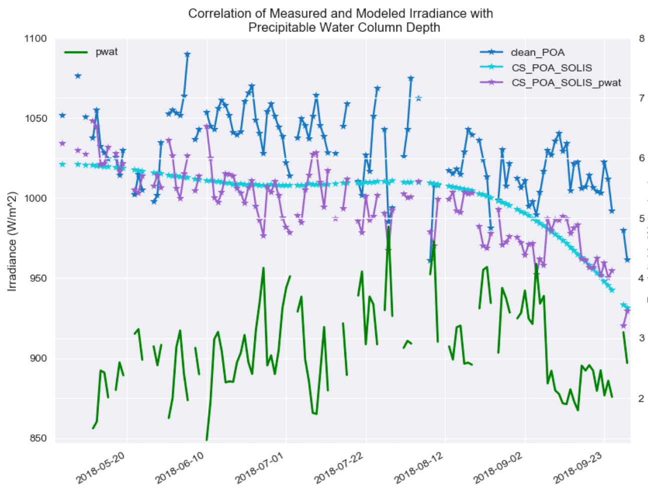

Fig. 5a. Variations in P_{wat} compared to the clean reference cell measurements (blue) and two SOLIS model results - one with fixed P_{wat} (cyan) and one with varying P_{wat} (purple) at UC Merced.

Fig. 5a. shows that the clean reference cell irradiance data (blue) is more highly correlated with the SOLIS model using variable P_{wat} (purple) than the SOLIS model using a fixed P_{wat} value of 2.5cm (cyan). This is consistent with the calculated correlation coefficients in Table 1. Figure 5a also shows that the clean reference cell data and SOLIS with varying P_{wat} seem to be negatively correlated with P_{wat}.

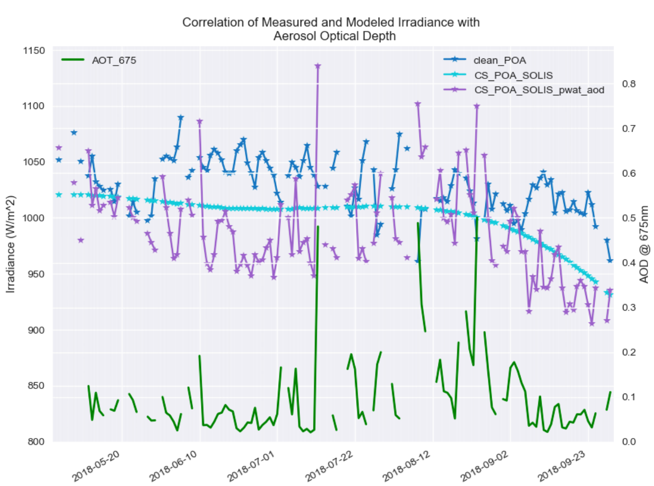

Fig. 5b. Variations in AOD compared to the clean reference cell measurements (blue) and the two SOLIS model results - one with fixed AOD (cyan) and one with varying AOD (purple) at UC Merced.

III. Results

TABLE I

Comparison Of Various Modeled Irradiances to the Measurements from the Clean Reference Cell After Filtering as Described in II-C.

UC MERCED

Model	Corr. Coef.	pValue
Satellite	0.70	1.7e-18
SOLIS variable P_{wat}, fixed AOD	0.67	4.2e-17
SOLIS fixed P_{wat}, fixed AOD	0.50	5.6e-09
Haurwitz	0.41	4.8e-06
Ineichen	0.40	5.0e-06
SOLIS variable P_{wat}, variable AOD	-0.05	5.9e-01

UC RIVERSIDE

Model	Corr. Coef.	pValue
Satellite	0.64	4.9e-15
SOLIS variable P_{wat}, fixed AOD	0.56	4.1e-11
Ineichen	0.49	2.7e-08
Haurwitz	0.48	3.8e-08
SOLIS fixed P_{wat}, fixed AOD	0.33	2.8e-04
SOLIS variable P_{wat}, variable AOD	0.21	2.2e-02

Table 1 shows that the satellite data, closely followed by the SOLIS model with variable P_{wat} were the first and second most highly correlated to the clean reference cell data at both locations in this study. The size of the variability with P_{wat} is consistent with modeling done in SMARTS2 to evaluate the impact of varying P_{wat} and AOD, that shows for ranges experienced at this location, irradiance is expected to vary by up to 5% due to P_{wat}, but by less than 1% due to AOD. See Fig.

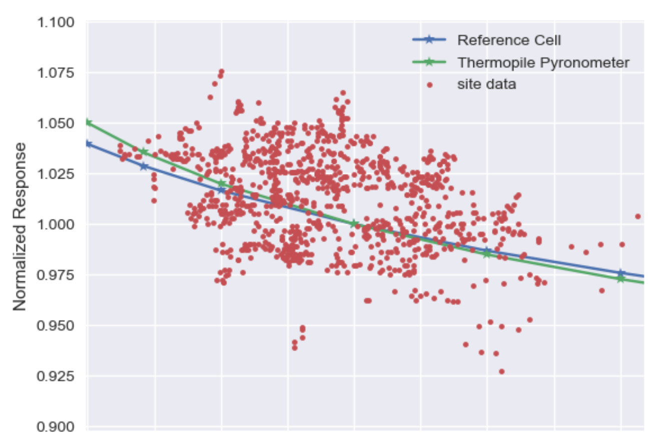

Fig. 6a. The modeled effect of P_{wat} on thermopile and reference cell irradiance overlaid with actual data from UC Merced.

6., which appears to reflect both the modeled trends and additional, unexplained variability from an uncontrolled parameter.

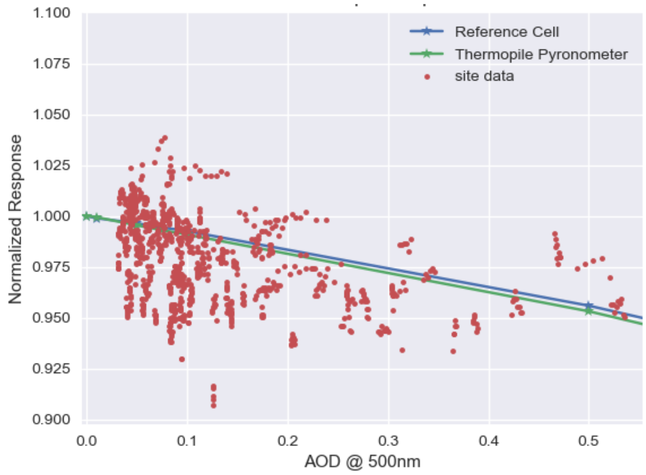

Fig. 6b. The modeled effect of AOD on thermopile and reference cell irradiance overlaid with actual data from UC Merced.

SMARTS2 suggests that irradiance should be correlated to P_{wat}. This was confirmed at both locations where using P_{wat} calculated from relative humidity to model clear sky irradiance using SOLIS improved the results seen in Table 1, above, and Figure 7, below. To the contrary, plugging AOD data at 700nm from Aeronet into the SOLIS model made it much worse. The actual site data reveals that there is no consistent variation of irradiance with AOD across a wide range of values.

Figure 6 also shows that spectral mismatch between the measured irradiance sensor data and broadband irradiance models is not an issue since their response appears to deviate by less than 0.5% for this location during the range considered.

IV. Discussion and Conclusions

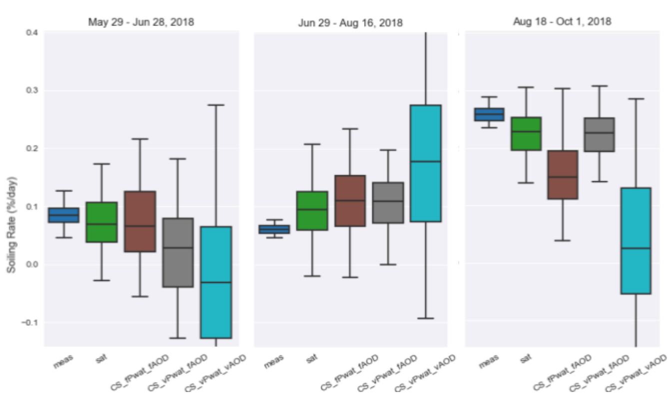

Fig. 7a. Comparison of soiling rates calculated for the dirty irradiance sensor using different models and measurements of irradiance at UC Merced.

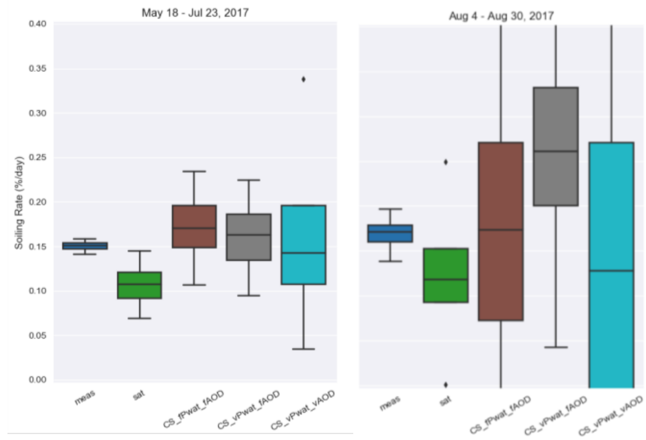

Fig. 7b. Comparison of soiling rates calculated for the dirty irradiance sensor using different models and measurements of irradiance at UC Riverside.

At UC Merced, we see that the true soiling rates measured in the first two soiling periods were around 0.07-0.09%/day, but for the third period in the fall it jumped to 2.5x that value. We suspect this to be due to almond harvesting season which runs from August to October in Merced. This kind of dramatic change in soiling rate at different times of the year has also been noted by M. Gostein et. al. [11] at other locations. At UC Riverside, on the other hand, the true soiling rate measured only varied from 015%-0.17%/day from one period to the next within the same year.

Consistent with the results in Table 1 for which irradiance model most accurately described the onsite reference cell, we find that the sensor soiling rates calculated using the satellite data to be the closest to the true sensor soiling rate, and the rates calculated using the SOLIS model with variable P_{wat} to be the second best for two of the three soiling periods in 2018 at UC Merced. However, at UC Riverside the soiling rates calculated with the SOLIS model are closer to the true rate measured than those derived from the satellite data. Although the uncertainty in those rates are higher than those calculated with the satellite data. The high uncertainty in the rates during the second soiling period at UC Riverside is an indication that there was insufficient good data points used in calculating the rate.

Again, we see that, for both locations studied, the AOD data made the models worse, in this case resulting in much higher uncertainties in the soiling rate estimates. This worsening of the clear sky models with the addition of AOD may be a result of the poor data quality attained at locations that were 50-70km away from the sites.

In four of the five periods analyzed, the uncertainty in the soiling rate when calculated using the satellite data was lower than that calculated with one of the clear sky models, even if the rate was in some instances further off. This is to be expected since Solargis are likely using a lot more inputs in their models, such as varying albedo which is lacking in the clear sky modeling done in this study. However, the rate itself was less accurate than when calculated using the clear sky models at Riverside.

It is important to note that this method relies on there being enough clear sky intervals detected at the plant, of which there were for the two locations in California studied. Conveniently locations with clear sky intervals tend to correspond to places that suffer from soiling due to lack of precipitation and clouds.

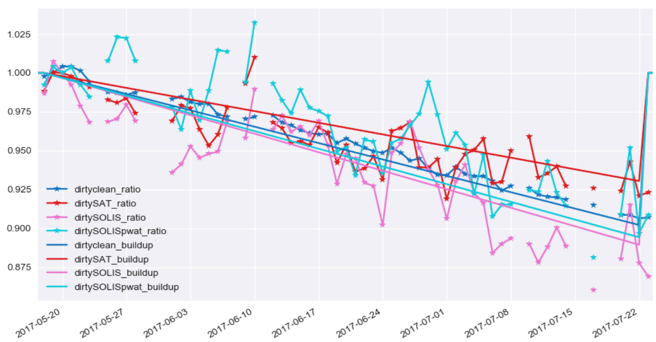

Fig. 8. Soiling ratios of the dirty reference cell to various un-soiled irradiances trending over time after normalization to a value of 1 at a known cleaning event on May 17th, 2017.

To get an estimate of the actual soiling level on any given day, one could either use the soiling level directly from the soiling ratio or use the rate multiplied by the number of days since the sensor last known to be clean. Fig. 8. shows for one soiling period how the daily soiling ratio compares to that derived from rates, and how each of these compares to the actual true soiling level shown as the dark blue line in the same figure.

The error in the daily soiling ratio appears to vary a lot more day to day than a soiling ratio derived from the rate. This is expected as there is a lot of uncertainty in daily estimates of insolation versus longer term averages for the satellite data and the clear sky models. Fig. 9. shows the overall root mean squared error for each period tends to be lower when using the rate to estimate the soiling ratio instead of using the soiling ratio directly. It also shows that in most cases the satellite data had a lower RMSE than when using the SOLIS with fixed or variable P_{wat} and that using SOLIS with variable P_{wat} tended to have a lower RMSE than when using a fixed value.

Which method to use for estimating the actual daily soiling level will depend on the particular application. If there has not been long enough of a dry period to confidently estimate the soiling rate, or if concerned about sudden soiling/cleaning events being common at a particular location, then it might be best to use the soiling ratio directly. On the other hand, if looking to the future to estimate when to next clean a dirty irradiance sensor or even PV array, using the rate with a precipitation forecast would be the better approach. However,

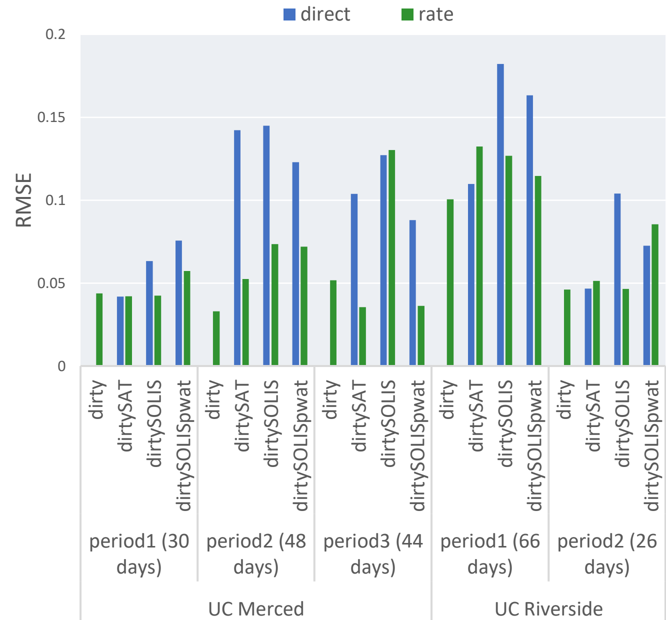

Fig. 9. The root mean squared error calculated by comparing the soiling ratios illustrated in Fig. 8. to the true soiling ratio for each of the five soiling periods analyzed in this study.

projecting soiling losses forward with historical rates may be problematic in some locations such as UC Merced where the soiling rate more than doubled from one period to the next due to agricultural activity.

Finally, we conclude that given the data sets considered, choosing to use purchased satellite irradiance data to estimate the irradiance of a reference cell sensor tends to yield the most accurate results, although there were some instances where a clear-sky model was better for estimating the soiling rate of the sensor. If cost is an important factor, the SOLIS clear-sky model in PVLIB with variable P_{wat}, which can be calculated from readily available ambient temperature and relative humidity, can also be used for estimating the soiling of a reference cell irradiance sensor.

References

[1] M. Gostein, K. Passow, M. Deceglie, L. Micheli, B. Stueve. "Local Variability in PV Soiling Rate" in *45th IEEE Photovoltaic Specialists Conference,* 2018.
[2] W. F. Holmgren, R. W. Andrews, A. T. Lorenzo, and J. S. Stein, "PVLIB Python 2015," in *42nd IEEE Photovoltaic Specialists Conference,* 2015, pp. 1–5.
[3] P. Ineichen and R. Perez, "A new airmass independent formulation for the Linke turbidity coefficient," in *Sol. Energy*, vol. 73, no. 3, pp. 151–157, Sep. 2002.
[4] F. Linke, "Transmissions-Koeffizient und Trubungsfaktor," *Beitrage zur Phys. der Atmosphare*, vol. 10, pp. 91–103, 1922.
[5] P. Ineichen, "A broadband simplified version of the Solis clear sky model," *Sol. Energy*, vol. 82, no. 8, pp. 758–762, 2008.

[6] W. M. Keogh and A. W. Blakers, Accurate Measurement, Using Natural Sunlight, of Silicon Solar Cells, Prog. in Photovoltaics: Res. and Appl. 2004, vol 12, pp. 1-19 (DOI: 10.1002/pip.517)
[7] Reno, M.J. and C.W. Hansen, "Identification of periods of clear sky irradiance in time series of GHI measurements" in *Renewable Energy, v90*, p. 520-531, 2016
[8] Muller, M., L. Micheli, and A.A. Martinez-Morales. "A Method to Extract Soiling Loss Data from Soiling Stations with Imperfect Cleaning Schedules", in *NREL/CP-5J00-67225*, 2017.
[9] M. G. Deceglie, M. Muller, Z. Defreitas, S. Kurtz, "A scalable method for extracting soiling rates from pv production data", in *43rd IEEE Photovoltaic Specialists Conference*, 2016, pp. 2061-2065..
[10] M. Mikofski, C. Hansen, W. F. Holmgren, G. M. Kimball "Use of Measured Aerosol Optical Depth and Precipitable Water to Model Clear Sky Irradiance," in *44th IEEE Photovoltaic Specialists Conference*, 2017.
[11] "A Quick Derivation relating altitude to air pressure" from Portland State Aerospace Society, Version 1.03, 12/22/2004.
[12] I. Reda and A. Andreas. "Solar position algorithm for solar radiation applications" in *Solar Energy, vol. 76,* no. 5, pp. 577-589, 2004.

Acknowledgement

This work was authored in part by Alliance for Sustainable Energy, LLC, the manager and operator of the National Renewable Energy Laboratory for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under Solar Energy Technologies Office (SETO) Agreement Number 34348. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.