EVALUATING A MODEL TO ESTIMATE GHI, DNI, & DHI FROM POA IRRADIANCE

Michael Gostein[1], Bill Stueve[1], Kendra Passow[2], Bill Marion[3]
[1]Atonometrics, 8900 Shoal Creek Blvd. Suite 116, Austin, TX 78757, USA
[2]First Solar, 135 Main Street, San Francisco, CA 94105, USA
[3]National Renewable Energy Laboratory, 15013 Denver West Parkway, Golden, CO 80401, USA

ABSTRACT: We evaluate the GTI-DIRINT model for estimating direct normal irradiance (DNI), diffuse horizontal irradiance (DHI), and global horizontal irradiance (GHI) from measured plane-of-array (POA) irradiance. Our motivation is to explore the potential for limiting ground-based irradiance measurements to POA to reduce instrumentation costs. We test the GTI-DIRINT model using meteorological data collected at seven First Solar PV power plants, comparing the GTI-DIRINT model, which uses POA as input, to the DIRINT model, which uses GHI as input. Furthermore, we include translation between reference module and thermopile pyranometer measurements to demonstrate the ability to use PV module POA performance data as a model input. The results indicate that the GTI-DIRINT model performs at least equivalently to the DIRINT model for fixed-tilt arrays and may have superior performance for large tilt angles encountered in single-axis tracking arrays.

Keywords: irradiance, measurement, decomposition model, system performance

1 INTRODUCTION

Solar resource assessments are essential to both pre-construction performance prediction and post-construction system validation, and may be performed with a combination of ground-based and satellite-derived weather data. Optimally, interrelating satellite and ground-based weather data with PV system performance requires knowledge of four different quantities: global horizontal irradiance (GHI), direct normal irradiance (DNI), diffuse horizontal irradiance (DHI), and plane-of-array (POA) irradiance. High-accuracy instrumentation to measure all four quantities can be deployed at meteorological stations for utility-scale projects. However, the expense may not be justified at all projects, particularly smaller power plants.

A number of models are in use to estimate one or more of the four irradiance quantities from the other quantities, allowing a reduction in the number of deployed sensors and therefore a reduction in instrumentation cost. One approach is to measure GHI only and to estimate DNI, DHI, and POA from the GHI measurements using decomposition and transposition models. However, this paper addresses an alternative approach: measuring only POA and using this to estimate the remaining three quantities. A potential advantage of deriving all quantities from POA measurement is that POA can be conveniently measured using a relatively low cost reference cell or reference module. This allows automatic spectral correction and also potential dual-purpose use for soiling measurement instrumentation which employs POA PV reference devices [1].

One of the authors, Marion, has recently developed the GTI-DIRINT model [2], [3] for estimating DNI and DHI from global tilted irradiance (GTI), which is equivalent to POA irradiance. Since GHI can be directly calculated from DNI and DHI, this model allows determination of all four quantities.

In this paper, we evaluate the GTI-DIRINT model which uses POA irradiance to determine the other three irradiance quantities, comparing its accuracy to the DIRINT model which uses GHI to determine the other three quantities. We perform this evaluation by testing both models with data collected from meteorological stations at seven First Solar PV power plants at locations in the southwestern U.S., Canada, and the Arabian Peninsula.

2 MODEL

The GTI-DIRINT model [2], [3] is a modification of the DIRINT model developed by Perez et al. which determines DNI and DHI from GHI [4]. In GTI-DIRINT, the DIRINT model is modified to use POA irradiance (or GTI, equivalently) in place of GHI [2], [3]. While the DIRINT model uses a global clearness index calculated from GHI, in GTI-DIRINT this is replaced with a global clearness index calculated from POA. Subsequently, the GTI-DIRINT model uses the same binning method and fit coefficients as DIRINT. However, GTI-DIRINT also includes an iteration procedure to ensure that the model outputs agree with the input data. In addition, the model includes special treatment for irradiance with angles of incidence on the plane-of-array which are greater than 90 degrees, a condition for which DIRINT has no provision since DIRINT uses GHI as input.

We have performed our analysis using the MATLAB version of the Sandia National Laboratories PV_LIB Toolbox, which includes an implementation of DIRINT as well as supporting functions. To implement GTI-DIRINT, we started from the DIRINT code in PV_LIB and modified it as needed per the description in [3]. However, in our implementation we also added spectral correction and inclusion of a step for incidence angle modifiers in the GTI-DIRINT iteration loop in order to use reference module data as input, as will be described further below.

3 EVALUATION DATA

For this work we have examined meteorological data collected at the seven First Solar PV power plants summarized in Table I, which include five fixed-tilt and two single-axis tracking arrays. The data from each site included secondary standard thermopile pyranometer measurements of both GHI and POA irradiance. In addition each site included pairs of First Solar CdTe reference modules used for POA soiling measurement [1]. The short-circuit current and back surface temperature of the modules are measured and used to compute irradiance. One of these modules is routinely cleaned, and we use the irradiance value from this clean module as a POA measurement. The GHI and POA thermopile pyranometers were also routinely cleaned. At the single-axis tracking sites all the POA instruments were installed

Table I: Summary of data sources

Site	Location	Array Type	Tilt (°)	Az. (°)	Years of Data
A	Southwest US	Single-Axis Tracking	-	-	2.8
B	Southwest US	Single-Axis Tracking	-	-	1.5
C	Southwest US	Fixed Tilt	25.0	180	2.7
D	Southwest US	Fixed Tilt	22.5	180	1.5
E	Southwest US	Fixed Tilt	22.5	190	1.7
F	Arabian Peninsula	Fixed Tilt	20.0	180	1.9
G	Canada	Fixed Tilt	25.0	180	3.3

on the trackers with the PV array. In addition to the above, the five fixed-tilt sites also included rotating shadowband radiometers for measurement of DNI and DHI. All sites included measurements of ambient temperature and humidity which were used as supporting inputs for the models. From each power plant we selected one instrument of each available type to use for the correlation analysis, choosing those instruments located in the lowest-numbered blocks of each power plant for consistency.

The available data from the sites spanned time periods ranging from 1.5 to 3.3 years. To perform the analysis, we aggregated the readings of each instrument into hourly averages. For each hour we used the midpoint of the hour as the timestamp, except for hours that included sunrise and sunset, for which we used the midpoint of the daylight portion of the hour as the timestamp, following [3].

4 CORRELATION EQUATIONS

We evaluated our correlation results using the mean bias deviation (MBD) and root-mean-square deviation (RMSD) statistics, expressed both in physical units and as a percent of the mean. These are calculated according to the following expressions from [3]:

$$\mathrm{MBD} = \frac{1}{n} \cdot \sum(y_i - x_i) \quad (\mathrm{W/m^2}) \quad (1)$$

$$\mathrm{MBD} = 100 \cdot \left[\frac{1}{n} \cdot \sum(y_i - x_i)\right] / \left[\frac{1}{n} \cdot \sum x_i\right] \quad (\%) \quad (2)$$

$$\mathrm{RMSD} = \left[\frac{1}{n} \cdot \sum(y_i - x_i)^2\right]^{1/2} \quad (\mathrm{W/m^2}) \quad (3)$$

$$\mathrm{RMSD} = 100 \cdot \left[\frac{1}{n} \cdot \sum(y_i - x_i)^2\right]^{1/2} / \left[\frac{1}{n} \cdot \sum x_i\right] \quad (\%) \quad (4)$$

Here x_i and y_i are the i^{th} values in the x and y series that are to be correlated and n is the number of pairs of values in the series.

5. REFERENCE MODULE VS. PYRANOMETER MEASUREMENTS

Our data set includes POA irradiance measurements from both thermopile pyranometers and PV reference modules. The pyranometers measure broadband irradiance with near cosine angular response, while the reference modules have a reduced spectral and angular sensitivity matching that of the PV array. For this work we wished to explore how POA and GHI measurements could be interrelated for the combined purposes of matching historical or satellite-derived irradiance data as well as predicting PV array performance. Therefore we used the thermopile pyranometer measurements for GHI but the PV reference module measurements for POA irradiance; the POA pyranometer was additionally used as a check and a calibration reference, although it was not used as a model input. Our modeling goal is to determine how well we can predict the reference module POA data from the pyranometer GHI data (using DIRINT) and vice-versa (using GTI-DIRINT).

Before examining the performance of the models, we first established the baseline degree of correlation between the measurement instruments. Table II illustrates the RMSD of the correlation in measurements between the POA reference module, the POA pyranometer, and the GHI pyranometer. The measurements used were drawn from the two sites using single-axis tracking and only for hours near noon when the tracker tables were nearly horizontal, so that the POA reference module and pyranometer could be compared not only with each other but also with the GHI pyranometer. A spectral correction factor [6] and an incidence angle modifier factor were applied to the reference module data, using functions included in PV_LIB.

Table II shows that the two pyranometers correlate extremely well with each other, while the correlation between the reference module and either of the

Table II: Correlation of irradiance measurements when plane of array is nearly horizontal

		GHI Pyranometer *vs.* POA Pyranometer				**POA Pyranometer *vs.* POA Ref. Module**				**POA Ref. Module *vs.* GHI Pyranometer**			
		MBD		**RMSD**		**MBD**		**RMSD**		**MBD**		**RMSD**	
Site	**Type**	**%**	**(W/m²)**	**%**	**(W/m²)**	**%**	**(W/m²)**	**%**	**(W/m²)**	**%**	**(W/m²)**	**%**	**(W/m²)**
A	Single-Axis Tracking	0.7	5.4	1.6	12.7	-0.8	-6.6	4.3	34.3	0.0	0.0	4.3	34.2
B	Single-Axis Tracking	1.4	11.6	1.7	14.2	-1.3	-11.3	2.9	24.5	0.0	0.0	2.5	21.3
	Avg. Abs. Value:	1.1	8.5	1.7	13.5	1.1	9.0	3.6	29.4	0.0	0.0	3.4	27.8

Table III: Modeled vs. measured results for POA and GHI

Model/Method:		DIRINT				GTI-DIRINT			
Input Parameter:		GHI Pyranometer				POA Reference Module			
Output Parameter:		POA Reference Module				GHI Pyranometer			
		MBD		RMSD		MBD		RMSD	
Site	Type	%	(W/m^2)	%	(W/m^2)	%	(W/m^2)	%	(W/m^2)
A	Single-Axis Tracking	-0.9	-6.1	7.8	51.6	0.9	4.8	5.5	28.6
B	Single-Axis Tracking	4.6	30.1	13.8	90.8	-1.3	-6.8	6.3	33.8
	Average Abs. Value:	2.8	18.1	10.8	71.2	1.1	5.8	5.9	31.2
C	Fixed Tilt	0.8	3.8	10.7	49.7	0.0	0.1	7.9	33.0
D	Fixed Tilt	1.6	8.0	8.0	40.3	-1.5	-7.3	9.2	44.5
E	Fixed Tilt	0.0	-0.2	3.6	18.4	0.2	0.9	3.8	17.6
F	Fixed Tilt	-0.1	-0.5	3.0	15.4	0.5	2.4	3.6	17.3
G	Fixed Tilt	1.5	4.9	15.2	48.9	-0.2	-0.5	12.3	37.6
	Average Abs. Value:	0.8	3.5	8.1	34.5	0.5	2.2	7.4	30.0

Table IV: Modeled vs. measured results for DNI and DHI

Model/Method:		DIRINT								GTI-DIRINT							
Input Parameter:		GHI Pyranometer								POA Reference Module							
Output Parameter:		DNI				DHI				DNI				DHI			
		MBD		RMSD		MBD		RMSD		MBD		RMSD		MBD		RMSD	
Site	Type	%	(W/m^2)	%	(W/m^2)	%	(W/m^2)	%	(W/m^2)	%	(W/m^2)	%	(W/m^2)	%	(W/m^2)	%	(W/m^2)
C	Fixed Tilt	-0.1	-0.3	24.4	116.2	1.7	2.1	44.7	54.6	-1.0	-4.6	29.1	138.3	16.8	20.6	61.4	74.9
D	Fixed Tilt	5.2	31.3	20.6	124.4	-7.0	-7.4	62.0	65.4	-7.0	-42.4	28.5	172.7	30.6	32.4	60.4	63.8
E	Fixed Tilt	0.4	2.7	15.0	93.5	-2.2	-2.3	39.8	40.4	-1.3	-7.8	15.9	98.8	10.3	10.4	44.9	45.6
F	Fixed Tilt	19.3	89.3	26.3	121.6	-30.3	-56.8	41.9	78.7	22.8	105.4	29.6	136.9	-31.3	-58.7	43.9	82.5
G	Fixed Tilt	11.1	29.8	38.2	102.0	-2.8	-3.7	33.2	43.7	7.6	20.4	47.8	127.7	4.4	5.8	40.4	53.2
	Average Abs. Value:	7.2	30.7	24.9	111.5	8.8	14.5	44.3	56.6	7.9	36.1	30.2	134.9	18.7	25.6	50.2	64.0

pyranometers is poorer, although still good. This residual non-correlation reflects the differences in the fundamental responses of the instruments, even though the spectral and angular corrections have been performed. We observed that when we eliminated partly cloudy days with highly variable irradiance from the dataset, the reference module vs. pyranometer correlation RMSD improved from ~30 W/m^2 to ~15 W/m^2, matching the pyranometer-pyranometer RMSD. This suggests that a possible explanation for the poorer correlations between the reference modules and the pyranometers in the full dataset is the differences in the temporal responses of these devices – the reference modules respond much more quickly than the pyranometers to changes in irradiance. Another possible explanation is poorer performance of the spectral correction factor on partly cloudy days.

In any case, for the full dataset, the correlation of the reference modules to the pyranometers shows RMSD of ~30 W/m^2. It should be understood that this value represents the cross-instrumental contribution to the RMSD of the correlations between model results based on either the POA reference module or the GHI pyranometer versus measurements from the other instrument, as will be discussed below.

In evaluating the models, we wished to use the MBD statistic in addition to RMSD. In order to ensure that the MBD represents the accuracy of the model results, and not any differences in instrument calibration, we matched the calibration of the reference module and the pyranometers. For the two single-axis tracking sites, we did this by setting the reference module calibration so that the spectrally corrected reference module irradiance measurements matched, on average, the GHI pyranometer during the hours when the tracker table was nearly horizontal. Note that the MBD values in the third column group of Table II are 0 as a result. For the fixed-tilt sites this method was not possible; therefore, for these sites we matched the spectrally and angularly corrected reference module irradiance measurements to the POA pyranometer. Based on the single-axis tracking sites shown in Table II, we made the assumption that at the fixed-tilt sites each POA pyranometer is also well matched (<2% MBD) with its corresponding GHI pyranometer. Although we could not directly verify this assumption, the model results indicate consistency.

6. RESULTS

Table III shows the results of the DIRINT and GTI-DIRINT models for POA and GHI. To apply the DIRINT model, we used the GHI pyranometer data as input, determined DNI and DHI from DIRINT, translated the resulting DHI to a tilted diffuse irradiance using the Perez

model [5] function in PV_LIB and added a diffuse ground reflection using the ground reflection model in PV_LIB (with albedo of 0.2) to yield a total diffuse tilted irradiance (DTI). We then applied incidence angle modifier and spectral correction factors appropriate for the PV modules and combined the DNI and DTI to yield a POA irradiance value. This modeled POA was then correlated with the reference module irradiance measurements to yield the DIRINT statistics shown in Table III for the MBD and RMSD comparing the modeled and measured values. To apply GTI-DIRINT, we used the spectrally corrected POA reference module irradiance as input, determined DNI and DHI from the GTI-DIRINT model (with albedo of 0.2 and with incidence angle modifiers included as described above), and then calculated GHI by combining the DNI and DHI components. This modeled GHI was then correlated with the pyranometer measured GHI yielding the GTI-DIRINT statistics in Table III. The bottom row of the table shows the average absolute value of each column, to provide a summary value for the results.

The results show that both the model approaches perform very well, with average MBD ~1% and RMSD 7-9%. Based on both the MBD and RMSD the GTI-DIRINT performance appears at least equivalent or possibly superior to that of DIRINT, since both the MBD and RMSD of the GTI-DIRINT method were lower than those for DIRINT.

The RMSD values shown in Table III for both DIRINT and GTI-DIRINT, on average ~30 W/m^2 for the fixed-tilt sites, are somewhat larger than the equivalent values found by Marion in [3], which were only ~20 W/m^2. However, in [3], thermopile pyranometer data were used for both GHI and POA measurements, while here we use a spectrally and angularly corrected reference module for the POA measurements. In Table II and its associated discussion we already showed that by correlating the pyranometer and reference module measurements we have an additional source of variance on the order of ~30 W/m^2 due to the differences in instrument sensitivities. Therefore the final RMSD values in Table III which are themselves on the order of ~30 W/m^2 indicate that the models perform better than indicated by Table III. We confirmed this conclusion by repeating the model calculations using only the pyranometer measurements for both POA and GHI and found that for both models the correlation of modeled to measured results was significantly improved. This does not indicate superiority of the pyranometer measurements but rather that there is some variance in going from pyranometer data to PV module data and vice versa, for the reasons already discussed.

Note in particular in Table III that for the fixed-tilt sites DIRINT and GTI-DIRINT have similar performance, while for the single-axis tracking sites GTI-DIRINT performs significantly better than DIRINT, as shown by better MBD and RMSD. Figure 1 illustrates this in more detail, showing the RMSD for the model results for Site A with the data filtered to exclude tracker tilt angles above the indicated maximum values. When only low tilt angles representing mid-day hours are included, both DIRINT and GTI-DIRINT perform equivalently. But when high tilt angles representing morning and evening hours are included, the performance of GTI-DIRINT is only marginally affected while DIRINT is significantly affected. Similar results were found for Site B, explaining the unusually large RMSD for DIRINT in Table III. The superior performance of GTI-DIRINT for large tracker tilt angles is likely due to the fact that the input to

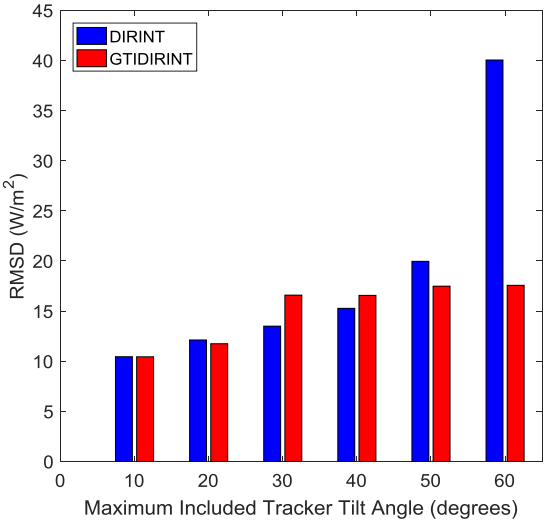


Figure 1: Variation of RMSD for modeled global irradiance translations (DIRINT: GHI to POA, GTIDIRINT: POA to GHI) versus measured values, for Site A, using only pyranometer data.

GTI-DIRINT, the POA irradiance, has a larger DNI component than the input to DIRINT, which is the GHI. Evidently the decomposition model performs better when using measurements from the plane tilted towards the sun.

In Table IV we compare the DNI and DHI results of each of the models with the DNI and DHI measured by the shadowband radiometers at the five fixed-tilt sites where these were available. The correlation statistics for DNI and DHI are not as good as those for POA and GHI, even though the modeled POA and GHI results are computed from the modeled DNI and DHI values. This is because the modeled DNI and DHI are somewhat anti-correlated; a deficit in DNI is compensated by an excess of DHI and vice versa. However, the average MBD and RMSD in Table IV are comparable to, though somewhat larger than, those in [3]. Overall the models appear to perform about equivalently, although in this case the DIRINT results are somewhat better than the GTI-DIRINT results.

7. CONCLUSIONS

We have evaluated the GTI-DIRINT model using data collected at seven sites spanning three geographic regions over periods from 1.5 to 3.3 years and found generally good performance, comparable to that obtained with the DIRINT model. We observed that the use of POA irradiance data with the GTI-DIRINT model is particularly beneficial, as compared to using GHI data with DIRINT, for the case of single-axis tracking systems. These results suggest the potential for using reference module POA measurement as the single irradiance measurement from which GHI, DNI, and DHI can be modeled, in situations where this may be advantageous. Some questions remain regarding the degree of variance in the correlation of reference module and pyranometer data, which may be explored in future work.

8. REFERENCES

[1] M. Gostein, J. R. Caron, B. Littmann, "Measuring Soiling Losses at Utility-scale PV Power Plants," in the 40th PVSC, 2014.

[2] B. Marion, "PV Derived Data for Predicting Performance," at Solar Power International, Anaheim, CA, 2015.

[3] B. Marion, "A model for deriving the direct normal and diffuse horizontal irradiance from the global tilted irradiance," Solar Energy, v. 122, pp. 1037-1046, 2015.

[4] R. Perez, P. Ineichen, E. Maxwell, R. Seals, A. Zelenka, Dynamic global-to-direct irradiance conversion models, ASHRAE Transactions—Research Series, 354-369, 1992.

[5] R. Perez, P. Ineichen, R. Seals, J. Michalsky, R. Stewart, "Modeling daylight availability and irradiance components from direct and global irradiance," Solar Energy 44 (5), 271–289, 1990.

[6] L. Nelson, M. Frichtl, A. Panchula, "Changes in Cadmium Telluride Photovoltaic System Performance due to Spectrum," IEEE Journal of Photovoltaics, v. 3, pp. 488-493, 2012.