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EVALUATION OF PHOTODIODE AND THERMOPILE PYRANOMETERS FOR PHOTOVOLTAIC APPLICATIONS

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ABSTRACT: Accurately determining photovoltaic (PV) module performance in the field requires measuring solar irradiance reaching the PV panel at a high level of accuracy and known uncertainty. Silicon detectors used in various solar energy measuring instruments that include reference cells are a potentially attractive choice for multiple reasons, including faster responsivity than thermopile detectors, cheaper cost, and lower maintenance. The main drawback, however, is that the silicon detectors are only spectrally responsive in a narrow part of the solar spectrum; therefore, to determine broadband solar irradiance, a calibration factor that converts the narrowband response to broadband is required. Normally, this calibration factor is a single number determined under standard conditions but used for various scenarios, including varying airmass, panel orientation, and atmospheric conditions. This would not have been an issue if all wavelengths that form the broadband spectrum responded uniformly to atmospheric constituents. Unfortunately, the scattering and absorption signature varies widely across wavelengths, and the calibration factor computed under certain test conditions is not appropriate for other conditions. This paper lays out the issues that will arise from the use of silicon detectors for PV performance measurement in the field. We also present a comparison of simultaneous spectral and broadband measurements from silicon and thermopile detectors and estimated measurement errors when using silicon devices for both array performance and resource assessment.

Keywords: spectral response, photodiodes, pyranometer, direct normal irradiance, global horizontal irradiance

1 INTRODUCTION

Silicon photodiode-based pyranometers have been used to measure global horizontal irradiance (GHI), primarily in agricultural networks, for decades. These radiometers are also popular for applications in solar energy conversion. They are currently used in numerous locations to measure GHI for various purposes, including solar resource assessment and photovoltaic (PV) performance [1]. PV performance testing requires accurate measurements of both power output by PV panels and solar energy incident on the panels (plane-of- array, or POA, irradiance). These silicon devices have become popular mainly because of their low cost, ease of maintenance, and fast time response for high frequency data. Silicon photodiode pyranometers provide limited spectral response, as shown in Fig. 1. The direct normal irradiance (DNI) spectral irradiance shown in Fig. 1 illustrates the magnitude of this limitation. The calibration of pyranometers is based on simultaneous measurements of solar irradiance by a broadband thermopile reference (REF) and the unit under test (UUT) [2]. The resulting pyranometer responsivity is computed as the ratio UUT (μV) / REF (Wm^{-2}). For the photodiode- based pyranometer, this calculation represents the energy collected by a silicon device to the total energy available in the solar spectrum. Calibration data are generally collected throughout the day under clear-sky conditions. Unfortunately, the solar spectrum does not change uniformly with increasing airmass; therefore, the ratio of the energy gathered by a silicon photodiode pyranometer compared with the total energy in the solar spectrum will vary during the day. This paper seeks to understand the impact of this variability and whether the use of a constant calibration coefficient results in significant error in estimation of broadband POA irradiance using a silicon photodiode pyranometer.

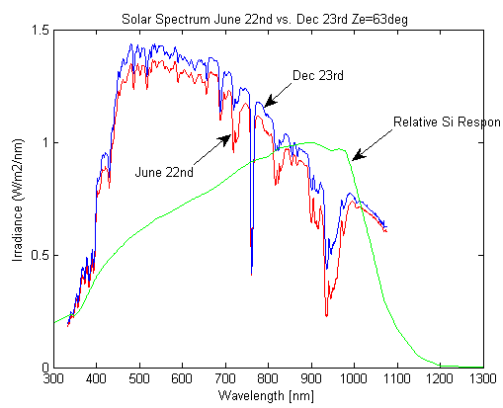

Fig. 1. Spectral response function of a silicon photodiode pyranometer (in green) shown along with a spectral DNI measurement from a summer and winter day (shown in red and blue, respectively).

2 MOTIVATION

We designed a single-axis tracking device at the National Renewable Energy Laboratory (NREL) and mounted multiple silicon devices, including a LICOR model LI-200, an Apogee model SP 110, an IMT reference cell, as well as a Kipp and Zonen model CMP 11 thermopile pyranometer. The goal of this instrument package was to investigate the possibility of deploying such single-axis tracking devices in the field for solar resource assessment relevant to a similarly tracking PV plant (Fig. 2). We observed that the silicon-based devices had significant measurement difference when compared to each other based on the manufacturer's calibration. We also observed

that although the LI-200 measurements agreed with the CM 11 at solar noon, over-prediction of GHI occurred earlier in the morning and later in the afternoon. (Fig. 2). The CM 11 thermopile device was validated against a reference CM 21 at solar noon.

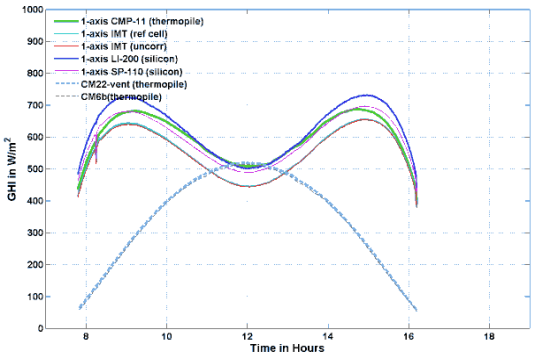

Fig. 2. Silicon and thermopile device measurement mounted on a single-axis tracker. GHI measurements from a well-calibrated instrument are also shown.

The silicon devices were scaled to the LI-200 using the solar noon offset as the correction, as shown in Fig. 3. It was clear that all silicon devices agreed with the CM 11 thermopile instrument at solar noon but over-predicted both in the morning and afternoon.

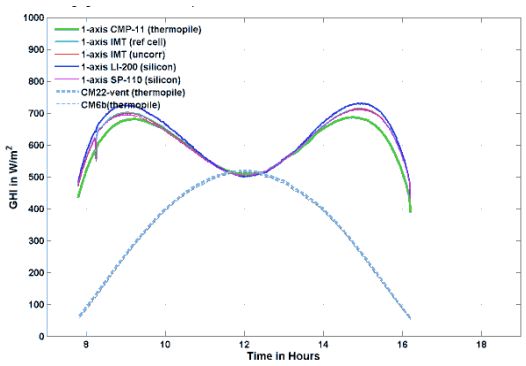

Fig. 3. Silicon and thermopile device measurement mounted on a single-axis tracker. The measurements from the silicon devices were scaled to the LI-200. GHI measurements from a well-calibrated instrument are also shown.

The difference between the silicon and thermopile devices was significant enough that over-prediction similar to that observed in this case will result in significant errors in PV performance evaluation if silicon devices are used. In this paper, we investigate the impact of spectral sensitivity of silicon devices and whether a static calibration of the silicon devices leads to errors in measurement when compared to broadband measurements by well-calibrated thermopile devices.

3 METHODOLOGY AND RESULTS

The spectral distributions of measured DNI and GHI changed as the solar zenith angle changes during the course of the day. Fig. 4 shows how the spectral DNI changed during the course of a clear day. Fig. 5 shows how the spectral GHI changed during the same day.

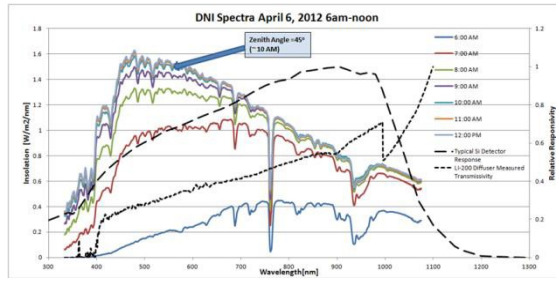

Fig. 4. Hourly DNI spectra for April 6, 2012, measured from 6 a.m. to 12 p.m. The dashed black line represents the spectral response of the LI-200 instrument. The dotted black line represents the spectral response of the diffuser on the LI-200.

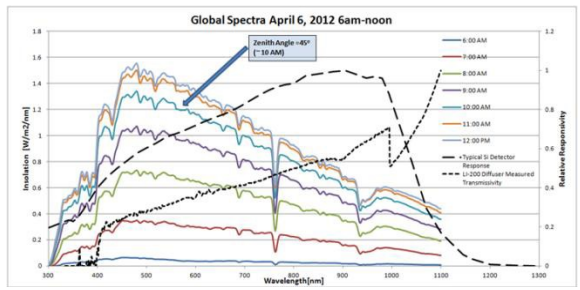

Fig. 5. Hourly GHI spectra for April 6, 2012, measured from 6 a.m. to 12 p.m. The dashed black line represents the spectral response of the LI-200 instrument. The dotted black line represents the spectral response of the diffuser on the LI-200.

The spectral DNI was measured using a Kipp and Zonen PGS 100 spectrophotometer with the spectra being measured from 350 nanometers (nm) to 1050 nm at a resolution of approximately 4 nm. A LI-COR LI-1800 spectroradiometer measures spectral GHI between the wavelengths of 350 nm and 1100 nm.

The DNI spectrum for various times showed that the distribution changed during the day as the airmass changed (see Fig. 4). As shown in Fig. 5, similar changes occurred in the GHI spectrum. The LI-200 instrument receives a signal from each of the solar wavelengths scaled to the product of the response of the photodiode and the diffuser. The total signal received is the sum of energy received from each of the wavelengths. To measure broadband solar radiation with the LI-200 under current practice, the instrument is calibrated to an airmass of 1.5. This static calibration can produce accurate broadband measurements at other times of the day only if the spectral distribution has the same shape as at calibration time, implying that the proportion of energy in various wavelengths remains the same. As in a Rayleigh scattering environment, shorter wavelengths are preferentially scattered the shape of the spectral distribution, especially in the DNI, which varies (Fig. 4); therefore, we expect that a static calibration for the LI-200 for an airmass of 1.5 will lead to a biased measurement at other times of the day with different airmass.

To investigate the impact of spectral shape changes on LI-200 measurement errors, we took the spectral DNI measurements from the PGS-100 instrument and convolved it with the sensor and diffuser spectral responses for a zenith angle of 45 degrees, corresponding approximately to an airmass of 1.5. We then summed the total energy in the convolved calculation for both DNI and GHI to arrive at an estimate of "actual energy" received at the sensor. To create a "calibration"

for measuring broadband DNI, we took the broadband measurement from the Kipp and Zonen CH-1 model pyrheliometer (a thermopile instrument) for exactly the same time and location and calculated a ratio of the broadband measurement to the "actual energy" from the PGS-100. We called this the "calibration coefficient," which was then applied to the convolved spectral sum from the PGS-100 at other times to obtain the broadband solar radiation. A similar method was applied to the spectral GHI measured using the LI-1800. The broadband measurement from the Kipp and Zonen CM-22, a thermopile instrument, was used to compute a similar "calibration coefficient" at airmass 1.5 for silicon devices.

Next, we applied the "calibration coefficients" for converting spectral DNI and GHI to the convolved spectral sum for measurements taken at various times on a clear day and compared them to the CH-1 measurements for DNI and CM-22 for GHI. We also took the DNI and GHI measurements from the rotating shadowband radiometer (RSR), which had a LI-200 for measurement, and calculated the differences between the RSR and thermopile instruments. In this experiment, if the differences between the RSR and thermopile instruments were similar to the difference observed in the spectral instrument versus thermopile comparison, we would be able to say definitively that spectral mismatch results in errors in broadband measurements when silicon based instruments are used.

4 RESULTS

June 22, 2011, was observed to be a clear day at NREL's Solar Radiation Research Laboratory in Golden, Colorado, as shown in Fig. 6. The results for the DNI comparison are shown in Fig. 7.

The red line in Fig. 7 is our estimate of errors from using a silicon instrument such as the LI-200 because of the change in the energy distribution of the observed spectra. The shape of our estimated errors matched the actual errors from comparing RSR and CH-1 measurements at the same location for the same day.

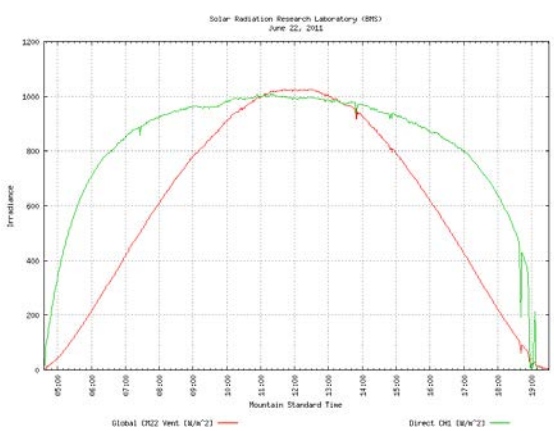

Fig. 6. The observed DNI from a CH-1 (red) and GHI from a CM-22 (green) for June 22, 2011, shows a clear day.

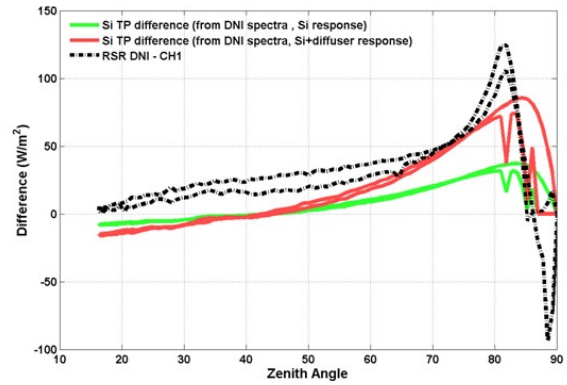

Fig. 7. Difference in broadband DNI calculated using the spectral DNI and measurements from the CH-1 thermopile instrument are shown by a red line as a function of zenith angle. Note that there was no difference between the two at a zenith angle of 45 degrees, the calibration point. The dashed black line shows the observed differences between the measurement using the LI-200 and the CH-1 for the same day. The green line shows the differences if the spectral response of the diffuser was excluded from the spectral "calibration" and calculation. Data used were from June 22, 2011.

The errors for high zenith angles were significant and can reach 50 W/m^2. It is notable that the morning and afternoon errors were slightly different, both in our estimates (red) and actual measurements (black). This difference in the errors is attributed to a difference in aerosol loading in the atmosphere, where the spectral distribution is again impacted because of scattering by the aerosol. A closer look at Fig. 4 and Fig. 7 clearly shows that the error grows as the spectral shape changes.

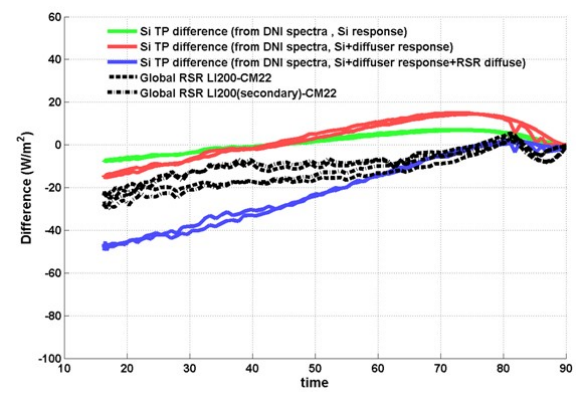

Fig. 8. Difference in broadband GHI (calculated using the spectral DNI difference plus the diffuse difference between the RSR diffuse and thermopile diffuse) is shown by the blue line as a function of zenith angle. The dashed black line shows the observed differences between the measurement using the LI-200 and the CM-22 for the same day. Data used were from June 22, 2011.

In Fig. 8, the blue line shows our theoretical estimate of GHI errors. To calculate the GHI errors, we first calculated diffuse errors using the diffuse measurements from the RSR and the diffuse from a shaded CM-22. We then scaled the estimated DNI difference from Fig. 7, scaled it by the cosine of the solar zenith, and added the diffuse difference to calculate the GHI error estimates. The dotted black lines show the actual errors. It

is interesting to note that the errors in GHI were not as high as observed for DNI. This observation was supported by the fact that the spectral GHI in Fig. 5 did not change shape as drastically as the spectral DNI in Fig. 4. This phenomenon can be explained by the fact that the blue light at shorter wavelengths that has been preferentially scattered out of the direct beam forms part of the diffuse radiation that reaches the surface as a component of the GHI.

Nevertheless, we found that both GHI and DNI measurements using silicon instruments have errors that are dependent on zenith angle. Other influences were the aerosol loading, as shown in both Fig. 7 and Fig. 8, where the morning and afternoon errors varied because of a change in aerosol loading.

5 SUMMARY

We found that broadband measurements using silicon devices deviate from measurements using a thermopile. All measurements were taken using a single-axis tracking platform. As silicon devices have a variable response across the solar spectrum, they are calibrated to broadband thermopile devices at solar zenith angles below 45 degrees, in accordance with protocol. The solar DNI spectrum does not vary uniformly with airmass, because blue light is preferentially scattered out with an increase in airmass; therefore, the calibration coefficient calculated at a particular zenith angle is no longer valid at higher solar zenith angles. This results in over-prediction of broadband solar radiation at higher zenith angles and under-prediction at lower zenith angles. This error must be corrected when determining the absolute efficiency of PV devices. It is expected that similar errors will occur if the calibration coefficient is calculated for a particular environmental condition and the silicon device is deployed in a different environment. As an example, higher aerosol loading will cause similar preferential scattering in the blue part of the solar spectrum and cause similar over-prediction. Additionally, calibrations conducted at higher elevations and low water vapor conditions will no longer be applicable at lower elevations and humid conditions; therefore, we concluded that the use of silicon devices for PV performance evaluation will lead to uncertainties that cannot easily be quantified. Empirical correction factors have been devised to correct for the spectral errors[4]. Such methods may not be able to provide accurate corrections for diverse conditions seen at various locations.

6 ACKNOWLEDGEMENT

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7 REFERENCES

[1] Stoffel, T.L., et al. *Concentrating Solar Power: Best Practices Handbook for the Collection and Use of Solar Resource Data.* NREL/TP-550-47465. Golden, CO: National Renewable Energy Laboratory, 2010; 146 pp. Accessed May 9, 2012. www.nrel.gov/docs/fy10osti/47465.pdf.

[2] Myers, D.; Stoffel, T.L.; Andreas, A.; Wilcox, S.; Reda, I. *Improved Radiometric Calibrations and Measurements for Evaluating Photovoltaic Devices.* NREL/TP-520-28941. Golden, CO: National Renewable Energy Laboratory, 2000; 43 pp. Accessed May 9, 2012: http://gisceu.net/PDF/U772.pdf.

[3] Solar Radiation Research Laboratory Baseline Measurement System. Accessed May 9, 2012: www.nrel.gov/midc/srrl_bms.

[4] King, D.L.; Boyson, W.E.; Hansen, B.R.; Bower, W.I. "Improved Accuracy for Low-Cost Solar Irradiance Sensors." *2nd World Conference and Exhibition on Photovoltaic Solar Energy Conversion Proceedings*; July 6–10, 1998, Vienna, Austria.