NATIONAL RENEWABLE ENERGY LABORATORY

Performance Testing Using Silicon Devices – Analysis of Accuracy

Preprint

Manajit Sengupta, Peter Gotseff, Daryl Myers, and Thomas Stoffel

Presented at the 2012 IEEE Photovoltaic Specialists Conference
Austin, Texas
June 3–8, 2012

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Conference Paper
NREL/CP-5500-54251
June 2012

Contract No. DE-AC36-08GO28308

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information

P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: mailto:reports@adonis.osti.gov

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/help/ordermethods.aspx

Cover Photos: (left to right) PIX 16416, PIX 17423, PIX 16560, PIX 17613, PIX 17436, PIX 17721

Printed on paper containing at least 50% wastepaper, including 10% post consumer waste.

Performance Testing using Silicon Devices – Analysis of Accuracy

Manajit Sengupta[1], Peter Gotseff[1], Daryl Myers[1] and Thomas Stoffel[1]
[1]National Renewable Energy Laboratory, Golden, CO, USA

ABSTRACT

Accurately determining PV module performance in the field requires accurate measurements of solar irradiance reaching the PV panel (i.e., Plane-of-Array – POA Irradiance) with known measurement uncertainty. Pyranometers are commonly based on thermopile or silicon photodiode detectors. Silicon detectors, including PV reference cells, are an attractive choice for reasons that include faster time response (10 µs) than thermopile detectors (1 s to 5 s), lower cost and maintenance. The main drawback of silicon detectors is their limited spectral response. Therefore, to determine broadband POA solar irradiance, a pyranometer calibration factor that converts the narrowband response to broadband is required. Normally this calibration factor is a single number determined under clear-sky conditions with respect to a broadband reference radiometer. The pyranometer is then used for various scenarios including varying airmass, panel orientation and atmospheric conditions. This would not be an issue if all irradiance wavelengths that form the broadband spectrum responded uniformly to atmospheric constituents. Unfortunately, the scattering and absorption signature varies widely with wavelength and the calibration factor for the silicon photodiode pyranometer is not appropriate for other conditions. This paper reviews the issues that will arise from the use of silicon detectors for PV performance measurement in the field based on measurements from a group of pyranometers mounted on a 1-axis solar tracker. Also we will 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.

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 being used in numerous locations to measure GHI for various purposes including solar resource assessment and 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 Figure 1. The Direct Normal Irradiance (DNI) spectral irradiance shown in Figure 1 illustrates the magnitude of this limitation. The calibration of pyranometers is based on simultaneous measurements of solar irradiance measured 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.

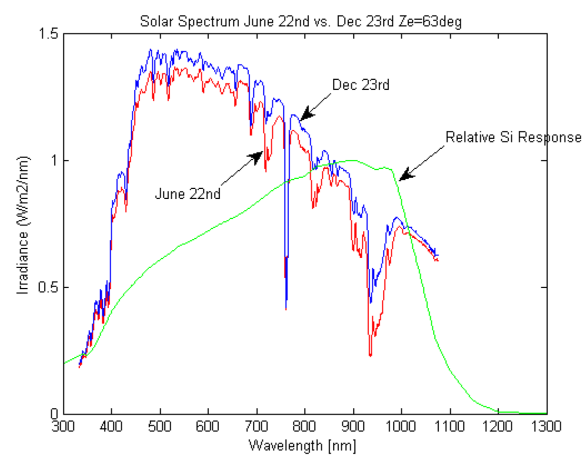

Figure 1: Spectral response function of a silicon photodiode pyranometer (in green) shown along with a spectral DNI measurement from a summer and winter day shown in red and blue respectively.

MOTIVATION

We designed a 1-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 1-axis tracking devices in the field for solar resource assessment relevant to a similarly tracking PV plant (Figure 2). It was observed that the silicon-based devices had significant measurement difference when compared to each other based on the manufacturer's calibration. It was also observed that while 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 (Figure 2). The CM 11 thermopile device was validated against a reference CM 21 at solar noon.

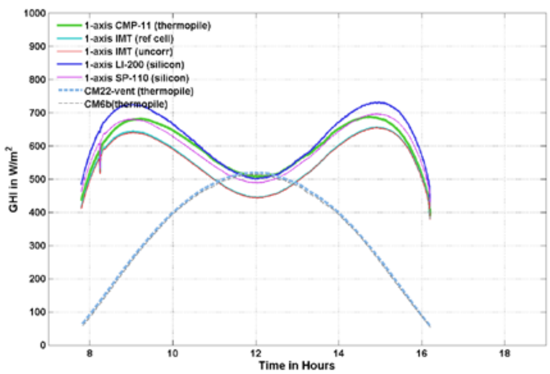

Figure 2: Silicon and thermopile device measurement mounted on a single-axis tracker. GHI from a well-calibrated instrument is also shown.

The silicon devices were scaled to the LI-200 using the solar noon offset as the correction as shown in Figure 3. It is clearly seen that all silicon devices agree with the CM 11 thermopile instrument at solar noon, but over-predicts both in the morning and afternoon.

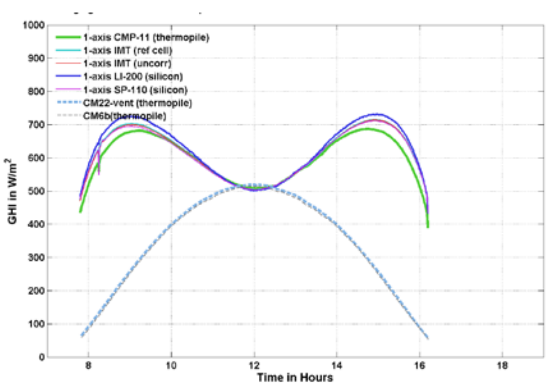

Figure 3: Silicon and thermopile device measurement mounted on a s1-axis tracker. The measurements from the silicon devices have been scaled to the LI-200. GHI measurements from a well-calibrated instrument are also shown.

The difference between the silicon and thermopile devices is 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.

METHODOLOGY AND RESULTS

The spectral distributions of measured DNI and GHI change as the solar zenith angle changes over the course of the day. Figure 4 shows how the spectral DNI changes over the period of a clear day while Figure 5 shows how the spectral GHI changes over the same day.

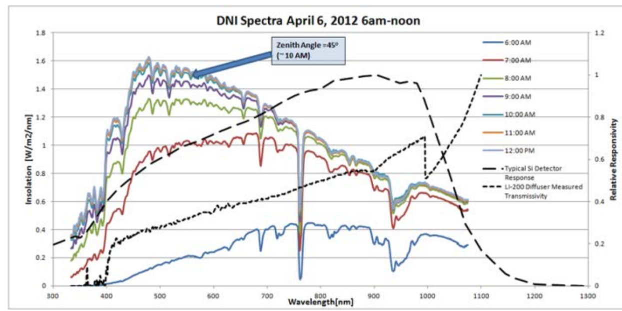

Figure 4: Hourly DNI spectra for April 6, 2012 measured from 6 am to 12 noon. The dashed black line represents the spectral response of the LI-200 instrument while the dotted black line represents the spectral response of the diffuser on the LI-200.

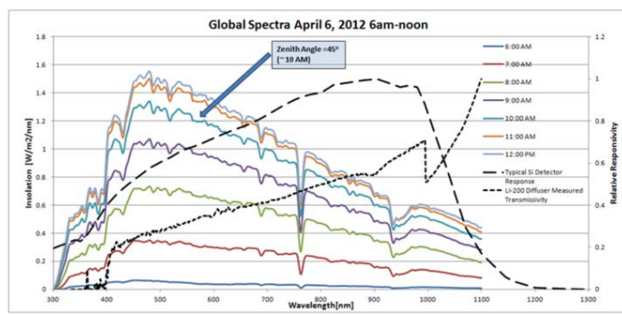

Figure 5: Hourly GHI spectra for April 6, 2012 measured from 6 am to 12 noon. The dashed black line represents the spectral response of the LI-200 instrument while the dotted black line represents the spectral response of the diffuser on the LI-200.

The spectral DNI is measured using a Kipp and Zonen PGS 100 spectrophotometer with the spectra being measured from 350 nm – 1050 nm at a resolution of around 4 nm. A LI-COR LI-1800 Spectroradiometer measures spectral GHI between the wavelengths of 350 nm and 1100 nm.

Looking at the DNI spectrum for various times shown in Figure 4 we see that the distribution changes over the day as the airmass changes. Similar changes are seen to occur in the GHI spectrum shown in Figure 5. The LI-200 instrument will receive 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 be able 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 only produce accurate broadband measurements at other times of the day if the spectral distribution has the same shape as at calibration time implying that the proportion of energy in various wavelengths is remaining the same. As, in a Rayleigh scattering environment, shorter wavelengths are preferentially scattered the shape of the spectral distribution, especially in the DNI, is seen to vary (Figure 4). We would therefore 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 take the spectral DNI measurements from the PGS-100 instrument and convolve it with the sensor and diffuser spectral responses for a zenith angle of 45^{o} corresponding approximately to an airmass of 1.5. We then sum the total energy in all the convolved calculation both for DNI and GHI to arrive at an estimate of “actual energy” received at the sensor. To create a “calibration” for measuring broadband DNI we then take the broadband measurement from the Kipp and Zonen CH-1 model pyrheliometer (a thermopile instrument) for exactly the same time and location and calculate a ratio of the broadband measurement to the “actual energy” from the PGS-100. We call this the “calibration coefficient” which can then be applied to the convolved spectral sum from the PGS-100 at other times to obtain the broadband solar radiation. A similar method is applied to the spectral GHI measured using the LI-1800. The broadband measurement from the Kipp and Zonen CM-22, a thermopile instrument, is used to compute a similar “calibration coefficient” at airmass 1.5 for silicon devices.

The “calibration coefficients” for converting spectral DNI and GHI are then applied to the convolved spectral sum for measurements taken at various times on a clear day and compared to the CH-1 measurements for DNI and CM-22 for GHI. We also take the DNI and GHI measurements from the Rotating Shadowband Radiometer (RSR) which has a LI-200 for measurement and calculate the differences between the RSR and thermopile instruments. In this experiment, if the differences between the RSR and thermopile instruments are similar to the difference observed in the spectral instrument versus thermopile comparison we are able to say definitively that spectral mismatch results in errors in broadband measurements when silicon based instruments are used.

RESULTS

June 22, 2011 was observed to be a clear day at the National Renewable Energy’s Solar Radiation Research Laboratory in Golden, CO as can be seen in Figure 6. The results for the DNI comparison are shown in Figure 7.

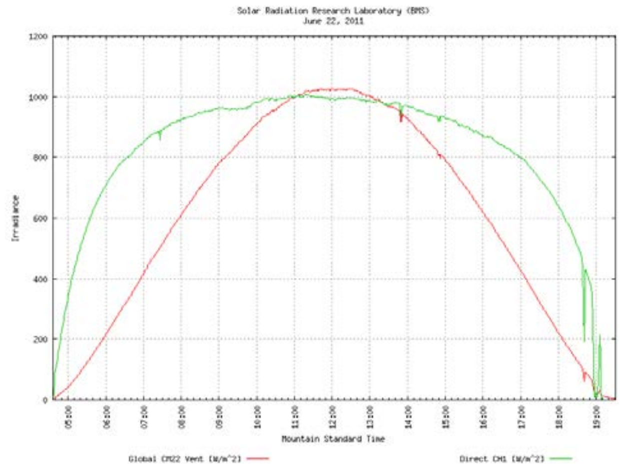

Figure 6: The observed DNI from a CH-1(red) and GHI from a CM-22 (green) for June 22, 2011 shows a clear day.

The red line in Figure 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 is seen to match the actual errors from comparing RSR and CH-1 measurements at the same location for the same day.

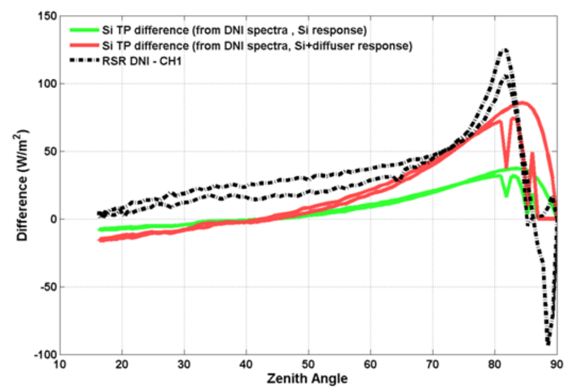

Figure 7: Difference in broadband DNI calculated using the spectral DNI and measurements from the CH-1 thermopile instrument are shown by red line as a function of zenith angle. Note that there is no difference between the two at a zenith angle of 45^{o} the calibration point. The dashed black line is 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 is excluded from the spectral “calibration” and calculation. Data from June 22, 2011 was used.

The errors for high zenith angles are seen to be significant and can reach 50 W/m^2. It is notable that the morning and afternoon errors are 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 Figure 4 and Figure 7 clearly shows that the error grows as the spectral shape changes.

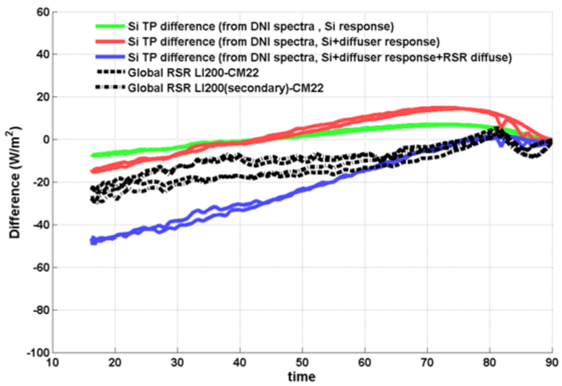

Figure 8: Difference in broadband GHI (calculated using the spectral DNI difference + the diffuse difference between the RSR diffuse and thermopile diffuse) is shown by the blue line as a function of zenith angle. The dashed black line is the observed differences between the measurement using the LI-200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

In Figure 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 Figure 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 shows the actual errors. It is interesting to note that the errors in GHI are not as high as observed for DNI. This observation is supported by the fact that the spectral GHI in Figure 5 does not change shape as drastically as the spectral DNI in Figure 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 find that both GHI and DNI measurements using silicon instruments have errors that are dependent on zenith angle. Other influences are the aerosol loading as can be seen in both Figure 7 and Figure 8 where the morning and afternoon errors vary due to a change in aerosol loading.

SUMMARY

We find that broadband measurements using silicon devices deviate from measurements using a thermopile device where all measurement 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 as per protocol. The solar DNI spectrum does not vary uniformly with airmass as blue light is preferentially scattered out with an increase in airmass. Therefore the calibration coefficient calculated at a particular zenith angles 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. Also, calibrations conducted at higher elevations and low water vapor conditions will no longer be applicable at lower elevations and humid conditions. We therefore conclude that the use of silicon devices for PV performance evaluation will lead to uncertainties that cannot easily be quantified. Empirical correction factors such as the King et al. (1998) correction have been devised to correct for the spectral errors. Such methods may not be able to provide accurate corrections for diverse conditions seen at various locations.

ACKNOWLEDGEMENTS

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

REFERENCES

[1] T. Stoffel et al., Concentrating Solar Power: Best Practices Handbook for the Collection and Use of Solar Resource Data, NREL Technical Report NREL/TP-550-47465, 2010.
[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, 2000.
[3] www.nrel.gov/midc/srrl_bms, last access date 05/09//2012
[4] King, D. L., Boyson, W. E., Hansen, B. R., and Bower, W. I., Improved Accuracy for low-cost solar irradiance sensors, *2nd World Conference and Exhibition on Photovoltaic Solar Energy Conversion, 6-10 July, 1998, Vienna, Austria,* 1998.