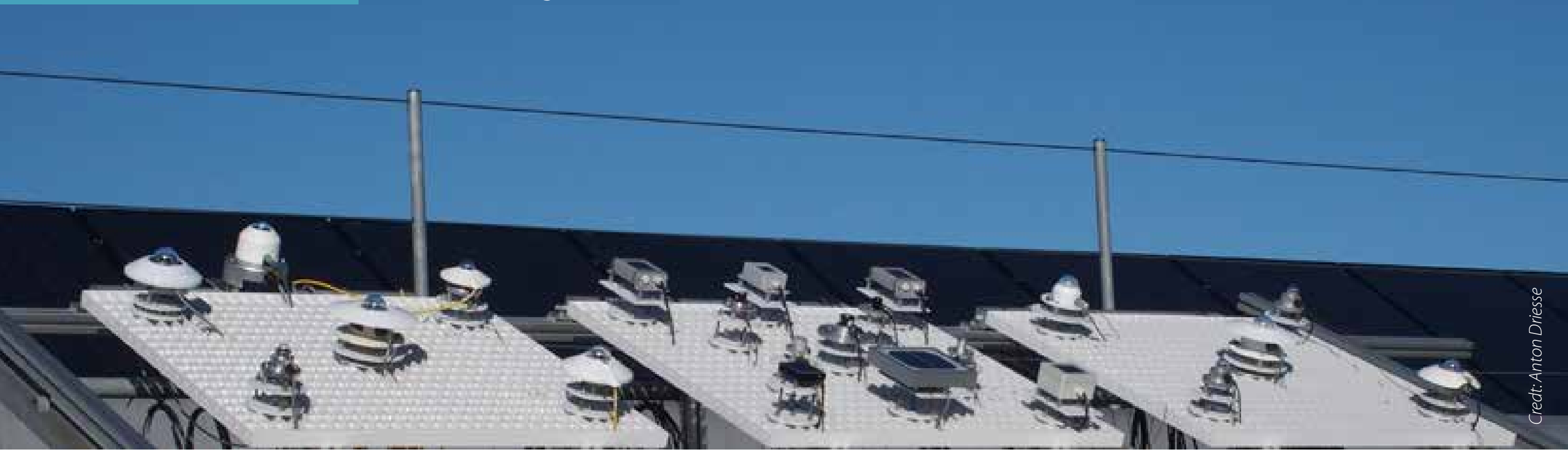

Credit: Anton Driesse

In pursuit of accurate irradiance measurements

Part 2: Sensors and beyond

Resource assessment | Irradiance sensors are vital tools for protecting investment in valuable solar power plants and ensuring they perform optimally. In the second of two articles on a major study they are leading to better understand these diminutive components, Anton Driesse and Joshua Stein discuss how inaccuracies in irradiance measurement can be quantified and managed

Solar irradiance measurements provide essential information at all stages of the PV system lifecycle. Historical measurements are used for selecting sites, designing systems and securing financing. High-resolution measurements in the period before construction can help fine-tune planning. When it's time to commission a system, irradiance measurements are a vital tool in ascertaining whether modules are performing as per manufacturer claims. And the story doesn't end here. Only a stable independent irradiance measurement will permit long-term changes in system performance to be detected and the source of emerging faults identified. As PV arrays age, decisions need to be made about upgrades, replacements, expansion and decommissioning. Irradiance measurements put everything into perspective.

In 2014 PV Performance Labs launched a comprehensive study to achieve a deeper understanding of the differences between common commercial instruments that are used to support PV plant planning and operations. The project, called PVSENSOR, included a series of indoor tests carried out at the Joint Research Center (JRC) in Ispra, Italy, and extensive outdoor testing at Sandia National Laboratories (Sandia) in Albuquerque, New Mexico, USA, as well as at PV Performance Labs in Freiburg, Germany. A period of extended outdoor monitoring to validate the laboratory results is still ongoing. (See photo above.)

Our goal with the study is ultimately to make more accurate statements and conclusions about PV system performance. This could be simple aggregate performance or more targeted metrics such as peak or low-light performance, seasonal variations, or evaluation of performance changes over time due to various causes such as soiling or material degradation. Many factors that influence PV system output also affect irradiance sensor readings, so the latter must be understood in detail in order to make conclusions about the former.

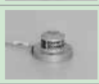
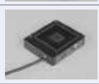
Accurate irradiance measurements are necessary, but it is equally important to *quantify* the accuracy of the measurements, in other words, every irradiance measurement should be accompanied by an uncertainty indicator such as ±3% or ±30W/m^2. Just as every performance claim or promise has a tolerance band (sometimes only seen in the fine print), so should every performance measurement have an implicit or explicit uncertainty factor. In practice the uncertainty in performance indicators is almost always dominated by the uncertainty in irradiance measurements; this is the driving force for investigating the sensors.

A report on the initial stages of the project and its aims appeared in Volume 07 of *PV Tech Power* in May 2016. In this follow-up article we discuss sensor specifications and sources of uncertainty and look at variability in measurements that can arise from systematic and non-systematic causes. We conclude with practical advice on maximising accuracy.

Instruments and specifications

To measure the irradiance in the plane of a PV array, a broad range of commercial instruments is available. These can be separated into three fundamental categories:

1. ***Thermopile pyranometers.*** These instruments have a black surface under a glass dome that absorbs solar radiation and produces a small voltage in proportion to the internal temperature rise, which is converted to irradiance.
2. ***Photodiode pyranometers.*** A miniature PV cell hidden under a translucent diffusor inside the body of these sensors produces a current proportional to the absorbed irradiance. They are designed to behave as much as possible like thermopile pyranometers.

	Manufacturer		Model	Response time	Zero offset A error	Zero offset B error	Non-stability error	Non-linearity error	Directional response error	Spectral selectivity error	Temperature response error	Tilt response error	Calibration uncertainty
				seconds	W/m²	W/m²	% per year	%	W/m²	%	%	%	%
Secondary standard thermopile pyranometers	***ISO 9060 requirements***			15	7	2	0.8	0.5	10	3	2	0.5	
	Eko Instruments		MS-802	5	6	2	0.5	0.2	10	1	1	0.2	0.66
	Eppley		PSP	15	4-6	1-2	0.5	0.5	10	1	1	0.5	1
	Eppley		SPP	5	5	2	0.5	0.5	10	2	0.5	0.5	1
	Eppley		GPP	5	5	2	0.5	0.5	10	2	0.5	0.5	1
	Hukseflux		SR20	3	5	2	0.5	0.2	10	3	1	0.2	1
	Kipp & Zonen		CMP 10	5	7	2	0.5	0.2	10	3	1	0.2	1.4
Second class thermopile pyranometers	***ISO 9060 requirements***			60	30	8	3	3	30	10	8	5	
	Eko Instruments		MS-602	17	10	6	1.7	1.5	25	1	2	2	0.77
	Hukseflux		SR03	1	15	4	1	1	25	5	3	2	1.7
	Hukseflux		LP02	18	15	4	1	1	25	5	3	2	1.4
	Kipp & Zonen		CMP 3	18	15	5	1	1.5	20	3	5	1	3.31
Photodiode pyranometers	Apogee Instruments		SP-110	1 ms	0*	0*	2	1	5 %		-0.04 %/°C	0*	5
	Eko Instruments		ML-01	1 ms	0*	0*	2		5 %		0.15 %/°C	0*	3.06
	Kipp & Zonen		SP Lite2	500 ns	0*	0*	2	2.5	10		-0.15 %/°C	0*	4.6
	LI-COR		LI-200	10 us	0*	0*	2	1	5 %		0.15 %/°C	0*	
	Skye Instruments		SKS-1110	10 ns	0*	0*	2	0.2	5 %		0.2 %/°C	0*	5
Silicon photovoltaic reference cells	EETS		RC01	0*	0*	0*					0.0302 %/°C	0*	3
	Fraunhofer ISE		11311102	0*	0*	0*					0.06363 %/°C	0*	
	Mencke & Tegtmeyer		SiS-02-Pt100	0*	0*	0*					0.07 %/°C	0*	
	Mencke & Tegtmeyer		Si-02-Pt100	0*	0*	0*					0.0725 %/°C	0*	
	Mencke & Tegtmeyer		Si-02-Pt100-x	0*	0*	0*					0.0725 %/°C	0*	
	NES		SOZ-03	0*	0*	0*	0.3				0.06 %/°C	0*	3

* These characteristics are relevant for thermal sensors and are considered to be zero for photovoltaic sensors even if not explicitly reported by the manufacturer

Table 1. Manufacturers' specifications for the products included in the PVSENSOR study. Most values indicate the maximum error attributable to a certain characteristic. Manufacturers specifications are generally subject to change without notice, and we have indeed seen some of them change. We have made every effort to ensure that this information is correct, but cannot guarantee this.

3. ***Reference cells.*** This category also uses the current generated by a PV cell, but the cells are larger and the physical construction and optics are more similar to a small PV module.

The first place to learn about product capabilities and differences between products is normally the manufacturer's literature. For the PVSENSOR study we selected 21 different commercial sensor models, focusing on those that are well known and widely used. Table 1 identifies these sensors and lists their most important specifications as found in public datasheets and product manuals. The information given in most product literature reflects the ISO 9060 classification criteria, and these are therefore shown in the column headings of Table 1.

The 10 thermopile instruments are grouped by their ISO 9060 quality classification as either *secondary-standard* (red) or *second-class* (yellow) and the corresponding requirements are listed above each group. (The study did not include any ISO *first-class* instruments.) The photodiode pyranometers in the third group (green) aspire to the same ideals as the thermopile instruments but they cannot completely meet the requirements for any defined class due to their narrow spectral responses. (The ISO 9060 standard is currently under revision and one or more new class definitions are expected that will accommodate photodiode pyranometers.)

The last group (blue) contains the PV reference cells. These are not designed to behave like pyranometers so significant differences in spectral and directional response errors are normal. Unfortunately there is no 'ideal' spectral response or directional response for reference cells, so it is not possible to define how much they might be in 'error'. For other aspects like non-linearity, non-stability and calibration uncertainty the same 'ideals' can be applied as for the pyranometers.

One difficulty with these specifications is that they are presented as worst-case errors. This makes it easy to verify that the classification requirements are met, but it makes it harder to determine what the accuracy of a specific measurement or series of measurements could be. As the classification criteria labels suggest, most errors are not purely random but have specific causes that presumably produce systematic error responses. So if the ambient temperature is moderate, then the temperature response error is likely to be smaller, and if the sun is high in the sky at mid-day, then the directional error is likely to be smaller than the worst case.

When one looks deeper into the data sheets, product manuals and calibration certificates, more information about the systematic nature of these errors is usually found, but the content and form of that information are often inconsistent between sources so can be hard to compare. Over the course of the PVSENSOR project we have evaluated many of these systematic responses and some were presented in Part 1 of this article (*PV Tech Power*, May 2016). This information is now in a consistent form and helps us make more informed instrument choices as well as evaluate and re-evaluate plant performance data based on the instruments that were deployed.

From instrument specifications to measurement uncertainty

The ISO procedure for evaluating uncertainty, the Guide to the Expression of Uncertainty in Measurement (GUM), contains clear rules for calculating an overall uncertainty for a measurement that involves multiple independent sources of uncertainty. The pyranometer specifications are in a form that makes it fairly easy to apply this procedure, and this is the basis of the newly approved and soon-to-be-published ASTM "Standard Guide for Evaluating Uncertainty in Calibration and Field Measurements of Broadband Irradiance with Pyranometers and Pyrheliometers". An important outcome of the procedure is that it assigns a specific uncertainty to each measurement rather than a global value for an instrument or measurement system. A closer look at the specifications table above shows that some of the errors are absolute and others are relative, which logically leads to larger relative uncertainties at low irradiance levels, and vice versa. As a result the same instrument and the same equipment can produce different aggregate uncertainties for different locations or even for different seasons at the same location. More complicated perhaps, but also more realistic.

Variation of systematic measurement errors over time

In the ASTM approach all error sources are treated as if they were random and independent. As mentioned earlier, however, the different types of error identified in the specifications are not purely random: many of them do have a systematic component. And if one or more of those systematic error components can be calculated, then that can potentially reduce the random error. The challenge is that this has to be done on a case-by-case basis for each measurement situation and location.

To illustrate this, we have used the temperature, directional and spectral responses measured in the PVSENSOR project to calculate the systematic measurement errors that would have occurred in Golden, Colorado when measuring the global irradiance on a surface tilted at 40°. This puts together data gathered about the instruments in the lab at JRC and on the outdoor test stand at Sandia, with environmental parameters and spectral irradiance measured at the NREL Solar Radiation Research Laboratory. Figures 2a to 2f show how each of those errors varies throughout a single sunny summer day, and throughout a whole year for a sample pyranometer, photodiode and reference cell. Some important notes: The top half of each diagram is an absolute scale, which is the same for all three instruments to facili-

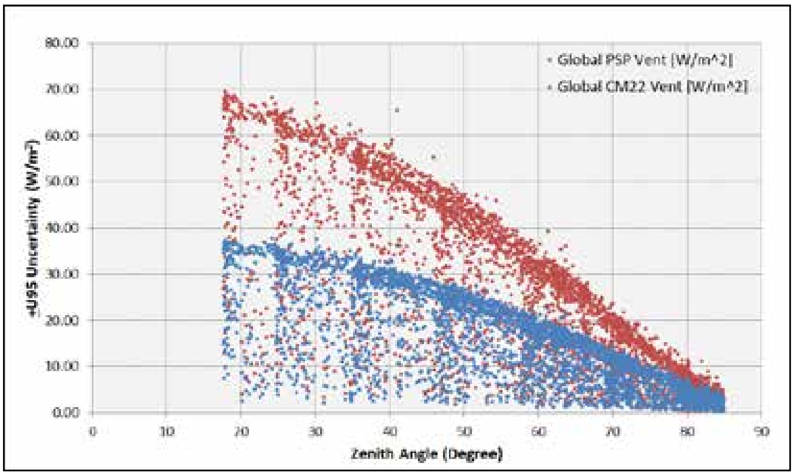


Figure 1. Absolute uncertainty for hourly GHI sums over a one-year period measured with a ventilated Eppley PSP or Kipp & Zonen CM22

Source: NREL, http://www.nrel.gov/midc/radiometer_uncert.xlsx

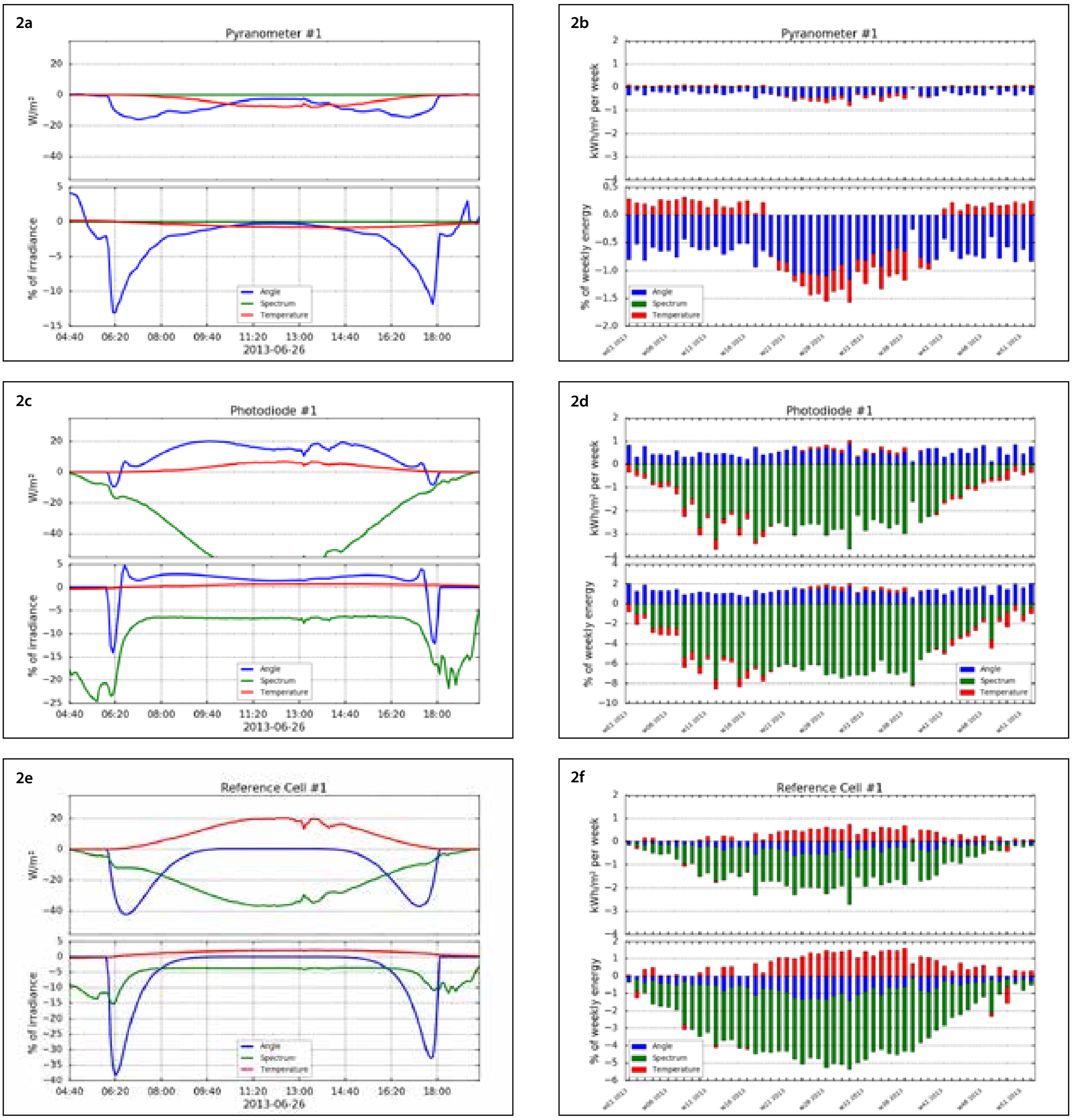
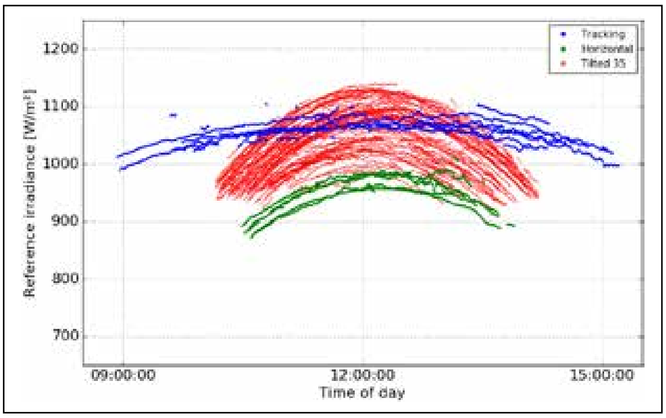


Figure 2. Daily and annual profiles of the measurement error caused by angle-of-incidence, spectrum and temperature for a thermopile pyranometer, photodiode pyranometer and a reference cell located in Golden Colorado, tilted 40° south

tate comparison; the bottom half of each diagram has a relative scale that is adapted to each instrument's data range. We are not (yet) able to calculate the systematic spectral error for thermopile pyranometer measurements, so this is not shown. Finally, the error bars that reach above and below zero cancel out partially, so the combined errors are sometimes smaller than might appear at first glance from the coloured area.

In this scenario we can see that the spectral response contributes the largest portion of the measurement error for the photodiode, whereas the reference cell—which is not intended to have a flat spectral response—actually comes closer to the pyranometer ideal. In terms of angular response, both the thermopile and photodiode pyranometers show a fairly uniform bias throughout the year whereas the reference cell's deviations are seasonal as they would be for a PV module. The errors caused by operating temperature are seasonal in all cases, but when the photovoltaic devices have a positive error, the thermopile has a negative error and vice versa. The larger temperature errors for the reference cell would usually be corrected inside the device or in the data logger using a separate temperature measurement.

There are some assumptions inherent in these calculations and illustrations. It is assumed that the directional error is zero when the sun is perpendicular to the instrument; that the temperature error is zero at 25 degrees Celsius; and that the spectral error is zero under AM1.5g spectral irradiance. These assumptions don't necessarily hold true because systematic biases are sometimes compensated for in the calibration. The pyranometer in Figure 2, for example, consistently has a negative directional error because the sun is rarely positioned perpendicular to it. If the calibration factor is determined for a 45-degree angle of incidence, as is sometimes done, much of this bias could be removed. To completely remove the bias, however, one would need a site and installation-specific calibration. Clearly a site and installation-specific *calculation* would be much more cost-effective!



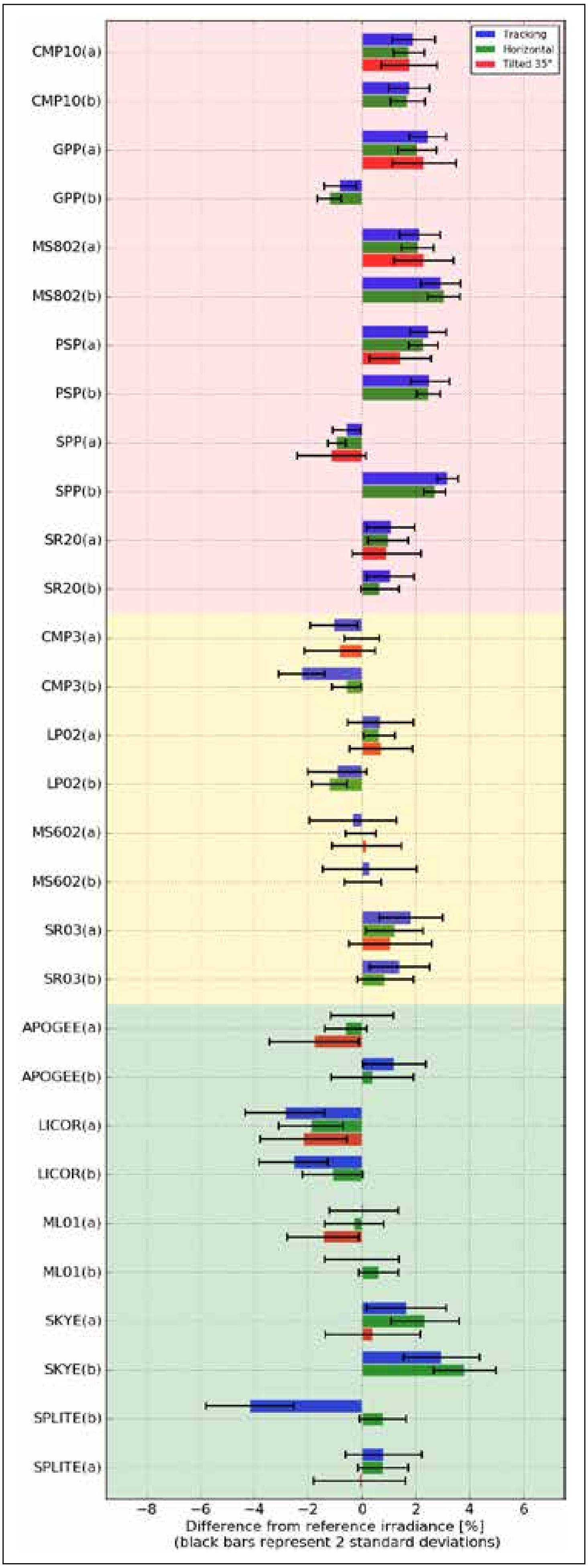
▲ **Figure 3. Clear-sky reference irradiance measured at Sandia in three orientations over multiple days. These conditions form the basis for the comparisons in Figures 4 and 5.**

Comparison of instruments under clear conditions

Outdoor calibration procedures require stable conditions with bright sun and clear skies to determine an instrument's calibration factor, also called responsivity. It stands to reason that if we compare the readings of several instruments under such conditions, they should agree within a small margin of error. Our outdoor measurements at Sandia provided ample sunny periods where we could compare each instrument's output with the others and also with the on-site reference instruments. From the available data we selected three subsets: instruments tracking the sun, instruments horizontal and instruments tilted 35° toward the south, with a total of between 80,000 and 100,000 points per sensor from multiple days in each subset. (See Figure 3.)

Using the manufacturer-supplied calibration factors we calculated each instrument's irradiance readings and the differences from our reference values. Figures 4 and 5 show the mean differences for each instrument and data subset. We also plot the standard deviation x 2 as an indicator of the spread of the values. The most important quality of the instruments is consistency—that is, they should have similar mean deviations in the three data subsets and low standard deviations. It is quite clear in Figure 4 that the second-class and photodiode pyranometers have more variability in their readings than the secondary standard instruments.

If the mean deviations are near zero that means the manufacturer's calibration agrees with our reference instruments. In Figure 4 we see that most of the secondary standard instruments have a positive bias, raising the possibility that our reference instruments themselves have a negative bias. For the reference cells in Figure 5 there is an almost universal negative bias on the outdoor tests but the indoor flash tests have more positive values across the board. These tests were done on different



▶ **Figure 4. Clear-sky irradiance measured with 20 thermopile and 10 photodiode pyranometers compared to reference values calculated from separate direct and diffuse measurements** continents with different reference instruments—but also using different methods. The bottom line is that calibration factors should not be taken for granted. Our measurements have their own inherent uncertainties, but if we were able to detect these biases—both systematic ones and outliers—then perhaps it's also possible to reduce or eliminate them.

Best practices for obtaining accurate irradiance measurements

Irradiance sensors are the heart of an irradiance measurement system, and understanding their detailed characteristics can help in both the initial instrument selection process and the later data processing and uncertainty analysis tasks. But there are many more aspects to measurement system design and operation that affect accuracy. Some important ways to maximise accuracy are:

- All components in the measurement chain contribute to the overall uncertainty, so ensure that all data acquisition equipment accuracy exceeds sensor accuracy by a factor of 10.
- Irradiance can change rapidly, so ensure that readings are taken at intervals shorter than the sensor response time for thermopile pyranometers; and not longer than one second for PV sensors. Less frequent readings lead to lower accuracy in average values.
- Ensure that sensors are installed with the correct slope and orientation for the PV system. It is not always clear what those angles should be, for example design when and build differ slightly, but some target should be set and confirmed.
- Sensor surfaces will accumulate varying degrees of snow, ice, frost, dew, dust, dirt and other substances that can cause periodic measurement errors far in excess of any listed on the spec sheets. Ventilation and heating options can reduce these problems significantly, but periodic cleaning and inspection/maintenance schedules must be adapted to the local conditions.
- Things can and do go wrong, so add redundancy to the system with multiple sensors, data loggers, communication links and/or power supplies. Even if it is not possible to continue measuring in all cases, it is important to be able to detect problems or failures and flag suspect measurements.
- Irradiance instruments need periodic calibration. The longer the interval between calibrations, the greater the measurement uncertainty. Redundant instruments that are sent for calibration on an alternating schedule are a great way to ensure continuity in data and maximise accuracy.

All the above measures will contribute very substantially to irradiance data accuracy—but none of this matters if it is not documented. Records about specifications, design, installation, operation, inspections, calibrations, maintenance and repairs all flow into the calculation of uncertainty estimates and are tangible evidence that bolster confidence in the data.

Conclusion

Measuring irradiance accurately in PV plants is absolutely necessary, but not easy. A broad range of instruments are commercially available, which have more subtle differences than are possible to infer from the manufacturers' specifications. There is still room for improvement and the good news is that the growth in the PV market has spurred on product development and many manufacturers have introduced new or improved products in the two years since the PVSENSOR study began. Innovations that improve not only basic accuracy, but also maintainability, calibration and data availability are all helping to produce more accurate irradiance data sets and PV plant performance assessments.

The related challenge of determining the level of accuracy (or uncertainty) of irradiance measurements will not recede with more accurate instruments or other innovations. On the contrary, we need to quantify the improvements in accuracy in order to justify the investments in new instruments or procedures. Thus there is a clear need and opportunity for the PVSENSOR project to develop into a continuous testing and evaluation activity.

Understanding systematic errors and the influence of the operating environment on instrument readings is crucial to making the most of past, present and future irradiance data sets. With site- and situation-specific data analysis we can reduce uncertanties not only on irradiance values but also on important PV plant performance indicators. Currently this type of analysis requires considerable effort, but as we streamline the processing this will become our standard practice for assessments of PV plant data for our clients. ■

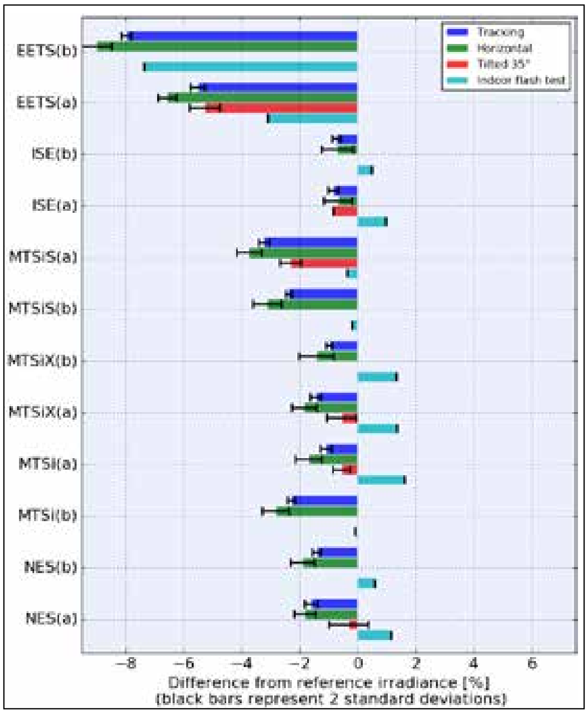


Figure 5. Clear-sky irradiance measured with 12 silicon reference cells compared to reference values determined by a WPVS reference cell. Indoor flash test results also shown for reference

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