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PV Derived Data for Predicting Performance

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Introduction

We have developed a method for providing solar irradiance data for modeling PV performance by using measured PV performance data and back-solving for the unknown direct normal irradiance (DNI) and diffuse horizontal irradiance (DHI), which can then be used to model the performance of PV systems of any size, PV array tilt, or PV array azimuth orientation. Ideally suited for using the performance data from PV modules with micro-inverters, the PV module operating current is used to determine the global tilted irradiance (GTI), and a separation model is then used to determine the DNI and DHI from the GTI.

Determining the GTI from the PV Module Current

With the micro-inverter peak-power tracking the PV module, the PV module current (Imp) is used to determine the GTI in a similar fashion to how the short-circuit current (Isc) from a reference cell is used to determine irradiance.

For crystalline silicon PV modules, there exists a linear relationship, for all practical purposes, between the Isc and the Imp. This is illustrated in Figure 1. Consequently, we may substitute Imp for Isc in the classic equation for determining irradiance from a reference cell. This results in Equation 1.

$$GTI = 1000 \cdot Imp / Imp_0 / [1 + \alpha \cdot (T - T_0)] \qquad (1)$$

where T is the cell temperature, ºC; α is the Isc correction factor for temperature, $^{o}C^{-1}$; and the zero subscripts denote performance at the Standard Test Conditions (STC).

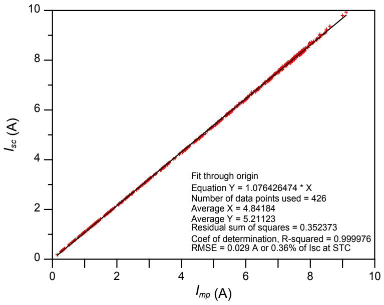

Fig. 1. Isc versus Imp for a multi-crystalline silicon PV module.

Determining the DNI and DHI from the GTI

Many separation models are available for determining the DNI and DHI from the global horizontal irradiance (GHI). One of the better models of this type is the DIRINT model developed by Perez et al. (1992). We modified the DIRINT model to use input values of GTI, in place of GHI, and refer to the modified model as the GTI-DIRINT model. The GTI-DIRINT model calculates the global clearness index, K_t, using Equation 2. This is similar to the DIRINT model, except the GTI replaces the GHI and the incident angle, θ, replaces the sun zenith angle, θ_Z.

$$K_t = GTI / [I_0 \cdot \max(0.065, \cos(\theta))] \qquad (2)$$

where I_0 is the extraterrestrial irradiance.

For small PV module tilt angles, DIRINT and GTI-DIRINT provide similar results for K_t but for larger PV module tilt angles the results differ because of the larger differences in the proportions of diffuse and direct irradiance for the GHI and GTI. The GTI also includes ground-reflected radiation and angle-of-incidence (AOI) effects. To compensate for errors introduced when using the GTI, we use the model in an iterative fashion until the measured GTI matches a modeled GTI determined by using the modeled values of DNI and DHI for the input to the tilted surface transposition model by Perez et al. (1990). A flow chart of the process is shown in Figure 2. More complete information on the GTI-DIRINT model is provided elsewhere (Marion, 2015).

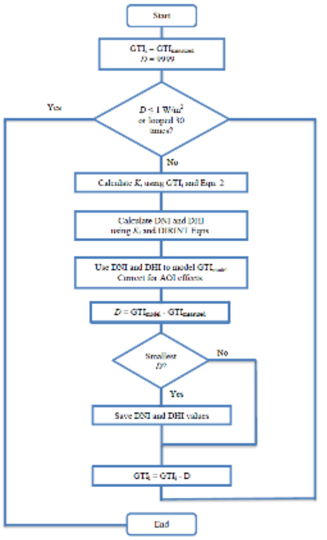

Fig. 2. Flow chart for the GTI-DIRINT model.

Validation Data and Method

We designed the validation experiment to include five identical PV module/Enphase micro-inverter systems, each with a different tilt and azimuth orientation. Each of the five systems is instrumented to measure ac power, dc voltage and current, PV module back-surface temperature, and the GTI. We used the existing DNI and DHI measurements from NREL's Solar Radiation Research Laboratory. The installed PV systems are shown in Figure 3. The performance of the model was evaluated using the root-mean-square deviation (RMSD) and mean bias deviation (MBD) statistics. The deviation is the measured value subtracted from the modeled value.

Figure 3. PV modules with micro-inverters installed at NREL. Three PV modules are south-facing, with tilts of 10º, 25º, and 40º from the horizontal. A 4th PV module is tilted 40º and faces 30º west of south. A 5th PV module (not shown) is installed on a nearby two-axis tracker.

Results for Modeling the DNI and DHI

For each fixed-tilt PV module orientation and for a one-year period, we used the measured Imp values to determine the GTI values per Equation 1, and then used the GTI-DIRINT model to model the DNI and DHI. MBD and RMSD statistics for modeling DNI and DHI were determined and are provided in Table 1. The convention (*Tilt, Azimuth*) identifies the fixed-tilt PV module providing the source of the Imp data. For comparison, similar statistics are provided for the original DIRINT model when using measured values of GHI for model input. For the PV modules facing south, the results for the GTI-DIRINT model were only slightly degraded from the results for the DIRINT model. For the PV module facing 30º west of south, the results were significantly degraded. This orientation results in more self-shading of the PV module.

Table 1. Mean bias deviation (MBD) and root-mean-square deviation (RMSD) for DIRINT and GTI-DIRINT modeled values of DNI and DHI

Model/Input	DNI MBD (%)	 RMSD (%)	 (W/m²)	DHI MBD (%)	 RMSD (%)	 (W/m²)
DIRINT	-6.0	19.9	93	10.8	38.0	55
GTI-DIRINT						
PV(10, 180)	-7.0	21.7	101	13.3	39.2	57
PV(25, 180)	-6.1	20.7	96	13.8	39.5	57
PV(40, 180)	-6.7	24.3	112	14.3	40.6	58
PV(40, 210)	-11.2	41.0	189	17.8	54.6	79

Results for Using the Derived DNI and DHI to Model the GTI

For each of the south-facing PV module orientations, we used the DNI and DHI values derived using the GTI-DIRINT model with the Perez tilted surface transposition model to model the GHI and the GTI for each of the five PV module orientations. For comparison, we also modeled the GTI using measured values of DNI and DHI and modeled values of DNI and DHI from the DIRINT model. The statistical results when comparing the modeled GTIs to those measured with Kipp and Zonel CM11 pyranometers are shown in Figure 4.

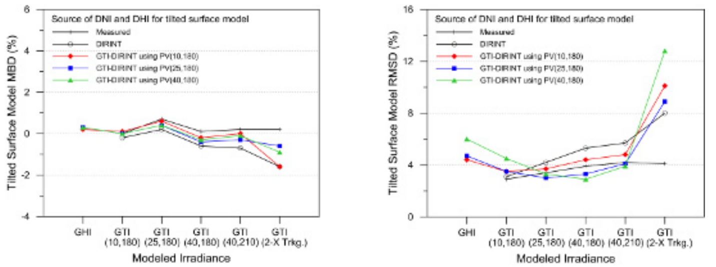

Fig. 4. MBD (left) and RMSD (right) statistics for tilted surface modeling of the GTI when using measured, DIRINT, and GTI-DIRINT sources of DNI and DHI. Except for 2-axis tracking, results are close to each other. 2-axis tracking has a large DNI component and measured inputs work best.

Results for Using the Derived DNI and DHI to Model the Pm

From the modeled values of GTI, the PV module power (Pm) was modeled by correcting for AOI and temperature effects and assuming linearity with irradiance. The statistical results when comparing the modeled Pms to those measured are shown in Figure 5.

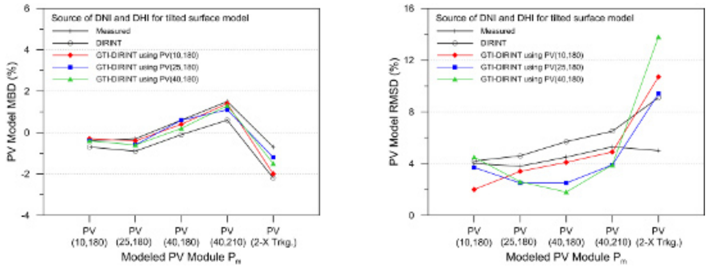

Fig. 5. MBD (left) and RMSD (right) statistics for modeling the Pm when using measured, DIRINT, and GTI-DIRINT sources of DNI and DHI. For MBD, results are close to each other. For RMSD, GTI-DIRINT is best for the fixed-tilt PV modules and measured is best for 2-axis tracking.

References

Marion, B., 2015. A model for deriving the direct normal and diffuse horizontal irradiance from the global tilted irradiance, submitted to Solar Energy.

Perez, R., Ineichen, P., Seals, R., Michalsky, J., 1990. Modeling daylight availability and irradiance components from direct and global irradiance, Solar Energy 44, 271-289.

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

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory.

Solar Power International 2015
Anaheim, CA
September 14-17, 2015
NREL/PO-5J00-64707