Soiling and Irradiance Measurements in Bifacial Systems Using In-Situ Module I-V and Rear-Side Reference Cells

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***Abstract* – We performed an 11-month field test to examine soiling and irradiance measurements in a bifacial PV system. We demonstrate two methods, denoted "module-module" and "module-cell", of determining soiling ratio – the ratio of actual power to expected power under clean conditions – using soiled module power measurements. In both methods we use in-situ module I-V measurement to directly measure power output of a soiled reference module within the plant, yielding the numerator of soiling ratio. In the module-module method, for the denominator of soiling ratio, the expected module power, we use measurements from another reference module that is routinely cleaned. In the module-cell method, for the denominator we use module power estimated from front and rear-side cleaned reference cells. We find that the total irradiance calculated from the combination of front and rear reference cells correlates well with the module short-circuit current and maximum power. Furthermore, we find that the module-module and module-cell soiling ratio measurement methods produce nearly identical results during the field test. These results support using automatically washed or soiling-compensated reference cells instead of full-size modules as a clean reference, simplifying instrumentation and operations and maintenance requirements.**

***Index Terms* – photovoltaic (PV) systems, soiling, irradiance, bifacial PV**

I. INTRODUCTION

PV soiling losses are quantified by the soiling ratio (*SR*), the ratio of actual PV power output to expected output under clean conditions [1]. In-situ module-level I-V measurement units now provide [2][3] the ability to directly measure maximum power of soiled power-producing modules, the numerator of *SR,* while they are still connected to a PV array, eliminating the need for standalone reference modules. Expected power, the denominator of *SR*, can be determined either by using clean modules identical to the soiled modules [4] ("module-module") or by using periodically cleaned reference cells [5] ("module-cell"). Using in-situ module I-V allows quantification of actual power losses due to soiling, which can only be determined with I-V measurements due to the effects of non-uniform soiling on module power losses and the potential for module coatings and frames to affect dust accumulation patterns [4][5][6][7].

For bifacial PV systems, measurement of soiling ratio based on measured soiled module power is more challenging than for monofacial systems. To compute the denominator of *SR*, a module's expected power when clean must be determined considering the impact of total irradiance including contributions from both front and rear sides. In the module-module approach, a clean module identical to the soiled module must be used, with care taken to ensure rear-side irradiance contributions are identical between soiled and clean modules. Factors to consider include position within a module row, albedo variations, and variations in structural shading [8][9]. In the module-cell approach, reference cells should be positioned on both the front and rear sides of the module, and rear-side reference cells should be placed in optimal locations for measuring average rear-side irradiance across the module area, as in [9][10].

Conceptually, the module-module approach is simple and easily understood, since it compares modules otherwise identical except for cleanliness state. However, routine cleaning of a full-size clean reference module is a burden for busy operations and maintenance (O&M) personnel, leading to irregular or infrequent cleaning schedules. In contrast, cleaning small reference cells for the clean reference in the module-cell approach is relatively easy and similar to other common sensor cleaning procedures performed by O&M staff. Furthermore, cell cleaning can easily be automated using an automatic reference cell washing system [11] or even eliminated and replaced with compensation by an optical soiling sensor [12].

In this work we report on our 11-month field study of soiling and irradiance measurement in a bifacial PV system using in-situ I-V measurements together with front and rear-side reference cells. We evaluate both module-module and module-cell methods for normalizing soiled module power to clean expectations based on total front plus rear-side irradiance contributions, with an aim to demonstrate effective and practical normalization methods for total irradiance contributions.

II. EXPERIMENT

Measurements were performed from June 2023 to May 2024 at a utility-scale single-axis tracking bifacial PV power plant operated by EDF Renewables in North America.

Fig. 1 depicts the instrumentation setup.

Two modules in the array were selected for measurement. One of these was designated as "clean" and the other as "soiled". In-situ I-V measurement units (RDE300i), shown in Fig. 1 and. Fig 2, periodically measure I-V sweeps on each

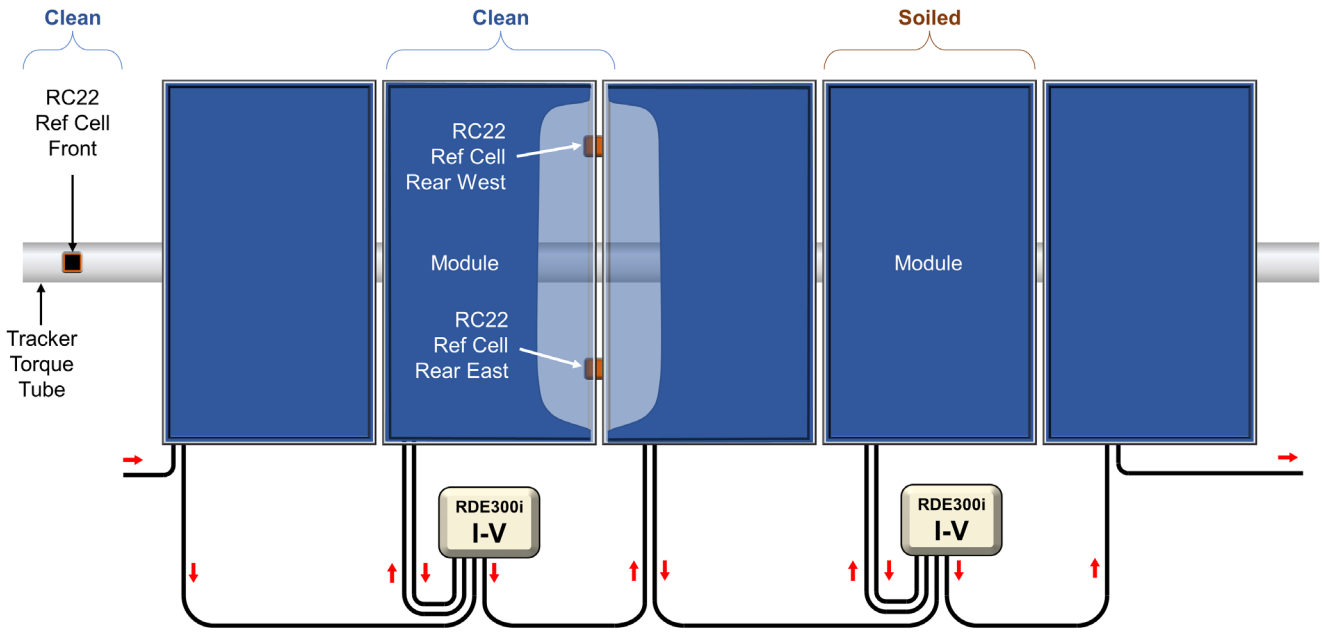


Figure 1: Equipment setup in single-axis tracking bifacial PV array, with in-situ I-V of clean and soiled modules and front and rear reference cells for total effective irradiance. In actual installation, clean/soiled modules are five modules from torque tube end.



Figure 2: Left: front-side RC22 reference cell. Middle: in-situ I-V unit (RDE300i) mounted beneath module racking. Right: rear-side reference cells (RC22), mounted compactly within the module frame area.

module during short time slices and determine standard I-V parameters, including short-circuit current (I_{sc}) and maximum power (P_{max}). In between I-V measurements the modules remain connected to the array and power-producing. Each RDE300i unit includes a back-of-module Pt1000 RTD affixed to the module rear side for temperature measurement.

To ensure that the clean and soiled modules see equal levels of ground-reflected irradiance, both modules are located at least five modules from the end of the torque tube, minimizing discrepancies in ground illumination [9].

Three bifacial-optimized PV reference cells (RC22) measure irradiance, as shown in Fig. 1. A single cell designated "front" measures irradiance in the front plane of array (POA) while two cells, designated "rear east" and "rear west", are mounted on the rear frame of the designated clean module and measure rear POA irradiance, as shown in Fig. 1 and Fig. 2. The

rear cells are positioned about 50% of the way between the module edges and the torque tube, as recommended in [8]–[10].

The clean module and all three reference cells are cleaned approximately every 2 weeks by site O&M staff. The cleaning schedule was adequate due to the very low rate of soiling at the site, which is also beneficial towards our goal of detecting any drift in the measurements with respect to normalization for total front plus rear irradiance.

III. Equations

We calculate soiling ratio as the ratio of the measured power of the soiled module to its expected power when clean, using the formula

$$SR = \frac{P_{\text{max}}^{\text{soiled}}}{P_{\text{max},0}^{\text{soiled}} \cdot \left(1 + \gamma \cdot (T^{\text{soiled}} - T_0)\right) \cdot (G_{\text{tot}}/G_0)} \qquad (1)$$

where $P_{\text{max}}^{\text{soiled}}$ is the maximum power of the soiled module determined from its I-V curve, $P_{\text{max},0}^{\text{soiled}}$ is the calibrated maximum power of the soiled module when it is completely clean and at reference conditions of irradiance and temperature, γ is the module's maximum power temperature coefficient, T^{soiled} is the module's measured temperature, T_0 is the reference condition temperature, G_{tot} is the total effective front plus rear POA irradiance, and G_0 is the reference condition irradiance. Here "reference condition" refers to an irradiance and temperature for calibration and could mean standard test conditions (STC), bifacial standard test conditions (BSTC), or another condition such as a field calibration condition.

The module-module and module-cell methods differ in how G_{tot} for eq. (1) is determined.

In the module-module method, we use the clean module's I_{sc} to estimate the effective G_{tot} seen by the soiled module, by the formula

$$G_{\text{tot}} = \frac{I_{\text{sc}}^{\text{clean}}}{I_{\text{sc},0}^{\text{clean}} \cdot \left(1 + \alpha \cdot (T^{\text{clean}} - T_0)\right)} \cdot G_0 \qquad (2)$$

where $I_{\text{sc}}^{\text{clean}}$ is the clean module's measured short-circuit current, $I_{\text{sc},0}^{\text{clean}}$ is the clean module's calibrated short-circuit current at the reference condition, α is the module's short-circuit current temperature coefficient, and T^{clean} is the clean module's temperature. Note that eq. (2) includes the contribution of both front and rear POA irradiance since both contribute to the module's I_{sc}.

In the module-cell method, we use the three reference cells to estimate the average total effective irradiance illuminating the soiled module from front and rear, according to the formula

$$G_{\text{tot}} = G_{\text{front}} + \varphi \cdot \left(G_{\text{rear,E}} + G_{\text{rear,W}}\right)/2 \qquad (3)$$

where G_{front} is the irradiance measured by the front reference cell, $G_{\text{rear,E}}$ and $G_{\text{rear,W}}$ are the irradiances measured by the rear east and west cells, and φ is the PV module bifaciality factor.

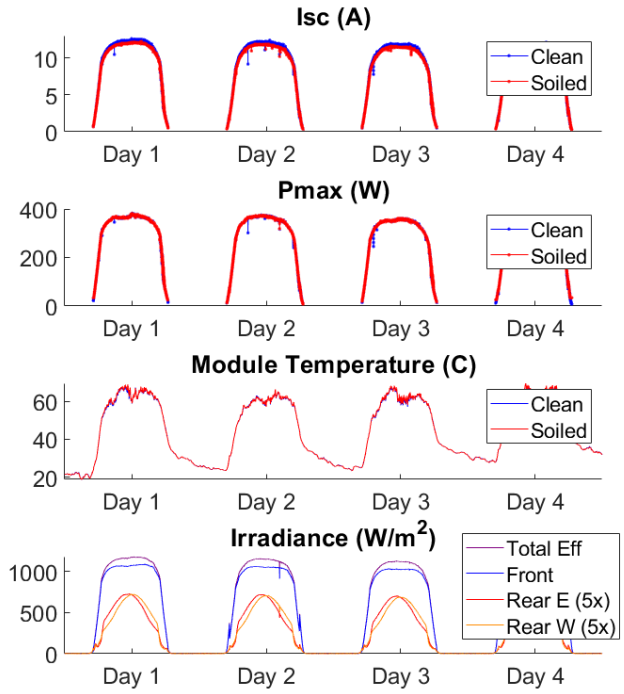


Fig. 3: Representative multi-day period, showing I_{sc}, P_{max} and temperature of the designated soiled and clean modules and irradiance readings from the three reference cells.

Averaging the two rear-side cells allows for estimating the average irradiance across the module's rear plane [8]–[10]. The bifaciality factor φ appears in eq. (3) to account for the lower responsivity of the module to rear side light relative to front side light.

IV. Results

A. Example Time Series Data

Fig. 3 depicts example time series data recorded over a four-day period. Recorded parameters include the I_{sc}, P_{max}, and temperature of each of the modules and the front and rear reference cell irradiance readings. The reference cell readings are added per eq. (3) to compute total effective irradiance. Note that the rear reference cell readings are scaled by 5x for better visibility in the plot. The figure shows that the two modules have nearly identical electrical output, I_{sc} and P_{max}, and that their output profiles generally match the profile of the reference cell total effective irradiance, with some minor exceptions discussed further below.

B. Module Output vs. Measured Total Effective Irradiance

To examine the correlation between reference cell and module total effective irradiance, we compared the normalized ratios of the temperature-corrected clean module I_{sc} and P_{max} to the reference cell total irradiance per eq. (3) over a representative clear sunny day. During the middle ~6 hours of

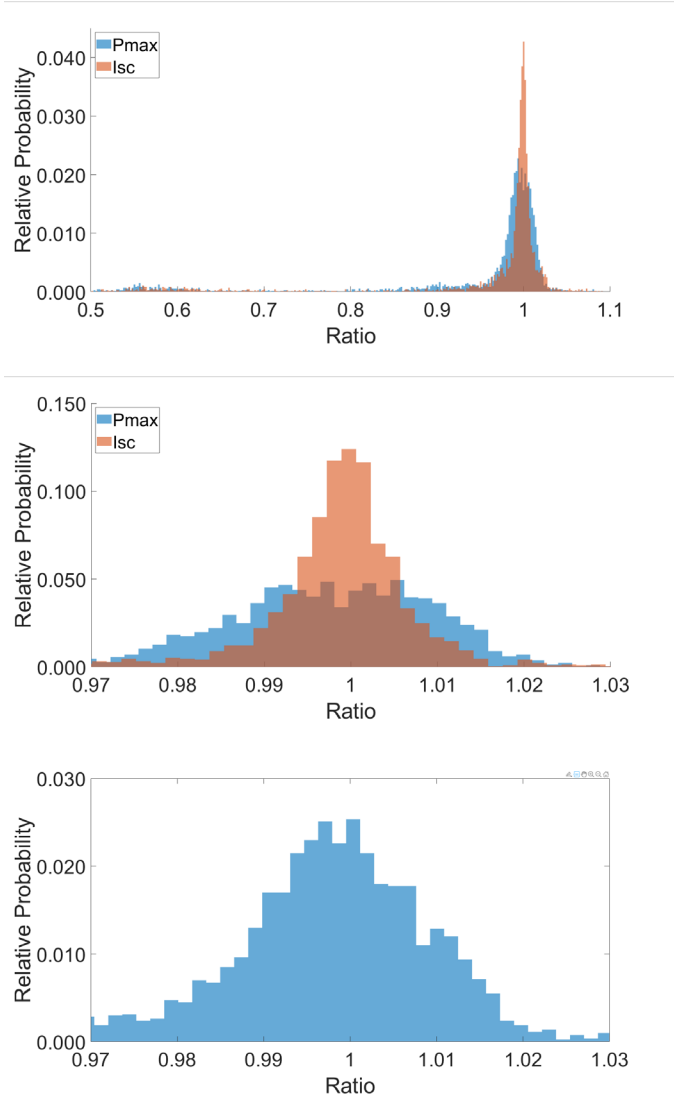


Fig. 4: Analysis of the relationship between total effective irradiance measured by the reference cells and the clean module electrical output over an 11-month period. Top panel: distribution of ratios of temperature-corrected I_{sc} and P_{max} to reference cell total irradiance. Middle panel: focused on data within 3 hours of noon, highlighting good agreement between I_{sc} ratio and total irradiance (SD=0.7%). P_{max} ratio shows more spread (SD=1.8%) due to factors beyond irradiance. Bottom panel: reinforces conclusions on middle panel by showing a similar distribution for the ratio of P_{max} to I_{sc} during midday (SD=1.6%).

the day the ratios are relatively constant (<0.5-1% variation), showing that the reference cell total irradiance profile well represents the module output in this time range, and that I_{sc} and P_{max} are proprtional to each other and to total irradiance.

Outside this time window, the ratios deviate by ~1-5% or more, especially early and late in the day. We attribute this to several factors. Most significantly, at high tracker angles that occur just after sunrise and before sunset, the tracker was intentionally operated with row-to-row shading to maximize power output by minimizing solar angle of incidence, which causes a deviation between module performance and effective irradiance over the module area as measured by the cells. In addition, we determined that a slight angular misalignment of the front-side reference cell resulted in significant deviations in the proportionality between measured front-side irradiance and module performance when angle of incidence was high. Non-uniformity of rear-side irradiance at high tracker angles could also contribute to the observed deviations in module performance versus total irradiance during early and late hours of the day.

Fig. 4 presents a statistical analysis of the proportionality between the total effective irradiance measured by the combination of the three reference cells, using eq. (3), and the module performance measured by the temperature-corrected I_{sc} and P_{max} of the clean module.

The top panel shows histograms of the distribution of the normalized ratios of temperature-corrected I_{sc} and P_{max} to the total effective irradiance from the reference cells, calculated for hourly-averaged periods over the entire 11-month data set. Note that while most of the data fall in the bins near 1.0, there is also a group of readings in the bins near 0.5 that arise from the periods of row-to-row shading at high tracker angles, as explained above, and a tail of readings between 0.8 and 1.0 arising from the other effects mentioned above.

The middle panel shows the same results but filtered to include only readings within three hours of noon. The standard deviation of the I_{sc} ratio distribution is 0.7%, indicating that the effective irradiance measured by the combination of the three reference cells well represents the module effective irradiance (quantified by its temperature-corrected I_{sc}, see eq. (2)), within the central hours of the day. The P_{max} ratio distribution is somewhat broader with standard deviation of 1.8%, indicating that there are additional sources of variance in the module power besides total irradiance. Possible sources of this variance include non-linearity of module efficiency versus irradiance, non-uniformity of irradiance, and non-linearity of temperature correction.

As a check, in the bottom panel we show the distribution of the ratio of temperature-corrected P_{max} to temperature-corrected I_{sc} for the same filtered period within three hours of noon. The width of this distribution, with standard deviation of 1.6%, accounts for most of the width of the P_{max} distribution in the middle panel. This supports the conclusions discussed above regarding the width of the P_{max} distribution in the middle panel being likely caused by factors other than variations in average irradiance measured by the cells.

Togehter these results show the ability of the combination of reference cells to measure the total effective irradiance determining module performance with good precision, at least during the central period of the day.

C. Soiling Ratio Results

Fig. 5 shows daily average soiling ratios calculated for the module-module and module-cell methods over the 11 months

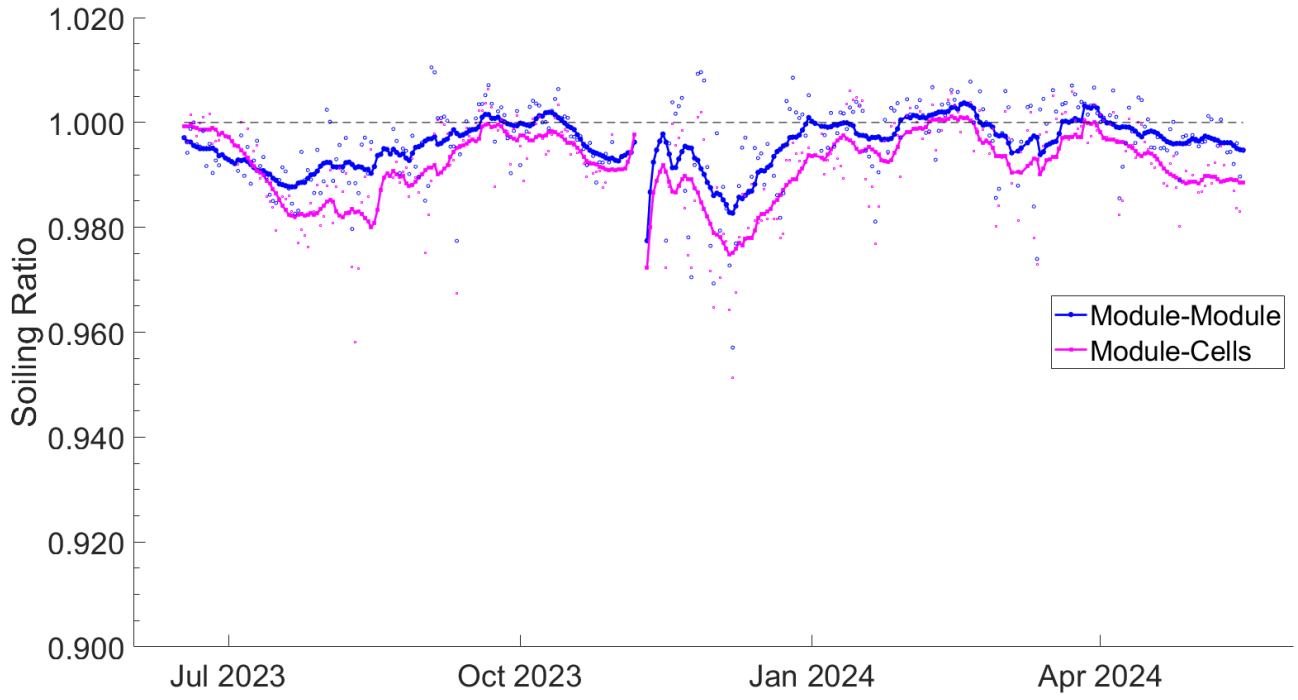


Fig. 5: Daily soiling ratios for both module-module and module-cell measurement methods. Both methods show good agreement throughout the period. Deviations likely arise from cloudy days or limited filtered data points.

of the study. The data set has two gaps when equipment was offline.

To calculate the daily average soiling ratios, we use eq. (1), substituting either eq. (2) (module-module) or eq. (3) (module-cell) for G_{tot}, separately averaging the numerator and denominator of eq. (1) over the time points in a 24-hour period prior to calculating a daily average ratio. The data were filtered by two conditions: only points within ~3 hours of noon and with irradiance exceeding 500 W/m^2 were included in the analysis. The filter for points within ~3 hours of noon was implemented by requiring agreement between the two rear-side irradiance sensors within a target threshold, eliminating the need for time synchronization.

Daily average soiling ratios were normalized to 1.00 on a selected clear-sky day near the start of the study period.

Points in Fig. 5 are daily values for soiling ratio and solid lines are smooth curves generated with a sliding 7-day smoothing window.

Results in Fig. 5 show that the soiling ratio values calculated using either the module-module or module-cell methods agree well with each other, within less than ~1%, over the entire period. We believe deviations on some days, as well as overall fluctuations in both metrics, are associated with cloudy days when irradiance was unstable or when there were few points passing the filter conditions, leading to noisier results. We continue to investigate these issues to optimize filtering.

Note that the soiling ratio values remained close to 1.00 during the study period, meaning that we did not observe much soiling at this site, which has a very low soiling rate. However, our aim here is not necessarily to detect soiling but to assess uncertainties in the soiling ratio measurements based on ability to account for the combined front and rear irradiance using different methods. For this purpose, large soiling losses are not required.

V. CONCLUSIONS

This study investigated methods for measuring soiling and irradiance in bifacial photovoltaic (PV) systems using in-situ I-V measurements. We compared two techniques for normalizing module performance against irradiance variation: using a full-size clean reference module (module-module) versus using a combination of clean reference cells (module-cell).

Results show that both methods of accounting for total irradiance yielded very similar results when used as the normalization in a soiling ratio calculation, suggesting that reference cells can be a viable alternative to using full-size clean modules. This approach simplifies instrumentation and maintenance by eliminating the need for routine cleaning of a large reference module.

Using a combination of reference cells, with one front plus two rear-side cells, was found to accurately measure the total effective irradiance during central daylight hours. However, in our study the correspondence between reference cell total irradiance and module performance deviated during early and

late hours of the day when tracker tilt angle was high, due to module row-to-row shading, sensitivity to sensor alignment, and other factors.

Overall, the study demonstrates that using a combination of front and rear reference cells to measure total effective irradiance in a bifacial PV system is an effective way of normalizing module performance against irradiance variation. By pairing this approach with in-situ I-V measurements for soiled module power, actual power loss due to soiling accumulations can be effectively measured while achieving the benefits of simplified operations and maintenance associated with cleaning of small reference cells versus full-size reference modules. We note that small reference cells are easily cleaned by operations and maintenance staff and that cleaning could also be automated or replaced with compensation by an optical soiling sensor.

Our conclusions on the use of reference cells for irradiance normalization in soiling measurement can be extended to other types of performance measurements, such as capacity, energy, and performance ratio tests and long-term degradation studies.

VI. ACKNOLWEGEMENTS

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VII. REFERENCES

[1] "IEC 61724-1 Ed. 1.0 en:2017 - Photovoltaic system performance - Part 1: Monitoring."

[2] J. E. Quiroz, J. S. Stein, C. K. Carmignani, and K. Gillispie, "In-situ module-level I-V tracers for novel PV monitoring," 2015 IEEE 42nd Photovolt. Spec. Conf. PVSC 2015, Dec. 2015, doi: 10.1109/PVSC.2015.7355608.

[3] A. Marquis, M. Gostein, and B. H. King, "Validation of In-Situ I-V Measurement Unit for PV System Monitoring Applications," in 2022 IEEE 49th Photovoltaics Specialists Conference (PVSC), Nov. 2022, pp. 0291–0294, doi: 10.1109/PVSC48317.2022.9938898.

[4] M. Gostein, T. Duster, and C. Thuman, "Accurately measuring PV soiling losses with soiling station employing module power measurements," 2015 IEEE 42nd Photovolt. Spec. Conf. PVSC 2015, Dec. 2015, doi: 10.1109/PVSC.2015.7355993.

[5] S. Kagan et al., "Impact of Non-Uniform Soiling on PV System Performance and Soiling Measurement," 2018 IEEE 7th World Conf. Photovolt. Energy Conversion, WCPEC 2018 - A Jt. Conf. 45th IEEE PVSC, 28th PVSEC 34th EU PVSEC, pp. 3432–3435, Nov. 2018, doi: 10.1109/PVSC.2018.8547728.

[6] Y. Cui, J. Xiao, J. Xiang, J. Sun, and E. M. Vitucci, "Characterization of Soiling Bands on the Bottom Edges of PV Modules," Front. Energy Res., vol. 9, no. April, pp. 1–7, 2021, doi: 10.3389/fenrg.2021.665411.

[7] M. Gostein, B. Littmann, J. R. Caron, and L. Dunn, "Comparing PV power plant soiling measurements extracted from PV module irradiance and power measurements," Conf. Rec. IEEE Photovolt. Spec. Conf., pp. 3004–3009, 2013, doi: 10.1109/PVSC.2013.6745094.

[8] M. Gostein et al., "Measuring Irradiance for Bifacial PV Systems," in 2021 IEEE 48th Photovoltaic Specialists Conference (PVSC), Jun. 2021, pp. 896–903, doi: 10.1109/PVSC43889.2021.9518601.

[9] C. Deline, S. Ovaitt, M. Gostein, J. Braid, J. Newmiller, and I. Suez, "Irradiance Monitoring for Bifacial PV Systems' Performance and Capacity Testing," vol. Submitted, 2024.

[10] N. Riedel-Lyngskar, M. Bartholomaus, J. Vedde, P. B. Poulsen, and S. Spataru, "Measuring Irradiance With Bifacial Reference Panels," IEEE J. Photovoltaics, Nov. 2022, doi: 10.1109/JPHOTOV.2022.3201468.

[11] M. Gostein et al., "Soiling measurement station to evaluate anti-soiling properties of PV module coatings," Conf. Rec. IEEE Photovolt. Spec. Conf., vol. 2016-November, pp. 3129–3131, Nov. 2016, doi: 10.1109/PVSC.2016.7750242.

[12] M. Gostein, W. Stueve, and S. Faullin, "Measuring soiling and non-uniform soiling of PV modules without a clean reference device," United States Patent 10,715,081, 2020.