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Effective Irradiance Monitoring Using Reference Modules

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Abstract*— We evaluate the use of reference modules for monitoring effective irradiance in PV power plants, as compared with traditional plane-of-array (POA) irradiance sensors, for PV monitoring and capacity tests. Common POA sensors such as pyranometers and reference cells are unable to capture module-level irradiance nonuniformity and require several correction factors to accurately represent the conditions for fielded modules. These problems are compounded for bifacial systems, where the power loss due to rear side shading and rear-side plane-of-array (RPOA) irradiance gradients are greater and more difficult to quantify. The resulting inaccuracy can have costly real-world consequences, particularly when the data are used to perform power ratings and capacity tests. Here we analyze data from a bifacial single-axis tracking PV power plant, (175.6 MW_{dc}) using 5 meteorological (MET) stations, located on corresponding inverter blocks with capacities over 4 MW_{dc}. Each MET station consists of bifacial reference modules as well pyranometers mounted in traditional POA and RPOA installations across the PV power plant. Short circuit current measurements of the reference modules are converted to effective irradiance with temperature correction and scaling based on flash test or nameplate short circuit values. Our work shows that bifacial effective irradiance measured by pyranometers averages 3.6% higher than the effective irradiance measured by bifacial reference modules, even when accounting for spectral, angle of incidence, and irradiance nonuniformity. We also performed capacity tests using effective irradiance measured by pyranometers and reference modules for each of the 5 bifacial single-axis tracking inverter blocks mentioned above. These capacity tests evaluated bifacial plant performance at ~3.9% lower when using bifacial effective irradiance from pyranometers as compared to the same calculation performed with reference modules.

Keywords—irradiance monitoring, reference module, capacity test, performance modeling, bifacial

I. Introduction

Irradiance monitoring has a few applications in real photovoltaic (PV) power plants. Most commonly, measured irradiance is used to perform long-term performance analysis and short-term capacity tests, wherein system energy yield is evaluated compared to performance guarantees from the developer or engineering, procurement, and construction company (EPC). Long-term irradiance measurements are used for operations and maintenance (O&M) performance monitoring to diagnose plant issues and schedule maintenance activities (e.g., cleaning). The irradiance measurement accuracy and system representativeness are incredibly important for these applications, to both system owners, EPCs, and O&M providers. However, the common use of point sensors to estimate the irradiance for the PV array causes inherent discrepancy in calculating the system energy yield.

Traditionally, plane-of-array (POA) irradiance sensors fall into two categories: pyranometers and reference cells. Pyranometers (photodiode or more often thermopile) are expensive but offer a flat absorption profile. However, they have a different spectral and thermal response than PV cells or modules. Reference cells consisting of an encapsulated silicon cell are better spectrally matched and offer lower measurement uncertainty compared to pyranometers [1], [2]. But as point sensors, both pyranometers and reference cells have inherent disadvantages for representing array-level irradiance. Point sensors can have installation differences from the modules in the array, such as different locations (e.g., on a weather station), tilt angle, and/or field of view. There can also be variability in the measured irradiance due to the device scale: a point sensor cannot capture the effects of irradiance gradients or partial shading on a module. This is especially problematic for bifacial PV arrays, where rear facing POA irradiance sensors cannot capture the spatial variation of irradiance that commonly occur on the back of the module [3]. Furthermore, spectral albedo can be of great consequence when coupled with the differences in spectral response of rear-facing pyranometers vs. reference modules [4].

To combat these disadvantages, we explore the use of reference modules for PV array irradiance monitoring. Broadly, this method uses I-V curves measured *in situ* on a module installed and located within the array. Lab characterization data of the same module (or nameplate values), along with module temperature, are used to convert the measured short circuit current (I_{SC}) to effective irradiance. We hypothesize that this

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method alleviates issues with traditional irradiance sensors including spectral and temperature mismatch, installation and fielding differences, irradiance variability related to scale, and issues with measuring effective irradiance for bifacial systems.

II. Methods

A. Dataset

Data for this study were provided by SOLV Energy and consist of 8 days of data from the utility-scale bifacial single-axis tracking PV power plant, recorded during the capacity testing phase shortly after commissioning. For this study, we examine the 5 inverters and their corresponding co-located weather stations. Each of these 5 stations has a monofacial and a bifacial reference module, 1 forward facing and 1 rear facing SR30 pyranometer, as well as windspeed and ambient temperature sensors. The rear facing pyranometers are mounted on the underside of the torque tube, 3 modules interior from the north end of the row. Reference module electrical and back-of-module temperature measurements were taken with an Atonometrics RDE300. All weather parameters are measured by LUFFT WS500.

B. Reference module irradiance monitoring approach

Previous studies using reference modules have used continuous I_{SC} measurements [5]. For the reference module method to accurately represent the conditions in the field, our approach uses a module physically located within the array (electrically isolated from the production modules within the array), connected to a RDE300 device which measures I_{SC} and an I-V curve at regular intervals. While nameplate coefficients may be used, the reference module should be characterized in a laboratory to determine the temperature coefficient for current (α) and 1-sun I_{SC}. Then outdoor I_{SC} measurements can be corrected with concurrent module temperatures and used to determine the effective irradiance for the array by:

$$E_e = 1000W/m^2 * \frac{I_{SC-m}}{I_{SC-1sun}} / \left(1 + \alpha\left(T_{ref} - T_m\right)\right)$$

where I_{SC-m} is the measured I_{SC}, T_{ref} is the reference temperature, usually 25 °C, and T_m is the measured module temperature. Temperature correction could also be performed using V_{OC} determined module temperature with necessary calibration.

C. Pyranometer irradiance monitoring approach

The use of pyranometers to monitor POA irradiance is well established for monofacial systems. Thermopile pyranometers have a flat absorption profile, so the measured irradiance is ~3% higher than that of a PV device and does not require temperature correction. In this work, our front side pyranometer measurements were spectrally corrected using the airmass spectral correction implemented through *pvlib-python* [6], and the angle of incidence response measured on the specific module model in the field (Fig. 1).

The current standard for irradiance monitoring of bifacial systems lacks detail on positioning and corrections necessary for measurement accuracy [7]. Waters et al. [8] suggest scaling the measured rear side POA irradiance by the module bifaciality constant and adding the front side POA to obtain the total irradiance. Gostein et al. [3] suggested that the bifaciality constant could be expanded to account for rear side shading and irradiance non-uniformity, and that additional factors could be used for spectral, angular, and mismatch losses. For the analysis

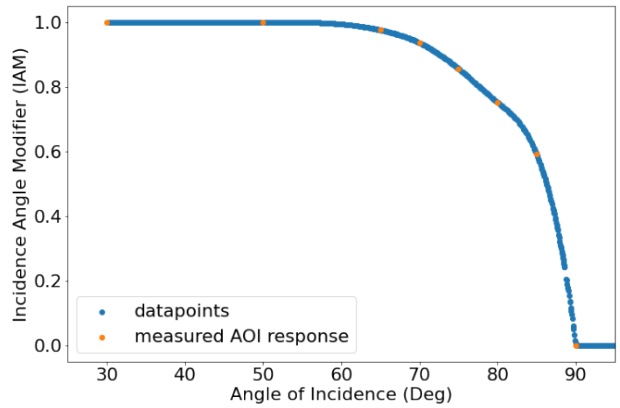

Fig. 1: Measured and interpolated front side angle of incidence response for the fielded modules in this study.

presented here, we scaled the front side POA according to the incidence angle modifier [9] to account for module reflective losses.

For the rear facing pyranometers in this work, the rear side POA was scaled using the tracker torque tube manufacturer's reported shading factor (0.123), and the modules' bifaciality constant (0.7).

D. Capacity test comparison

To compare pyranometer and reference module irradiance measurements for use in a real-world application, we performed capacity test regression according to ASTM E2848 [10], implemented with the python package *pvcaptest* [11], using each effective irradiance measurement method. This procedure filters the power and irradiance data for range (200 to 2000 W/m^2) and outliers, then uses multilinear regression to model measured system power as a function of irradiance, ambient temperature, and windspeed. Then the parameters determined via multilinear regression are used to predict the system output at a reference condition determined based on the range of available data, also according to the ASTM E2848 standard. After performing this regression and evaluation on measured data, it is repeated on modeled power data, here using PVWatts [12]. The last step of the capacity test is to calculate the ratio of the measured power and modeled power regressions evaluated at the reference condition, which is here referred to as the capacity ratio.

III. Results

Here we compare effective irradiance measurements made with pyranometers and reference modules and evaluate their effects on capacity test results for 5 bifacial PV systems.

A. Pyranometer vs. reference module effective irradiance

First, we directly compare effective irradiance measured by thermopile pyranometer and reference module for a monofacial configuration. Because this site has monofacial reference modules in addition to bifacial reference modules for all 5 inverters, we can directly compare these front side POA irradiance measurements. The linear regression for one such

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comparison is shown in Fig. 2. For all 5 weather stations, the pyranometer measured effective POA irradiance is 2.6-3.7% higher than that measured by monofacial reference module (measured by linear regression), after accounting for spectral and angle of incidence corrections.

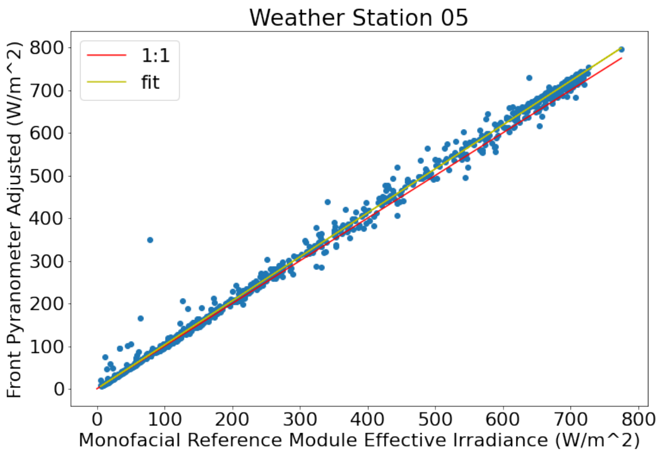

Fig. 2: Linear regression of effective irradiance calculated from monofacial reference module vs. POA irradiance measured by front-facing pyranometer. R2=0.995, slope = 1.031, with intercept fixed at the origin.

Next we compare bifacial effective irradiance as measured by forward and rear facing pyranometers to that measured by bifacial reference module. Rear facing pyranometer measurements were adjusted based on module bifaciality and torque tube shading factor, in addition to spectral corrections also applied to the forward facing pyranometer. Only the forward facing pyranometer had angle of incidence correction. For all 5 weather stations, the bifacial effective irradiance averaged 3.6% higher when measured with a pair of pyranometers than when measured by bifacial reference module. The pyranometers irradiance overreporting percentages are given in TABLE II.

TABLE I. BIFACIAL EFFECTIVE IRRADIANCE PERCENT DIFFERENCE FROM REFERENCE MODULE TO PYRANOMETERS, MEASURED BY LINEAR REGRESSION. PYRANOMETERS EFFECTIVE IRRADIANCE WAS CORRECTED FOR ANGLE OF INCIDENCE, SPECTRAL RESPONSE, AND REAR SHADING.

Station	Pyranometers Effective Irradiance Overreporting %
1	3.478
2	3.650
3	3.615
4	2.967
5	4.421
Average	**3.626**

B. *Capacity test comparison*

Here we compare the regressions for measured and modeled power using reference module and pyranometers measured bifacial effective irradiance, evaluated at a) common (averaged) reference condition values for irradiance windspeed, and ambient temperature, and b) individual reference condition values for each irradiance measurement type. We report the evaluated DC power regression values for each case in the sections below.

1) Measured DC Power Regression Evaluation:

We first evaluate the regressions on measured DC power at a common reference condition, that is the same values for effective irradiance, windspeed, and ambient temperature. A scatterplot for the values used in one such pair of regressions is shown in Fig. 3. The lower effective irradiance values measured by reference module result in a higher slope for the power regression on this variable as compared to the pyranometer effective irradiance.

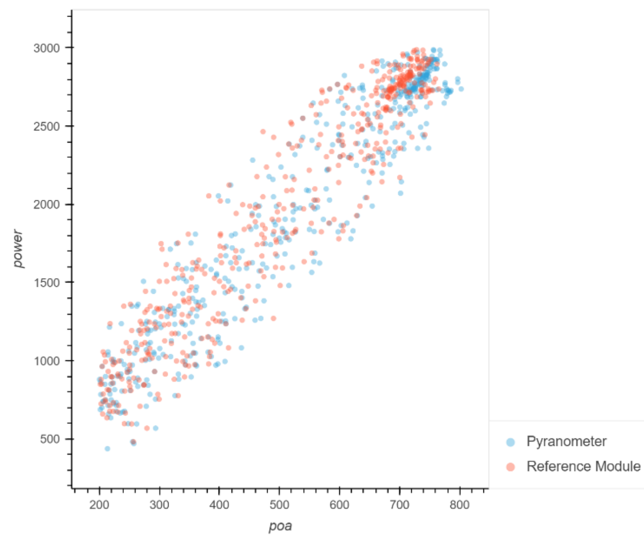

Fig. 3: Filtered measured DC power vs. bifacial effective irradiance measured by pyranometers (blue) or reference module (red), used for multilinear regression analysis.

TABLE II. REPORTED DC POWER % DIFFERENCE FROM REFERENCE MODULE TO PYRANOMETERS, EVALUATED FROM CAPACITY TEST REGRESSIONS USING A COMMON REFERENCE CONDITION.

Station	Pyranometers Measured Power Underreporting %
1	4.334
2	3.998
3	4.184
4	2.830
5	4.727
Average	**4.014**

The difference in measured power regression evaluations for each irradiance measurement type at a common (averaged) reference condition are given in TABLE II. The regression evaluated measured DC power is consistently higher when using the reference module data when using common reference condition values between the two effective irradiance measurement methods, due to the lower measured irradiance values for the reference modules. When using individually determined reference condition values (based on the distribution of filtered irradiance and weather data values), there is little to no difference between effective irradiance methods for the regression evaluated measured DC power values.

2) Estimated DC Power Calculation and Regression Evaluation:

We use the PVWatts method to predict system DC power, which uses the effective irradiance, module temperature, and maximum power point temperature coefficient. We employed this method to predict the DC power for each data point across all 5 inverters using both pyranometers and reference module measured irradiance.

We then performed multilinear regressions on the modeled DC power with effective irradiance, windspeed, and ambient temperature (as for the measured DC power). The modeled power regression for one pair of irradiance sensors is shown in Fig. 4.

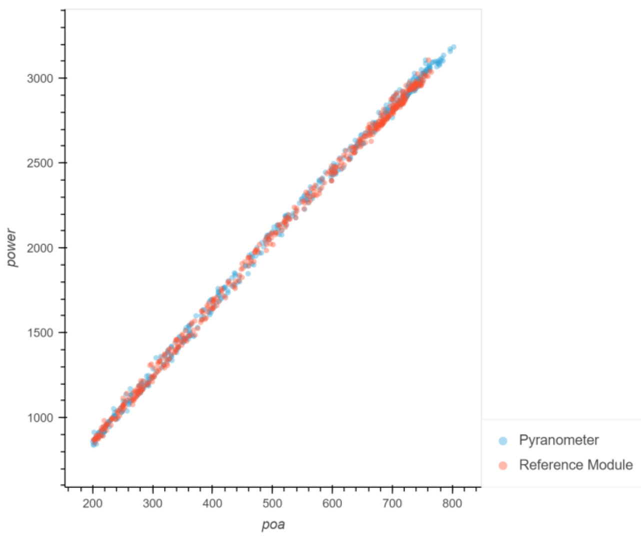

Fig. 4: Filtered expected DC power data modeled with PVWatts vs. effective irradiance as measured by pyranometers (blue) and reference module (red), as used for capacity test multilinear regressions.

As can be seen in the figure above, the expected DC power and regression lines align well between the two effective irradiance measurement methods. Therefore, at a common reference condition, the expected DC power regression evaluations are very similar (as these are essentially multilinear regressions of the PVWatts model). However, when evaluated at individual reference conditions, based individually on the distributions of effective irradiance measurements of each type, the expected DC power averages 1.4% lower when determined with the reference module compared to pyranometers.

Finally, we compare the capacity ratios calculated using each effective irradiance measurement method. The capacity ratios evaluated at common reference conditions between the two methods, as well as the percent differences, are shown in TABLE III. On average, the capacity ratio at a common reference condition is 4.02% higher when regressions are performed with reference module measured effective irradiance versus pyranometers.

TABLE III. CAPACITY RATIOS EVALUATED AT COMMON REFERENCE CONDITIONS ON REGRESSIONS PERFORMED ON REFERENCE MODULE AND PYRANOMETERS EFFECTIVE IRRADIANCE MEASUREMENTS.

Station	Pyranometers Capacity Ratio	Reference Module Capacity Ratio	% Difference
1	0.918	0.960	4.34
2	0.939	0.978	4.01
3	0.922	0.962	4.17
4	0.936	0.962	2.73
5	0.958	1.006	4.82
Average	**0.934**	**0.974**	**4.02**

We also evaluated the capacity ratios at individually determined reference conditions for each effective irradiance measurement type at each inverter/weather station. The capacity ratios at individual reference conditions average 3.84% higher when calculated with reference module effective irradiance vs. pyranometers. The results for each station are shown in TABLE IV.

TABLE IV. CAPACITY RATIOS EVALUATED AT INDIVIDUAL REFERENCE CONDITIONS ON REGRESSIONS PERFORMED ON REFERENCE MODULE AND PYRANOMETERS EFFECTIVE IRRADIANCE MEASUREMENTS.

Station	Pyranometers Capacity Ratio	Reference Module Capacity Ratio	% Difference
1	0.925	0.965	4.12
2	0.945	0.982	3.78
3	0.928	0.965	3.84
4	0.937	0.965	2.88
5	0.963	1.009	4.61
Average	**0.940**	**0.977**	**3.84**

3) Inverter Expected DC Power vs. Inverter Measured DC Power

To further evaluate the difference being seen in with the use of pyranometers vs reference modules for system performance analysis, a perfectly clear sky day from this site was evaluated. On the clear sky day, the timeseries expected DC power, per station, was calculated by:

$$DC\ Power_{exp}\ (kW) = DC\ Capacity\ (kW) * TA * IA * (1 - WL)$$

where the DC Capacity is the rated STC dc capacity of the inverter on the corresponding station, TA is the temperature adjustment factor calculated by:

$$TA = 1 + \gamma(T_{ref} - T_m)$$

where γ is the maximum power (P_{max}) temperature coefficient of installed PV modules within the array, T_{ref} is the reference temperature, 25 °C, and T_m is the measured module temperature, IA is the irradiance adjustment factor calculated by:

$$IA = \frac{POA_{total}}{POA_{ref}}$$

where, POA_{total} is the effective total irradiance measured by pyranometers (using the same adjustment factors as outlined in Section II part *C*, of this paper) and POA_{ref} is the reference irradiance condition, 1000 W/m^2, WL is the overall DC ohmic wire loss, of the corresponding station, calculated based on the cable gauge size and total installed wire length. As seen in *Fig.*

5, the expected inverter DC power calculated using the bifacial reference module irradiance is observed to be very close in alignment to the total measured inverter DC power. As can be seen, the expected inverter DC power as calculated using the pyranometers deviates significantly from the measured power.

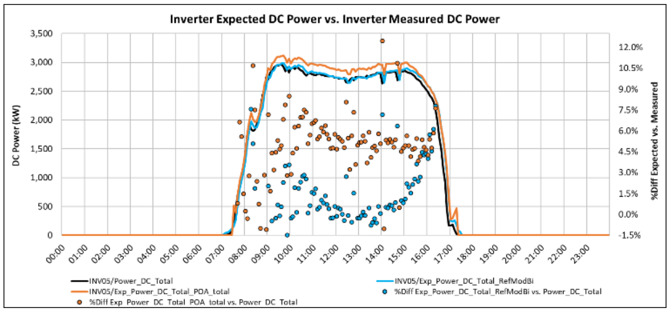

Fig. 5: Inverter Expected DC Power derived using the effective irradiance as measured by pyranometer (orange) and reference module (blue) vs. Inverter Measured DC Power (black)

As previously mentioned, the datasets used were from the site's capacity test period, and thus any potential DC health or other field related issues are minimal, if at all present. On an average the expected inverter DC power calculated using the reference module is 0.9% higher than the measured DC power whereas the inverter DC power calculated using the pyranometers effective irradiance is 5.3% higher than the measured inverter DC power.

4) Reference Module Expected DC Power vs Reference Module Measured DC Power

As seen in *Fig. 6* the total effective irradiance from the front side facing POA and rear side facing POA, from the same weather station used to derive the expected inverter DC power in *Fig. 5*, were also used to derive the expected power of the corresponding bifacial reference module to further validate the results. As previously described, the reference modules are measuered with use of RDE300 units that perform full I-V curve sweeps. This thus allowed for measured P_{max} of the reference module to measured and collected throughout the testing perioed. The expected reference module power was calculated by:

$$DC\ Power_{exp}\ (W) = STC\ Rated\ Pmax\ (W) * TA * IA$$

where the STC Rated Wattage is the flashtested Pmax of the reference module, TA is the temperature adjustment factor using the back of module temperature sensor installed on the reference module, and IA is th total effect irradiance of the pyranometers (adjusted per Section II part *C* of this paper). As can be seen in *Fig. 6*, the calculated expected power of the reference module is deviating significantly compared to the actual measured P_{max} of the bifacial reference module.

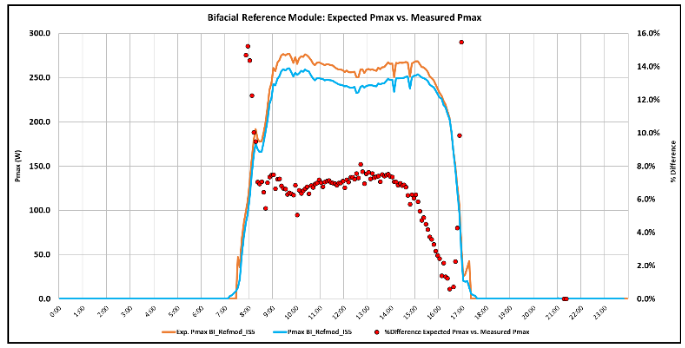

Fig. 6: Bifacial Reference Module Measured Pmax (Blue) vs Expected Pmax (Orange) using Pyranometers effective total irradiance

The expected P_{max} is on an average of 6.4% higher than that of measured P_{max} of the bifacial reference module. This result is in alignment with the results described in the previous section where the expected inverter DC power, when calculated with pyranometers, averaged 5.3% higher than the measured inverter DC power. With the bifacial reference modules having been previsouly flashed and newly installed, the modules are known to not be underperforming, thus the difference in the expected vs. measured P_{max} is directly attributeable to the differnece in total irradiance measured by pyranometers (even with adjustments) as compared to the usable irradiance "seen" by the reference module.

IV. Discussion

We have shown that effective irradiance measured with reference modules averages 3.1% lower for monofacial POA irradiance and 3.6% lower for bifacial POA irradiance when compared to equivalent pyranometer measurements adjusted for spectral, non-uniformity, and angle of incidence effects. While additional measurements could be made to further adjust pyranometer measurements to reflect the effective irradiance more accurately for a PV array, we have demonstrated that reference modules offer a simple method for representative irradiance measurement without these corrections. We have also shown that effective irradiance monitoring with reference modules yields ~3.9% higher capacity ratios in standard ASTM E2848 capacity tests as compared with pyranometers, across 5 bifacial PV arrays at a large scale utility PV site. This result demonstrates that the calculated expected DC power more closely aligns with the measured DC power when reference modules are used in place of pyranometers for bifacial effective irradiance measurement.

We evaluated the sensitivity of the capacity test results by running the capacity tests again using nameplate (rather than flash test) I_{SC} values. The results showed that the capacity tests performed with reference module effective irradiance calculated on nameplate values varied from the flash test equivalent by the same percentage and direction as the difference between the nameplate and flash test I_{SC} values. That is, a nameplate I_{SC} value 2.5% lower than the flash test value results in a capacity ratio ~2.5% lower than the flash test equivalent capacity ratio. This both emphasizes the need for accurate flash test I_{SC} values for reference modules and provides a basis for uncertainty determination.

The reference module data collected and used in this abstract was obtained with an Atonometrics RDE300, which holds the modules at short circuit or open circuit condition (the latter used here) when not performing measurements. This means that the reference module is not at the same operating point or temperature as the rest of the array, and that the reference module is not an active power producer within the system. GroundWork Renewables is addressing these issues by developing a device that can be attached to a module in series with the rest of the array, but which electrically disconnects the module from the array for short time periods to measure I_{SC} and an I-V curve at a specified frequency. This will allow for the reference module to participate in power production with the rest of array and remove the need for adjustments in array string wiring and additional independent modules for measurement.

Reference modules also provide additional advantages over pyranometers and reference cells for irradiance monitoring. Generally, reference modules and associated hardware are lower cost and can serve dual purposes – performance monitoring and soiling monitoring. Alongside irradiance monitoring, the timeseries I-V curves measured on reference modules can be used for more advanced power loss analysis, such as outdoor Suns-V_{OC} [13]. This type of performance loss monitoring can be used to inform O&M activities, as well as diagnose mechanisms of long-term degradation in fielded modules, but is not possible without time series I-V characterization.

V. Conclusion

In this work, we have directly compared effective irradiance measured by reference PV modules to standard pyranometers. We showed that in the case of both monofacial and bifacial effective irradiance, pyranometers overestimate the irradiance reaching a PV array by 2.5-4.5%, even after adjusting for PV angle of incidence, spectral response, and irradiance nonuniformity effects. Additionally, we showed that when using effective irradiance measurements to perform capacity tests, this difference in measured irradiance results in a ~3.9% lower capacity ratio when using pyranometers instead of reference modules to evaluate the performance of bifacial single axis tracking PV arrays. These results are consistent when comparing the expected DC power calculated by use of pyranometer at both the system level as well as module level. In addition to more accurately predicting and evaluating the performance of a PV system, the reference module approach to effective irradiance monitoring has several inherent advantages over the use of pyranometers or reference cells, including cost, reduction or elimination of correction factors, and ease of implementation, particularly for bifacial systems. Inaccuracies in effective irradiance measurements have real world consequences for system developers and owners, so it is critical that new methods are explored and developed to keep up with advances in PV system technologies.

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