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Pyranometers and Reference Cells: Part 2: What Makes the Most Sense for PV Power Plants?

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As described in Part 1 of this two-part series, thermopile pyranometers and photovoltaic (PV) reference cells can both be used to measure irradiance; however, there are subtle differences between the data that are obtained. This two-part article explores some implications of uncertainty and subtleties of accurately measuring PV efficiency in the field. Part 2 of the series shows how reference cells can be used to more confidently predict PV performance, but how this could best be accomplished if historic irradiance data could be available in PV-technology-specific formats.

Globally, equity investors (owners) and debt providers (lenders) for PV power plants evaluate projects based on expected return on investment, perceived risk, and the magnitude of the capital cost. Projects are typically financed with a combination of debt and equity. From a capital cost perspective it is often best for the project to maximize the amount of debt that the project incurs. This is because debt typically has a lower capital cost than equity. The amount of debt a project can incur is a function of size, risk, and variability of the expected project revenues. By reducing the risk that project revenues will be lower than expected it is possible that the project will be able to take on more debt, and therefore reduce the working capital cost of the owner. This translates into a plant with a higher rate of return and a lower Levelized Cost of Energy (LCOE).

In specific cases it is possible that reducing the uncertainty in the solar resource by approximately 1 percent will allow the project to take on approximately 1 percent more debt. This may seem insignificant for a 30-kW project that is valued at $120,000 as this reduction in uncertainty translates into increasing the loan size by approximately $1,200. However, for a 30-MW project valued at $120,000,000 this reduction in uncertainty can translate into increasing the loan size by approximately $1,200,000.

Performance Measurement: Can Reference Cells Reduce the Uncertainty?

When measuring the performance of a power plant the two considerations are:

1. Fuel In (useable sunlight)
2. Electricity Out (kilowatt-hours)

Commercially available revenue grade AC kWh meters measure the electricity out with high precision (0.2% or better) [1]. This article focuses on the measurement of fuel in, or sunlight available to the solar cells for energy conversion. Useable sunlight is defined as the light incident upon a solar cell that can be converted into electricity. Spectral components of light that can't be converted by solar cells (e.g. infrared light) and light that is reflected from the glass are not considered useable sunlight.

PV power plants are a variable electricity source. In other words, as the weather varies the output of the PV system changes. This is caused by variations in the temperature, sunlight intensity, wind, spectral shifts of irradiance, the angle of incidence between the sun and the PV modules, the ratio of diffuse to direct light, and several other factors. PV modules do not respond to all colors of light equally and, thus, have some non-flat spectral response as seen in Figure 1. The spectrum of the incident sunlight changes with time of day, time of year, location, albedo and local atmospheric aerosol and moisture content. Additionally, PV modules are constructed with flat glass whose reflectance is a function of sunlight incidence angle.

Solar reference cells that utilize the same bill of materials (cell, glass, encapsulant, backsheet, etc.) as the PV modules comprising the PV power plant will exhibit a matching response with respect to spectrum and angle of incidence. In contrast to reference cells, thermopile pyranometers are constructed with a black disc covered by a single or double glass or quartz dome. The disc absorbs all sunlight that is transmitted through the dome. In part due to the air gap between the black disk and the glass or quartz dome, pyranometers exhibit a unique angle of incidence response. Pyranometers also exhibit a flat spectral response to all incident photons passing through the dome, as seen in Figure 1. In other words, they respond to the energy in all colors of light transmitted through the dome equally. Because of this, pyranometers measure broadband incident sunlight, which is similar to, but not exactly the same as useable fuel for the solar cells. Pyranometers may also exhibit a response to diffuse light that differs from PV devices, introducing additional measurement differences on cloudy days.

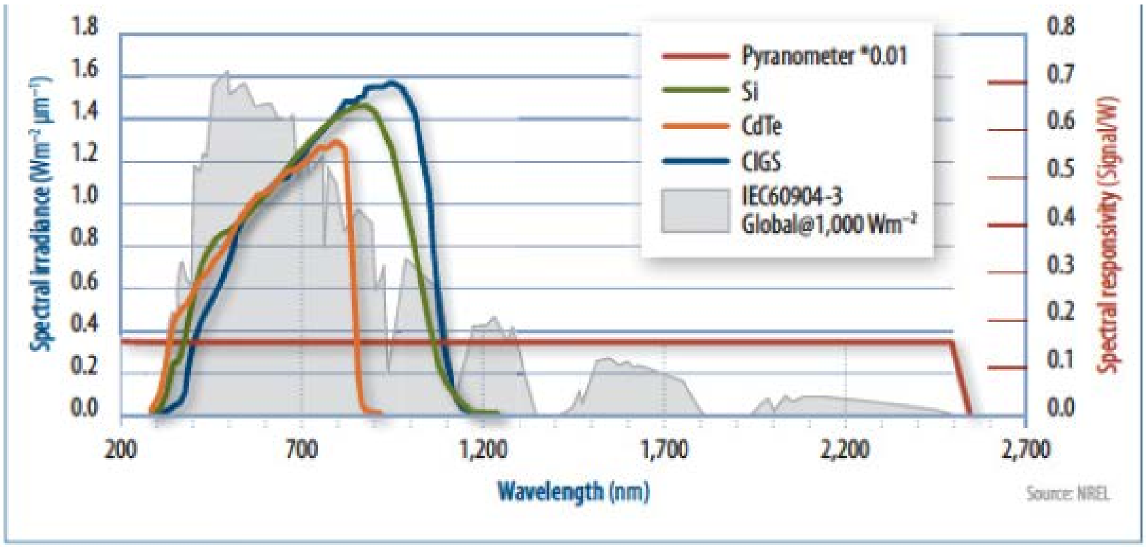

Figure 1. Spectral response (right axis) of several PV technologies and of a thermopile pyranometer. The spectral irradiance (left axis) of the standard global-irradiance solar spectrum is also shown.

Variations in efficiency over time can occur because of manufacturing defects in any of the PV system components. For example, if the PV module develops a poor electrical connection, the associated resistive losses will cause greater reduction in efficiency at high-irradiance conditions. The emergence of localized shunts in the solar cell will result in reduced low-light performance. The challenge of identifying whether the PV manufacturer meets the terms of the contract is in accurately quantifying if the efficiency varies with the weather as expected. Thus, the ideal irradiance sensor for monitoring PV performance would also vary with the weather in a way that mimics how a "good" or "defect-free" PV product is expected to vary. In other words, if one can accurately measure the total useable incident irradiance under any environmental condition (fuel in) by using a matched (*i.e.*, PV) reference device, one can determine if the PV system is generating electricity per expectations (energy out).

Two of the authors recently published an uncertainty analysis of irradiance measurement for PV power plant performance assessment [2]. That work evaluated the uncertainty in typical measurements of the useable fuel available to a PV system as measured with a thermopile pyranometer and PV reference cell.

The uncertainty calculations were performed for a fixed-tilt system on a single, clear day, and assumed simultaneous, side-by-side measurements with a PV reference device and a thermopile pyranometer. Although a full explanation of those results is beyond the scope of this paper, we show in Tables 1 and 2 a snapshot of the uncertainty analysis corresponding to a PV-matched irradiance intensity of 1000 W/m^2. In both tables the major sources of uncertainty are first listed as standard uncertainties, which may be thought of as a combination of random and non-random error sources. The standard uncertainties are combined using a root sum-of-squares method, and the total expanded uncertainties, corresponding to confidence intervals of 95% in the measured quantity, are calculated by multiplying the combined, total standard uncertainties by a coverage factor, *k*, of ~2.

Table 1. Constituent standard uncertainties and combined expanded uncertainty associated with typical thermopile pyranometer measurements of useable fuel for PV systems. The uncertainties shown here correspond to clear sky conditions at 1000 W/m^2.

Pyranometer Responsivity Standard Uncertainty	2.69%
Pyranometer Measured Voltage Standard Uncertainty	0.23%
Total Standard Uncertainty (Root Sum of Squares)	2.70%
Total Expanded Uncertainty (95% Confidence Interval)	**5.29%**

In Table 1 the two standard uncertainties listed correspond to the responsivity of the pyranometer, *R*, which relates the pyranometer output voltage, *V*, to the measured irradiance through the expression *Irradiance = V/R*, and the uncertainty in the voltage measurement of the pyranometer's output. The major contributors to the uncertainty in the pyranometer responsivity are the calibration of the pyranometer (taken from a calibration certificate), the spectral mismatch of the pyranometer with respect to PV devices, the angular response of the pyranometer, and the thermal offset of the pyranometer. Smaller contributions to the uncertainty in pyranometer responsivity are made by the variation in pyranometer output with temperature, the angular alignment error between the pyranometer and the plane of array, and the nonlinearity in the pyranometer's output with irradiance intensity.

Table 2. Constituent standard uncertainties and combined expanded uncertainty associated with typical PV reference cell measurements of useable fuel for PV systems with a response that matches the PV reference device. The uncertainties shown here correspond to clear sky conditions at 1000 W/m^2.

PV Ref Device Isc Calibration Value Standard Uncertainty	1.11%
PV Ref Device Isc Measurement Standard Uncertainty	0.39%
Isc Temperature Coefficient Standard Uncertainty	0.39%
Measured Device Temperature Standard Uncertainty	0.09%
Total Standard Uncertainty (Root Sum of Squares)	**1.24%**
Total Expanded Uncertainty (95% Confidence Interval)	**2.44%**

In Table 2, the PV reference cell Isc calibration value uncertainty is taken from a calibration certificate. The major contributors to the uncertainty in the measurement of Isc are the measurement electronics, the nonlinearity of the PV reference cell Isc with irradiance, and the angular alignment error between the PV reference cell and plane of array. It is assumed that the reference and test devices have identical spectral responses, allowing the uncertainty in the spectral correction factor to be neglected. The major contributors to the PV reference cell temperature measurement are due to the temperature sensor, the temperature transducer, and, if the temperature sensor is mounted on the back of the cell package, the difference between the reference cell package back temperature and the cell junction temperature. The uncertainty associated with temperature may be larger in climates with extreme temperatures.

The expanded uncertainties shown in Tables 1 and 2 should be thought of as the intervals about the measured effective irradiance within which the true value of the effective irradiance is believed to lie with a confidence of 95%. From Tables 1 and 2 we see that under clear sky conditions typical irradiance measurement uncertainty intervals are on the order of ±5.3% for thermopile pyranometers, and ±2.4% for PV reference cells. For a more complete explanation of these results we refer the reader to Reference [2], and the references contained therein.

The uncertainties listed in Table 1 correspond to high-quality thermopile pyranometers under clear-sky conditions. For thermopile pyranometers, measurement uncertainties may be significantly higher if a lower quality instrument is used (*e.g.*, a second-class pyranometer), or if atmospheric conditions differ from the clear-sky conditions assumed. The uncertainties listed for PV reference cell irradiance measurements in Table 2 should be relatively easy to obtain as long as the PV reference cell is constructed from a stable, single junction (*e.g.,* silicon) cell in a suitable package with a matched spectral response. In principle, PV matched reference cell measurement uncertainties of useable fuel for PV systems should not change with atmospheric conditions [3]. In all cases, the uncertainties listed assume that the measurements are implemented by a skilled individual using standard calibration protocols. (Footnote: Calibration of the sensors may be done at both the beginning and end of the test to check for any drift in the sensor calibration. Pyranometers may drift either up or down; a matched reference cell could degrade at a rate similar to that of the overall system, but typical PV degradation rates are ~ 0.5%/y or less, which is likely to be less than the uncertainty of the calibration.)

We note that an additional source of error not included in our analysis above is due to the time response of the pyranometer, which is much slower than the response of a reference cell. If it is desired to obtain instantaneous agreement between the predicted and measured output of a PV system, then the reference cell provides a more accurate response. However, given that the pyranometer may be sampling the conditions for a large area around it and that the performance guarantee usually applies more to the long-term performance than to the instantaneous performance, the difference in time response may have little impact in the choice between the two for performance guarantees. We therefore have not included in our analysis errors attributed to the varying time responses of the two devices.

The emphasis in this work is on measuring the amount of useable fuel available to a PV system, not on measuring the "total" or broadband amount of solar radiation. As a result, the analysis summarized in Tables 1 and 2 attributes sources of uncertainty such as spectral and angle of incidence errors to irradiance measurements made with pyranometers. After all, the PV module manufacturer is in a good position to guarantee the PV module efficiency with respect to a reference spectrum as given in Reference [4] but, obviously, is not in control of the local spectral distribution or the weather. Similarly, an EPC firm responsible for commissioning a PV power plant can't control weather effects that could lower the apparent efficiency of a PV power plant when calculated using a broadband irradiance measurement made with a thermopile pyranometer. These effects can be separated from performance assessments of PV modules by using matched PV reference cells for irradiance measurements. Nevertheless, when predicting the performance of a PV project, someone must bear the risk associated with weather variability.

The wide availability of broadband irradiance data for locations throughout the world facilitates prediction of performance of new PV projects. For example, Typical Meteorological Year (TMY) data are available for hundreds of sites; similarly, other datasets are available. In a minority of cases, site-specific irradiance data may be available, but for the purposes of discussion, we will focus on the common approach of using TMY-type data.

For a given system design and appropriate TMY data set, a prediction of the PV performance can be obtained using software such as PVSyst [5] or SAM [6]. The calculation involves multiple steps, but these may be simplified into (see Fig. 3):

1. Translate the broadband irradiance data from horizontal or other surface to Plane-Of-Array (POA) irradiance,
2. Estimate the expected temperature of the PV modules from the TMY conditions and the module properties, and
3. Predict the PV performance based on the POA irradiance and estimated module temperature.

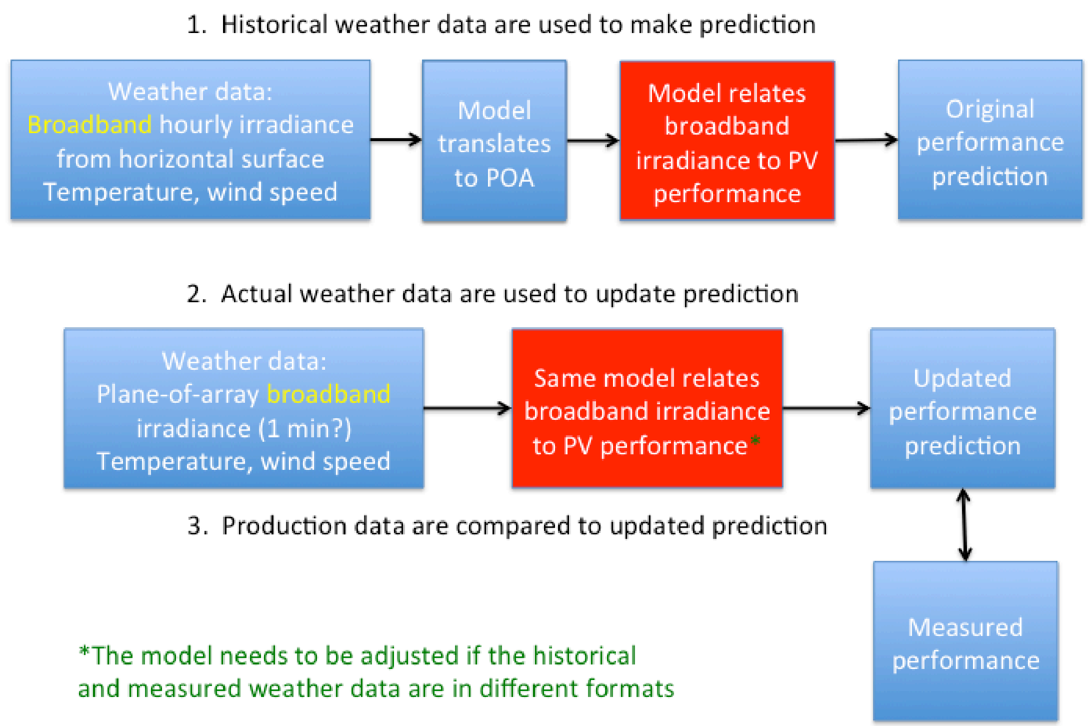

Figure 3. Basic description of the steps needed to create and verify a performance guarantee for a new PV system. Details vary, but, today, the vast majority of contracts use broadband irradiance data as the heart of the performance prediction.

One major problem with this method is that errors are introduced when relating broadband historical irradiance data to PV performance due to spectral errors, angle of incidence errors, etc. However, this problem would be resolved if historical data were available for PV-matched irradiance data. Alternatively, if a model is created that translates the historical broadband data into standardized PV-matched data sets, the models used for the original and updated predictions could be aligned in an unambiguous way as shown in Figure 4. The colors of the boxes for the models shown in Figures 3 and 4 are intended to indicate the level of uncertainty (red for higher uncertainty and green for lower uncertainty), but the uncertainties are much more complicated than can be captured with this simple color scheme.

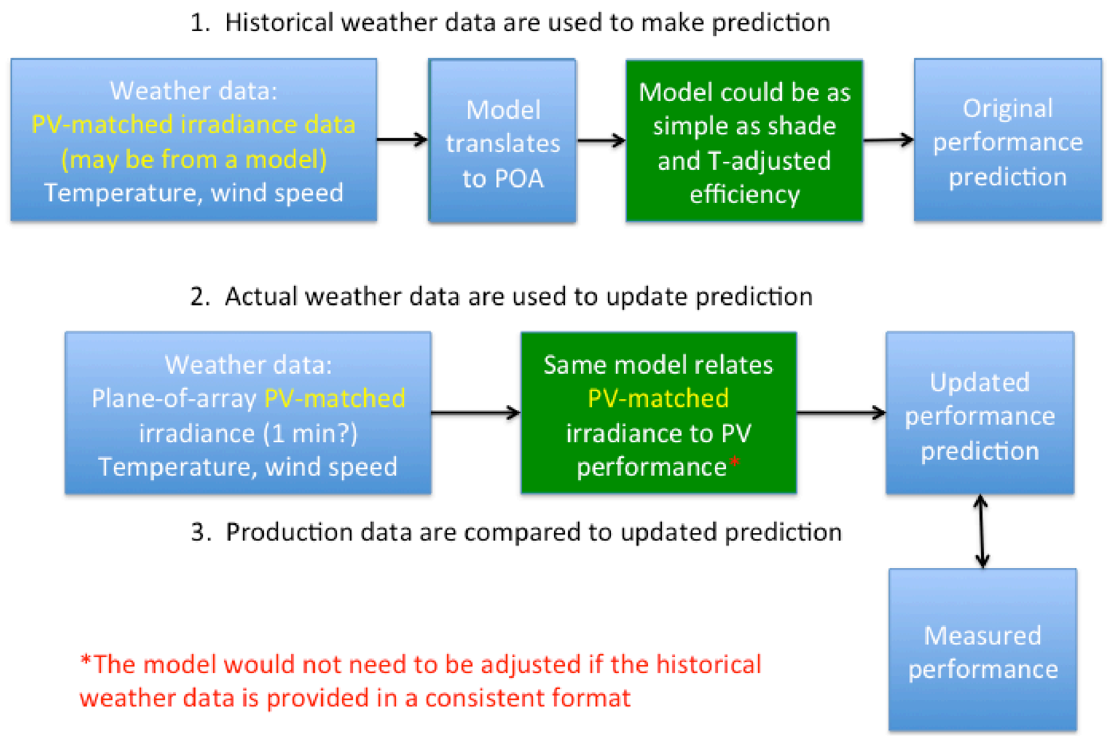

Figure 4. Method for creating and verifying performance guarantee if PV-matched irradiance data could be made available.

As an example of the results of such an implementation, we show in Figure 5 the results of a calculation of the difference between clear-sky daily irradiance as measured with a c-Si PV reference cell and a thermopile pyranometer in Houston, Texas, and Phoenix, Arizona, calculated using TMY data and a solar spectrum simulation program [8]. From Figure 5 it is evident that errors in daily insolation between a thermopile pyranometer and a c-Si PV reference cell due solely to spectral effects can be as large as 3%, and that this error is highly variable over days, weeks, and months. We emphasize that these results include spectral effects only: angle of incidence and other effects that may further exacerbate the errors between broadband irradiances measured with pyranometers and actual usable fuel available to PV power plants have not been included.

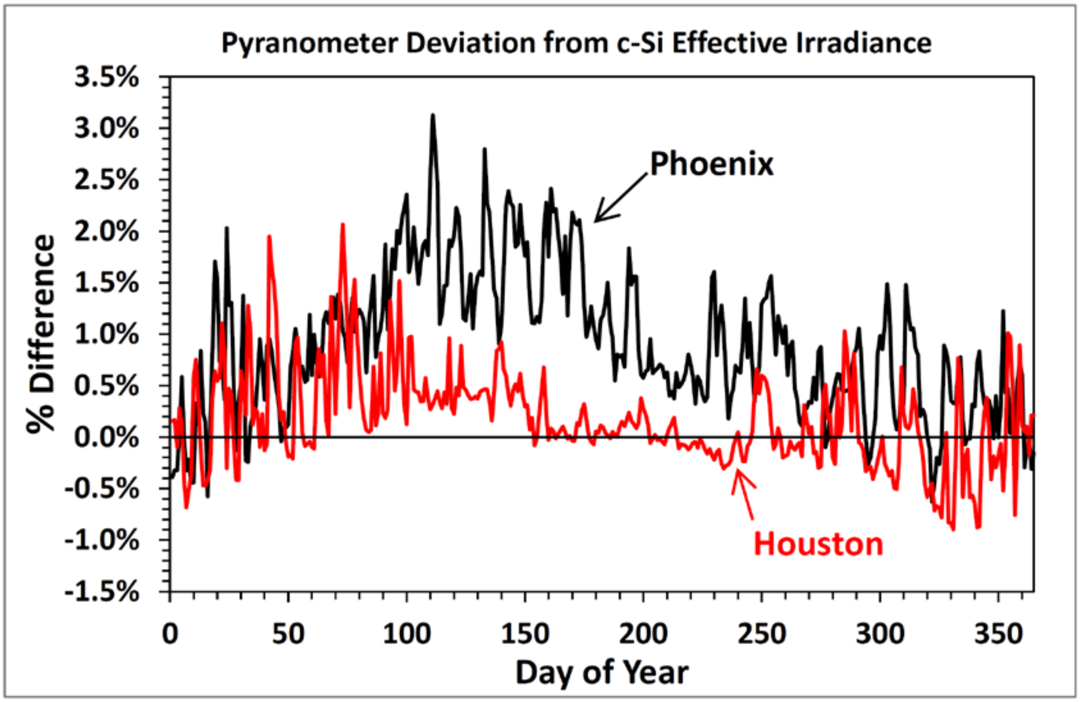

Figure 5. Example calculated differences (using clear-sky spectral modeling) from TMY data between daily insolation as measured with a thermopile pyranometer and a c-Si PV reference cell. Differences shown are due solely to spectral effects.

Broadband Irradiance Measurement Uncertainties

Even in the case that the goal of the user is to measure broadband irradiance, a PV reference cell may exhibit the same or better (under other conditions) measurement uncertainties than thermopile pyranometers. We calculated broadband irradiance uncertainties using the same method for calculating irradiance measurement uncertainties described in detail in Reference [2], but assigning the spectral error to the PV reference cell instead of the thermopile pyranometer. The results, summarized in Table 3, show typical irradiance measurement uncertainties for both broadband and spectrally matched irradiance measurements. These measurement uncertainties correspond to clear sky conditions at 1000 W/m^2, and confidence intervals of 95%. We emphasize that lower-class pyranometers, rapidly varying irradiance, or deviations from clear sky atmospheric conditions will result in higher thermopile pyranometer measurement uncertainties.

Table 3. Combined expanded uncertainties associated with typical PV reference cell and thermopile pyranometer measurements of broadband irradiance, as well as spectrally corrected irradiance (*i.e.*, useable fuel for PV systems). The uncertainties shown here correspond to clear sky conditions at 1000 W/m^2.[1]

Resource data	Thermopile Pyranometer	Matched reference cell
Broadband	~4.3%	~4.3%
PV "useable" fuel	~5.3%	~2.4%

When is a Reference Cell Most Advantageous?

Use of a PV reference cell:

1. Improves the accuracy of performance measurements, which should reduce the cost of capital and LCOE. This requires that the initial performance projections be performed with appropriate resource data, which can be accomplished by modeling the spectrum, as is shown in Figure 5, or collecting resource data with a reference cell during site assessment.
2. Enables precise measurement of PV performance to detect degradation or deviation from expected performance.

Currently most long-term resource datasets contain only broadband irradiance data and, therefore, most resource assessments and initial performance projects are conducted using broadband irradiance data. When the initial performance projections are modeled with broadband irradiance data the uncertainties in predicted PV power generation will be larger than if the portion of the solar resource available to PV modules were measured using a spectrally matched reference cell. Thermopile pyranometers exhibit increased uncertainty relative to solar reference cells and do not respond to changes in environmental conditions in exactly the same way as PV modules. Use of pyranometers may still be useful for comparing observed broadband irradiance to historic broadband irradiance, but the adoption of PV performance projections made using PV-matched irradiance data[2] coupled with measured performance using PV reference cells should 1) reduce uncertainty in performance, 2) reduce the working cost of capital to the plant owner, and, therefore, 3) decrease the LCOE of electricity from PV power plants.

[1] One subtle issue here is the angular response of the PV reference cell and its effect on the measurement of the diffuse component of global radiation. We assume here that this source of uncertainty is minimized by the use of a PV reference cell that has been calibrated outdoors under clear-sky conditions, thus incorporating the diffuse-light contribution to measured irradiance during its calibration. This effect is automatically corrected when using a matched PV reference cell to measure "useable fuel" for PV modules. Interested readers are referred to Reference [9] for a more detailed discussion.

[2] Irradiance data is usually documented by its direct and diffuse components, facilitating translation to surfaces of arbitrary orientation. Currently, commercially available instruments do not facilitate measurement of direct and diffuse irradiance with matched reference cells.

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References

[1] ANSI C12.20, "Electricity Meters - 0.2 and 0.5 Accuracy Classes," American National Standards Institute.

[2] "Comparison of Pyranometers vs. PV Reference Cells for Evaluation of PV Array Performance," by L. Dunn, M. Gostein, and K. Emery. Presented at the 38th IEEE Photovoltaic Specialists Conference, Austin, TX, 2012.

[3] "Improved Test Method to Verify the Power Rating of a Photovoltaic (PV) Project," by A. Kimber, T. Dierauf, L. Mitchell, C. Whitaker, T. Townsend, J. NewMiller, K. King, J. Granata, K. Emery, C. Osterwald, D. Myers, B. Marion, A. Pligavko, A., Panchula, T. Levitsky, J. Forbess, and F. Talmud. Presented at the 34th IEEE Photovoltaic Specialists Conference, Philadelphia, PA, 2009.

[4] IEC 60904-3:2008: Photovoltaic devices - Part 3: Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data. International Electrotechnical Commission, Geneva, Switzerland, 2008.

[5] www.pvsyst.com

[6] https://sam.nrel.gov

[7] "Method to Calculate Uncertainties in Measuring Shortwave Solar Irradiance Using Thermopile and Semiconductor Solar Radiometers," by Ibrahim Reda. Technical Report Number NREL/TP-3B10-52194. National Renewable Energy Laboratory, 2011.

[8] http://rredc.nrel.gov/solar/models/spectral/

[9] "Effect of the Angle Dependence of Solar Cells on the Results of Indoor and Outdoor Calibrations," by S. Winter, D. Friedrich, T. Gerloff. Presented at the 25th European Photovoltaic Solar Energy Conference, Valencia, Spain, 2010. p. 4304.