Novel Static Sensor Array for Diffuse Irradiance Measurement

Michael Gostein[1], Audrey Marquis[1], and Bruce H. King[2]

[1]Atonometrics, Austin, USA; [2]Sandia National Laboratories, Albuquerque, USA

Abstract **We report on an updated field trial to test measurement of diffuse horizontal irradiance (DHI) using a novel low-cost combination of static sensors with no moving parts. The system pairs two tilted reference cells, one of which measures global irradiance and the other of which is modified with an isolator tube that admits only diffuse light contributions from a limited region of the sky. Using reference data from a research-grade tracking diffusometer, we trained a neural network model to use the readings of the two static sensors to estimate DHI. In this work, we have updated our field testing to include almost 1 year of data from the test site. A second test site at different latitude was recently installed and will be used for additional validation in subsequent work.**

Index Terms **— photovoltaic systems, resource assessment, diffuse irradiance, pyranometer, reference cell**

I. Introduction

As PV systems become more sophisticated, irradiance modeling for system performance prediction is becoming more complex and measurements of diffuse irradiance have increasing importance. For example, in single-axis tracking systems, predicting and optimizing performance during row-to-row shading or cloudy sky conditions requires an accurate assessment of diffuse light contributions. And in bifacial systems, modeling must include both front-side and rear-side irradiance, which may have components of direct beam, sky diffuse, and ground-reflected light. Often irradiance quantities must be transposed from a measurement plane to a plane of array (POA), also requiring modeling of direct and diffuse irradiance components.

High-accuracy systems for measuring direct normal irradiance (DNI) and diffuse horizontal irradiance (DHI) typically employ sensors on a two-axis sun-tracking motorized stage or other, simpler, motorized systems. However, due to the cost and maintenance requirements of such equipment, DNI and DHI measurements are typically omitted from resource assessment and PV power plant meteorological stations. Instead, DNI and DHI are usually estimated at these sites from global measurements, such as GHI or POA irradiance, using one of a number of decomposition models [1]. Estimation via decomposition models is often incorporated directly into PV performance modeling software as an intermediate step in calculations. However, the accuracy of decomposition models is limited [1], so this approach may add to uncertainties in overall PV system performance modeling.

Therefore, the availability of low-cost instrumentation with moderate accuracy for DNI or DHI measurement could help lower PV performance modeling uncertainties in commercial

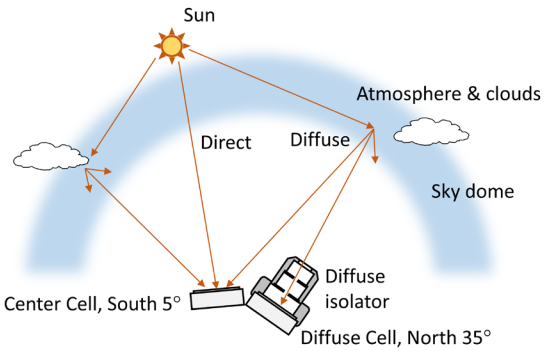


Fig. 1: Measurement concept comprising two sensors. The north-tilted cell with diffuse isolator senses diffuse contributions from a limited region of the sky which always excludes the sun. The center tilted cell responds to whole sky diffuse and direct light.



Fig. 2: Static sensor array deployed at Sandia National Laboratories in Albuquerque, New Mexico, USA. The array comprises five sky-facing PV reference cells, four tilted north, south, east, and west at 35° and one center cell tilted south at 5°. The north-facing cell is fitted with a diffuse isolator tube blocking all direct and ground-reflected light.

sites. Only one of DNI and DHI, plus GHI, is required, since these three quantities are related by $\mathrm{GHI} = \mathrm{DNI} \cdot \cos(Z) + \mathrm{DHI}$, where Z is the zenith angle.

We have previously reported on a low-cost concept for DHI measurement using a novel array of static sensors [2][3]. In this work we present an updated field trial of the novel sensor array with almost one year of data from the test site, to demonstrate the applicability of the concept throughout seasonal variations.

II. Experiment

Fig. 1 depicts the sensor concept for the current work. A PV reference cell tilted 5° south measures global tilted irradiance. A second modified reference cell tilted 35° north is covered with a diffuse isolator tube comprising a series of apertures which only admit diffuse light contributions from a limited region of the northern sky. We denote the reading of this cell "diffuse polar". Together these two readings may be used to estimate DHI, as explained below. Note that south/north tilts assume northern hemisphere placement and would be reversed in the southern hemisphere.

Fig. 2 shows a sensor array prototype we installed in May 2023 at Sandia National Laboratories in Albuquerque, New Mexico, USA for testing the concept. This prototype is an updated version of that described in earlier work [4]. It comprises five sky-facing reference cells (RC22), four facing nominally north, east, south, and west on a 35° tilt, and one center cell on a 5° tilt to the south. An additional ground-facing cell is not shown. The north cell additionally has a diffuse isolator tube as discussed above and shown in Fig. 1. The shunt resistance used in this cell was increased to enable sensitivity to the very small irradiance levels reaching the cell through the reduced angular acceptance of the isolator tube. The central cell is intended to be nominally horizontal, with a 5° tilt for water roll-off. In the present work and in our most recent reports [2], [3], only the north (diffuse polar) and center cells of the reference cell array are used.



Fig. 3: Tracking pyrheliometer and diffusometer at Sandia National Laboratories. The tracked ball blocks direct light from reaching the pyranometer on the right.

The Sandia National Laboratories site also includes, shown in Fig. 3, a research-grade two-axis sun-tracking system (SOLYS2) with a pyrheliometer for DNI measurement and a shaded pyranometer for DHI measurement, which we denote a "tracking diffusometer." We used the tracking diffusometer as a reference instrument for training and testing the prototype sensor array measurements. The tracking diffusometer is located approximately 150 meters from the sensor array.

Data from all sensors is recorded once per minute.

Data acquisition at Sandia began in May 2023 and is ongoing. Results presented here were acquired between May 2023 and May 2024.

III. Analysis Model

We trained a neural network model to process the sensor array data to estimate DHI. The model contains the following inputs selected as predictors: diffuse polar irradiance signal (output signal of the north-facing reference cell modified with the diffuse isolator tube); global tilted irradiance reading of the center RC22; expected clear sky reading of the center RC22 (based on known latitude, longitude, altitude, and orientation of the center cell, and its incidence angle response, using the Ineichen clear sky model in the open source MATLAB PV_LIB toolbox [5][6]); additional metrics derived from the preceding list of signals.

We implemented and trained the neural network regression model in MATLAB, using the inputs listed above, to produce an output for estimated DHI, with the tracking diffusometer data providing the reference data for training. We trained the neural network model using only four weeks of data beginning in early May 2023. Therefore, the remainder of the data set serves as a test of the model, including resilience against seasonal variation.

IV. Results & Discussion

Following the training period, we process the input data to estimate DHI using the neural network model and compare the estimated values against the reference readings of the tracking diffusometer.

For most commercial PV projects, the alternative to low-cost DHI measurements is simply to estimate DHI from decomposition models, as discussed above. Various decomposition models are in use. An evaluation of decomposition model accuracy [1] found that the DIRINT model was among the best performing.

In Fig. 4 we compare the accuracy of the prototype sensor array results for DHI with those of the DIRINT decomposition model calculated using the MATLAB version of the open source PV_LIB toolbox [7][8]. The figure plots hourly average

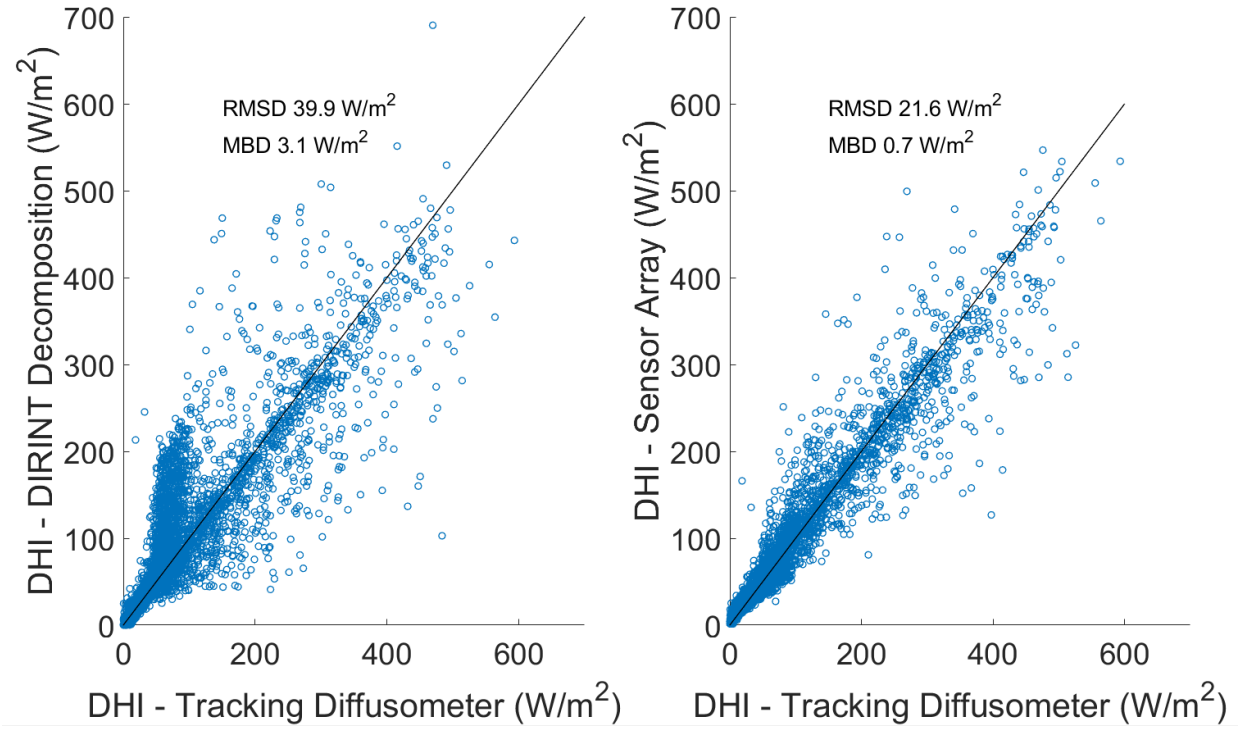


Fig. 4: Comparison of DHI prediction accuracy for the DIRINT decomposition model (left) versus the results of the sensor array and neural network model (right). Each plot shows the predicted DHI versus the reference value of DHI from the tracking diffusometer, for hourly averaged results. Results are from an eleven-month period beginning in June 2023.

predicted DHI for both DIRINT and the sensor array plus neural network model against the hourly-average DHI measured by the tracking diffusometer. The plot contains all data generated from the Sandia site over an eleven-month period between June 2023 and May 2024, excluding the four-week neural network training data period beginning in early May 2023. The DIRINT DHI values were computed from GHI readings of an SR30 pyranometer co-located with the sensor array. Note that the DIRINT model tends to over-predict DHI during clear-sky (low-DHI) conditions. Mean bias deviation (MBD) and root-mean square deviation (RMSD) correlation statistics are listed on the plots.

MBD and RMSD of the results from the prototype sensor array and neural network model are significantly improved versus results from the DIRINT decomposition model using GHI measurements alone, as shown in Fig. 4. Note that the RMSD values for both the DIRINT and sensor array results are likely elevated at least partially by the fact that the GHI pyranometer and sensor array are both co-located approximately 150m from the tracking diffusometer, and therefore may indeed register different amounts of diffuse light during any time interval during partly cloudy conditions.

A preliminary assessment of the monthly performance of the sensor array results did not reveal any clear pattern of seasonal bias.

Results presented so far are promising and show the potential ability of the sensor array approach to produce DHI results with significantly improved accuracy versus using decomposition models alone.

To test the neural network model's ability to work across different locations, we plan to analyze data from a new test site with a different latitude, using a single, unified analysis model to process data from both the original and new sites. In May 2024, we completed setting up an additional experimental setup near Austin, Texas, with the same instrumentation as currently installed in Albuquerque at Sandia National Laboratories. Data collection and analysis from this new site will begin in June. We plan to present future work comparing the model's performance at both locations.

ACKNOWLEDGEMENT

This material is based upon work supported by the U.S. Department of Energy's Solar Energy Technologies Office under Award Number DE-SC0020831.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

REFERENCES

[1] M. Lave, W. Hayes, A. Pohl, and C. W. Hansen, "Evaluation of global horizontal irradiance to plane-of-array irradiance models at locations across the United States," *IEEE J. Photovoltaics*, vol. 5, no. 2, pp. 597–606, Mar. 2015, doi: 10.1109/JPHOTOV.2015.2392938.

[2] M. Gostein and B. H. King, "Field Trial In Progress for Measuring Global, Direct, Diffuse, and Ground-Reflected Irradiance Using a Static Sensor Array," pp. 1–2, Dec. 2023, doi: 10.1109/PVSC48320.2023.10359889.

[3] M. Gostein, B. H. King, and J. Horst, "Measuring Diffuse Horizontal Irradiance Using a Static Sensor Array," *40th Eur. Photovolt. Sol. Energy Conf. Exhib. (EU PVSEC)*, 2023, doi: 10.4229/EUPVSEC2023/4DV.4.2.

[4] M. Gostein, A. Hoffman, B. H. King, and A. Marquis, "Measuring Global, Direct, Diffuse, and Ground-Reflected Irradiance Using a Reference Cell Array," in *2022 IEEE 49th Photovoltaics Specialists Conference (PVSC)*, Nov. 2022, pp. 0285–0290, doi: 10.1109/PVSC48317.2022.9938489.

[5] B. H. King, D. Riley, C. D. Robinson, and L. Pratt, "Recent advancements in outdoor measurement techniques for angle of incidence effects," *2015 IEEE 42nd Photovolt. Spec. Conf. PVSC 2015*, Dec. 2015, doi: 10.1109/PVSC.2015.7355849.

[6] B. H. King and C. D. Robinson, "Differential Analysis of the Angle of Incidence Response of Utility-Grade PV Modules," in *2019 IEEE 46th Photovoltaic Specialists Conference (PVSC)*, Jun. 2019, pp. 77–81, doi: 10.1109/PVSC40753.2019.8981355.

[7] "PV Performance Modeling Collaborative | PV_LIB Toolbox." https://pvpmc.sandia.gov/applications/pv_lib-toolbox/ (accessed May 19, 2022).

[8] W. F. Holmgren, C. W. Hansen, and M. A. Mikofski., "pvlib python: A python package for modeling solar energy systems," *J. Open Source Softw.*, vol. 3, no. 29, p. 884, 2018, doi: 10.21105/joss.00884.