Pyranometers versus PV reference cells

6 reasons why pyranometers are the best choice for utility scale PV system performance monitoring

Pyranometers dominate PV system performance monitoring for utility scale PV power plants. This is why.

1 PV reference cells have no defined measurand, data is not bankable
To generate bankable data you should know what is measured. With PV reference cells this is not clear. The 2022 NREL report states: *PV reference cells lack a clear and complete specification of their measurand—the quantity they measure.* [1#] The below examples of undefined temperature dependence and directional response serve as examples. Lacking a clearly defined measurand, measured data cannot be part of a bankable performance assessment. The measurand of a pyranometer measurand is irradiance in [W/m^2]. Sensors are standardised in ISO 9060. Pyranometers data are bankable, i.e. considered a reliable basis for financial analysis.

2 Measurements with PV reference cells have no connection to performance models
The most commonly used software for PV system performance analysis, like PVSyst, use pyranometer measurements -irradiance- as input. In particular, these models use Global Horizontal Irradiance (GHI) as primary input and optionally Plane of Array irradiance (POA). [2#]
Using data of PV reference cells as POA, the PV system performance will systematically be overestimated. The main cause is that PV reference cells have a non-ideal directional response. The IEA report about good practices says "*on average, the annual irradiation measured by crystalline silicon sensors is 2 – 4 % less than the irradiation measured by pyranometers*".[3#] The International Energy Agency (IEA) therefore recommends pyranometers for outdoor PV performance assessment.

3 Data measured with commonly used PV reference cells is not supported by accredited calibration, not bankable and not internationally recognised
To generate bankable data, a common requirement is that calibration of the critical measurements is "accredited" i.e. performed by an ISO / IEC 17025 accredited laboratory. An added advantage is that measured data supported by accredited calibrations are internationally recognised by Mutual Recognition Agreements.[#4]
In practice, no known commercially available PV reference cell is provided with such accredited calibration "from the box" by the manufacturer. Market leading pyranometers, such as those from Hukseflux, are supplied by the manufacturer accredited calibration. Pyranometers data are bankable and internationally recognised.

4 Use of PV reference cells complicates O & M and makes it more costly than necessary
PV reference cells are only suitable for POA measurement. In PV monitoring, GHI is also required, so in IEC 61724-1 "Class A" monitoring systems as used on utility scale PV power plants users will need a pyranometer anyway. [5#] Pyranometers can be used for both GHI and POA, so using pyranometers you need one instrument type only, which makes logistics around servicing and calibration easy.
In addition, there are many service providers that offer ISO / IEC 17025 accredited calibration for pyranometers. For PV reference cells, this service is hard to find, and tends to be more expensive.

5 The temperature correction of PV reference cells is not standardised
In PV system performance assessment, temperature dependence of the PV modules and of the reference cells is a major source of potential error. For both, the temperature dependence is in the order of 0.4% / K. The PV reference cell temperature dependence should either be corrected for in the instrument, or be measured and corrected in post-processing. As there is no standardisation, users have to be extremely careful how they process data. All pyranometers used in PV system performance monitoring are individually characterised and have a temperature dependence that is corrected in the instrument.

6 For common modules with an AR coating, a PV reference cell without a coating is not a "reference"
PV modules are nowadays supplied with a glass or plastic cover with an anti-reflection, AR, coating. Commercially available PV reference cells do not have AR coatings.
The coated glass or plastic of the PV modules not only have a higher transmission at a solar zenith angle of 0 (normal incidence). They also have a significantly different directional response. This translates in a systematic underestimation of the available resource by the PV reference cell. A PV reference cell without an AR coating is not a good reference cell for modules with an AR coating.

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What is a pyranometer?

A pyranometer measures the solar radiation in available [W/m^2]. The measurement in Plane of Array (POA) represents the maximum possible yield for any type of PV cell mounted in the same plane. The measurement with a pyranometer mounted in a horizontal position is the reference for traditional meteorological observations of Global Horizontal Irradiance (GHI). The GHI is used as input for solar atlases and irradiance maps. It is also the primary input for photovoltaic modelling programs. GHI observations or estimates are the reference for financial ratings, which makes a pyranometer the proper reference for assessments relative to ratings.
Pyranometers have a flat spectral response so that they can be calibrated and used without spectral corrections. The uncertainty due to the directional response of modern pyranometers is so low that it does not play a significant role in the measurement uncertainty except at very low angles of incidence. See figure 1. Traditionally the calibration uncertainty of pyranometers was larger than that of PV reference cells. This is no longer an issue. Like PV reference cells, modern pyranometers are traceable to normal incidence solar radiation. Their calibration uncertainty is < 1.2 % (k = 2). [#6]
Pyranometers and their measurement specifications are standardised according to ISO 9060 [7#].

What is a PV reference cell

PV reference cells were originally developed for indoor comparisons to identical PV cells, typically during production, under lamp-based solar simulators, at normal incidence or a solar zenith angle of zero at around 20 °C.
Their spectral response is identical to that of other PV cells or modules, which makes them ideal for comparison purposes under normal incidence and at uniform laboratory temperatures.
They were later used in short-term outdoor experiments under "perfect" sunny conditions on solar trackers, for example according to IEC 60904-1 [8#].
PV reference cells are calibrated at normal incidence, for a standard spectrum at a standard irradiance level and temperature together called Standard Test Conditions (STC). In indoor tests, they are typically used under these conditions.
Under outdoor conditions, the spectrum as well as the angle of incidence may differ from STC.
When used outdoor, a PV reference cell measures the maximum possible yield of PV modules with an identical (or "matched") PV cell type. This is also called "usable fuel" for that particular PV cell type.
The geometry of PV reference cells is standardised according to IEC 60904-2. However, detailed specifications like temperature dependence and directional properties or directional error, are not standardised [9#].
Implicit assumptions often made when measuring with PV reference cells are that the PV reference cells have the same spectral properties and directional properties (surface index of refraction [n]) as the PV modules they are compared with, and that the temperature dependence is known. If not corrected, most PV reference cells will have a temperature dependence similar to that of the PV modules; in the order of -0.4 % / K.

Standardisation of PV system performance monitoring

The latest and most influential standard is the IEC 61724-1 (2021) [5#]. Other influential recommendations are written by ASTM and IEA [10#,3#]. The IEC allows use of both pyranometers and PV reference cells for POA. However, use of pyranometers is required for the GHI measurement.

For monitoring and performance analysis, the International Energy Agency clearly prefers pyranometers over PV reference cells. A quote from IEA Report IEA-PVPS T13-03:2014, Chapter 1 – State of the Art:

".. recent studies such as [X] and [Y] have shown that the use of silicon reference devices for PV performance evaluation can lead to uncertainties that cannot easily be quantified. Thus the use of a thermopile pyranometer for PV performance evaluation is recommended."

ASTM allows the use of PV reference cells as an option only if mutually agreed. A quote from ASTM 2848-13R23 *Standard Test Method for Reporting Photovoltaic Non-Concentrator System Performance* Chapter 7:

"A calibrated hemispherical pyranometer is the most common choice for measurement of the incident solar irradiance. A calibrated photovoltaic reference device may be used in place of a pyranometer if it is mutually agreed by the parties to the test prior to the start of the test."

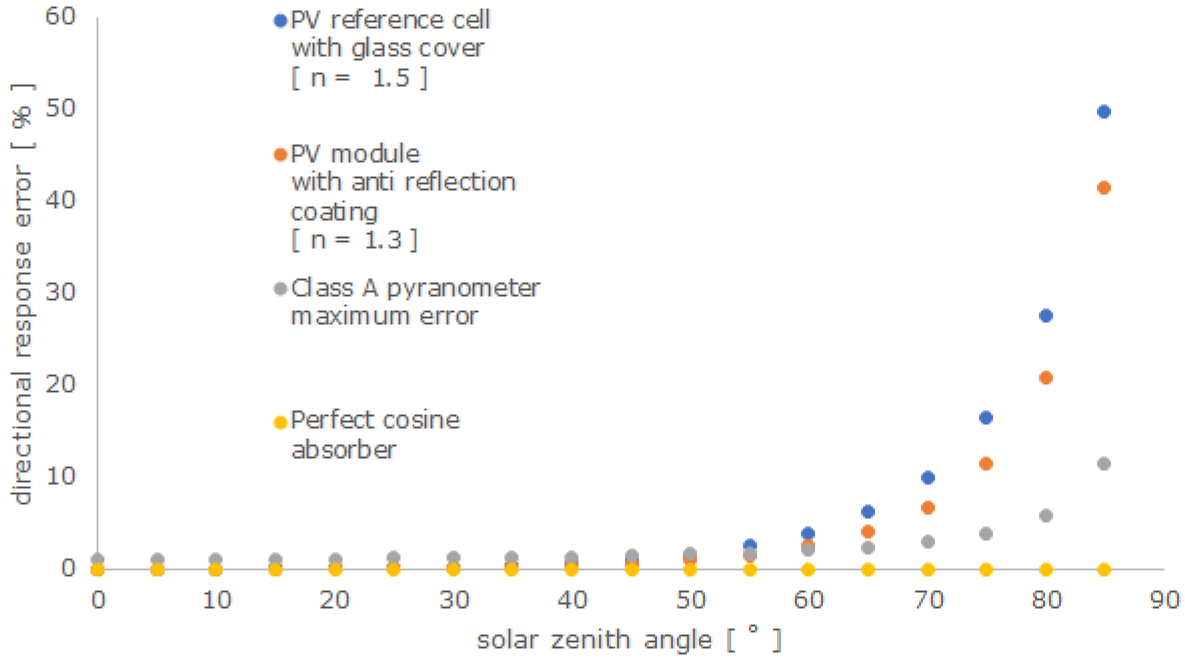

Figure 1 *Comparison of the directional properties of pyranometers, PV reference cells and PV modules. The perfect cosine absorber, ideal for irradiance measurement, is the reference for most performance models. A Class A pyranometer makes a maximum error (allowed under ISO 9060) in the order of 1 % up to 50 ° zenith angle, up to 10 % at 85 °, which is considered almost ideal.*
A glass-covered PV reference cell [n = 1.5] makes errors relative to the perfect cosine absorber of up to 50 % at 80 ° solar zenith angle. This accounts for the larger part of the 2 - 4 % deviations in daily totals observed between pyranometers and PV reference cells, using the reference cell to measure [W/m²].
A PV reference cell with AR coating, as common on most modern modules [n = 1.3], behaves in between a pyranometer and a glass-covered PV reference cell. Reference cell behaviour is calculated using Fresnel equations.

Difficulties for PV reference cells: use of anti-reflection coatings

Comparing PV reference cells to pyranometers, as can be seen in figure 1, the deviation of non-coated cells from the ideal directional response is > 5 % above 55 ° solar zenith angle. Using reference cells to measure POA solar irradiance, the error in daily radiant exposure in [J/m²] on a typical day is more than 2 %.
Using PV reference cells for GHI measurement is not recommended, because a cell with a flat window tends to get soiled when mounted horizontally. Apart from this practical consideration, errors in GHI due to the directional response would typically become 2 times larger at mid-latitudes for GHI measurement than errors relative to POA. How large exactly depends not only on the latitude, but also on the season.

Using PV reference sensors to compare to PV modules is also problematic. PV module covers are increasingly equipped with anti-reflection (AR) coatings [11#]. The coating has a typical index of refraction [n] of 1.3, compared to the usual 1.5 for glass [12]. This leads to a higher, 2 %, overall transmission at normal incidence; single air – glass transmission is 0.98 for n = 1.3 and 0.96 for n = 1.5).
More importantly for PV reference cells, the AR coating also leads to another directional response than that of uncoated glass, see figures 1 and 2. On top of the 2 % improvement of "normal incidence" transmission, this leads to an improvement of daily average yields of around 1.5 %. Improvement of transmission at higher zenith angles is higher than the 2 % at normal incidence.
In case uncoated PV reference cells are used to compare to PV modules with AR coating, this results in a typical systematic error in daily totals of 1.5 %. As figure 2 shows, measurements between 0 and 30 ° angle of incidence can very well be used.

The use of AR coatings has consequences for the design of a PV reference cell for outdoor use; not only must the cell type match the module type used in the power plant, but also the AR properties must match. We have not seen PV reference cells with AR coatings.

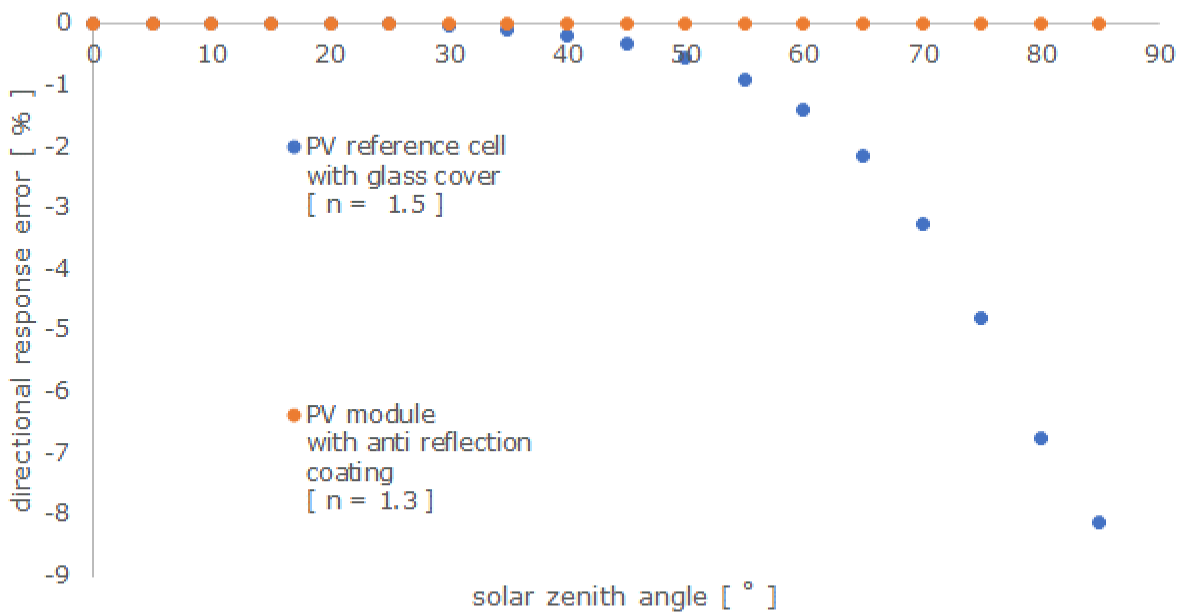

Figure 2 *Light transmission improvement of the cover of PV modules as a function of the angle of incidence when coated with an AR coating, relative to the transmission of normal glass. The use of AR coating improves the transmission by around 2 % at normal incidence, but also changes its directional response giving even more improvement of transmission at higher zenith angles. PV reference cells for these panels, when used outdoor, should copy this behaviour.*

Table 1 *Summary of pyranometer and PV reference cell properties.*

	Pyranometer	**PV reference cell**
Standardised measurand	yes	no
Suitable for use as input to PV performance models (PVSyst, ..)	yes	no
Suitable for POA, according to IEC 61724-1	yes	yes*
Suitable for GHI according to IEC 61724-1	yes	no
Bankable data: ISO/ IEC 17025 accredited calibration from manufacturer	yes	no
Internationally recognised data: calibration internationally recognised	yes	no
Standardised temperature dependence	yes	no
Standardised directional response	yes	no
Directional response as PV module with AR coating	no	no
Standardised sensor stability	yes	no
Standardised spectral response	yes, spectrally flat black	no, but typically as crystalline silicon
Recommended for PV performance assessment by IEA	yes	no

* accepting around 2 % systematic error in the integrated daily total [W/m^2]

1#. Driesse, Anton (2022). *PV Reference Cells for Outdoor Use: Comparison of First-Year Field Measurements.* National Renewable Energy Laboratory report NREL/SR-5D00-82086

2#. PVSyst *Photovoltaic software, version 7.4.* published on internet, accessed 27-feb-2024

3#. IEA, (2014), Report IEA-PVPS T13-03:2014, *Analytical Monitoring of Grid-connected Photovoltaic Systems, Good Practices for Monitoring and Performance Analysis*, published on internet, accessed 22-feb-2024

4#. BIPM *Mutual Recognition Agreement*, explanation given on internet, accessed 27–feb-2024.

5#. IEC, (2021), IEC 61724-1 *Photovoltaic System Performance – part 1 Monitoring*, published by IEC, *www.iec.ch*

6#. RvA (2020), *scope of accreditation Hukseflux Thermal Sensors*, accreditation number K179, published on internet, accessed 22-feb-2024

7#: ISO (2018), ISO 9060 *Solar energy — Specification and classification of instruments for measuring hemispherical solar and direct solar radiation* published by ISO *http://www.iso.org*

8#. IEC (2020), IEC 60904-1 *Photovoltaic devices – Part 1: Measurement of photovoltaic current-voltage characteristics* published by IEC, *www.iec.ch*

9#. IEC (2023) IEC 60904-2 *Photovoltaic devices - Part 2: Requirements for photovoltaic reference devices*, published by IEC, *www.iec.ch*

10#. ASTM, (2011), ASTM 2848-13R23 *Standard Test Method for Reporting Photovoltaic Non-Concentrator System Performance*, published by ASTM, *www.astm.org*

11#. First Solar, *series 4V3 datasheet*, document PD-5-401-04-3 of September 2018, published on internet, accessed 27-feb-2024

12#. Artigao, A, Cunningham D. W. et al (2006), *4% higher energy conversion from BP 7180 modules*, presented at the 21st European PVSEC, published on internet, accessed 22-feb-2024

Conclusions

When to use pyranometers:

- all applications that require bankable PV system performance data
- input for PV modelling
- intercomparisons and assessment of meteorological conditions measuring GHI

When to use PV reference cells:

- indoor performance testing of PV modules or cells under lamps at normal incidence and at around 20 °C
- outdoor performance assessment of PV system performance, however only using reference cells with the same anti-reflection coating as the modules under observation and with correction for temperature dependence

About this white paper

Readers should be aware that Hukseflux is a manufacturer of solar radiation sensors. Our product range includes pyranometers. This review intends to provide objective information about competing products, in this case PV reference cells. We appreciate suggestions for improvement of this review.

About Hukseflux

Hukseflux is the leading expert in measurement of energy transfer. We design and manufacture sensors and measuring systems that support the energy transition. We are market leaders in solar radiation and heat flux measurement.
Customers are served through our headquarters in the Netherlands, and locally owned representative sales offices in the USA, Brazil, India, China, Southeast Asia and Japan.

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