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Pyranometers versus PV reference cells in outdoor PV system performance monitoring

There are good reasons why pyranometers are the standard for outdoor PV system performance monitoring. Read why in this white paper.

For organisations monitoring PV system performance at many different locations, possibly employing different PV cell types, use of pyranometers is easy; you can employ one instrument type, independent of PC cell type, suitable for both Global Horizontal Irradiance (GHI) and Plane of Array (POA). There is no post-processing of measurement data. For PV reference cells, the cell type (spectral response) as well as the use of anti-reflection coating (directional response) of the cell must match that of the PV system. Use of anti-reflection coatings has recently become the standard, while PV reference cells do not have such coatings.
For O&M organisations, the use of PV reference cells is difficult to manage. You need to choose 1 out of 4 different models. PV reference cells are not suitable for GHI measurement so that a power plant needs a pyranometer anyway. In the past, pyranometers had larger calibration uncertainties than PV reference cells; this is no longer an issue.
Therefore the International Energy Agency (IEA) and ASTM standards for PV monitoring recommend pyranometers for outdoor PV monitoring. **PV reference cells do not meet IEC 61724-1 class A requirements for irradiance measurement uncertainty**: their directional response makes them systematically overestimate daily radiant exposure in J/m^2 (or W·hr/m^2) by more than 2 %, larger on hourly basis. Spectral errors in the uncorrected data are in the order of 5 %.
The non-stability of PV reference cells is a loose end. A formal uncertainty evaluation is not possible, unless the reference cell is subject to very frequent recalibration.

Executive summary

Outdoor PV system performance monitoring

There are different purposes for outdoor PV system monitoring. The most common are:

- **System efficiency assessment**: the PV system efficiency in Watts generated per Watts available
- **System stability assessment:** the efficiency over several years compared to the first day of operation
- **PV cell stability assessment**: part of the system assessment may be an assessment of the stability of the PV cells, separating their performance from that of the other system components
- **Assessment relative to rating**: the PV system performance relative to the rated performance according to the original site survey that was used for financial rating
- **Assessment of meteorological conditions**: above assessments are often combined with the analysis of local meteorological conditions, comparing these to historical records
- **Site intercomparisons**: the PV system performance relative to performance of nearby sites

These assessments require data analysis over different periods of time. Some may require filtering for specific boundary conditions. For example, assessments relative to ratings are often performed by comparing one year to the next (so on a yearly scale). System stability assessments are often performed with reference to cloudless days around solar noon, with minimal relative influence of disturbing effects such as shading by nearby objects and radiation reflected by the ground.

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Standardisation of PV system performance monitoring

The latest and most influential standard is the IEC 61724-1 (2017) [19]. Other influential recommendations are written by ASTM and IEA [14,15]. The IEC allows use of both pyranometers and PV reference cells. This paper shows that this is a mistake. PV reference cells do not meet the irradiance measurement uncertainty requirement of 3 % for class A systems. ASTM and IEC clearly express preference for pyranometers.

Pyranometers

A **pyranometer** measures the solar radiation in available Watts per square meter. 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 also is the reference for** traditional **meteorological observations of global horizontal irradiance (GHI)**, which is used as input for solar atlases and irradiance maps. 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. 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). [5] Older calibration practices involved calibration over a full day, which resulted in larger uncertainties. Combined with the modern practice to use a total of 5 hours centred around solar noon for system stability and efficiency assessment (according to ASTM 2848), **the measurement uncertainty using pyranometers now is comparable to or better than when using PV reference cells. This is why IEA as well as ASTM recommend pyranometers for PV system performance monitoring [14, 15].**

PV reference cells

PV reference cells were originally developed for indoor **comparisons to identical PV cells** (typically during production) under lamp-based solar simulators. They were later used in short-term outdoor experiments under “perfect” sunny conditions on solar trackers (IEC 60904-1). PV reference cells are calibrated at normal incidence, for a certain standard spectrum at a certain irradiance level and temperature together specified as Standard Test Conditions for PV cells (STC). Under outdoor conditions the spectrum as well as the angle of incidence may differ from STC, and a **PV reference cell measures the maximum possible yield of a PV cell with an identical (or “matched”) PV cell type with exactly the same cover material with exactly the same reflection properties, mounted in the same plane of array. This is also called “usable fuel**” for that particular PV cell type.

There are 4 common PV reference cell models to choose from, see table 1.

In case the spectral composition of the radiation and spectral response and panel temperatures of the PV cells are available, it is possible to trace outdoor conditions to STC. **When using PV reference cells outdoors, post-processing using spectral corrections to STC is part of the standard procedure.** Using uncorrected measurements is not an option: spectral distribution of GHI changes over the day with air mass and aerosol concentration. Errors in uncorrected irradiance measurements can be up to 5 % at high zenith angles. [13]

Due to their directional response **PV reference cells are fundamentally unsuitable for efficiency assessment, assessment of meteorological conditions and site-to-site comparisons**. Reflecting at low angles (an inherent property of the plastic and glass covers of PV cells), **the total radiant exposure in J/m^2 over a day is always underestimated, and the PV system efficiency is always overestimated**. The deviation of non-coated cells from the ideal directional response is > 5 % above 55 degrees angle of incidence. [1, 15] In POA the error in daily radiant exposure is more than 2 %. Depending on the latitude and season, when mounted in a horizontal position for GHI measurement this error becomes at least 2 times larger at mid-latitudes.

This is why **PV reference cells have a low "achievable accuracy" for radiant exposure measurements, even when measuring irradiance in plane of array (POA). With a measurement uncertainty of more than 4 %, PV reference cells are considered unsuitable for GHI measurement. Also, their standardised flat cover makes PV reference cells very sensitive to fouling when installed in a horizontal position.**

Additional difficulties for PV reference cells: use of anti-reflection coatings

PV panel covers are increasingly equipped with anti-reflection (AR) coatings [16]. The coating has a typical index of refraction of 1.3, compared to the usual 1.5 for glass [17, 18]. This not only leads to a higher overall transmission (at normal incidence) but also a different directional response compared to uncoated glass, see figure [1]. For PV panels this leads to 2 % more light reaching the cell which can be attributed to the better overall transmission (this can be corrected for when comparing to normal glass) plus a daily average of around 1.5 % to the better directional properties (it is hard to correct for directional response mismatch because it varies with angle of incidence).

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 cell type used in the power plant, but also the AR properties must match.

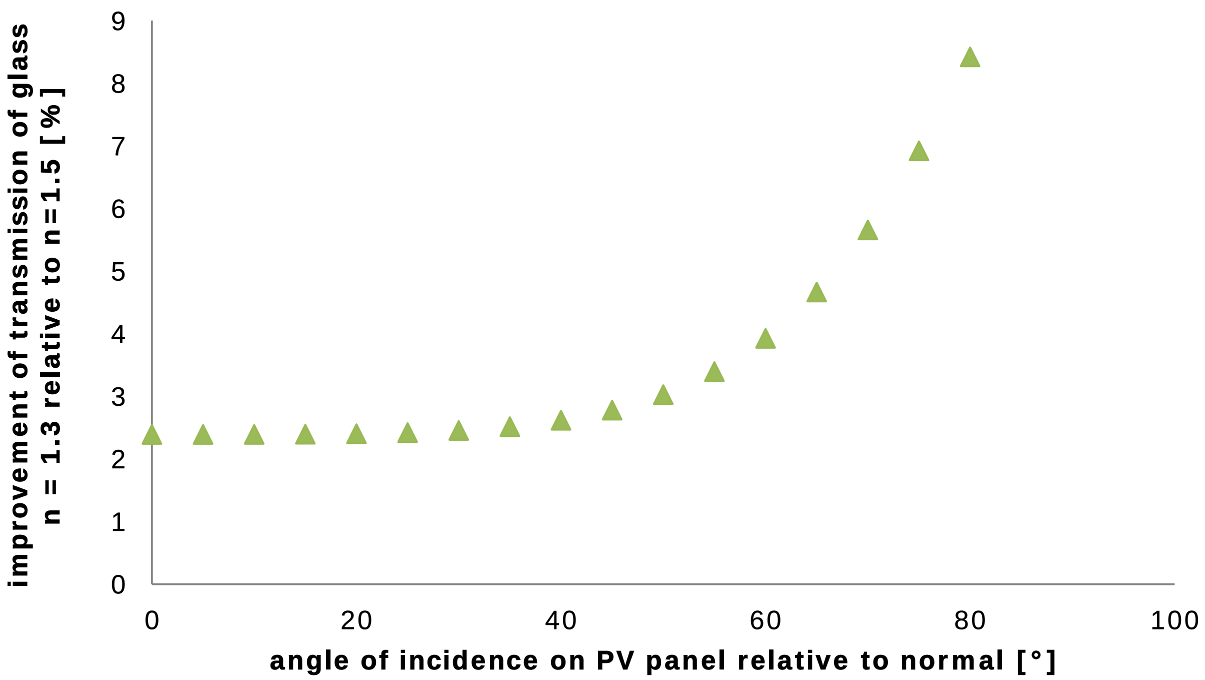

Figure 1 *Light transmission improvement of the cover of PV panels as a function of the angle of incidence when coated with an anti-reflection coating, relative to the transmission of normal glass. The use of anti-reflective coating improves the transmission by around 3 % at normal incidence, but also changes its directional response giving even more improvement at higher zenith angles. PV reference cells for these panels, when used outdoor, should copy this behaviour.*

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PV reference cells: 4 main models to choose from

As a PV reference cell user, you must make sure the PV reference cell matches your PV power plant cell type.

Table 1 *The most common 4 options for PV reference cells. A power plant owner must make sure that the reference cell matches the PV cells used in the power plant. Managing 4 different reference cell types is a problem from the point of view of Operations and Maintenance.*

PV reference cell type	cell type used	AR coating used
A	polycrystalline	AR coated
B	monocrystalline	plain glass
C	polycrystalline	AR coated
D	monocrystalline	Plain glass

Loose ends: unspecified non-stability of PV reference cells

Traditionally used for indoor experiments, the exposure of PV reference cells involved low levels of UV-B radiation while the humidity level was low. In addition, silicon cell material is very stable. The PV reference cell and its cover did not suffer from significant aging under indoor conditions. During long-term outdoor monitoring, the risk of non-stable behaviour is much higher than indoors, while **modern thin-film and multi-junction PV cells tend to be less stable than silicon. Hukseflux has found none of the commercially available PV reference cells specify non-stability during outdoor use.** Plastic covers are often used instead of the recommended and more stable glass ones. We see no reason why PV reference cells are more stable than normal PV cells, with a typical specification of a 20 % reduction in 20 years with a rapid change of < 3 % in the first year of operation. [2] Their unspecified non-stability makes PV reference cells a weak link in any measurement chain. **A solid formal uncertainty evaluation is not possible, unless the reference cell is subject to very frequent recalibration. For PV reference cells a non-stability of ± 1 % / yr is a reasonable estimate**. For secondary standard pyranometers, using glass domes and non-degradable carbon-based absorbers, the non-stability is formally specified and 2 times better; ± 0.5 %/yr.

Why pyranometers are the de-facto standard

- **The measurement uncertainty using pyranometers working close to normal incidence nowadays is comparable to or better than that of PV reference cells.** Past statements about larger measurement uncertainty of pyranometers are no longer valid. Modern pyranometers for use in solar energy applications are calibrated, just like PV reference cells, at normal incidence with achievable uncertainty levels in the ± 2 % range for hourly totals near solar noon.
- **Measurements with pyranometers may be used as a reference independent of the exact PV cell type, and independent of the reflective properties (AR coating) of the cover and also may be used for assessment of meteorological conditions and site intercomparisons.** Measured data can also be supplied to meteorological databases without any further processing.
- **The IEC 61724-1 requires an irradiance measurement. PV reference cells in POA systematically underestimate the daily radiant exposure in J/m^2 by more than 2 % [15].** For this reason **PV reference cells are not used to estimate total available energy in J/m^2 for system efficiency assessment nor for assessment relative to rating;** these require accurate assessment of meteorological conditions which PV reference cells cannot offer. Using well-maintained secondary standard pyranometers, on a sunny day the achievable uncertainty level of measurements of daily total radiant exposure in POA is in the ± 2 % range. This **meets the IEC 61724-1 requirement for uncertainty of the irradiance measurement (hourly totals) of Class A systems of 3 %. PV reference cells do not attain this level of uncertainty at high zenith angles.**
- The non-stability of PV reference cells is not specified by their manufacturers. **The unspecified non-stability makes PV reference cells a weak link in any measurement chain**. A solid formal uncertainty evaluation is not possible, unless the reference cell very frequently recalibrated.
- The long-term non-stability of secondary standard pyranometers is specified by manufacturers. Hukseflux estimates non-stability for top quality pyranometers to be 2 times better than that of PV reference cells. Compared to PV reference cells, **pyranometers can be used with a 2 times longer recalibration interval at the same level of measurement uncertainty.**
- **For parties monitoring multiple PV system sites, using pyranometers is cost-effective and easy for quality assurance.** An organisation may standardise on one instrument and one calibration procedure without significant data post-processing. By contrast, data post-processing, maintenance and calibration of different PV reference cell types, (amorphous, mono- and polycrystalline, thin-film and more coming) and reflective properties (with index of refraction either 1.5 or 1.3), is costly because all these steps require a high level of quality assurance.

When to consider use of PV reference cells

In exceptional situations outdoor measurements with PV reference cells may have added value:

- In all cases the PV reference cell properties should exactly match the cell properties of the PV system, including the cover, which determines the exact spectral and directional response.
- In system stability assessment, it is useful to **separate the non-stability of the PV cells** from that of other system components (“**system” versus “PV cell” stability assessment**). For PV cell stability assessment by comparison with identical PV reference cells, it is not necessary to enter spectral corrections (for cloudy conditions). Also measurements above 55 degrees angle of incidence are possible because, by having the same cover material, the directional response is identical.
- **Frequently calibrated, and used for comparison with identical PV cell type, cover material and AR coating, PV reference cells offer the lowest uncertainty for PV cell stability assessment.**
- **Site assessment for investment rating / bankability studies** typically requires very high measurement accuracy. It usually involves a survey before installation of the PV system. **To attain the highest accuracy level a pyrheliometer and shaded pyranometer are used.** The data obtained with this set of sensors can be used for different PV cell types, for further modelling and for comparison to historical meteorological data. Contrary to POA measurements, the pyrheliometer / shaded pyranometer measurements do not suffer from errors due to ground reflection. In case we know the PV cell type and orientation of the future system, it is good practice to use a **PV reference cell of exactly the same type in a supporting role**.

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Table 2 *Comparison of PV reference cells to pyranometers used for long-term outdoor PV system performance monitoring*

	ISO 9060 CLASSIFIED PYRANOMETER	**PV REFERENCE CELL**
Standardisation: applicable standard	ISO 9060 standard for pyranometers	IEC standard 60904-2 for PV reference cells
Standardisation: standardised calibration	Yes	Yes Calibration requires different spectral corrections for every PV cell type
Standardisation: use of one sensor type	Yes, suitable for GHI (horizontal mounting) as well as POA	No, POA only
Uncertainty: calibration at normal incidence (k = 2)	< ± 1.2 % secondary standard < ± 1.8 % first class	± 2 % [12]
Uncertainty: non-stability	< ± 0.5 %/yr secondary standard < ± 1 %/yr first class	Unspecified estimates by Hukseflux ± 1 %/yr [2] (higher for non-silicon cell types)
Uncertainty evaluation: general	According to ASTM G213-2017 see manual SR20, for POA use equatorial region	Questionable because non-stability is not specified. Only in case of frequent recalibration.
Uncertainty evaluation: achievable uncertainty daily totals without contributions of non-stability and fouling	GHI and POA ± 2 % secondary standard ± 3.5 % first class	> ± 3 % Estimate by Hukseflux "Usable fuel" ± 2.5 % [12]
Uncertainty evaluation: added uncertainty under a 1 x / 2 yr recalibration schedule	± 1 % secondary standard ± 2 % first class	± 2 % [2] Estimate by Hukseflux
RECOMMENDED USE IN OUTDOOR PV SYSTEM PERFORMANCE MONITORING		
Recommended use by IEC 61724-1	Yes	POA only. Not suitable for GHI (horizontal mounting)
Recommended use by ASTM 2828 and IEA-PVPS T13-03: GHI, POA	Yes	POA only. Not suitable for GHI (horizontal mounting) ASTM allows use after mutual consent. Only with spectral correction to STC requiring data post-processing according to Annexes A1 and A2.
Recommended use: system efficiency assessment	Yes	No, systematic underestimation of POA daily radiant exposure by more than 2 %, spectral errors in uncorrected data around 5 % [13]
Recommended use by ASTM 2828 and IEA-PVPS T13-03: system stability assessment	Yes, independent of PV cell type (using sunny days around solar noon as reference)	No, PV cell stability assessment only using exactly the same cell type with exactly the same AR coating as the PV system
Recommended use by ASTM 2828 and IEA-PVPS T13-03: assessment relative to rating	Yes	No, systematic underestimation of POA daily radiant exposure by more than 2 %, spectral errors in uncorrected data around 5 % [13]
Recommended use: Assessment of meteorological conditions / site intercomparisons	Yes, using GHI (horizontal mounting) Also feeding data to independently obtained meteorological data series	No, not suitable for GHI (horizontal mounting)
Recommended use: Site assessment for investment rating / bankability studies	Yes	No, systematic underestimation of daily radiant exposure by more than 2 %, spectral errors in uncorrected data around 5 % [13] In a supporting role only in case the PV cell type and POA orientation of the future system are known.

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Conclusions

When to use pyranometers:

- All long-term outdoor PV system performance monitoring, mounted in POA
- Site intercomparisons and assessment of meteorological conditions measuring GHI, mounted horizontally
- All applications that require a bankable, solid formal uncertainty evaluation

When to use PV reference cells:

- Indoor comparison under lamps to PV cells of exactly the same type
- Outdoor stability assessment of PV cell stability comparing to exactly the same cell type with exactly the same anti-reflection coating on its cover
- Outdoor site surveys, in a supporting role, in case the PV cell type, PV cell reflective properties and POA angle are known

About this white paper

Readers should be aware that Hukseflux Thermal Sensors is a manufacturer of solar radiation sensors. Our product range includes pyranometers, pyrheliometers and pyrgeometers. This review intends to provide objective information about competing products (such as PV reference cells). We appreciate suggestions for improvement of this review.

About Hukseflux

Hukseflux Thermal Sensors offers measurement solutions for the most challenging applications. Our main area of expertise is measurement of heat transfer and thermal quantities such as solar radiation, heat flux and thermal conductivity. Hukseflux is ISO 9001:2015 certified. Hukseflux sensors, systems and services are offered worldwide via our office in Delft, the Netherlands and local distributors.

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