Pyranometers versus reference cells for solar monitoring

On-site monitoring | As the solar industry gains momentum, there is an increasing need for on-site resource monitoring using pyranometers and reference cells. Peter N. Johnson of AWS Truepower introduces the technical specifications and limitations of industry-standard pyranometers and reference cells, and outlines best practices for monitoring with this equipment. How solar measurements can be used to improve resource and energy estimates for utility-scale PV projects is also discussed

Pyranometers and reference cells offer different options for solar plant monitoring.

Credit: Kipp & Zonen

In recent years, an increasing number of large utility-scale PV projects have been developed, particularly in the desert south-west of the USA. The emphasis on larger projects has led to an increase in on-site solar monitoring. On-site monitoring reduces investment risk and helps to meet the requirements of power off-takers, utilities and jurisdictional authorities. The monitoring data are especially valuable for larger projects (>50MW) and for those in poorly-defined resource areas; in these cases, financial risks and grid-integration concerns may be greater.

On-site monitoring provides information about the solar resource and project performance that cannot be reliably obtained with modelled data sets alone: on-site measurements from pyranometers and reference cells can reduce uncertainty in energy estimates by 3–4% compared with modelled data. On-site measurements are also the most effective for characterising seasonal trends, diurnal trends and short-term ramp events, all of which are critical for estimating time-of-day energy pricing and supporting grid integration. These data are used as inputs for pre-construction, operational and short-term energy forecasts, helping to inform financial models, and quantifying investment risk for developers and financiers.

Pyranometers

Applications for pyranometers

For pre-construction applications, on-site pyranometer measurements can be used in combination with other regional data sources to accurately characterise a PV project's long-term solar resource and energy potential. Because of inter-annual variability in the solar resource, shorter on-site measurement periods must be correlated to a high-quality longer-term data set of ten years or more. This combined approach leverages the complementary strengths of multiple data sets, taking account of high measurement accuracy as well as long-term regional trends. Long-term reference data sets may be modelled data or regional ground measurements from public meteorological networks. Reference data sets should be scrutinised to confirm accuracy, consistent trends, high data recovery, agreement with concurrent regional measurements and equipment maintenance when possible. Using less than a year of on-site measurements may result in a seasonal bias and is not recommended. The adoption of a blended approach leads to an overall solar resource uncertainty between 2 and 4%, depending on the pyranometer used, the regularity of site maintenance, the inter-annual variability, and the reference data set's quality and recording period.

During a project's operational phase, on-site pyranometer measurements serve three purposes. The first is supervisory control and data acquisition (SCADA). It is common to collect high-quality plane-of-array irradiance measurements at multiple locations within a large PV array; these measurements are incorporated into the project's SCADA system and can be used to help identify underperforming sections of the PV project. Second, on-site measurements can be used to support operational energy assessments. In this application, the measurements are employed to develop a correlation with the PV project's power output and to adjust the analysis results to long-term estimates. The third application is short-term forecasting. Measurements during the operational phase can be incorporated into short-term resource and energy models to develop forecasts for sub-hourly, hourly, daily, monthly and seasonal time periods.

Characterising the solar resource with pyranometers

The primary purpose of pyranometers is to collect high-accuracy solar resource data. The most important measurement collected for PV projects is global horizontal irradiance (GHI). On-site measurements from well-maintained high-quality pyranometers can achieve annual GHI uncertainties as low as 1%.

In addition to GHI, pyranometers are used to measure other solar parameters and to project irradiance measurements to the plane of a PV array. By blocking direct sunlight, a pyranometer can measure diffuse sunlight only, known as 'diffuse horizontal irradiance' (DHI). From GHI and DHI, the direct normal irradiance (DNI) can be calculated – this is the direct sunlight observed on the plane orthogonal to the sun's rays.

Measurements of DHI and DNI are often obtained using a rotating shadowband radiometer (RSR), shown in Fig. 1. The RSR measures DHI by blocking out the direct rays of the sun every thirty

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seconds using a black rotating arm, or 'shadowband'. DNI is then computed from the observed GHI and DHI using the sun's zenith angle. From these three components, the solar resource can be transposed to any project's plane of array (POA), for fixed-tilt as well as tracking systems.

Pyranometers may also be used to directly collect POA irradiance; to accomplish this, the pyranometer is mounted at the exact tilt angle of the PV modules (Fig. 2). POA irradiance can then be used for energy simulations and for correlating with plant output during the project's operational phase.

Credit: NREL.

Figure 1. Rotating shadowband radiometer.

Credit: Brenda Cody.

Figure 2. Plane-of-array measurement from a LI-COR LI-200 pyranometer.

Types of pyranometer

There are two distinct designs for pyranometers, each with a different mechanism for measuring irradiance. Silicon-based pyranometers, such as the LI-COR LI-200SZ shown in Fig. 3, measure the solar resource by an electrical signal generated from the photovoltaic effect, thus acting like a tiny PV cell. These pyranometers have a short response time and are therefore appropriate for RSR applications. Costing between US$200 and US$700, depending on the type and required application, they have an annual irradiation uncertainty of 2–5%.

Thermopile pyranometers, such as the CMP series pyranometers manufactured by Kipp & Zonen (see Fig. 4), cost between US$2,000 and US$3,000 per instrument, but also tend to be more accurate, with an uncertainty in the range 1–3%. These pyranometers measure the solar resource using a thermoelectric surface. Because they are temperature based, thermopile pyranometers have a slower response time (a few seconds up to half a minute) than their silicon-based counterparts (approximately 10μs – almost instantaneous); this makes thermopile pyranometers less effective for ramp event characterisation. Despite their slower response time, thermopile-based pyranometers can achieve higher measurement accuracy than their silicon-based counterparts over time periods of one minute or more.

Figure 3. LI-COR LI-200SZ pyranometer.

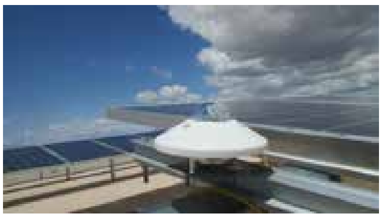

Figure 4. Kipp & Zonen CMP series pyranometer.

Thermopile pyranometers are often designed to achieve secondary-standard quality, which is the highest-quality instrument available for field deployment. The name 'secondary standard' refers to the sensor's calibration using a lab-based primary standard pyranometer that is certified by the World Radiation Center. Pyranometers of this calibre must meet rigorous requirements for response time, non-stability (drift), non-linearity, spectral selectivity, temperature and tilt response, and achievable uncertainty. Silicon-based pyranometers, on the other hand, do not meet all the technical requirements of secondary-standard equipment, but are still useful for a variety of applications, including long-term resource assessment, short-term forecasting, correlations with plant performance, and measurement networks.

Pyranometer best practices and maintenance

In order to achieve the lowest solar resource uncertainty, pyranometers installed in the field must be properly configured and maintained. Pyranometers should be sited higher than surrounding instrumentation to avoid being shaded. They should also be

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installed on steady but adjustable mounting arms to prevent non-levelness, which would lead to poor measurement results: non-levelness to the east or the west leads to skewed diurnal patterns, while non-levelness to the north or south leads to measurements being lower or higher than actual. Redundant pyranometers are recommended as a quality-control measure, to achieve high data recoveries in the event of equipment failure and to validate data using comparison techniques.

Daily, semi-weekly or weekly on-site maintenance of pyranometers is essential to maximise measurement accuracy. When maintenance is neglected for long periods, measurement accuracy can degrade by as much as 5–10% because of a change in the orientation of the sensor or because of the accumulation of dust, snow or bird droppings.

The standard maintenance procedure includes re-levelling the pyranometer and carefully cleaning its surface with compressed air, distilled water and a streak-free, scratch-free cloth (Figs. 5 and 6).

Pyranometer data are commonly

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Figure 5. Sensor levelling of the LI-200 pyranometer.

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Figure 6. Cleaning the CMP11 pyranometer.

collected at three-second, one-minute, hourly and daily time intervals. The higher temporal resolution data are valuable for understanding ramp events and for forecasting purposes, while the hourly and daily data are useful for longer-term energy estimates and resource correlations respectively. Using remote communications and validation protocols, data should be regularly screened – at least once or twice a week – to confirm proper system operation and valid data collection. The screening process involves quality-control protocols as well as communication with the maintenance technician to troubleshoot suspicious observations in the data.

During commissioning and decommissioning, field pyranometer performance may be confirmed through a verification procedure where a higher-quality instrument is set up in parallel for a few hours, and observations are compared. Pyranometers should be recalibrated or replaced every one to two years to prevent measurements from being impacted by sensor non-stability.

Supplementary meteorological measurements

In addition to irradiance data collected by pyranometers, other meteorological data are often collected concurrently to help validate irradiance data and support energy simulation and loss assumptions (Fig. 7). Precipitation data are helpful for confirming rain events associated with cloud cover and for correlations to estimate the PV array soiling loss. Wind speed and ambient temperature data can be used to estimate thermal losses of PV arrays during the energy simulation process. Together, the ensemble of measurements characterises site conditions and allows intelligent judgement to be made when validating irradiance data.

Figure 7. Example of a solar monitoring system with pyranometers and associated weather equipment.

"Reference cell data are used to characterise site-specific PV performance and loss factors for proposed and operational projects"

Reference cells

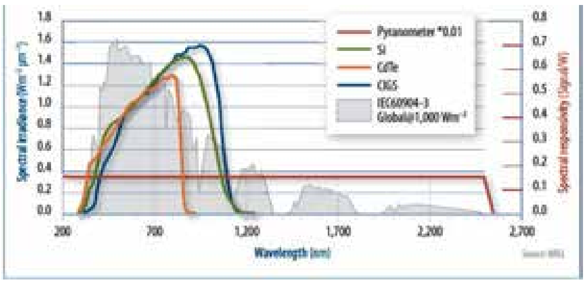
Applications for reference cells

Reference cell data collected through solar monitoring are used to characterise site-specific PV performance and loss factors for proposed and operational projects. These data are obtained by measuring the reference cell's electrical current output from the voltage drop across a supplier-provided resistor [1]. Reference data may be employed in the following ways: 1) pre-construction energy simulation models; 2) incorporating into short-term energy forecasting models; and/or 3) use as a benchmark to help identify underperforming components in an operating PV array.

Reference cells are inferior indicators of irradiance, and their function is different from that of pyranometers. Designed for the specific purpose of resource measurement, pyranometers are less impacted by temperature and have a much broader spectral response than reference cells, as shown in Fig. 8. Pyranometers also accept irradiance across a wider range of incidence angles than reference modules, which are limited to approximately 80°[1]. In contrast, reference cells highlight the performance of PV materials in the site environment.

Most state-of-the-art solar monitoring systems therefore feature both pyranometers and reference cells to accurately capture the solar resource and PV performance respectively. Used in combination with pyranometer measurements, reference cell data can

Figure 8. Spectral response of a pyranometer compared with various PV materials.



Source: NREL.

help to calibrate specific loss factors and overall expected PV performance.

Reference cells versus reference modules

There is a distinction between reference cells and full reference modules, as shown in Fig. 9. Reference cells cost from US$800 to US$1,500 each, and are used primarily for soiling-loss studies.. Reference modules are most effective when the reference cell material is the same as the PV array's material: usually crystalline silicon, amorphous silicon thin film or cadmium telluride thin film.

Credit: Larry Cox.

Credit: Brenda Cody.

Figure 9. Examples of a reference cell and reference modules in the field.

Characterising performance with reference cells

Several performance metrics and loss factors can be assessed with high-quality reference cell data. Site-specific soiling losses are often quantified by configuring two reference cells identically on the same POA and at the same azimuth; one reference cell is cleaned frequently (e.g. twice a week), while the other is left untouched and serves as a control. The difference in power output, corrected for the effect of temperature, can be correlated with precipitation data to estimate long-term monthly soiling losses (see Fig. 10). These data help to determine the appropriate threshold for array cleaning schedules, informing O&M activities and aiding in tuning operational expenditure budgets.

In the case of a reference module, field performance can help to assess

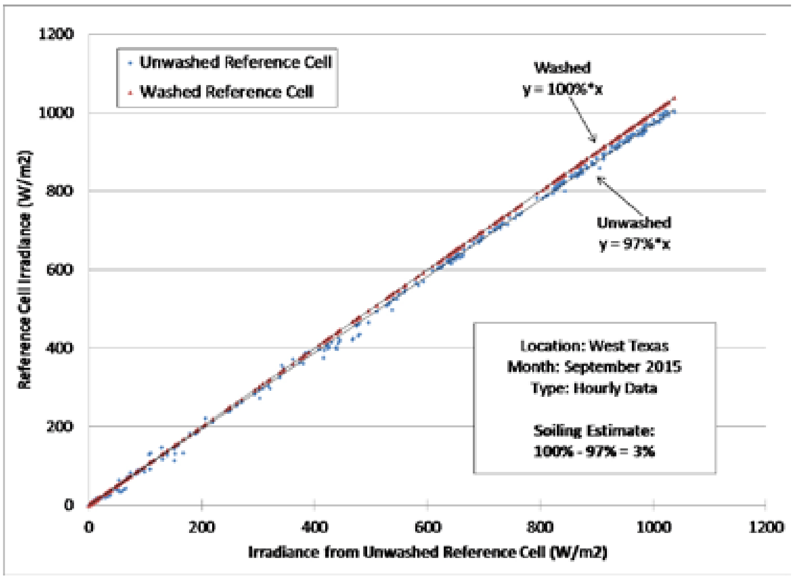


Figure 10. Soiling of an unwashed reference module in Texas (September 2015).

the performance impact of module operating temperature, the irradiance spectrum, and overall module quality. In particular, the module's thermal performance loss for non-standard test conditions (non-STC) can be evaluated, which can range from 3 to 12%. For this application, cell operating temperature (using a sensor applied to the back of the module) is measured along with POA irradiance and ambient temperature to generate a profile of module performance for a range of operating conditions.

Reference cell best practices and maintenance

While reference cells differ in purpose from pyranometers, best practices and maintenance procedures are similar. Like pyranometers, reference cells (and modules) should be sited so they are free of any shading from nearby equipment, foliage or fencing, and be carefully configured to match the desired tilt angle and azimuth. Moreover, like pyranometers, reference cells should be recalibrated or replaced every one to two years to prevent measurements from being influenced by non-stability and material degradation.

In cases where full field modules are installed, back-of-module temperature and other diagnostic measurements may be taken to characterise performance for a range of operating conditions. A shunt resistor is also necessary for higher-watt reference modules to reduce their electrical signal prior to being connected to the data logger. Daily, semi-weekly or weekly maintenance is essential to confirm reference cell tilt angle, as is careful cleaning of the surface from soiling and debris using a streak-free, scratch-free cloth. A weekly review of the data to confirm proper system operation is recommended.

Conclusion

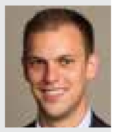
High-quality pyranometer and reference cell data, for both short-term and long-term energy forecasts, have been shown to reduce project performance risk in the pre-construction and operational phases. When properly installed and maintained, pyranometers can reduce energy uncertainty by 3–4%; similarly, reference cells can help to characterise site-specific losses, including soiling, non-STC temperature and irradiance losses, and overall module performance. The use of monitoring equipment, summarised in Table 1, contributes to better financing terms for larger projects and to aiding developers in assembling stronger project portfolios.

	Silicon pyranometer	Thermopile pyranometer	Reference cell
Purpose	Resource assessment, RSR, ramp events, plant performance correlation, forecasting	Resource assessment, operational assessment, forecasting (highest accuracy)	Characterising PV module performance in specific environments, soiling studies
Benefits	High response time, lower economic cost	High accuracy, greater spectral range	Field data depicting equipment performance
Inappropriate for	Highest-accuracy results	Ramp event characterisation, RSR	Solar resource assessment
Accuracy (GHI or POA)	2–5%	1–3%	Not recommended for resource assessment because of the narrow spectral response
Maintenance	Weekly/bi-weekly	Weekly/bi-weekly	Weekly/bi-weekly
Cost	US$200–700	US$2,000–3,000	US$800–1,500 per reference cell
Calibration/ replacement	Replace after 1–2 years of service	Recalibrate after 1–2 years of service	Replace after 1–2 years of service

Table 1. Summary of pyranometer and reference cell applications.

Author

Peter Johnson is a project manager for AWS Truepower's solar department with a background in engineering. He actively supports solar resource data collection and validation activities, long-term resource assessment, solar energy modelling, energy assessment, loss assumptions and uncertainty estimates, while regularly conducting research to further refine methods. He has performed cost assessments and cash flow analysis for utility-scale solar projects and on- and offshore wind projects. His background includes familiarity with solar and wind monitoring equipment, best practices, and project siting considerations in North America and abroad.



Reference

[1] Meydbray, J., Emery, K. & Kurtz, S. 2012, "Pyranometers and reference cells, what's the difference?", Report NREL/JA-5200-54498 [www.nrel.gov/docs/fy12osti/54498.pdf].