Field Trial of Meteorological Station Using PV Reference Cells

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***Abstract*—We report on a field trial of a new meteorological station concept for resource assessment at the site of a prospective utility-scale photovoltaic (PV) power plant to be developed by 7X Energy. Cost savings are achieved by substituting Atonometrics PV reference cells for thermopile pyranometers in a unique multi-reference-cell array configuration that allows accurate determination of global horizontal irradiance (GHI) and by using advanced remote diagnostics to minimize the need for on-site visits for sensor cleaning. Reference data are also obtained from a second station at the site employing thermopile pyranometers and maintained through weekly site visits for pyranometer cleaning. Data from both stations are compared to industry-leading SolarAnywhere® satellite-derived irradiance measurements from Clean Power Research and are used for tuning of the satellite model for long-term irradiance prediction and site resource assessment. Results comparing the new station concept employing PV reference cells versus the traditional one based on thermopile pyranometers showed that both compared equivalently with the satellite data and tuning model within instrument uncertainties, although small bias differences require more investigation.**

***Index Terms*—photovoltaic (PV) systems, resource assessment, pyranometer, reference cell**

I. Introduction

Meteorological ("met") stations play a key role in the development and operations of utility-scale photovoltaic (PV) solar projects for both pre-construction resource assessment campaigns and operational performance monitoring.

Pre-construction resource assessment is performed to qualify a prospective site and evaluate its long-term expected energy in support of project financing. The current industry standard approach to irradiance assessment combines satellite-based irradiance measurements, which provide long-term history and inter-annual variability data, with at least 12 months of ground-based global horizontal irradiance (GHI) data for site-specific high accuracy measurements and tuning of the satellite model [1] [2].

Acquisition of ground data represents a material pre-construction expense for project developers, for both met station hardware and ongoing maintenance. Typical resource assessment met stations employ thermopile pyranometers for GHI measurement and require weekly visits for pyranometer cleaning. However, often such weekly maintenance visits are missed or not performed, especially at remote sites, causing data quality issues or requiring extended measurement campaigns.

Here we report on a field trial of a new met station concept by Atonometrics that achieves cost savings by employing an array of multiple photovoltaic (PV) reference cells for GHI measurement in place of thermopile pyranometers and both on-site instrumentation and remote diagnostics to minimize site visits for sensor cleaning. The unique station concept solves several important issues typically associated with using PV reference cells to measure GHI, including minimizing soiling and correcting for incidence-angle dependence.

The field trial has been conducted at a prospective 7X Energy site over a 10-month period, during which reference data were also collected at the site by a traditional station using thermopile pyranometers with weekly maintenance. Data obtained from the two ground stations are compared with each other and with SolarAnywhere® satellite irradiance data from Clean Power Research and are also both used to perform site tuning of the satellite irradiance model.

II. Experimental

All data were obtained between July 2019 and May 2020 from the pre-construction site, near San Antonio, Texas, that is under consideration for construction of a utility-scale PV power plant.

The experimental met station measures GHI, albedo, ambient temperature, wind speed, and soiling, and all data were transmitted from the site via cell modem. For this paper we are specifically concerned with the instrumentation for measuring GHI and soiling, shown in Fig. 1.

Three PV reference cells (Atonometrics, RC18) are mounted at 25° tilt with two south-facing and one north-facing. This arrangement is a prototype of the Atonometrics Pyramid™ system for PV-based irradiance measurement. The tilt angle helps minimize soiling as compared to a horizontal orientation [3], while the use of a multiple reference cell array allows determination of direct normal irradiance (DNI) and diffuse horizontal irradiance (DHI) components [4] [5] [6] and therefore calculation of GHI and correction for incidence angle dependence, which will be discussed further below. The precise azimuthal orientations of the PV reference cells were determined after installation by analysis of their daily irradiance profiles under clear-sky conditions. Data from all three reference cells are analyzed at each time point by employing an Angled Multisensor Irradiance Decomposition (AMID) analysis [6] which performs a fit to an irradiance

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Fig. 1. Close-up of GHI and soiling measurement instrumentation in experimental met station.

model to determine DNI and DHI values that produce the measured tilted plane irradiance values, taking into account the known incidence angle response of the reference cells. GHI is then determined from DNI and DHI according to $GHI = \cos(\theta_Z) \cdot DNI + DHI$ where θ_Z is the solar zenith angle calculated from latitude, longitude, and time.

Soiling measurement is performed with a maintenance-free optical soiling sensor (Atonometrics, Mars™). The soiling sensor, which has a flat glass window similar to a PV device, has been shown to be a good measure of the soiling of PV reference cells due to atmospheric dust deposition [7] and is especially sensitive to low soiling levels. In addition, occasional fouling of individual PV reference cells was detected by inter-comparison of the three cells, for which instrument redundancy is an advantage, and by comparison of the PV reference cell data to clear-sky models during clear-sky conditions as in [8]. Data from the soiling sensor and the clear-sky models were used to determine a daily soiling ratio for each PV reference cell, and the measured irradiance data were corrected, if needed, to account for soiling in between occasional site visits for sensor cleaning, performed approximately once every 3 months. This method minimizes the cost of site visits while permitting visits on an as-needed basis when prompted by results of the remote diagnostics.

A second more traditional met station is also present at the site. This station includes two horizontally mounted thermopile pyranometers (Hukseflux, SR30) for GHI measurement, as well as other meteorological instruments. Data from this station were used for comparison to the experimental reference-cell based station.

The PV reference cells were calibrated at Atonometrics following IEC 60904-2 and using a reference PV device calibrated at the National Renewable Energy Laboratory (NREL), while the thermopile pyranometers were calibrated by their manufacturer prior to shipment according to ISO 9847. Both sets of calibrations are traceable to the World Radiometric Reference, although via different instrument paths and procedures applicable to each instrument type.

III. Results

A. Reference Cell Array

Fig. 2 demonstrates the ability of the AMID analysis method to correctly extract GHI data from the reference cell array while correcting for incidence-angle dependence. The figure shows GHI versus time on a representative day that was almost completely clear from sunrise to sunset. Solar zenith angle varies from approximately 50° at noon to 90° at sunrise/sunset. Data from the reference cell array are shown together with data from the pyranometer station (average of the two pyranometers) and overlap almost perfectly. Also shown (dashed) is the measurement that would be expected if using a single reference cell in horizontal orientation without correction for incidence angle dependence, which would result in a 6% lower full-day integrated irradiance for the clear day shown.

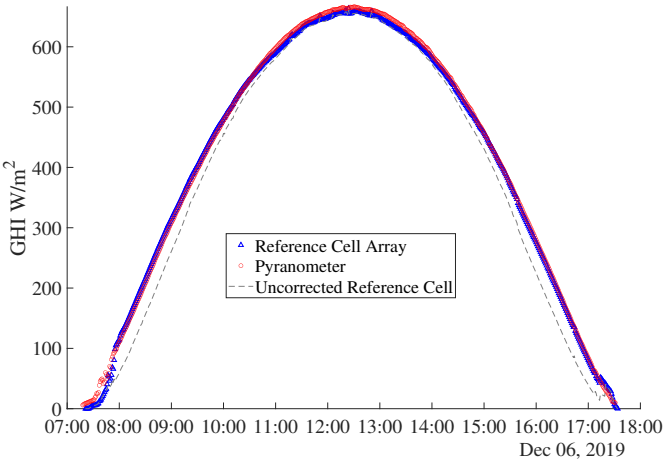


Fig. 2. Reference cell array and pyranometer angular response on a representative clear day.

Fig. 3 shows the correlation between the daily mean GHI results from the reference cell and pyranometer stations for the entire 10-month period. The consistent correlation over the entire irradiance range indicates that the AMID analysis method for the reference cell array works well for both clear sky and diffuse irradiance conditions. Summary statistics for the correlation of the daily reference cell array to the pyranometer average over the 10-month period are shown in Table I together with statistics for correlation of the two pyranometers to each other. The relative mean bias error (rMBE) of the reference cell vs. pyranometer data is similar to the rMBE when comparing the two pyranometers to each other, and both values are within the daily irradiance uncertainties of the instruments ($\sim \pm 2.5\%$, 95% confidence). The low relative

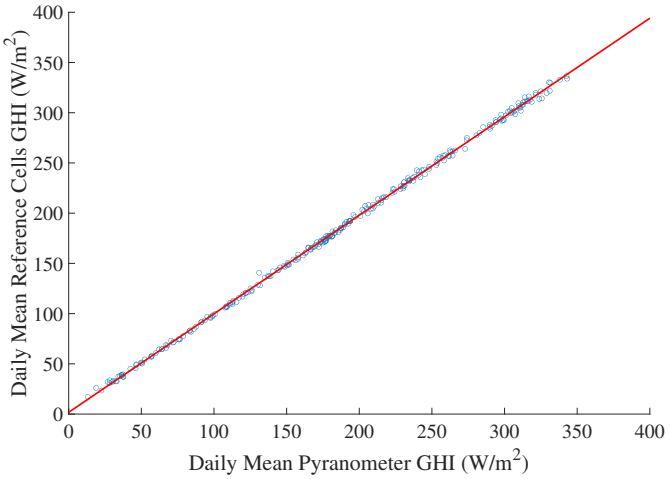


Fig. 3. Correlation of daily mean GHI between the reference cell array and the average of the two pyranometers for the 10-month period.

	Reference Cell Array vs. Pyranometers	Pyranometer 1 vs. Pyranometer 2
rMBE (%)	-0.97	-0.73
rRMSE (%)	1.80	0.97

TABLE I
10-MONTH DAILY GROUND MEASUREMENT CORRELATION STATISTICS

root mean square error (rRMSE) is also similar to the daily uncertainty and indicates good repeatability and consistency. For definitions of rMBE and rRMSE see [9] [10].

B. Satellite Data

Satellite-derived irradiance values for the site were generated using the industry-leading SolarAnywhere data product from Clean Power Research. Fig. 4 compares the monthly mean GHI from the native (untuned) satellite data to the results from the reference cell and pyranometer ground stations. The 95% confidence interval uncertainty in the monthly mean GHI of the native satellite data is approximately ±8%, which

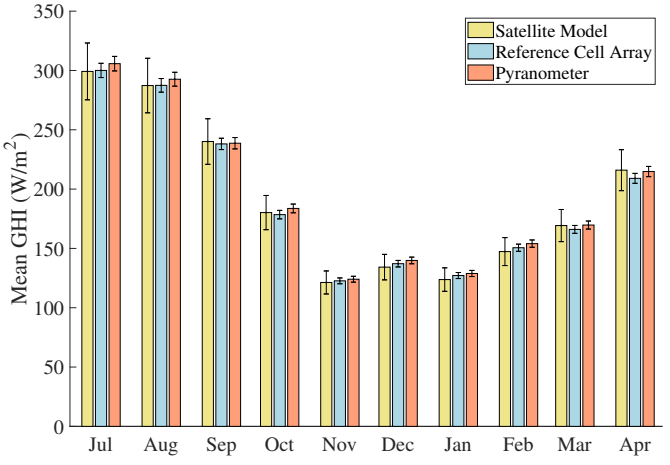


Fig. 4. Comparison of native satellite and ground station irradiance results.

	Pyranometer	Reference Cell Array
Native SolarAnywhere rMBE for Overlapping Data Period	-1.8%	-0.1%
Tuned SolarAnywhere rMAE for Overlapping Data Period	1.1%	1.0%
Coefficient of Variation	4.0%	3.9%
Year-to-Year Variance	18.7%	18.4%
P50 Annual GHI (kWh/m^2)	1799	1767
Long Term Average Annual GHI (kWh/m^2)	1803	1772

TABLE II
SATELLITE TUNING STATISTICS

reduces to approximately ±4.5% for 1 km resolution data annual averages [9]. The 95% confidence uncertainties for the reference cell and pyranometer monthly mean GHI are taken as approximately ±2.5% based on manufacturer guidance. Fig. 4 shows that the monthly mean GHI for the satellite data and both ground stations all agree to within their respective uncertainties. The native satellite data matched the reference cell results more closely than the pyranometers, with rMBE of only -0.1% versus -1.8%, as shown in Table II, although this result is based on only one sample.

Data from both the reference cell and pyranometer ground stations were used to tune the satellite model as described in [1] [2], with summary results shown in Table II. The tuned SolarAnywhere relative mean absolute error (rMAE), defined in [9] [10], the coefficient of variation, and the year-to-year variation were all similar for both ground stations. Tuning to the reference cell array data resulted in a marginally lower monthly rMAE, which indicates more consistency and less unexplained error. However, given the study was for one location and for a period less than one year, its not possible to generalize the results. Using the tuned satellite model the 50% probabiliy (P50) annual and long-term GHI averages were predicted using tuning data from both ground stations.

C. Discussion

For this location and time period, using the reference cell array data for tuning the satellite model resulted in a 1.8% difference in the P50 solar resource when compared to the pyranometer ground station. While this difference may be material to the project valuation, it was also within the range of uncertainty for the satellite model tuning process and different measurement techniques, and also within the stated instrumental uncertainties of both the reference cells and the pyranometers. For comparison, the standard deviation of mean bias error of the tuning study process using ten months of ground data is 2.1%. In addition, [11] found differences of 2% in the measurement of annual GHI due to different measurement techniques.

While the relative bias differences between the reference cell and pyranometer ground stations are within the uncertainty of all of the instruments, because of the material significance

for project valuation it is compelling to better understand the differences between the readings and determine if there could be systematic variations due to measurement principles, calibration sources, or other factors. The results presented here were generated for a single site using only two ground stations, one of each type, during a 10-month period. To draw better conclusions, further data should be collected from the test site and additional sites and stations should be studied. Further work in these areas is ongoing.

For this paper we only addressed the validation of the reference cell array GHI results, while a separate validation of the DNI and DHI results from the reference cell array AMID analysis will be performed at another site [6]. If validation shows sufficient accuracy for the DNI and DHI measurements it would be interesting to compare them to the satellite model, which might provide an opportunity to improve tuning accuracy.

IV. Conclusions

The results overall demonstrate the capability for using the new met station concept based on reference cells and optical soiling measurement to produce nearly equivalent results to a traditional met station employing thermopile pyranometers, but with lower cost and less frequent maintenance. A tuned satellite model was used to produce long-term irradiance predictions based on both ground stations. Results from both ground stations at the test site were equal within the measurement uncertainties, although the small observed differences could be material to project valuation. Additional work is ongoing to explore the small bias differences between the two station approaches observed at the test site, and to include additional test sites and ground stations to expand the significance of the findings.

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