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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.

When monitoring PV systems at many different locations, possibly employing different PV cell types, use of pyranometers is easy; one instrument type, no post-processing of data, one calibration procedure. In the past, pyranometers had larger calibration uncertainties than PV reference cells; this is no longer an issue.
PV reference cells are not suitable for PV system efficiency assessments, site intercomparisons and assessments relative to ratings: their directional response makes them systematically overestimate daily radiant exposure in J/m^2 (or $W \cdot hr/m^2$) by more than 2 %. 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.

Outdoor PV system performance monitoring

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

- **System efficiency assessment**: assessing the PV system efficiency in Watts generated per Watts available
- **System stability assessment:** assessing the stability of the PV system 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**: assessing 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
- **Site intercomparisons**: assessing the PV system performance relative to performance of nearby sites

These assessments require data analysis over different periods of time. Some may require selection of 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.

Pyranometers

A **pyranometer** measures the solar radiation in available Watts per square meter. The measurement 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 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 used in the solar industry 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 ASTM2848), **the measurement uncertainty using pyranometers now is comparable to or better than when using PV reference cells.**

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, a certain irradiance level and temperature, 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 PV cell type with exactly the same window, mounted in the same plane of array. This is also called "usable fuel**" for that particular PV cell type.
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 from the ideal directional response is > 5 % above 55 degrees angle of incidence.[1] 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 GHI measurements, even when measuring irradiance in plane of array (POA).**

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 window did not suffer from significant aging. 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 close to normal incidence in POA may be used as a reference independent of the exact PV cell type, and also for assessment of meteorological conditions and site intercomparisons.** Measured data can also be supplied to meteorological databases without any further processing.
- **PV reference cells in POA systematically underestimate the daily radiant exposure in J/m² by more than 2 %.** For this reason **PV reference cells are not used to estimate total available energy in J/m² 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.
- 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 is subject to very frequent recalibration.
- 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), is costly because all these steps require a high level of quality assurance.

When to consider use of PV reference cells

In some 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 window material the directional response is identical.
- **Frequently calibrated, and used for comparison with identical PV cell (and cover) type, 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 overestimation of irradiance due to radiation reflected by the ground. In case the exact PV cell type and orientation of the future system are known, it is good practice to use a **PV reference cell of exactly the same type in POA in a supporting role**. The uncertainty evaluation of the measurement requires care; the POA measurement also measures reflected radiation, which is not part of the true solar climate.

Table 1 *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: use in outdoor PV system performance monitoring according to ASTM E2848	Yes, recommended	Optional (paragraph 7.2.3) but not recommended. Only with spectral correction to STC requiring elaborate data post-processing according to Annexes A1 and A2.
Standardisation: standardised calibration	Yes	Yes Calibration requires different spectral corrections for every PV cell type
Standardisation: use of one sensor type	Suitable for GHI (horizontal mounting) as well as POA	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	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	"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 LONG-TERM OUTDOOR PV SYSTEM PERFORMANCE MONITORING		
Recommended use: GHI, POA	Yes	POA only. Not suitable for for GHI (horizontal mounting)
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: 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 window as the PV system
Recommended use: 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 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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NOTE: general reflective properties of glass and plastics determine the directional response of silicon reference cells
2. ET Solar, (2011) *Linear power performance warranty*, published on internet, accessed 03-nov-2013
NOTE: Typical is a 20 % reduction of PV cell efficiency in 20 to 25 years with a rapid change of < 3 % in the first year of operation. Hukseflux has found none of commercially available reference cells specify stability during outdoor use.
3. Daryl Myers, (2011), *Quantitative analysis of spectral impacts on silicon photodiode radiometers*, NREL/CP-5500-50936, published on internet, accessed 03-nov-2013
4. Kipp & Zonen, (2013), manual, *Manual CMP pyranometers CMA albedometers*, modification date February 2013, published on internet, accessed 03-nov-2013
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12. Lawrence Dunn et al., (2012), *Comparison of Pyranometers vs. Reference Cells for Evaluation of PV Array Performance*, proceedings of the 38th IEEE Photovoltaic Specialists Conference (PVSC), Austin, TX, June 3-8, 2012
13. Manajit Sengupta et al., (2012), *Performance Testing Using Silicon Devices – Analysis of Accuracy*, presented at the 2012 IEEE Photovoltaic Specialists Conference Austin, Texas, Conference paper, NREL/CP-5500-54251 , published on internet, accessed 01-dec-2013

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 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
- outdoor site surveys, in a supporting role, in case the PV cell type and POA 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 aims to advance thermal measurement. We offer a complete range of sensors and systems for measuring heat flux, solar radiation and thermal conductivity. Customers are served through the main office in Delft in the Netherlands, and locally owned representations in the USA, China and Japan.

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