Comparison of Pyranometers vs. PV Reference Cells for Evaluation of PV Array Performance

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Abstract

- We estimate typical uncertainties in irradiance measurements made with pyranometers vs. PV reference devices.
- We assert that the quantity of interest in monitoring a PV power plant is *the equivalent irradiance under the IEC 60904-3 reference solar spectrum that would produce the same electrical response in the PV array as the incident solar radiation.*
- For PV-plant monitoring applications we find the uncertainties in irradiance measurements of this type to be on the order of ± 5% for thermopile pyranometers and ± 2.4% for PV reference devices.

I. Introduction

Measuring Irradiance

- PV industry uses both thermopile pyranometers (a.k.a. "pyranometers") and calibrated PV reference devices (PVRDs).
- Which is best suited for PV applications?

Pyranometers


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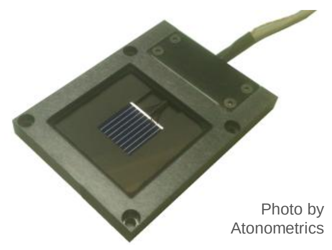
- Measure irradiance via temperature rise of absorber [1].
- Flat spectral response ~400 nm to ~2700 nm (transmittance of quartz).
- Well suited to measure total incident shortwave radiation, *independent of spectral composition*.
- Uncertainties usually quoted with respect to *total* incident solar radiation.

PV Reference Devices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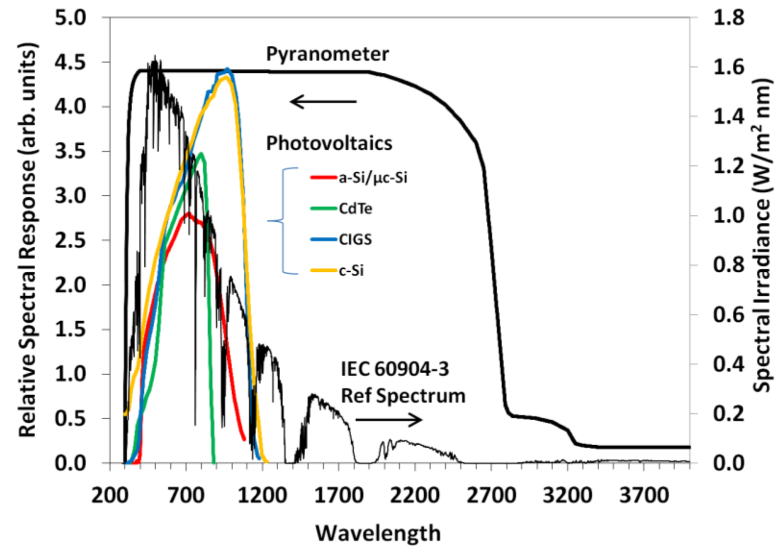
- PVRDs measure via the photovoltaic effect.
- Efficiency is wavelength-dependent function specific to each PV technology.
- Spectral Responsivity (SR) is amps at I_{SC} per watts of incident radiation at wavelength λ.
- I_{SC} of a PV device is given by:

$$I_{SC} = A\int_{\lambda_1}^{\lambda_2} E(\lambda)\cdot SR(\lambda)d\lambda \qquad (1)$$

A = *PV device area* (m^2)
λ_1 *to* λ_2 = *~300 to ~1200 nm, e.g. c-Si*
$E(\lambda)$ = *spectral irradiance* ($Wm^{-2}nm^{-1}$)
$SR(\lambda)$ = *PV device spectral response* (AW^{-1})



PVRD Calibrations

- For PVRD calibrations, calibrated I_{SC} normally reported using IEC 60904-3 reference spectrum [2] for $E(\lambda)$.
- When calibrated PVRD is illuminated by a different spectrum, the irradiance indicated is the irradiance *as if the PVRD were illuminated by the reference spectrum*.
- In exactly the same way, the power generated by a PV array will depend upon the $E(\lambda)$ of the incident radiation and the $SR(\lambda)$ of the PV modules comprising the array.

Irradiance$_{PV}$

- The specific irradiance quantity that best correlates to PV plant power output is *Irradiance$_{PV}$*, the equivalent irradiance under the IEC 60904-3 reference solar spectrum that would produce the same electrical response in the PV array as the incident solar radiation.
- We quantify uncertainty in representative measurements of *Irradiance$_{PV}$* made with pyranometers ($Irradiance_{PV}^{PYR}$) and PVRDs ($Irradiance_{PV}^{PVRD}$).
- We follow the International Guidelines of Uncertainty in Measurement GUM [3-6].

II. Thermopile Pyranometers

- Measurement equation:

$$Irradiance_{PV}^{PYR} = \frac{V}{R} \qquad (2)$$

V = *pyranometer output voltage* (μV)
R = *responsivity* ($\mu V/Wm^{-2}$)

- See uncertainty analyses [7–9], particularly Reda [7].
- We follow Reda's example, but for *Irradiance$_{PV}$*, instead of total irradiance.
- In contrast to Reda, we assume pyrgeometer data are not available, which is more typical.

Voltage Measurement Uncertainty

- We estimate a voltage measurement expanded uncertainty for a representative instrument, following Reda [7]: 0.07% of the reading + the offset, where the offset is 4.01 µV.

Responsivity Measurement Uncertainty

- We follow Reda [7] except include uncertainty due to spectral mismatch and thermal offset, and exclude aging. Also do not include uncertainty due to response time.
- Uncertainty contributions summarized in Table II.

Table II: Thermopile Pyranometer Responsivity Expanded Uncertainty

Calibration	3.0%
Spectral Mismatch with Respect to PV	3.0%
Angular Response AOI <30° & >60°	2.0%
Thermal Offset	2.0%
Angular Alignment	0.5%
Nonlinearity	0.5%
Temperature Response	1.0%
Total (Root Sum of Squares)	5.24%

- <u>Spectral Mismatch with Respect to PV</u>: Pyranometers measure total broadband radiation, therefore mismatch with PV devices. Est. ~3% for monthly periods [10].
- <u>Angular Response:</u> Non-ideal angular response for angles of incidence (AOI) <30° & >60° [7].
- <u>Thermal Offset</u>: Arises from cooling of absorber via net radiation to sky [1,11]. At 1 sun ~2% for all-black receivers, 0.2% for black & white receivers. Could be minimized by measuring IR radiation with a co-located pyrgeometer [12].
- <u>Angular Alignment</u>: Due to uncertainties in aligning the pyranometer with the PV array.

Details of Uncertainty Calculation

- We take R to be independent of zenith angle - representative of a typical use case.
- We calculate standard uncertainties for pyranometer plane-of-array (POA) measurements made throughout the course of a representative day.
- For a representative pyranometer, we take the responsivity, R (19 $\mu V/Wm^{-2}$), and global horizontal irradiance (GHI) values from an NREL compilation of calibration results [15].
- The pyranometer is assumed to be mounted co-planar with a PV array.
- GHI data from Golden, CO. Latitude 39.742°.
- We calculated *Irradiance$_{POA}$* values from the GHI data collected at NREL given in Ref. [15], using an expression from Ref. [16] to translate GHI to POA.

III. PV Reference Devices

- *Isc* proportional to incident light intensity [18].
- Measurement equation:

$$Irradiance_{PV}^{PVRD} = \frac{I_{sc,M}}{1+\alpha_{Isc}\left(T_{Cell}-T_{ref}\right)}\cdot\frac{G_{ref}}{I_{sc,ref}} \qquad (4)$$

$I_{sc,M}$ = *measured short-circuit current (amps)*
α_{ISC} = *temperature coefficient of* $I_{sc,M}$ *(%/°C)*
T_{Cell} = *cell temperature (°C)*
T_{ref} = *reference calibration temp. (typ.25 °C)*
G_{ref} = *ref. cal. irradiance (typ. 1000* W/m^2*)*
$I_{sc,ref}$ = *reference short circuit current (amps)*

Isc Measurement Uncertainty

- Uncertainty contributions are summarized in Table III.
- Assume PVRD spectral responsivity matches PV array.
- Uncertainty due to measurement electronics: 0.2% of reading + 0.06% of scale, @ 0.8 suns (representative).

Table III: PV Device $I_{sc,M}$ Expanded Uncertainty

Measurement Electronics (@ 0.8 suns)	0.35%
Nonlinearity with Light Intensity	0.30%
Deviation of ~2% of Voc from V = 0	0.1%
Angular Alignment	0.5%
Total (Root Sum of Squares)	0.63%

- Assume measurement electronics hold PVRD at $V = 0$ (short circuit) within ~2% of *Voc* value.
- Angular Alignment: Due to the uncertainties in aligning the PVRD with the PV Array.

Uncertainty in α_{Isc}

- Based on data from various internationally recognized test labs [20,22] we use a conservative estimate of expanded uncertainty of ± 50% of the typical c-Si *Isc* temperature coefficient of 0.05 %/°C.

Uncertainty in T_{Cell}

- Combining data on typical temperature measurement device uncertainty and typical cell to package-back-side temperature measurement differences [25], we assign a total expanded temperature measurement uncertainty of ± 3.11 °C.

Uncertainty in $I_{sc,ref}$

- NREL expanded uncertainty for certified measurements of a PV cell *Isc* at STC is ±1.27% [21].
- Complete uncertainty analysis of the outdoor calibration of a secondary PV device using a calibrated PV cell from NREL results in a total expanded uncertainty in $I_{SC,Ref}$ of ± 2.05% to ± 2.17%, for calibrations performed at POA irradiances above ~300 W/m^2 [26].

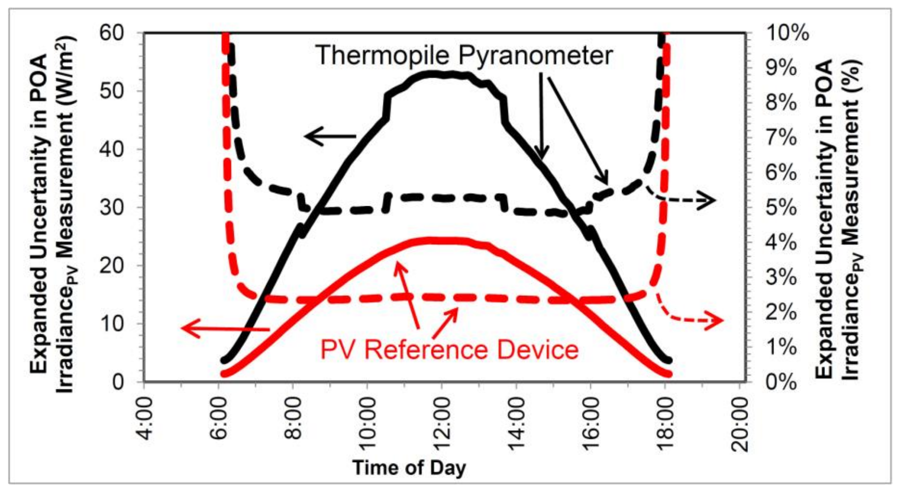
Details of Uncertainty Calculation

- Same GHI data used for pyranometer uncertainty calculations were used in the calculations of the input parameters in Eq. (4) as a function of time of day.
- T_{Cell} was estimated from the GHI data and ambient temperature combined with typical TMY3 wind speed data [27] using an expression from Ref. [25].
- $I_{SC,M}$ was calculated as a function of time of day using the *Irradiance$_{POA}$* values assuming an *Isc* temp. coeff. of 0.05%/°C and $I_{SC,Ref}$ = 2 Amps @ G_{Ref} = 1000 W/m^2.
- For each irradiance data point throughout the day the total expanded uncertainty was calculated.

Results and Discussion

- Fig. 3 shows total expanded uncertainties in POA *Irradiance$_{PV}$* measurements during a representative day for a thermopile pyranometer and a PV reference device.

Fig. 3: Expanded uncertainties



- The PVRD yields an expanded uncertainty that is a factor of ~2 lower than the thermopile pyranometer: +/-2.4% during the majority of the day versus +/-5%.
- We therefore conclude that PVRDs provide superior irradiance measurements for PV power plant monitoring applications.

Acknowledgements

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