MEASURING DIFFUSE HORIZONTAL IRRADIANCE USING A STATIC SENSOR ARRAY

Michael Gostein[1*], Bruce H. King[2], Josh Horst[1]
[1]Atonometrics, Austin, USA
[2]Sandia National Laboratories, Albuquerque, USA
*Corresponding author: michael.gostein@atonometrics.com

ABSTRACT: We report on a field trial in progress to test measurement of diffuse horizontal irradiance (DHI) using a 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. Testing over a 3-month period shows the static sensors coupled with the neural network model yielded DHI values with significantly lower root-mean-square deviation (RMSD) versus the reference diffusometer as compared to results obtained from standard estimations of DHI from decomposition of global horizontal irradiance (GHI) using the DIRINT model.
Keywords: photovoltaic (PV) systems, irradiance, diffuse

1 INTRODUCTION

Predicting and assessing the performance of a photovoltaic (PV) system requires modeling its response to measured irradiance. As PV systems become more sophisticated, irradiance modeling is becoming more complex. For example, in single-axis tracking systems, predicting and optimizing performance during row-to-row shading or cloudy sky conditions requires a detailed 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.

The most complete assessments of solar irradiance include determination of both direct and diffuse irradiance, typically measured as direct normal irradiance (DNI) and diffuse horizontal irradiance (DHI). Together with measurements of ground-reflected irradiance, this allows projection of irradiance onto any plane.

High-accuracy systems for measuring DNI and 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. For example, in both pre-construction resource assessment and operating plant meteorological stations, global horizontal irradiance (GHI) may be measured and then used to predict POA irradiance. If measured DNI and DHI are not available, modeling software may estimate the DNI and DHI components of GHI as a step in transposing GHI to POA. However, the accuracy of decomposition models is limited [1], so this approach may add to uncertainties in

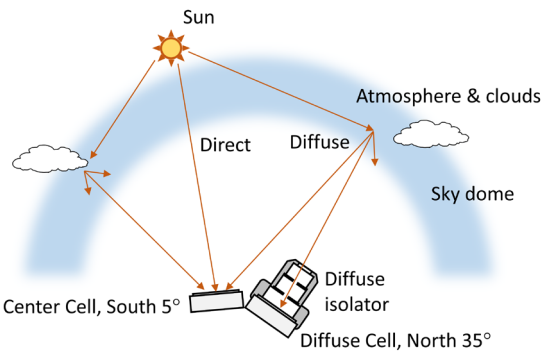


Figure 1: Measurement concept comprising two sensors. The north-tilted cell with diffuse isolator senses diffuse contributions from a limited region of the sky which always excludes the sun. The center tilted cell responds to whole sky diffuse and direct light.



Figure 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.

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 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.

A DHI measurement device with static (non-moving) sensors has been developed using multiple photodiodes which are alternately shaded during the day by a cutout pattern in a shade screen. This device has been widely used with reported good performance [2], but has some cost and technical limitations motivating interest in alternatives.

Our aim in the present work is to test a low-cost concept for DHI measurement using an array of static sensors based on PV reference cells. We previously reported results from related work using an array of reference cells in different orientations [3]. In this work we report on an updated configuration with better sensitivity to low DHI.

2 EXPERIMENT

Fig. 1 depicts the concept for the current work. A PV reference cell tilted 5° south measures global tilted irradiance. A second 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 reference cell array prototype we have installed at Sandia National Laboratories in Albuquerque, New Mexico, USA for testing the new concept. This prototype is an updated version of that described in our previous work [3]. 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 of 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, only the north and center cells of the reference cell array are used.

Co-located with the reference cell array is a secondary-standard thermopile pyranometer (SR30) measuring GHI.

The site also includes 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, shown in Fig. 3. 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 acquisition began in May 2023 and is ongoing. Data from all sensors is recorded once per minute.

As a precursor to analyzing the RC22 reference cell data from the sensor array, we experimentally measured the RC22 device's angular responsivity. This is quantified by the incidence angle modifier (IAM), the ratio of the sensor's reported irradiance to the product of direct beam irradiance and cosine of angle of incidence, normalized at normal incidence. IAM measurements were performed on four separate RC22 units mounted in each of four clock orientations on a dual-axis tracker system over three clear days. Procedures were similar to those described in [4], [5]. Fig. 4 shows the average of the measured IAM. Only minor deviations were observed between the different sensors and measurement days. Results shown in Fig. 4 were used in the subsequent analysis of the sensor array data as discussed below.

3 ANALYSIS MODEL

We trained a neural network model to process the sensor array data to estimate DHI. The model contains the following five inputs selected as predictors:

- Diffuse polar irradiance signal. This is the output signal of the north-facing reference cell modified with the diffuse isolator tube.
- Global tilted irradiance reading of the center RC22. This signal measures the irradiance received from the whole sky on the 5° tilted plane.
- Expected clear sky reading of the center RC22. Using the known latitude, longitude, altitude, and orientation of the center cell, and its incidence angle response (Fig. 4), we calculate the expected irradiance reading of the cell under clear sky



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

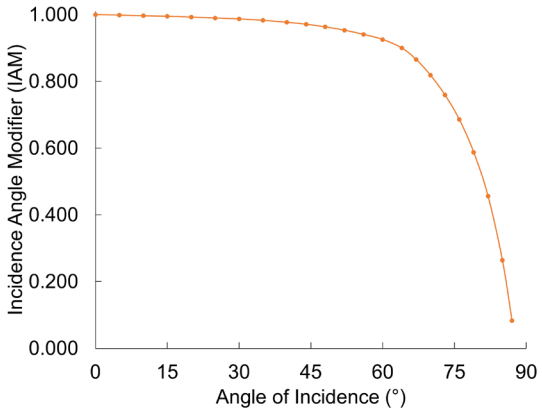


Figure 4: Measured average incidence angle modifier (IAM) of the RC22 reference cell.

conditions using the Ineichen clear sky model in the open source MATLAB PV_LIB toolbox [6][7]. With the model we calculate both beam and diffuse irradiance, apply the IAM to the beam component, and then project the beam and diffuse components onto the tilted cell.

- Trailing 10-minute standard deviation of the diffuse polar signal.
- Trailing 10-minute standard deviation of the center cell irradiance.

The selection of these five signals can be understood as follows. Under clear sky conditions, the diffuse polar irradiance signal is a strong predictor of DHI. Under partly cloudy conditions, the diffuse polar signal may over- or under-estimate DHI at any given time point, depending on whether clouds are present within the field of view of the diffuse isolator tube. In these conditions, comparing the global tilted irradiance reading of the center cell with its expected clear-sky reading allows an estimate of overall cloudiness, which is a whole-sky predictor of DHI. In addition, the two trailing 10-minute standard deviations indicate the degree of partly cloudiness and therefore the degree to which instantaneous readings of the diffuse polar signal may over- or under-estimate DHI.

The neural network regression model was implemented in MATLAB and contains the five inputs listed above, two intermediate layers containing ten nodes each, and a single output for DHI. The rectified linear unit (ReLU) activation function is used for each node.

We trained the neural network model using four weeks of data beginning in early May 2023. The training data comprises the five input signals and reference values for DHI obtained from the tracking diffusometer. Training was performed in the MATLAB regression learner toolbox by optimizing the model to minimize the root mean square deviation (RMSD) between the predicted and reference values of DHI.

4 RESULTS

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.

Fig. 5 shows a representative period of hourly-averaged results spanning approximately four weeks, which does not include the training data period. The figure indicates general agreement between the sensor array results and the reference instrument. Note the good agreement during stable, clear-sky conditions when DHI is low.

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. 6 we compare the accuracy of the sensor array results for DHI with those of the DIRINT decomposition model calculated using the MATLAB version of the open source PV_LIB toolbox [6][7]. The figure plots hourly average 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 recorded over a three-month period beginning in early June 2023 and excludes the four-week neural network training data period beginning in early May 2023. The DIRINT DHI values were computed from GHI readings of the SR30 pyranometer co-located with the sensor array. Note that the DIRINT model tends to over-

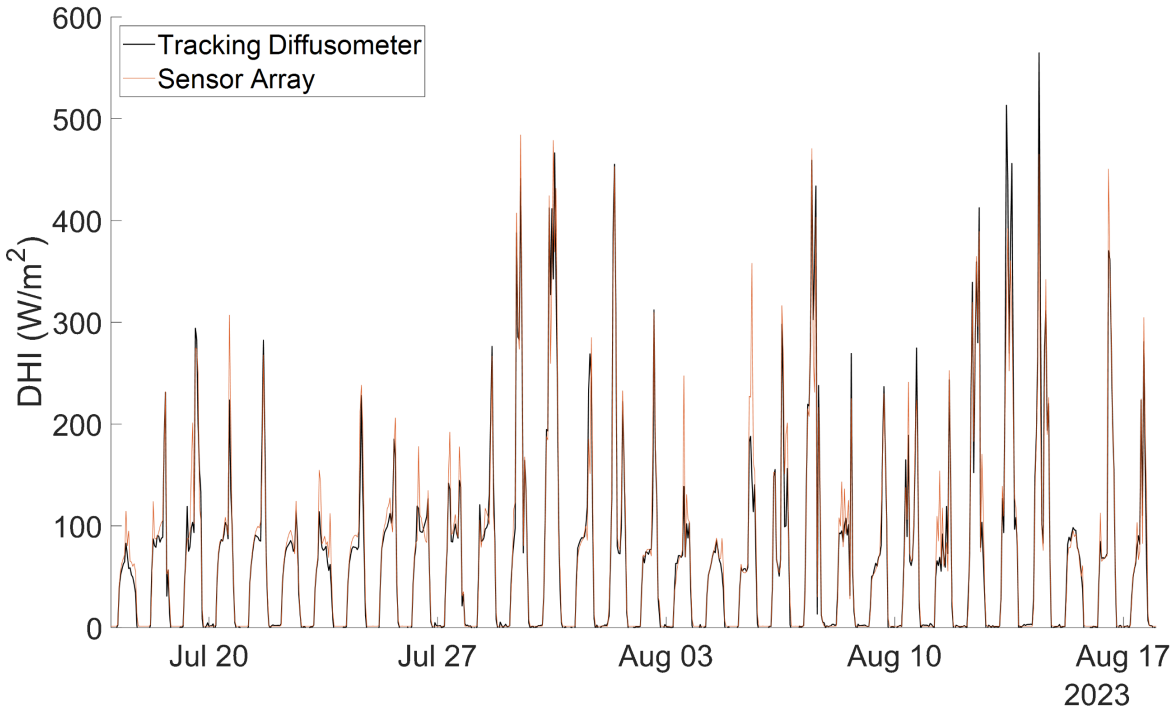


Figure 5: Hourly averaged time series data from a representative ~four-week period, comparing DHI determined from the sensor array to DHI measured by the tracking diffusometer.

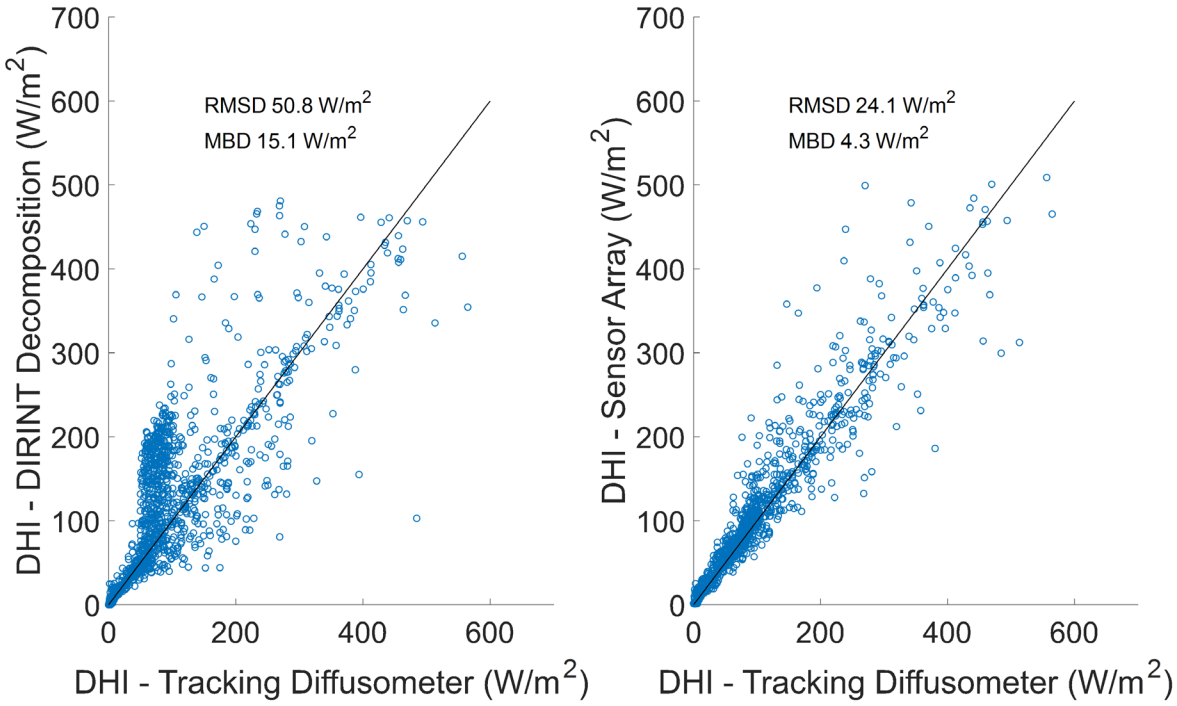


Figure 6: Comparison of DHI prediction accuracy for the DIRINT decomposition model (left) versus the results of the sensor array and neural network model (right). Each plot shows the predicted DHI versus the reference value of DHI from the tracking diffusometer, for hourly averaged results. Results are from a three-month period beginning in June 2023 and exclude the neural network training period from May 2023.

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.

Expressed as a percentage of mean GHI, the DIRINT MBD and RMSD are 4.8% and 16.1%, respectively, while the sensor array MBD and RMSD are 1.4% and 7.6%, significantly better. The DIRINT RMSD result is consistent with observations in [1] over a collection of sites, although it is at the upper end of the range. 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.

5 DISCUSSION AND ONGOING WORK

Results presented in Fig. 5 and Fig. 6 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. Compared with our previous approach in [3], fewer sensors are required and the results have better performance particularly for clear-sky conditions with low DHI. Therefore, the new concept could provide a low-cost DHI measurement device suitable for pre-construction resource assessment and PV power plant meteorological stations, helping reduce PV performance modeling uncertainties.

However, additional work is needed to fully test this concept.

We envision that the two sensors used in the present work would be deployed together with a processing unit that would automatically calculate DHI results from the trained neural network model. It will be important to demonstrate that the neural network model trained at one site can be deployed at other sites and remain accurate without retraining.

Therefore, we plan to deploy the sensor array experiment to additional sites for further testing. Additional sites will be chosen to have different latitude than the Albuquerque site, since the diffuse polar irradiance signal may depend on angular separation between the sun and the observed sky region, which depends on latitude, time of day, and time of year. Testing therefore also will be conducted over a longer period that includes more seasonal variation.

6 ACKNOLWEGEMENTS

This material is partially based upon work supported by the U.S. Department of Energy's Solar Energy Technologies Office under Award Number DE-SC0020831 and 38268.

Sandia National Laboratories is a multi-mission 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.

7 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] V. Estelles, D. Serrano, S. Segura, J. Wood, N. Webb, and M. Utrillas, "Evaluation of the Delta-T SPN1 radiometer for the measurement of solar irradiance components," *Proc. EGU Gen. Assem. 2016, Vienna, Austria*, 2016.

[3] 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.

[4] 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.

[5] 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.

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

[7] 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.