Pyranometers and Reference Cells, What's the Difference?

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Part 1 of 2

Pyranometers and Reference Cells, What's the Difference?

Jenya Meydbray, Keith Emery, and Sarah Kurtz

As the photovoltaic industry has grown exponentially in the past decade, large photovoltaic (PV) fields have become more common. The investors for these projects calculate the expected return on investment based on expected electricity generation and adjust the interest rates and other financial terms according to the perceived risk. These calculations usually assume worst case according to the listed warranty and any uncertainty in the measurement is translated directly into a reduced predicted performance. Because a 1% difference in predicted output could represent a large fraction of the expected return on investment, a small reduction in uncertainty translates into a much larger value to the entity making investment decisions. To reduce perceived risk in large-scale solar investments power plant performance (or production) guarantees have become increasingly common. This two part article explores some subtleties of accurately measuring PV efficiency in the field.

Weather versus PV efficiency

PV output is determined by two factors:

1. Weather (solar resource)
2. PV system efficiency

Investors often seek guarantees from the EPC (Engineering, Procurement and Construction) firm and/or PV module manufacturer to protect themselves against underperforming PV modules. The PV module manufacturer is in a good position to guarantee the PV module efficiency with respect to standard test conditions defined as 25 °C PV temperature, 1000 Wm^{-2} total irradiance and the spectral irradiance given in IEC 60904. The module manufacturer may be able to predict the system efficiency but can't be expected to guarantee the weather and resulting energy delivered. These performance guarantees require two pieces of information to accurately assess the performance of the PV modules: the amount of useable solar resource (fuel in) and energy out. Additionally, the investors typically require measurement of the PV performance (efficiency) before full payment. The question then arises about the best way to perform measurement of the PV system performance. This article addresses one small part of that question: what irradiance sensor will give the lowest uncertainty in characterizing PV performance?

As the weather varies, the output of the PV system changes. Key factors affecting the PV system performance include not only the irradiance, but also the spectrum, angle of the irradiance, temperature, wind speed, and wind direction. Much of this variability is predictable because of how all solar cells work, but variations in efficiency over time can occur because of manufacturing defects in any of the system components. For example, if the PV module develops a poor electrical connection, the associated resistive losses will reduce the efficiency the most at high irradiance conditions. Whereas, the emergence of localized shunts in the solar cell will result in disproportionately reduced low-light performance. The challenge of identifying whether the PV manufacturer meets the terms of the contract is in quantifying whether the efficiency varies with the weather in the way we expect it to or in some other way. 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 conditions (fuel in) one can determine if the PV system is generating electricity per expectations (energy out).

Pyranometers

Meteorologists around the world use pyranometers to quantify the sunshine. Pyranometers respond to the change in temperature when the sunlight heats a black surface. The pyranometer gives a voltage signal that is directly proportional to the irradiance as measured in watts per square meter. The pyranometer is specially designed to accept light from all angles, to have a flat response to light from the ultraviolet to the far infrared, and to have a stable output regardless of sky conditions and changing ambient conditions. A variety of products are on the market today, typically with the most stable instruments having the highest prices. Typically pyranometers are recalibrated about once per year, since the output can drift. A photograph is shown in Fig. 1 of a typical state-of-the-art commercial unit.

Reference cells

PV reference cells can also be used to measure irradiance. However, they work in a very different way: photons with energy above the band gap of the PV material are converted directly into positive and negative charges that can be collected and used in an external circuit. The reference cell generates a current that is dependent on the number and spectral distribution of the photons. Typically, the current of the reference cell is measured by measuring the voltage across a small resistor that is included in the reference cell package. This voltage is calibrated under the reference spectrum [ASTM G173, or IEC 60904-3 spectrum] at 1000 W/m^2, 25 °C using standard techniques [IEC 60904-1]. Figure 2 shows an ESTI type reference cell where two half cells are utilized to measure irradiance and cell temperature. Figure 3 compares the responsivity of thermal based pyranometers with PV sensors and the reference spectrum. Like a PV module a reference cell responds to light from all angles, but typically shows an increased reflectance, and, therefore, a decreased efficiency for light that arrives at a glancing angle. If a solar reference cell is constructed with typical PV cells, glass, encapsulant, and backsheet the spectral and angular response will closely match that of the PV modules generating energy in the power plant. The reference cell does not respond to photons with energy less than the band gap, implying that they will be insensitive to changes in this part of the spectrum when used for quantifying the broadband meteorological irradiance. Or, in other words, a reference cell is designed to measure the irradiance that is available to a PV module for conversion into electricity (fuel in) rather than being designed to measure the broadband irradiance. The close spectral match of the reference cell to a PV system minimizes scatter in the data due to variable spectral conditions. The attributes that introduce uncertainty when reference cells are used to characterize the weather are the same as the attributes that make them more ideal for characterizing the PV system performance.

Comparison

Table 1 compares pyranometers and reference cells when they are used for measuring the efficiency of PV at reference conditions and when they are used as radiometers (to measure weather). Reference cells are especially useful for precise characterization of the PV performance, allowing better detection of changes in PV system performance with time and shorter time assessment of the PV operating efficiency. However, because predictions of PV performance are almost universally based on irradiance data that were derived from pyranometer measurements, it may be most useful to simultaneously use reference cells to characterize the PV efficiency and pyranometers to compare performance relative to historical-type weather data. Both reference cells and pyranometers are calibrated to international standards. ISO 17025 accredited reference cell and pyranometer calibrations are commercially available. An in-depth comparison will be presented in part 2 of this article. Figure 3 shows the output and efficiency of different devices across the spectrum of sunlight. Thermopile pyranometers clearly show a very flat or broadband output but do not respond in the IR past the transmittance of quartz about 2500 nm. When utilizing this device for measuring useable incident energy for a PV power plant uncertainty is introduced when the spectrum changes because the pyranometer and PV plant respond differently to different spectra. Part 2 of this article will explore this uncertainty. Financial implications of this uncertainty will also be presented.

Table 1. Comparison of use of solar reference cell and thermopile pyranometer for two types of measurements.

	Measurement of PV efficiency at reference conditions		Solar Radiometric measurement (Weather)	
	Reference cell	**Thermopile pyranometer**	**Reference Cell**	**Thermopile pyranometer**
Spectral response	Can be made to closely match solar panel	Broadband response needs to be corrected	Narrow wavelength response treated as an error	Broadband response requires essentially no correction
Angle of incidence	Can be made to closely match solar panel	Response to all angles	Response falls off at > 80°	Glass dome provides wide angle acceptance (especially useful for > 80°)
Temperature response	Temperature response is similar to PV system; Linear temperature response allows for corrections	Are designed to minimize sensitivity to temperature. Not corrected for temperature	Need to be corrected for temperature; usually treated as an error	Are designed to minimize sensitivity to temperature; uncertainty may be ~1%
Time response	< milliseconds; matched to PV response	Up to 30 seconds; Can be problematic for measuring PV performance	< milliseconds	Slow (up to 30 seconds) response is fine when using average irradiance
Other issues		Emission to cold sky and transients in ambient temperature affect output		Emission to cold sky and transients in ambient temperature affect output
International standards for calibration	IEC 60904	ISO 9847, ISO 9845, ISO 9846	IEC 60904	ISO 9847, ISO 9845, ISO 9846

Fig. 1. Photograph of thermopile pyranometer. Source: NREL

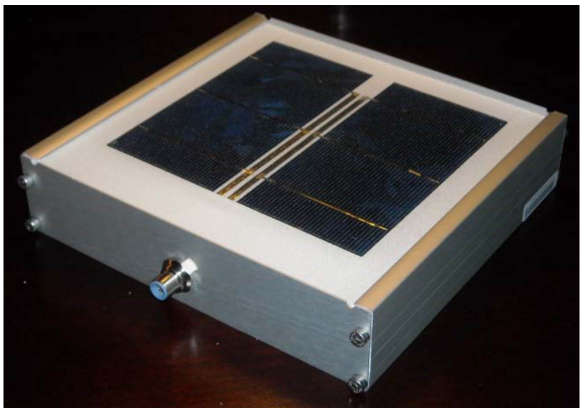

Fig. 2. Photograph of Suntech ESTI type reference cell built and calibrated by PV Evolution Labs. Source: PV Evolution Labs.

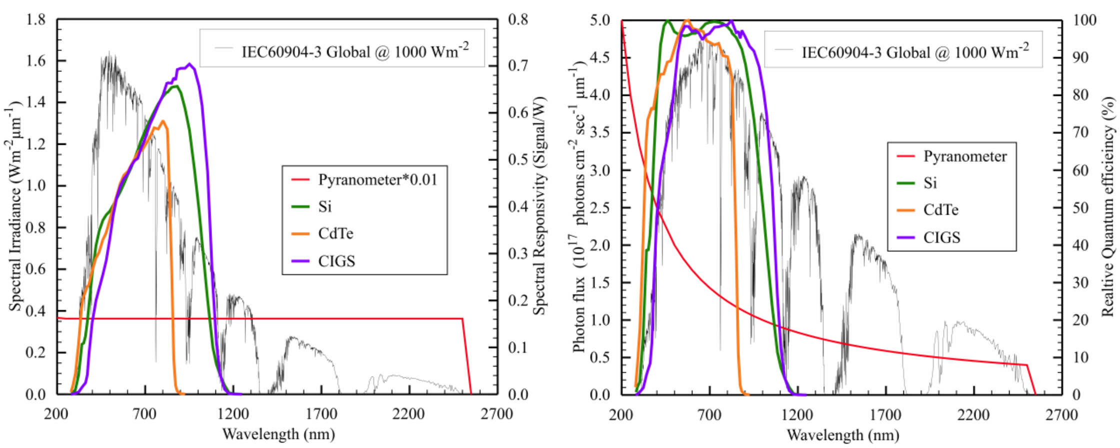

Fig. 3. **Left**: The spectral responsivity of several photosensitive devices in units of signal per incident watt at a given wavelength. The spectral irradiance is in units of power per unit area per unit wavelength.
Right: The quantum efficiency with which each of these devices converts incident photons to electrons is compared.