The Baseline Performance Reference for Irradiance in PV System Applications

Anton Driesse,[1] Aron Habte,[2] and Manajit Sengupta[3]

1 PV Performance Labs

2 National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5D00-86847
September 2023

The Baseline Performance Reference for Irradiance in PV System Applications

Anton Driesse,[1] Aron Habte,[2] and Manajit Sengupta[2]

1 PV Performance Labs
2 National Renewable Energy Laboratory

Suggested Citation
Driesse, Anton, Aron Habte, and Manajit Sengupta. 2023. *The Baseline Performance Reference for Irradiance in PV System Applications*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5D00-86847. https://www.nrel.gov/docs/fy23osti/86847.pdf.

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5D00-86847
September 2023

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

NOTICE

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

U.S. Department of Energy (DOE) reports produced after 1991 and a growing number of pre-1991 documents are available free via www.OSTI.gov.

Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

NREL prints on paper that contains recycled content.

Acknowledgments

We are grateful to the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office subprogram for supporting this project. Specifically, we acknowledge Dr. Tassos Golnas and Dr. Lenny Tinker for their support and encouragement. We appreciate the communication support provided by Katie Wensuc with the National Renewable Energy Laboratory. We also thank the reviewers Dr. Sarah Kurtz with the University of California Merced School of Engineering, Dr. Michael Gostein with Atonometrics Inc., and Dr. Chris Deline from the National Renewable Energy Laboratory.

List of Acronyms

AOI	angle of incidence
BPR	baseline performance reference
IAM	incidence angle modifier
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
NREL	National Renewable Energy Laboratory
NSRDB	National Solar Radiation Database
POA	plane of array
PV	photovoltaic
Si	silicon
SMM	spectral mismatch
WPVS	World Photovoltaic Scale
WRR	World Radiometric Reference

Executive Summary

This report proposes the definition of a new *baseline performance reference* (BPR). The definition goes beyond existing standards pertaining to photovoltaic (PV) reference cells and devices to define the response under all possible operating conditions in the field. Field evaluations using BPR devices will be more sensitive to performance anomalies than pyranometers because they track PV system power output more closely. At the same time, they will be able to detect a broader range of performance anomalies than traditional matched reference devices, which might have matching defects. The BPR definition also opens the door to new practices in resource assessment and yield prediction. Solar resource data can be collected or modeled and validated directly as BPR irradiance, and PV system simulations based on BPR irradiance need fewer assumptions and less processing to obtain the effective irradiance on modules. As a result, lower uncertainty in yield assessments can be expected.

Table of Contents

List of Figures

List of Tables

1 Introduction

Photovoltaic (PV) cells (and therefore modules and arrays) respond in a complex manner to the many variables that define their operating environment. Irradiance has spectral and spatial dimensions that interact with the spectral-directional response of cells, which, in turn, is influenced by cell operating temperature. Many of these effects are fundamental in nature, but they can be adjusted by material choices and design or manufacturing parameters to optimize power or energy ratings, which leads to substantial variety in commercial device characteristics.

PV reference cells for irradiance measurement are not fundamentally different from other PV cells, but in their role as reference devices, it is important to distinguish between the characteristics of operational PV modules they should share and those they should not. If a reference device shares *all* the normal characteristics of an operational module, then it can be an excellent tool for detecting faults in such a module. But it is less useful for detecting faults in other module types or for comparing performance with other module types that are evaluated with different matching reference cells. A more neutral common reference device is needed for such tasks.

Pyranometers are well-defined reference devices for irradiance measurement and can be considered neutral because their characteristics are defined in a standard unrelated to PV technology; however, the relationship between broadband hemispherical irradiance measured by pyranometers and the magnitude of light-generated current in PV devices is complex. For this reason, performance indicators based on pyranometers strongly fluctuate. In fact, important differences in performance between PV modules can be masked by such fluctuations, especially when comparing measurements from different time periods or different locations.

What is needed, then, is a well-defined generic PV reference cell whose characteristics are close enough to the majority of operational PV devices to make stable performance indicators possible but whose characteristics are not necessarily identical to any one of them.

Figure 1 illustrates the essence of this idea using relative distances to indicate magnitudes of differences. The blue flag represents the well-defined broadband hemispherical irradiance reference quantity. High-quality pyranometers are clustered very near this flag, whereas lower-quality instruments and photodiode pyranometers stray somewhat farther afield. The family of PV devices on the right is a considerable distance away. The present proposal plants a new flag on the right to serve as a new well-defined reference quantity for outdoor PV measurements, which we call the *baseline performance reference* (BPR). This quantity to be measured, also known as the *measurand*, will be defined for all relevant operating conditions. The initial definition is aimed at silicon PV technologies and might be referred to as BPR-Si to distinguish it from potential future variations aligned with other technologies.

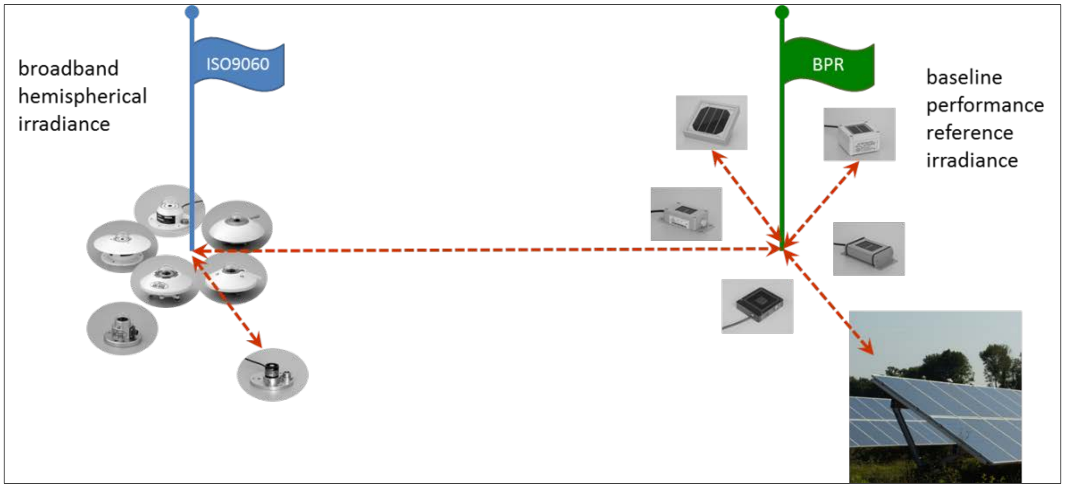

Figure 1. High-level view of the irradiance measurement landscape

The distances between devices represent the differences in operating characteristics. A well-defined broadband irradiance measurand on the left (blue flag) substantially differs from PV devices and the proposed BPR irradiance on the right (green flag).

Note that this proposal does not call into question the existence or usefulness of current PV reference devices that might be designed to match specific module types as well as possible. Instead, it recommends the definition of a generic reference cell type to serve a complementary role as a common baseline for performance comparisons. This will be particularly useful for outdoor measurements.

A key benefit of the BPR definition is that the measurand is completely defined under all operating conditions. This allows measurement error and measurement uncertainty in BPR measurements to be quantified, similar to what is done for pyranometer measurements.

Finally, the BPR definition opens the door to new practices in resource assessment and yield prediction. Solar resource data can be collected or modeled and validated directly as BPR irradiance rather than broadband irradiance, and subsequent PV system simulations based on BPR irradiance need fewer assumptions and less processing to obtain the effective irradiance on modules. As a result, lower uncertainty in yield assessments can be expected.

2 Existing Standards

Relevant existing standards fall into two categories: those that apply to PV reference cells and those that apply to broadband irradiance measurement devices.

2.1 ISO 9060

The International Standards for Organization (ISO) 9060 standard (ISO 2018) defines the ideal instrument characteristics that are important for consistent broadband irradiance measurements and sets thresholds for deviations from those characteristics to define several accuracy classes. All these characteristics are relevant for PV reference cells as well, but there are differences in the ideal responses (such as spectral and directional response) as well as in the practical challenges (such as the influence of tilt angle and temperature).

2.2 IEC 60904-2

International Electrotechnical Commission (IEC) 60904-2 (IEC 2015), titled "Photovoltaic Devices – Part 2: Requirements for Photovoltaic Reference Devices," is the primary source of requirements and recommendations for PV reference cells and reference modules for both indoor and outdoor use. It covers several physical and performance characteristics as well as calibration; however, it relies on a significant number of additional IEC standards to provide important details. The packaging descriptions are recommendations, not requirements, and there is no prescribed spectral or directional response.

2.3 WPVS

The definition of a World Photovoltaic Scale (WPVS) is detailed in Osterwald et al. (1999). Its main purpose is to improve worldwide calibration reproducibility and consistency with the broadband World Radiation Reference (WRR). To help achieve these goals, a very detailed physical package design was developed that is consistent with the IEC requirements but is much more detailed. It requires cell dimensions of 20 mm by 20 mm, for example. The main intended use is in a laboratory setting operating at or near reference conditions (AM1.5 and 25°C) rather than in all possible field conditions. The WPVS design was never formally adopted as an international standard but nevertheless is closely adhered to by products for laboratory use, and it can be considered a de facto standard.

2.4 ASTM E1040

ASTM E1040, "Standard Specification for Physical Characteristics of Non-concentrator Terrestrial Photovoltaic Reference Cells" (ASTM 2020), briefly describes two reference cell designs: The small-cell package design closely resembles the WPVS design, whereas the module package design more closely resembles a PV module design. This standard covers the physical package characteristics, not the performance characteristics.

2.5 Summary

In broad terms, the WPVS design is a subset of ASTM E1040, which, in turn, is a subset of IEC 60904-2; however, none of the three provide a complete set of operational characteristics in the manner of ISO 9060. The proposed BPR will be less prescriptive than the first three in terms of packaging and dimensions, but it will be more prescriptive in terms of performance characteristics in a manner similar to ISO 9060. Ideally, future BPR devices will satisfy all the requirements of IEC-60904-2 (although perhaps not all recommendations) and thus be considered legitimate reference devices under that standard as well.

3 Commercial Products

Reference cells can be divided into two categories: relatively inexpensive cells targeting the PV system monitoring market (the largest market and majority of products) and relatively expensive WPVS cells targeting test laboratories. A variety of commercial products—including a WPVS cell—are deployed at the Solar Radiation Research Laboratory test site at the National Renewable Energy Laboratory (NREL) (Figure 1).

Figure 2. Ten commercial reference cells under evaluation at NREL.

Multiple studies have been done over the years to compare commercial irradiance sensors, including reference cell products, for outdoor use (Zehner et al. 2009; Schulz et al. 2010; Driesse and Zaaiman 2015). Some observations emphasized in the most recent study at NREL (Driesse, Gotseff, and Sengupta 2022) are :

- Reference cell models substantially vary in packaging, which appears (in most cases) to be minimally guided by recommendations and requirements of the existing standards.
- Different models exhibit different performance characteristics, especially in the critical areas of directional and spectral response.
- Most manufacturers do not provide detailed performance characterizations as part of their documentation.

The lack of uniform behavior among models combined with a lack of information about that behavior add to the uncertainty in comparative performance measurements and undermine the products' applicability in solar resource assessment. At worst, this can lead to biased conclusions about the short- and long-term performance of PV modules and systems.

4 Baseline Performance Reference Definition

This section describes the ideal characteristics of BPR devices (in other words, the definition of the BPR measurand) as well as the information that must be supplied by their manufacturers about the products' ability to meet those ideal targets. Reasonable limits for deviations from the ideal are suggested for some characteristics, whereas recommendations for others still need to be developed in future work. Less stringent limits could be set in the future to create lower accuracy classes akin to those used for pyranometers.

BPR devices can make use of hardware or software to make corrections to the raw output signal and improve compliance with the ideal characteristics.

The relevant characteristics are divided into two categories: those that are shared with pyranometers and those that are different.

4.1 Characteristics Shared With Pyranometers

4.1.1 Response Time

Response time characterizes the delay between a change in irradiance and a corresponding change in output signal. The ideal BPR responds instantaneously.

For pyranometers, the response time is defined as the time taken for the output signal to reach 95% of its final value after a step change in irradiance from zero, which can be as long as 30 s for Class C instruments. Pyranometers having response times shorter than 0.5 s are called "fast response" pyranometers (ISO 2018).

PV cell current changes nearly instantaneously in response to changes in irradiance, and thus for outdoor operation, this natural response time is adequate; however, integrated analog and/or electronics can delay output signals, and therefore the response time must be evaluated and reported for BPR devices. The definition of response time in ISO 9060 is adequate for this purpose, and a reasonable limit for BPR devices would be to meet the fast response pyranometer target of 95% in 0.5 s.

4.1.2 Zero Offset

A nonzero output signal in the absence of irradiance is called a zero offset. The ideal BPR has a zero offset of zero.

A PV cell does not generate current in the absence of irradiance, which means that its zero offset is naturally zero; however, integrated electronics can produce a zero offset, and therefore this must be evaluated and reported for BPR devices. A reasonable limit for BPR devices would be ±1 W/m^2, which is one order of magnitude better than the Class A pyranometer requirement.

4.1.3 Stability

The characteristics of the ideal BPR do not change over time.

If any changes occur in a BPR device over time, they will likely affect the calibration factor; therefore, the long-term stability of the calibration factor must be evaluated and reported for BPR devices. A reasonable limit for BPR devices would be a maximum change in the calibration factor of ±0.5% per year under field operating conditions.

4.1.4 Linearity

The ideal BPR output signal varies linearly with irradiance from zero to the highest possible irradiance level. (The proportionality constant is the calibration factor or responsivity.)

IEC 90604-2 defers to IEC90604-10 (IEC 2020) for linearity measurements and requirements for PV reference devices. Both IEC 60904-10 and ISO 9060 quantify the nonlinearity at a certain irradiance level, G, as the difference between the observed responsivity at G and the responsivity at a reference condition, G_{ref}. ISO 9060 sets the reference condition at 500 W/m^2, whereas IEC 60904-10 sets the reference condition at the calibration condition, which is usually 1,000 W/m^2. The range of irradiance levels over which the linearity is assessed is 100–1,000 W/m^2 in ISO 9060 but is left unspecified in the IEC standard.

A reasonable target for BPR devices would be a maximum deviation of 0.5% or 1 W/m^2 over the irradiance range from 0–1,000 W/m^2, using the irradiance at calibration for reference. The value 0.5% corresponds to the ISO 9060 Class A pyranometer requirement as well as the IEC 60904-10 short-circuit linearity threshold, and the value 1 W/m^2 corresponds to the suggested maximum allowable zero offset for the BPR, which will dominate at low irradiance levels.

4.1.5 Tilt Response

The ideal BPR output signal is not affected by orientation.

The responsivity of a thermopile pyranometer can change when the instrument is tilted away from a horizontal position due to changes in internal convection. There is no obvious mechanism for the responsivity of PV devices to be influenced by tilt. Nevertheless, for completeness, the BPR device manufacturer must consider this possibility and document the tilt response for BPR devices.

4.2 Characteristics Differing From Pyranometers

4.2.1 Directional Response

The ideal directional response of a pyranometer is that of a flat, black surface that absorbs all radiation and reflects none. For this receiver surface, the ratio of the measured irradiance to the incident irradiance is equal to the cosine of the angle of incidence (AOI), which is the reason directional response is often referred to as *cosine response*. Although this ideal cosine response would be an excellent directional response for PV modules as well, it cannot be achieved in actual flat-plate modules due to both internal and external reflections. This leads to substantial discrepancy between the irradiance measured by pyranometers and the irradiance that reaches PV cells within modules, especially at high incidence angles.

The existing standards pertaining to PV reference cells and their use recommend using similar or identical materials and package designs to achieve directional responses that match the PV modules whose performances are being measured; however, the precise directional response is neither prescribed nor required to be measured or reported, and there is no metric to evaluate similarity.

Because the BPR serves as a generic reference, its directional response should not replicate that of a specific module, but it should be independently defined. Some options for the definition are: (1) an average of many measured module responses, (2) an empirical model based on such measured responses, or (3) a physical model of a simple PV module construction. To avoid reliance on physical devices and measurements, either directly or indirectly, we chose a simple physical model option that considers only the external reflection at the air-glass interface using uncoated glass with an index of refraction of 1.5 independent of wavelength. The reflectance, ρ, is calculated as a function of the AOI using the well-known Fresnel equations (Duffie and Beckman 2006, Chapter 5) and converted to the normalized incidence angle modifier (IAM), which is the ratio between the actual directional response and the ideal cosine response:

$$IAM(AOI) = \frac{1 - \rho(AOI)}{1 - \rho(0°)}$$

The IAM for the BPR is shown in Figure 3. The chosen definition brings the ideal BPR directional response much closer than pyranometers to the directional response of flat-plate PV modules while remaining independent of specific module materials, designs, and constructions.

The directional response of future BPR devices should be measured and reported at angles from 0° to 95° at 5° intervals. To identify potential rotational asymmetries, the measurements must be repeated after rotating the BPR device around the axis normal to its receiving surface in the following increments: +45°, +45°, +90°, +90°. Reasonable targets for the maximum deviation from the ideal BPR directional response will be defined in future work.

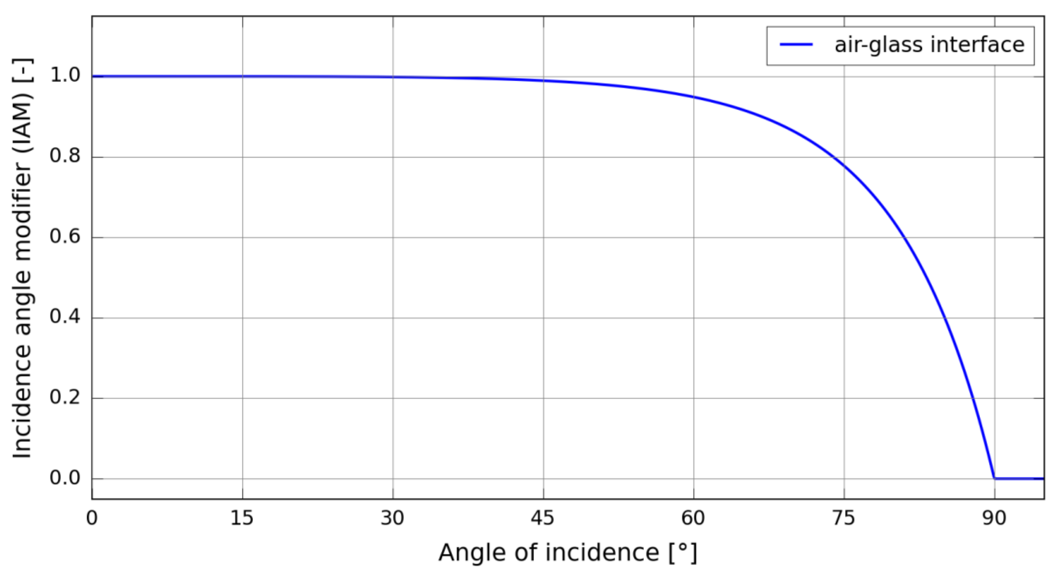

Figure 3. IAM of the air-glass interface that defines the BPR directional response

4.2.2 Temperature Response

The responsivity of the ideal BPR does not change in response to changes in operating temperature or ambient temperature.

Both the thermopile voltage of pyranometers and the short-circuit current of PV reference devices are influenced by operating temperature, and in both cases, a correction is needed to reduce or eliminate the temperature dependency and obtain more accurate irradiance measurements; however, the underlying causes, resulting characteristics, and correction methods are very different for the two instrument types. In PV cells, an increase in temperature leads to a reduction in the bandgap energy and a widening of the spectral response curve toward longer wavelengths. The resulting change in short-circuit current depends on the spectrum of the incident light in the region of the bandgap. A nominal linear temperature coefficient of the short-circuit current is usually determined at or for reference conditions (AM1.5 spectrum, 25°C), but in field conditions, the apparent coefficient will vary with both the operating temperature and the spectral irradiance. There could be additional effects of operating temperature on shunt resistors or built-in electronics.

Note that the effect of temperature dependencies on the output signal can be mitigated by means of corrections or by reducing the fluctuations in operating temperature. In the extreme case, built-in heating and cooling can maintain a constant operating temperature and completely eliminate the need for corrections.

The manufacturer of BPR devices must provide both expected operating temperatures and their effect on responsivity for a range of operating conditions, including different ambient temperatures as well as irradiance conditions. More precise guidelines for thresholds and reporting need to be developed in future work.

4.2.3 Spectral Response

Spectral response represents the most fundamental difference between pyranometers and PV devices because it relates to the semiconductor properties of the PV device. Although most thermopile pyranometers absorb irradiance quite uniformly between roughly 300 and 3,000 nm, limited mostly by the glass dome transmittance, the response of PV devices is nonuniform and covers a much smaller wavelength range. It is also clear from the set of spectral response curves shown in Figure 4 that there is substantial variation in spectral response among similar PV devices, primarily in the ultraviolet region, from 300–400 nm, and in the infrared region, from 1,000–1,200 nm.

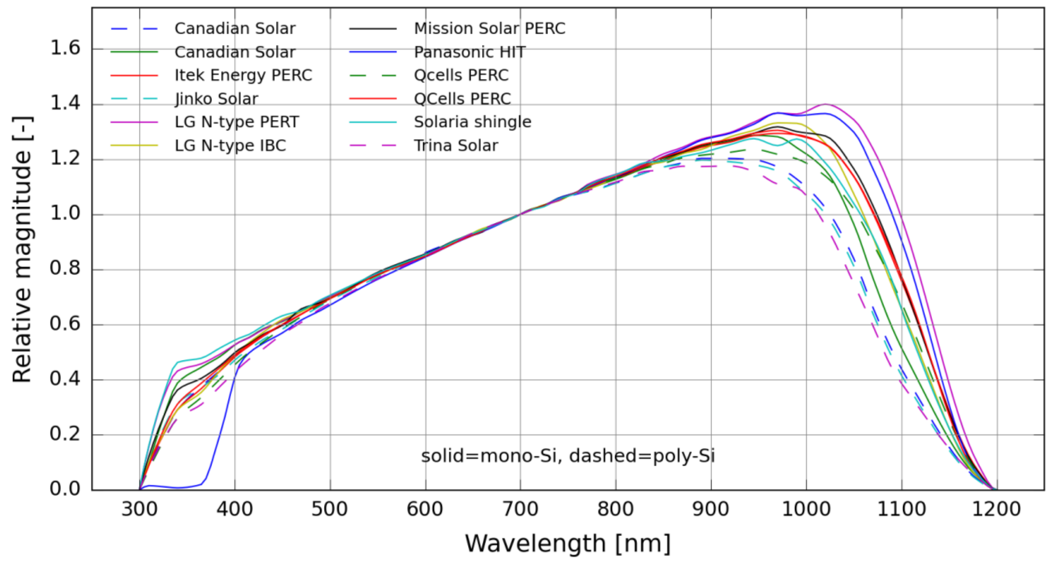

Figure 4. Spectral responses of a variety of commercial PV modules measured at NREL on behalf of Sandia National Laboratories (Driesse, Theristis, and Stein 2023)

In laboratory settings, these spectral response curves can be measured, and together with the measured spectral irradiance, spectral mismatch (SMM) factors can be calculated to make meaningful comparisons between devices. In field applications, however, this much information is typically not available—the spectral response curves shown here are not published by the manufacturers, and field spectral irradiance measurements are (still) rare and costly. Uncertainty about the actual SMM between modules and reference cells at any point in time therefore adds to uncertainty in performance evaluations and comparisons, especially when different module types, reference device types, or geographic locations are involved. Even the magnitude of this uncertainty is difficult to assess.

Existing standards for reference cells do not prescribe a specific spectral response but recommend the use of matched devices to minimize SMM. Given the range of responses in commercial devices (not to mention the lack of published data), this seems difficult to achieve in field applications. But it also has the disadvantage that field comparisons between multiple PV systems having different spectral responses, each evaluated using matching reference cells, provide an incomplete picture of the relative performance. For these reasons, we recommend that a single spectral response curve be designated for the BPR.

As for directional response, it does not matter which spectral response is chosen for the BPR as long as it is well-defined and substantially closer to the typical PV module response than the pyranometer response. Some options are: an average of measured module responses; or a realistic modeled response produced by cell simulation software; or something that might be less realistic but easier to describe. We recommend the latter option, and we chose a definition inspired by Appendix 3 of IEC-60904-9. This standard describes a prototypical spectral response composed of straight line segments: Between 400 and 1,000 nm, the spectral response is ideal, which means the quantum efficiency is 1.0; beyond 300 or 1,200 nm, the response is zero; and in the transition regions, the spectral response increases or decreases linearly. This is depicted by the dashed blue line in Figure 5. The BPR spectral response is based on the same transition wavelengths but makes smooth rather than abrupt transitions. To create the BPR spectral response, the upper- and lower-limit wavelengths are shifted by 25 nm to 1,175 and 325, respectively (shown in red in Figure 5), and a moving average filter of width 50 nm is applied to produce the black curve in Figure 5. Figure 6 and Figure 7 show the BPR spectral response along with the measured spectral responses for a set of reference cells for outdoor use and a set of PV modules.

The BPR spectral response is idealized in other ways as well: It does not change with temperature or with AOI. The reason for this is to be able to make it possible to observe the performance differences that result when the spectral responses of PV modules exhibit these effects.

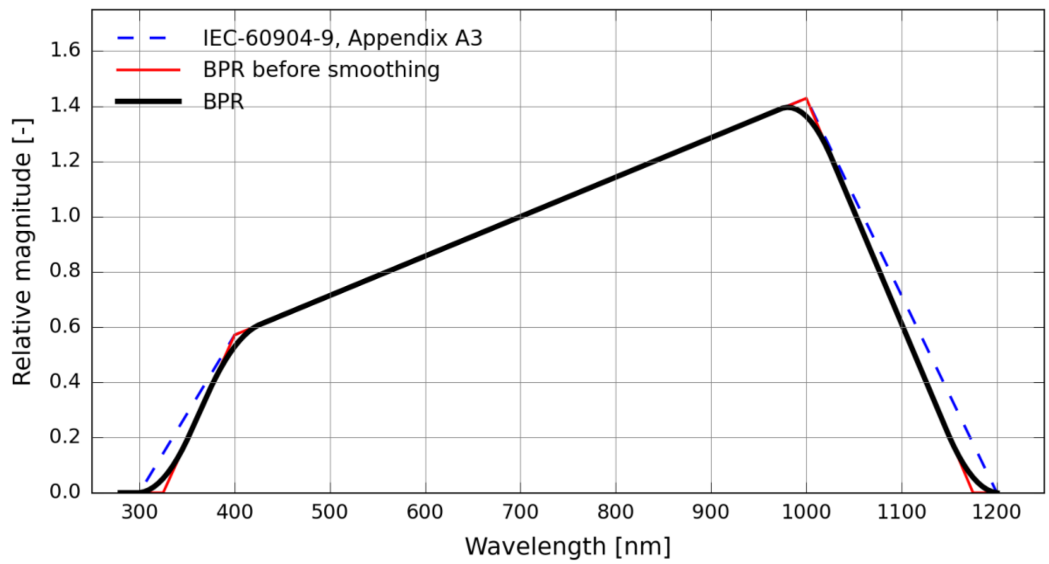

Figure 5. Construction of the idealized BPR spectral response

The quadrilateral form of IEC-60904-9 (dashed blue) has its endpoints shifted (red), and a moving average filter is applied (black).

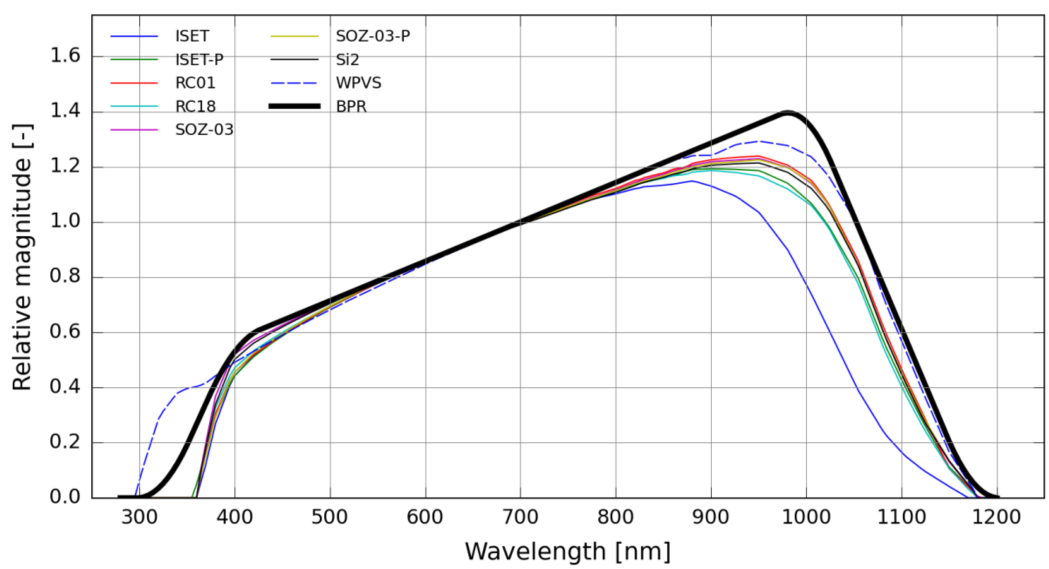

Figure 6. The idealized BPR spectral response shown in relation to commercial reference cells

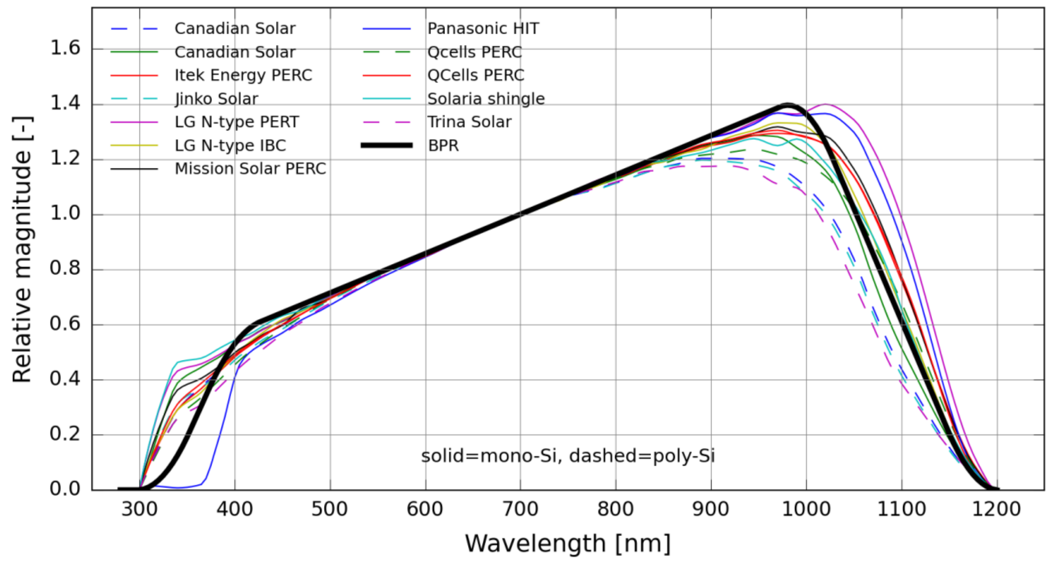

Figure 7. The idealized BPR spectral response shown in relation to commercial PV modules

Assessing how well a BPR device conforms to the prescribed BPR spectral response is done indirectly by comparing SMM values rather than curve shapes. ISO 9060 provides a set of simulated spectra representing a range of atmospheric conditions and sun positions for the purpose of calculating the spectral error of pyranometers. The global horizontal, diffuse horizontal, and direct normal irradiance are provided separately for a total of 54 spectra. These 54 spectra can be used to calculate 54 SMM values between a BPR device and the idealized response, which, in turn, can be used to assess the level of similarity or compliance.

Figure 8 and Figure 9 show the means and standard deviations of pairwise SMM percentage errors between all the reference devices shown in Figure 6 and the PV modules shown in Figure 7. A positive mean value means that the PV module output will be higher than predicted using the irradiance reported by the corresponding reference device. Many observations could be made about the individual products, but here we make only a few general ones because the objective is to illustrate the principle. There is a clearly apparent bias ranging from 0.3%–0.6% between the majority of the reference cells and the majority of the PV modules, whereas the WPVS cell and the BPR deviate by less than 0.3% with respect to most PV modules. The standard deviation cannot be ignored because the module/cell combination with the highest standard deviation (5.22%) actually has a mean bias near zero (0.01%).

We propose, therefore, that the degree of conformity of the BPR products' spectral response be evaluated based on the mean (μ) and standard deviation (σ) of the SMM errors calculated using the 54 spectra published with ISO 9060:2018. Suitable targets for these will be developed in future work.

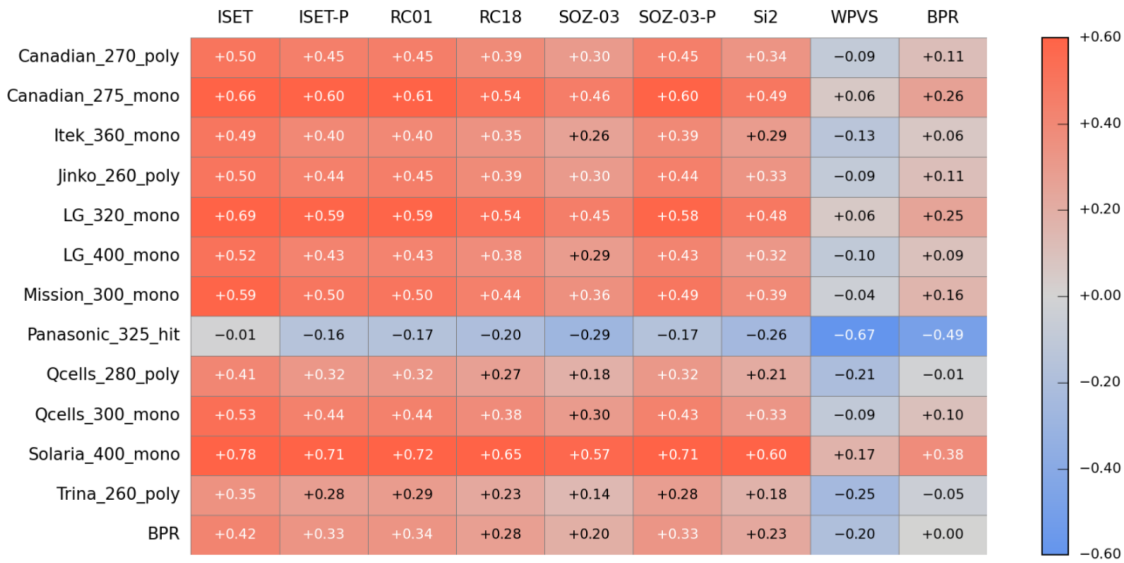

Figure 8. Mean SMM errors in percent for combinations of reference cells and PV modules

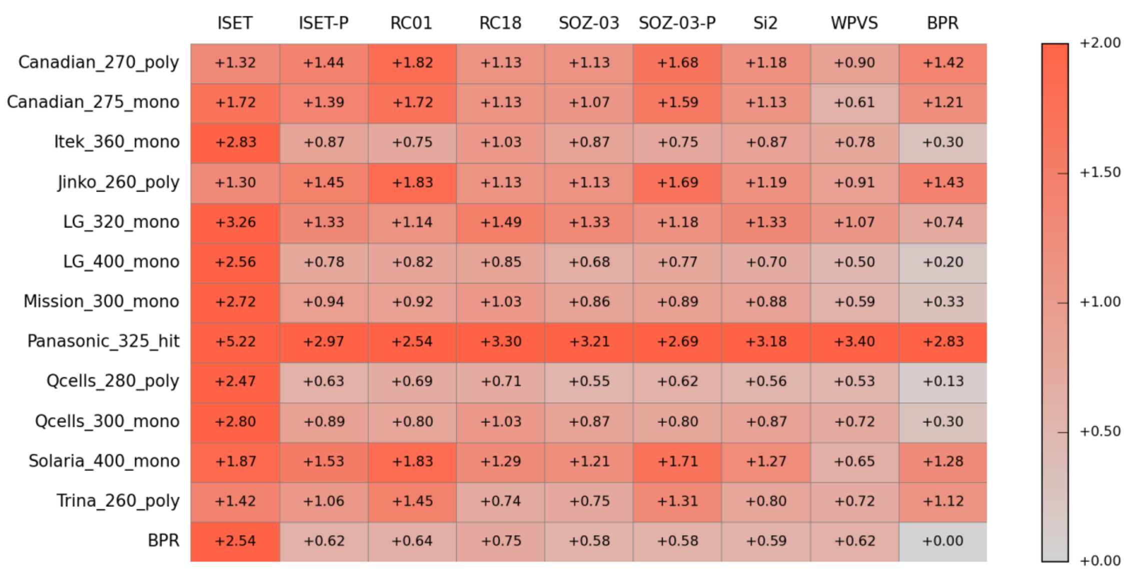

Figure 9. Standard deviations of SMM errors in percent for combinations of reference cells and PV modules

4.2.4 Summary

The three main characteristics that distinguish PV reference devices from pyranometers are summarized in Table 1. Requirements of the existing standards pertaining to reference cells are listed for comparison.

Table 1. Key Differences Between Reference Device Requirements

	ISO 9060	IEC 60904-2	ASTM E1040	WPVS	BPR
Directional response	Lambertian	Incompletely specified by physical package constraints			One air-glass interface
Temperature response	Flat	Linear correction	Linear correction	Operation at 25°C	Flat
Spectral response	Flat	Matched to the device under test			Simple idealization

4.3 Calibration and Traceability

The responsivity of the BPR reference cells is determined using existing requirements and methods, as described in IEC 60904-2, based on the AM1.5g spectrum, 25°C operating temperature, and 0° AOI. The new BPR goes beyond this to specify how the responsivity must change with spectrum and AOI.

4.4 Packaging

As long as the performance requirements can be met, there is no need for separate packaging requirements. It is likely that some of the performance requirements will lead to some common design choices by manufacturers, but they could also lead to creative new packaging design ideas. But it is not only performance requirements themselves that will drive designs—it is also the need to *measure* those performance characteristics. If a cell is mounted in or on an air-filled enclosure, for example, it becomes more difficult to run a test to measure the temperature response. Creative solutions can be found for testing as well, such as offering an alternate package specifically for that purpose.

4.5 Integrated Electronics

Scientific and laboratory users most often measure raw reference cell output as an analog current or voltage. Industrial users tend to prefer products with built-in analog-to-digital conversion and a digital connection to their monitoring systems. Ideally, such electronics do not change the overall performance characteristics of the reference cell, but in practice there could be an additional offset, nonlinearity, response time, temperature dependency, long-term drift, or other new effect, such as influence of power supply voltage. Similar to certain packaging choices, the electronics could also make some tests more difficult to carry out—for example, the response time could be too slow for tests using a light impulse (flash tester). All BPR requirements apply to the overall behavior, including electronics.

4.6 Device Testing

A comprehensive discussion about testing needed to verify and document BPR performance is beyond the scope of this document; however, to assuage potential concerns about the number of required measurements, note that many characteristics only need to be evaluated on representative samples of BPR products as long as product consistency can be demonstrated. Also, given the naturally fast response time of PV cells, many tests could be carried out more quickly than the corresponding tests for thermopile pyranometers.

5 Summary and Conclusions

In this report, we propose the definition of a new *baseline performance reference*, BPR. The definition goes beyond existing standards pertaining to PV reference cells and devices to define the response under all possible operating conditions in the field. With the measurand thus completely defined, it becomes possible to evaluate measurement error and measurement uncertainty. BPR devices are not *matched* reference devices—that is, their characteristics are not chosen to match specific PV modules. Rather, their characteristics match a generic, partly idealized PV module behavior.

Field evaluations using BPR devices will be more sensitive to performance anomalies than pyranometers because they track PV system power output more closely. At the same time, they will be able to detect a broader range of performance anomalies than traditional matched reference devices, which might have matching defects.

The BPR definition also opens the door to new practices in resource assessment and yield prediction. Solar resource data can be collected or modeled and validated directly as BPR irradiance, and PV system simulations based on BPR irradiance need fewer assumptions and less processing to obtain the effective irradiance on modules. As a result, lower uncertainty in yield assessments can be expected.

As with any standardization, whether formal or informal, consensus and support are needed on the way to widespread use. This report takes a first step by documenting the BPR in detail. In future work we will examine how this generic non-matched reference relates to various PV module technologies using field-measured as well as simulated spectral irradiance. In parallel, the BPR will be implemented in the National Solar Radiation Database (NSRDB) so that it becomes available for lead users active in solar resource assessment and yield prediction.

References

ASTM. 2020. “ASTM E1040-10 Specification for Physical Characteristics of Nonconcentrator Terrestrial Photovoltaic Reference Cells.” ASTM International. https://doi.org/10.1520/E1040-10R20.

Driesse, Anton, Peter Gotseff, and Manajit Sengupta. 2022. “PV Reference Cells for Outdoor Use: Comparison of First-Year Field Measurements.” NREL/SR-5D00-82086, 1866986, MainId:82859. https://doi.org/10.2172/1866986.

Driesse, Anton, Marios Theristis, and Joshua Stein. 2023. “Global Horizontal Spectral Irradiance and Module Spectral Response Measurements: An Open Dataset for PV Research.” SAND2023-02045. Albuquerque: Sandia National Labs.

Driesse, Anton, and Wim Zaaiman. 2015. “Characterization of Global Irradiance Sensors for Use with PV Systems.” In *2015 IEEE 42nd Photovoltaic Specialist Conference (PVSC)*, 1–5. New Orleans, LA: IEEE. https://doi.org/10.1109/PVSC.2015.7356004.

Duffie, John A., and William A. Beckman. 2006. *Solar Engineering of Thermal Processes*. 3rd ed. Hoboken, N.J: Wiley.

IEC. 2015. “IEC 60904-2: Photovoltaic Devices – Part 2: Requirements for Photovoltaic Reference Devices.” Third edition. Geneva: IEC.

———. 2020. “IEC 60904-10: Photovoltaic Devices – Part 9: Methods of Linear Dependence and Linearity Measurements.” Third edition. Geneva: IEC.

ISO. 2018. “ISO 9060:2018 Solar Energy — Specification and Classification of Instruments for Measuring Hemispherical Solar and Direct Solar Radiation.” International Standard. Geneva: ISO.

Osterwald, C. R., S. Anevsky, K. Bücher, A. K. Barua, P. Chaudhuri, J. Dubard, K. Emery, et al. 1999. “The World Photovoltaic Scale: An International Reference Cell Calibration Program.” *Progress in Photovoltaics: Research and Applications* 7 (4): 287–97. https://doi.org/10.1002/(SICI)1099-159X(199907/08)7:4<287::AID-PIP259>3.0.CO;2-I.

Schulz, B., T. Glotzbach, C. Vodermayer, G. Wotruba, M. Mayer, and S. Grünsteidl. 2010. “Evaluation of Calibrated Solar Cells and Pyranometers Regarding the Effective Irradiance Detected by PV Modules.” Application/pdf. *25th European Photovoltaic Solar Energy Conference and Exhibition / 5th World Conference on Photovoltaic Energy Conversion* 6-10 September 2010: 4 pages, 3349 kb. https://doi.org/10.4229/25THEUPVSEC2010-4BV.1.116.

Zehner, M., P. Fritze, M. Schlatterer, T. Glotzbach, B. Schulz, C. Vodermayer, M. Mayer, and G. Wotruba. 2009. “One Year Round Robin Testing of Irradiation Sensors - Measurement Results and Analyses.” Application/pdf. *24th European Photovoltaic Solar Energy Conference* 21-25 September 2009: 6 pages, 6185 kb. https://doi.org/10.4229/24THEUPVSEC2009-4BV.1.64.