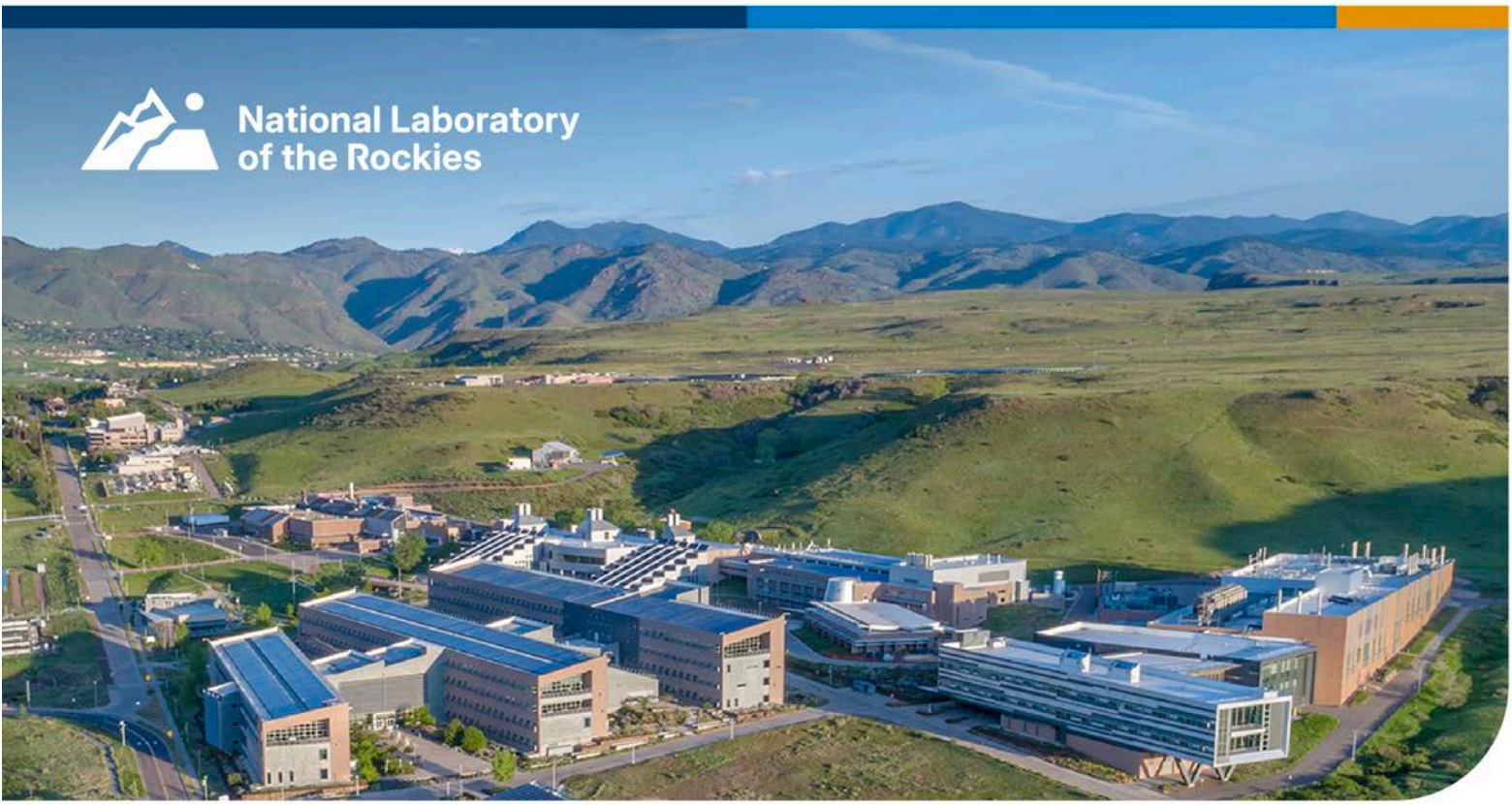

Solar Radiation Research Laboratory (SRRL) Core Project Final Report: Fiscal Years 2022–2024

Manajit Sengupta,[1] Aron Habte,[1] Yu Xie[1], Afshin Andreas,[1] Shawn Jaker,[1] Ibrahim Reda,[1] Jaemo Yang,[1] Christian Gueymard,[2] Tom Stoffel,[3] Steve Wilcox,[3] Anton Driesse,[4] Frank Vignola,[5*] and Josh Peterson[5]

1 National Laboratory of the Rockies
2 Solar Consulting Services
3 Solar Resource Solutions
4 PV Performance Labs
5 University of Oregon
** Deceased*

The National Laboratory of the Rockies is a national laboratory of the U.S. Department of Energy, Office of Critical Minerals and Energy Innovation, operated under Contract No. DE-AC36-08GO28308.

Technical Report
NLR/TP-5D00-98206
May 2026

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National Laboratory of the Rockies

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List of Acronyms

ACP	absolute cavity pyrgeometer
ARM	Atmospheric Radiation Measurement
BIRCAL	Broadband Indoor Radiometer Calibration
BMS	Baseline Measurement System
BORCAL	Broadband Outdoor Radiometer Calibration
BPR	baseline performance reference
BSRN	Baseline Surface Radiation Network
CRADA	cooperative research and development agreement
CSP	concentrating solar power
DHI	diffuse horizontal irradiance
DNI	direct normal irradiance
DOE	U.S. Department of Energy
ENA	Eastern North Atlantic
GHI	global horizontal irradiance
GUM	Guide to the Expression of Uncertainty in Measurement
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IPC	International Pyrheliometer Comparison
IPgC	International Pyrgeometer Intercomparison
IRIS	Infrared Integrating Sphere
ISO	International Organization for Standardization
KCG	Kennaook/Cape Grim, Tasmania, Australia
MIDC	Measurement and Instrumentation Data Center
NIST	National Institute of Standards and Technology
NLR	National Laboratory of the Rockies
NPC	National Laboratory of the Rockies Pyrheliometer Comparisons
NSA	North Slope of Alaska (NSA)
NSRDB	National Solar Radiation Database
PMOD	Physical Meteorological Observatory in Davos
PV	photovoltaic
PVPS	Photovoltaic Power Systems Programme
R&D	research and development
RMS	Research Measurement System
SAM	System Advisor Model
SCL	Spectral Calibration Laboratory
SGP	Southern Great Plains
SMARTS	Simple Model of the Atmospheric Radiative Transfer of Sunshine
SRRL	The Solar Radiation Research Laboratory
SUNI	Solar Uncertainty Integrator
UV	ultraviolet
WMO	World Meteorological Organization
WRR	World Radiation Reference

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Executive Summary

The Solar Radiation Research Laboratory (SRRL) at the National Laboratory of the Rockies (NLR, formerly NREL) is a solar calibration and measurement facility that maintains and disseminates the World Radiation Reference (WRR) (essentially the $W \cdot m^{-2}$) for the United States, which is essential for traceable and accurate measurements of solar radiation at all solar generation facilities. The SRRL operates two calibration facilities that meet the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC) standards (ISO/IEC 17025) and provide unique high-quality radiometer calibrations to NLR and other U.S. Department of Energy laboratories. The Baseline Measurement System (BMS) at the SRRL provides a high-quality record of solar irradiance and surface meteorological conditions. SRRL capabilities are used to develop (1) improved methods for the calibration of solar radiometers; (2) new standards through the ISO, the IEC, and ASTM International; (3) solar radiation and meteorological models; and (4) advanced instrumentation and methods for operating solar measurement stations. The SRRL datasets are also critical for the validation of new models and datasets, such as the National Solar Radiation Database (NSRDB).

The research and development of solar radiation measurement systems and resource modeling techniques are essential for advancing the scientific basis for producing reliable resource data. Specifically, the spatial, temporal, and spectral (wavelength dependency) characteristics of the solar resource are required in several different time frames for various project phases and applications. This agreement has three tasks that conduct research on advancing solar resource measurements:

- Task 1: Applied solar radiation and measurement
- Task 2: Standards development and knowledge sharing
- Task 3: Development of state-of-the-art instrumentation and measurement techniques.

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1 Background

The Solar Radiation Research Laboratory (SRRL) at the National Laboratory of the Rockies (NLR, formerly NREL) is a solar radiometer calibration and measurement facility. It operates world-class calibration facilities accredited by the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC) (ISO/IEC 17025) to provide unique high-quality calibrations to NLR, other U.S. Department of Energy (DOE) laboratories, and other organizations. The SRRL effectively maintains the irradiance standard (i.e., $W \cdot m^{-2}$) for the United States. Its capabilities are used to develop improved methods for the calibration of solar radiometers and advanced instrumentation and methods for operating solar measurement stations. The SRRL (Figure 1) also provides a continuous record of solar irradiance and surface meteorological conditions for use in modeling and validation studies through its Baseline Measurement System (BMS).

SRRL provides some of the most accurate and comprehensive solar radiation measurements in the world, including global horizontal irradiance (GHI), direct normal irradiance (DNI), diffuse horizontal irradiance (DHI), ultraviolet (UV) irradiance, spectral irradiance, sky imagery, and meteorological data. These high-quality datasets support the solar energy industry by improving resource assessment, validating satellite remote-sensing models, optimizing photovoltaic (PV) system design, and evaluating new PV technologies. For concentrating solar power (CSP), SRRL's high-quality DNI measurements are essential for performance modeling, heliostat design, thermal storage optimization, and bankable resource assessments. The data are also widely used in building energy efficiency, supporting various tools for load modeling, daylighting design, and code development.

Beyond energy, SRRL plays a major role in material weathering and durability research, where spectral and broadband UV measurements drive aging models for polymers, coatings, sealants, and PV module materials. Its long-term datasets also underpin atmospheric science and climate studies by validating radiative transfer models, evaluating aerosol impacts, analyzing cloud dynamics, and monitoring long-term irradiance trends. SRRL's UV measurements support public health applications ranging from UV index forecasting to studying skin cancer risk and vitamin D synthesis. The data also benefit agriculture and ecology through photosynthetically active radiation-based crop and photosynthesis modeling.

SRRL serves as a national reference site for instrument calibration and standards development, making it a basis for solar measurement accuracy across multiple industries and research domains. SRRL collaborates with national and international organizations to advance research in solar radiation and serves as DOE's lead laboratory for radiometer calibrations traceable to the World Radiometric Reference (WRR). To maintain WRR traceability, NLR's SRRL team conducts the NLR Pyrheliometer Comparisons (NPC) annually to provide stakeholders such as calibration laboratories with access to the WRR. Using the WRR working standard absolute cavity radiometers, the team developed a unique Broadband Outdoor Radiometer Calibration (BORCAL) method for calibrating pyrheliometers, pyranometers, and pyrgeometers for field measurements. The BORCAL and the NPC are conducted at the ISO/IEC 17025-accredited calibration facilities at an outdoor location at the SRRL, and the spectral irradiance calibrations are conducted at the indoor Spectral Calibration Laboratory (SCL) at the SRRL. The calibrations

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performed at the SRRL form the basis for state-of-the-art PV solar simulator measurements and national and international standards development. The BORCAL and SCL are essential for other ISO-accredited facilities at NLR that measure PV performance.

SRRL and the International Energy Agency's (IEA's) Photovoltaic Power Systems Programme (PVPS) Task 16 on solar resource measurement modeling and forecasting brought together the world's foremost experts in solar energy meteorology to develop the fourth edition of the *Best Practices Handbook for the Collection and Use of Solar Resource Data for Solar Energy Applications (Sengupta et al. 2024)*. This handbook serves the needs of the solar energy community for a single document addressing the key aspects of solar resource characterization as it relates to solar energy technologies. SRRL has been leading the ASTM International subcommittee on radiometry and statistics and leads the U.S. effort to develop international standards for solar radiation measurement and modeling, for example, through the ISO. Current ASTM standards for solar spectral irradiance, radiometer calibration, and PV performance testing are based on work done at SRRL since the 1980s. In the last 3 years, SRRL team contributed to the development and update of ASTM and ISO standards for various solar radiometer calibrations, UV irradiance data, classification associated with solar measurements, and the reference solar spectrum. SRRL effort at developing standards and best practices ensures that best-in-class models and measurement practices are followed while deploying instruments to understand solar variability. It also ensures that grid integration studies use validated solar radiation datasets, thereby increasing the accuracy of those studies. The solar industry follows these standards while deploying radiometers at solar power plants. Industrial assessment of weathering and degradation of various materials including paints and coatings also depend on these standards.

To meet solar energy technology deployment goals, it is essential to predict and reduce the production uncertainty at both PV and CSP plants. The biggest uncertainty in PV and CSP production arises from uncertainty in estimating the solar resource available for these generation technologies, and the research and development (R&D) at the SRRL directly addresses this issue.

Further, to enable grid integration under high-solar deployment and provide methods to address variability, it is necessary to develop capabilities that will provide high temporal and spatial measurement resolutions at a low cost and a high accuracy for grid operations. R&D at the SRRL focuses on developing the capability to deploy a network of measurement systems in a cost-effective manner that ultimately accelerates the integration of solar energy into the electric grid.

This report discusses the applied solar radiation measurement research activities that occurred at the SRRL in fiscal years 2022–2024.

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Figure 1. Aerial view of SRRL facility.

The SRRL is the building in the foreground. The BMS and BORCAL systems are mostly deployed on the raised deck to the left (west). Equipment benches for the NPC are located for optimum solar access.
Photo by Dennis Schroeder, NLR

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2 Objective

This project sought to use the SRRL facilities to enable the DOE Office of Critical Minerals and Energy Innovation to achieve its cost targets and enable the large-scale integration of solar on the electric grid by reducing costs and uncertainty in resource measurements through the following:

- Increase ease of access to the updated WRR to ensure traceable radiometer calibrations nationwide.
- Improve calibration methods for solar radiometers to enhance measurement accuracy.
- Improve access to high-quality datasets from various locations for standards and model development and improve the evaluation of models and methods.
- Develop standards and best practices in solar measurement and modeling to reduce the cost of deployment.
- Disseminate best practices for measurements to facilitate high-quality irradiance measurements.
- Enable the development of new low-cost high-quality measurement systems to reduce deployment costs.
- Collaborate with national and international experts to develop and disseminate innovative methods to improve solar resource assessment and forecasting.
- Develop the capability for trusted solar resource measurements to support the adoption of new module technologies.
- Enable PV and CSP R&D by developing and providing enhanced measurement and modeling capabilities to meet their research needs.

The project provided calibration traceability to the WRR for reference radiometers used by DOE and numerous stakeholders participating in each NPC. Instruments deployed at SRRL were calibrated using the BORCAL or the SCL, thereby providing ISO-accredited calibrations to broadband and spectral radiometers for instruments that are deployed at SRRL BMS and numerous other sites and providing research-quality data that are important for advancing solar resource characterization, solar resource modeling for various technologies, and the validation and verification of new solar resource models. Moreover, the project sought to develop state-of-the-art instrumentation and techniques that enable the adoption of new solar energy technologies. Finally, ASTM, ISO, and IEC standards and the IEA *Best Practices Handbook* were developed using well-characterized measurements of high accuracy from the BMS to enable industry to reduce the cost of solar project development and to develop the capability to use low-cost measurements for effective grid integration.

All data collected through the SRRL project are disseminated through the Measurement and Instrument Data Center (MIDC),[1] which collects data from multiple locations around the United States and continues to be accessed by more than 100,000 users annually. The data and models available from the website enable all stakeholders to easily access information for improving the quality and reducing the cost of projects. The SRRL provides an opportunity for various instrument manufacturers to deploy new instruments at the SRRL for field evaluations.

[1] See https://midcdmz.nlr.gov/.

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Overall, the SRRL project continues to ensure that relevant instruments are:

- Deployed and maintained following the best measurement practices through the BMS
- Optimal deployment of instrumentation within the BMS to represent both long-term continuity and accurate representation of current deployments.
- Calibrated on an annual basis in ISO/IEC 17025-accredited facilities through using the BORCAL facility or the SCL.
- Traceable to the WRR through mechanisms such as the NPC.

The task also ensured that:

- Measurements at the SRRL are collected, quality-controlled, and disseminated in a timely manner through the MIDC.
- The website is updated for ease of use as necessary.
- Strategic partnership projects and/or cooperative research and development agreements (CRADAs) with industry are developed as necessary.
- New calibration methodologies, including the development of a capability for the calibration of digital sensors in the BMS system, are developed.

Through this task, knowledge generated through R&D was disseminated to stakeholders. SRRL also provided leadership in the development of standards within ASTM and ISO to reduce the cost of solar deployment and integration. Through this task, SRRL continues to provide leadership within the IEA PVPS Task 16, participate in collaborative research, and lead the development of the next edition of the *Best Practices Handbook for the Collection and Use of Solar Resource Data for Solar Energy Applications*.[2]

[2] See https://docs.nlr.gov/docs/fy24osti/88300.pdf.

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3 Project Results and Discussion

3.1 Task 1: Applied Solar Radiation and Measurement

Although solar measurement science has improved over time, uncertainties and errors in field measurements still exist. These uncertainties can be a result of (1) instrument design and performance characteristics; (2) calibration of measurement and test equipment; or (3) instrument deployment, maintenance and data acquisition. Removing specific error sources results in advancement in the science of solar measurement and reduces project costs through reduced performance uncertainty. Long-term solar resource—such as broadband, spectral, UV, and plane-of-array—and meteorological measurements of the lowest uncertainty and highest quality are needed for measurement research, standards development, model development and evaluation, as inputs to performance and economic analysis tools, and for other system integration applications. This requires that the instruments are (1) deployed and maintained following best measurement practices, (2) calibrated on an annual basis (in ISO-accredited facilities), and that (3) data are collected, quality-controlled, and disseminated in a timely manner.

The availability of world-class continuous measurements of solar radiation and meteorological parameters such as at the SRRL enables numerous R&D activities that span many applications. These applications include research activities performed under this project as well as other projects in PV; CSP; grid modernization; the development of ASTM, ISO, and IEC standards; the development and evaluation of models; and use in performance and economic analysis tools, such as the System Advisor Model™ (SAM) and PVWatts®. The unique SRRL platform containing BMS enables the development of new and improved instruments in collaboration with top manufacturers, including Kipp & Zonen, Hukseflux, EKO, Eppley, and others.

The SRRL project provides calibration and characterization of broadband and spectral radiometers traceable to the WRR and spectral irradiance standards in compliance with ISO/IEC 17025 accreditation requirements. This involves the operations and maintenance of the BMS to provide high-quality long-term solar irradiance and atmospheric measurements. The SRRL maintains the national standard for solar measurements and disseminates accurate solar measurement and modeling methods and best practices to various stakeholders, including academia, industry, and other laboratories.

This task ensures that relevant instruments:

- Are deployed and maintained following best measurement practices through the BMS
- Maintain the optimal deployment of meteorological instrumentation within the BMS to represent both long-term continuity and accurate representation of current deployments.
- Are calibrated on an annual basis in ISO/IEC 17025-accredited facilities through using the BORCAL facility or the SCL
- Are traceable to the WRR through mechanisms such as the NPC and the International Pyrheliometer Comparisons (IPC)
- Produce data that is quality-controlled and disseminated in a timely manner through MIDC.

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Measurements at the SRRL are supported by the existing infrastructure. Also, the MIDC website is regularly updated to enhance navigation ease and to accommodate new R&D efforts.

Further, the task continues to enable new measurement technologies by:

- Continuing to develop strategic partnership projects and/or CRADAs with industry for the purpose of evaluating and deploying meteorological instruments to provide more accurate, site-specific, long-term, continuous measurements of the solar resource needed by the PV industry to increase the deployment and improve the operations of PV and CSP plants.
- Continuing to collect solar irradiance data from spectroradiometers in horizontal and plane-of-array positions. The data from these spectroradiometers are used to characterize broadband and PV reference cells. SRRL Optical Metrology Laboratory calibrates these spectroradiometers using the National Institute of Standards and Technology's (NIST's) traceable lamp standards of spectral irradiance. This task also includes:
    - Introduction of digital sensors into the BMS by developing calibration and characterization methods
    - Outreach to discuss new challenges for the solar measurement industry. An example is the exchange of ideas with industry partners during revisions of the SRRL *Best Practices Handbook for the Collection and Use of Solar Resource Data for Solar Energy Applications*.

The work performed under this task was divided into two subtasks:

1. Calibration and measurement
2. Dissemination of data and models.

3.1.1 Calibration and Measurement

The work within this subtask includes maintaining the broadband and spectral irradiance calibration traceability to:

- The WRR through conducting the annual NPC (except IPC years) at the SRRL and publishing an annual report
- Maintaining spectral traceability through a National Metrology Institute, in this case NIST.

Similarly, the calibration of broadband and spectral radiometers has been conducted in accordance with ISO/IEC 17025, which is an international standard that specifies the competency requirement for calibration. On an annual basis, SRRL conducted calibrations in compliance with ISO/IEC 17025 of the SRRL radiometers and spectroradiometers that are deployed mainly within the BMS or used in the PV Calibration and Performance Laboratory.

- Characterization of spectroradiometers: Spectroradiometers are used in the many solar energy projects requiring knowledge of the spectral distribution of solar irradiance. One application of a spectroradiometer is to characterize optical solar simulators that are, in turn, used to characterize PV reference cells and /or modules; therefore, it is important that the performance of spectroradiometers is well characterized. Some performance

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characterizations include directional, spectral, and temperature response error characteristics. The methods developed here are intended for use by laboratories performing the calibration of a spectroradiometer for spectral irradiance measurements, spectroradiometer manufacturers, and solar energy projects that deploy spectroradiometers for resource assessment and/or PV reliability analysis purposes.

- Operation and update of the BMS:
    - Through this activity, SRRL collected continuous, high-quality, and complete solar and ancillary measurements by maintaining and operating all instruments—broadband solar for GHI, DNI, DHI; spectral, UV, and infrared; temperature, wind speed, humidity, aerosol, water vapor, precipitation, and snow and cloud imagery—at the SRRL to provide research-quality measurements. The measurements are for use in standards, model and forecast development, validation, and new instrument R&D with manufacturers.
    - Continued to work with and develop strategic partnership projects and/or CRADAs with industry for the purpose of evaluating and deploying meteorological instruments to provide more accurate, site-specific, long-term, continuous measurements of the solar resource needed by industry to increase the deployment and improve the operations of PV and CSP plants.
    - Explored and developed calibration and characterization methodologies for the inclusion of digital sensors into the BMS system. Discussed and developed these methodologies in coordination with manufacturers.

3.1.1.1 National and International Pyrheliometer Comparison

SRRL team serves as DOE's primary laboratory for radiometer calibration that is linked to the WRR, which is essential for ensuring accurate solar irradiance measurements. The WRR is a detector-based measurement standard maintained by a set of well-characterized absolute cavity radiometers, termed the World Standard Group (WSG), developed and maintained by the World Radiation Center (WRC), located in Davos, Switzerland. At the invitation of the WRC, SRRL team engages in the IPCs, held every 5 years, to uphold the integrity of the WRR for the U.S. In between the 5 years, SRRL offers stakeholders access to the WRR through the NLR NPC.

The NPC is an annual side-by-side comparison of SRRL absolute cavity radiometers with devices from U.S. government, academic, and industry participants. This comparison serves to periodically calibrate these devices and to check the stability of the instruments. During this project cycle, the IPC-XIII was held in 2021, as it was delayed by 1 year due to the COVID pandemic, and the NPC was held in 2022, 2023, and 2024 (Reda, Andreas, Stoddard, et al. 2022; Reda et al. 2023b; Reda et al. 2024b; Reda, Andreas, Kutchenreiter, et al. 2022; Reda et al. 2023a; Reda et al. 2024a).

SRRL absolute cavity radiometers are calibrated to the WRR at the WRC (Physical Meteorological Observatory in Davos [PMOD]) in Davos, Switzerland, every 5 years during the IPC. The NPC therefore serves to transfer the calibration from the WRR to the NPC participants (Figure 2). The Transfer Standard Group of reference radiometers for the NPC consisted of four SRRL radiometers with direct traceability to the WRR, each having participated in the IPC. As a result of the NPC, each participating absolute cavity radiometer was assigned a new WRR transfer factor, which is computed as the reference irradiance determined by the Transfer

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Standard Group divided by the observed irradiance from the participating radiometer. The measurement performance of the Transfer Standard Group allowed the transfer of the WRR to each participating radiometer with an estimated uncertainty of ± 0.33% with respect to the International System of Units.

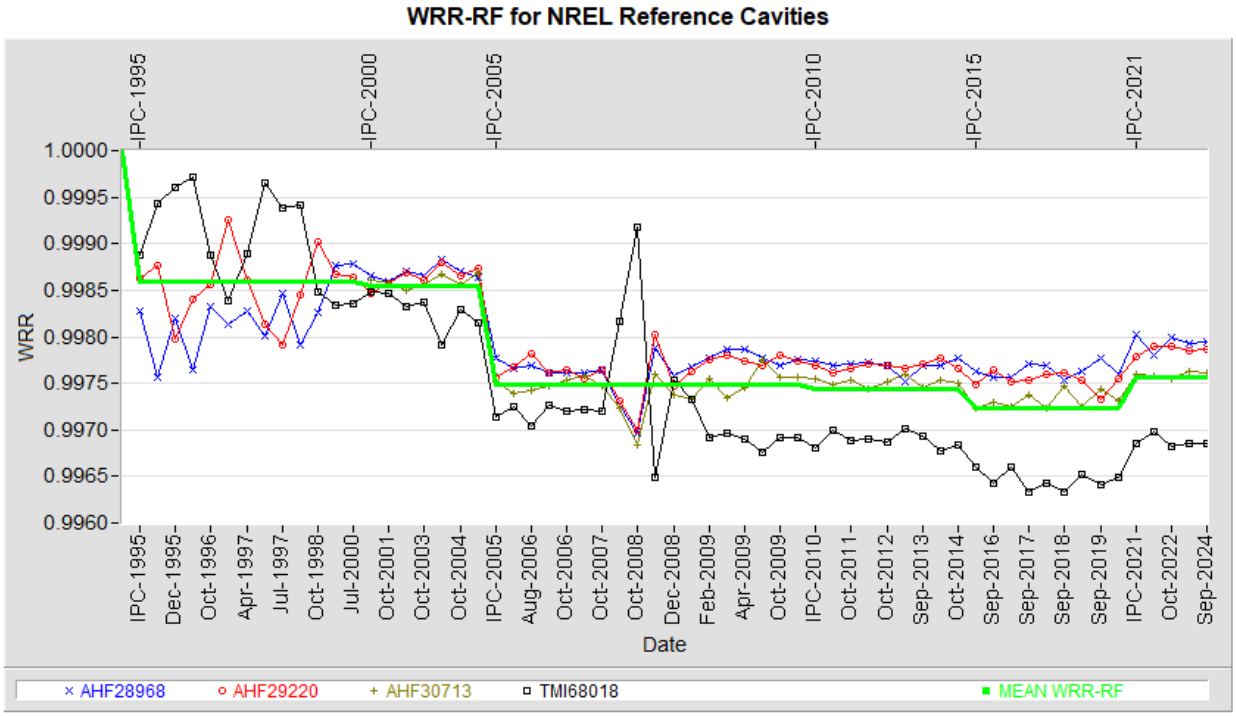

Figure 2. History of WRR reduction factors for SRRL reference cavities.

Source: (Reda et al. 2024b)

SRRL supports the NPC through site access, shipping and receiving of equipment, and a proven measurement and data analysis protocol. The NPC is accredited by the ISO/IEC 17025, which is an important requirement for SRRL BORCAL ISO/IEC 17025-accreditation process because SRRL absolute cavity radiometers are used in the BORCAL process. The ISO/IEC 17025 accreditation requires that the instruments are inter-compared on an annual basis with traceability to the WRR, and the NPC fulfills this requirement both for the SRRL and other ISO-accredited facilities. Further, because participants are experts in this field, the event facilitates sharing knowledge and new R&D ideas.

During the NPC 2022–2024, participants from various organizations operated multiple absolute cavity radiometers to simultaneously measure clear-sky direct normal solar irradiance (Figure 3).

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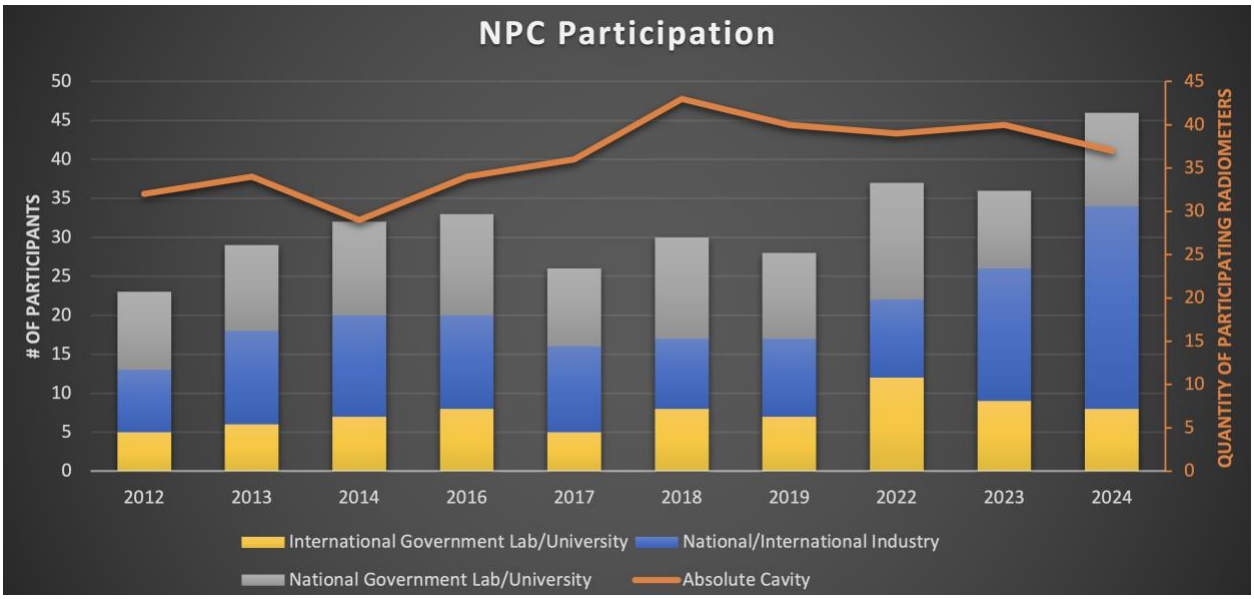

Figure 3. NPC participation over the years.

The primary y-axis shows the number of participants from various entities, and the secondary y-axis shows the number of absolute cavity radiometers. *Image from NLR*

Similarly, during this project cycle, the PMOD through the third World Meteorological Organization (WMO) International Pyrgeometer Intercomparison (IPgC-III) and SRRL hosted the Absolute Cavity Pyrgeometer (ACP) and Infrared Integrating Sphere (IRIS) Comparisons event in 2021 and 2022–2024, respectively. After each intercomparison event, SRRL Metrology Laboratory analyzed the data and published technical reports (Reda, Andreas, Kutchenreiter, et al. 2022; Reda et al. 2023a; Reda et al. 2024a). At SRRL, multiple pyrgeometers were compared during this period, including SRRL -developed ACPs, PMOD's IRIS, the Eppley precision infrared radiometer pyrgeometers, and the Kipp & Zonen pyrgeometers traceable to the World Infrared Standard Group. Figure 4 shows the results of the comparison between the ACPs and IRIS.

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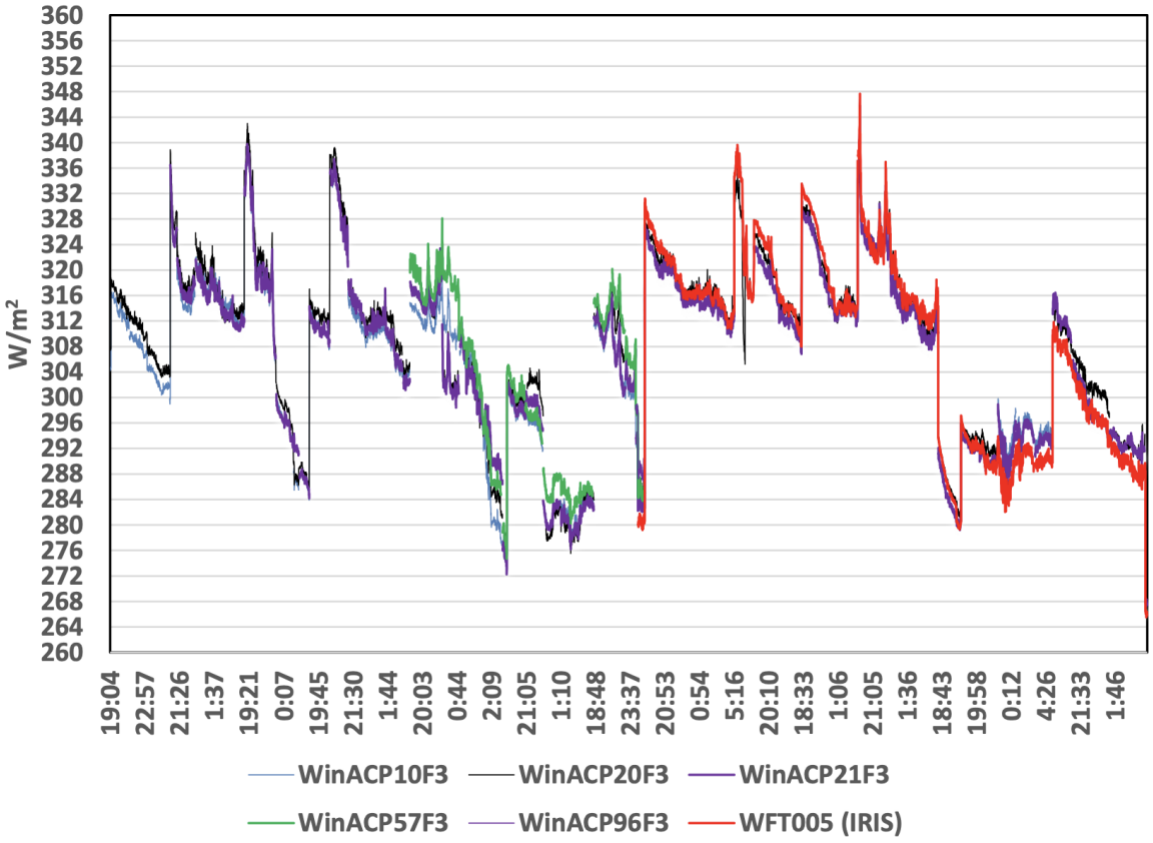

Figure 4. ACPs and FT005 (IRIS) irradiance comparison in 2024.

Source: (Reda et al. 2024a)

3.1.1.2 Shortwave and Longwave Outdoor Radiometer Calibration

BORCAL, which is an ISO/IEC 17025-accredited method, conducts radiometer calibrations outdoors using natural sunlight and sky conditions rather than artificial light sources. It provides traceable, high-accuracy calibrations for solar and infrared radiometers with direct linkage to the WRR and the World Infrared Standard Group. The method captures true environmental influences, ensuring that radiometers perform accurately under actual field conditions. Supported by the DOE Office of Critical Minerals and Energy Innovation BORCAL follows a rigorous quality system and delivers internationally recognized, repeatable, and low-uncertainty radiometer calibrations for reliable solar irradiance measurements.

On an annual basis, SRRL calibrates radiometers using the BORCAL process (see Figure 5 for an example BORCAL setup). During FY 2022–FY 2024, 378 shortwave radiometers and 41 longwave radiometers (Table 1) were calibrated. Calibration services using the BORCAL process were offered for internal and external customers. Non-NLR instrumentation at SRRL are calibrated under the Metrology Services Agreement for a fee.

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Table 1. Total Number of Radiometers Calibrated During FY 2022–FY 2024

FY	Shortwave Radiometers	Longwave Radiometers
22	125	13
23	119	15
24	134	13

Figure 5. Example BORCAL calibration radiometer setup

Photo by NLR

3.1.1.3 Optical Metrology Laboratory for Spectral Irradiance Calibration

SRRL Optical Metrology Lab maintains the NIST traceable lamp standards of spectral irradiance. These lamps come with a calibration data sheet from NIST that indicates the irradiance ($W \bullet m^{-2}\ nm^{-1}$) as a function of wavelength (nm). The data sheet is valid when the lamp is operated under the conditions specified by NIST. These lamps are used to maintain the calibration of spectroradiometers owned by the SRRL group as well as the instrumentation used by other NLR facilities. The lab also calibrates non-NLR instrumentation at SRRL under the Metrology Services Agreement for a fee. In turn, the calibrated spectroradiometers were used to calibrate filtered radiometers and characterize solar simulators (Table 2).

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Table 2. Total Number of Spectral Devices Calibrated and/or Characterized During FY 2022–FY 2024

FY	Spectroradiometers	Solar Simulators	Filtered Radiometers
22	10	4	13
23	11	8	—
24	7	8	14

3.1.1.4 Standard Operating Procedure for Optimally Deployed Instruments Within BMS to Represent Long-Term Continuity

Each year, a standard operating procedure report is released outlining the protocols for the commissioning and decommissioning of instruments to guarantee the long-term continuity and representativeness of current technologies. Since 1981, SRRL has maintained continuous operations with the goal of collecting and using high-quality solar radiation datasets to promote the broader adoption of solar technologies; thus, optimizing the use of this facility is crucial to maintaining its status as a leading global solar radiometer calibration and measurement center. It is important to establish a standard operating procedure for effective deployment within the SRRL that applies to both the BMS and the Research Measurement System (RMS). This ensures that instrumentation maintains long-term continuity, remains state of the art, and is representative of industry standards. According to the standard operating procedure, instruments are assessed annually for continued use. Any instrument that fails to meet the standard operating procedure guidelines is decommissioned, and new instruments that fulfill the criteria are introduced. The 2023 and 2024 reports can be found in (Aron Habte, Sengupta, and Andreas 2024, 2023).

3.1.1.5 NLR's BMS Data Quality Assessment

Evaluating the performance of PV cells, modules, and arrays that form large solar deployments relies on accurate measurements of the available solar resource; therefore, determining the accuracy of these solar radiation measurements provides a better understanding of investment risks. This becomes especially important as the deployment size and investment costs increase to hundreds of millions of dollars. The accuracy of measurements is also important for acceptance testing and operations. SRRL offers a suite of the highest-quality solar radiation measurement systems that are upheld according to industry best practices. These instruments provide a continuous stream of research-quality data for baseline research through the continuous application of data quality evaluation using the SRRL SERI-QC software (Maxwell, Wilcox, and Rymes 1994). The results of the assessment for the past years are illustrated in Figure 6.

Overall, the quality assessment tool demonstrates that less than 5% of the data show flags indicating data higher uncertainty, likely due to contaminated optics by changing weather conditions, i.e., precipitation, dew, and frost.

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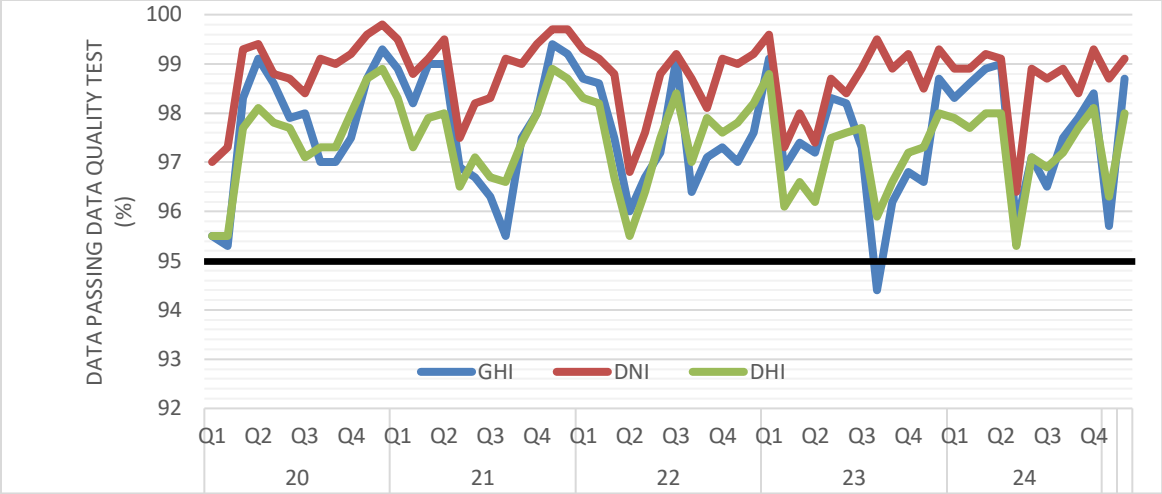

Figure 6. BMS data quality in percent through the years

Similarly, the SRRL performs data quality assessments for sites from which data are collected by the MIDC. One of these stations, which is located at the University of Arizona, has been operating and maintaining the suite of radiometers and associated equipment installed under a CRADA. To collect high-quality measurements, the University of Arizona deployed SRRL-supplied Class A radiometers (per ISO 9060:2018 (ISO 2018)), which represents the highest standard of solar radiation measurement equipment. These instruments have been continuously operated and maintained according to best practices, ensuring consistent and traceable data quality. The dataset includes measurements of the three primary solar irradiance components: GHI, DNI, and DHI. SERI-QC was employed to assess the quality of the data using a three-component quality control method based on an analysis of clearness indices derived from the measured irradiance values. The clearness indices—*Kt* (global), *Kn* (direct), and *Kd* (diffuse)—are calculated by normalizing each respective irradiance component to the computed extraterrestrial solar radiation at the top of the atmosphere. Overall, the assessment shows that fewer than 5% of the measurements were flagged for quality concerns (see Figure 7, for 2023, as an example). This demonstrates a consistently high level of data integrity, affirming the suitability of the dataset for high-confidence solar energy analysis and decision-making. The leftmost chart in Figure 7 displays the most severe quality flags detected among the three clearness components (*Kt*, *Kn*, *Kd*) for each time interval. Flag severity is color-coded, ranging from dark blue (low error or no issue) to red (high-severity flags). The subsequent three charts illustrate clearness indices for each irradiance component individually. These charts provide insight into sky conditions over time, with dark indicating overcast conditions and white denoting clear skies.

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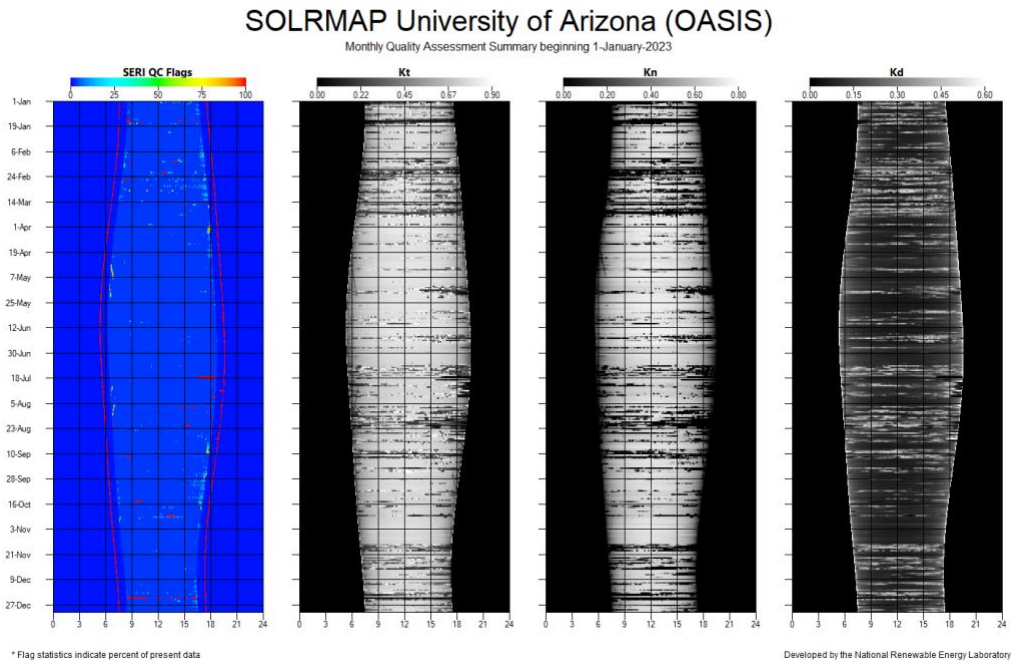

Figure 7. 2023 SERI-QC DQ cylinder plot outputs

3.1.1.6 Procurement and Status of New Instrumentation for Calibration and Characterization of Radiometers

The SRRL procured the Broadband Indoor Calibration System (BIRCAL) system at the end of FY 2024 (Figure 8). The reasoning behind the purchase was that outdoor calibrations using sun as a light source is performed under unpredictable environmental conditions and is limited to certain sky conditions and season (solar positions), whereas indoor calibrations is performed under a controlled environment and uses a stable artificial light source.

Further, manufacturers primarily favor indoor calibrations because they allow for year-round calibrations and more accurate quantification of calibration uncertainty. This capability will enable the SRRL team to take the lead in developing and updating international standards for both outdoor and indoor calibrations. As an independent entity, the SRRL will also play an essential role in validating the manufacturer's performance specifications for radiometers.

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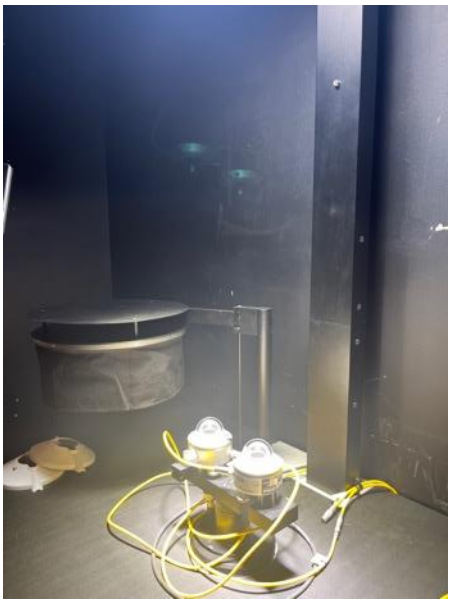

Figure 8. Automated SRRL indoor calibrator performing a pyranometer calibration

Photo by NLR

The BORCAL and BIRCAL systems demonstrated similar results at similar solar zenith angles (16° outdoors versus 0° indoors) (Figure 9 and Table 3). An example of the differences is that the indoor calibration process is repeatable, whereas outdoor calibrations provide directional response information under a variety of sky conditions.

Table 3. BIRCAL and BORCAL Comparison Results for Various Pyranometer Models

Model	SN	Indoor New R	Outdoor Old R at 45°	Outdoor Old R at 20°	% Change Relative to 20°	% Change Relative to 45°	Comment—Outdoor Calibration Method
CM22	010034	10.88	10.93	10.89	-0.07	-0.42	BORCAL
CM22	010047	9.79	9.79	9.80	-0.08	-0.05	BORCAL
CMP22	080017	10.61	10.63	10.68	-0.66	-0.22	BORCAL
CMP22	170535	9.80	9.62	9.67	1.35	**1.86**	BORCAL
CMP22	230953	10.10	10.11	---	---	-0.13	Shade/unshade
8-48	32331	8.95	9.08	8.99	-0.49	**-1.48**	BORCAL
8-48	32871	9.10	9.09	---	---	0.08	Shade/unshade

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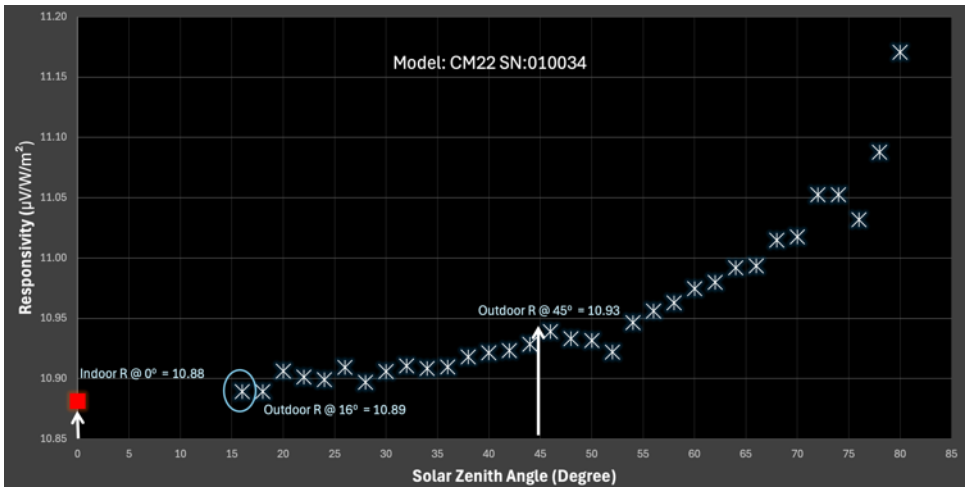

Figure 9. Example comparison of one Kipp & Zonen pyranometer between BORCAL and BIRCAL results

Additionally, the SRRL acquired a new solar simulator and temperature chamber that meets the precision requirements established by ISO 9060 (ISO 2018) for characterizing radiometers. This simulator and temperature chamber will be pivotal in characterizing the directional and temperature response of radiometers.

3.1.2 Dissemination of data and models

The MIDC provides a service that conducts quality control and delivery of the BMS data and for many other facilities within the United States in near real time. Models developed and validated using BMS data are also available.[3] The MIDC continues to be accessed by more than 100,000 users annually. The data and models available from the website enable all stakeholders to easily access information for improving the quality and reducing the cost of solar energy projects. The SRRL provides an opportunity for various instrument manufacturers to deploy new instruments at the SRRL. Figure 10 shows the current and historical locations where the MIDC collects data.

[3] See https://www.nlr.gov/grid/solar-resource/renewable-resource-data.

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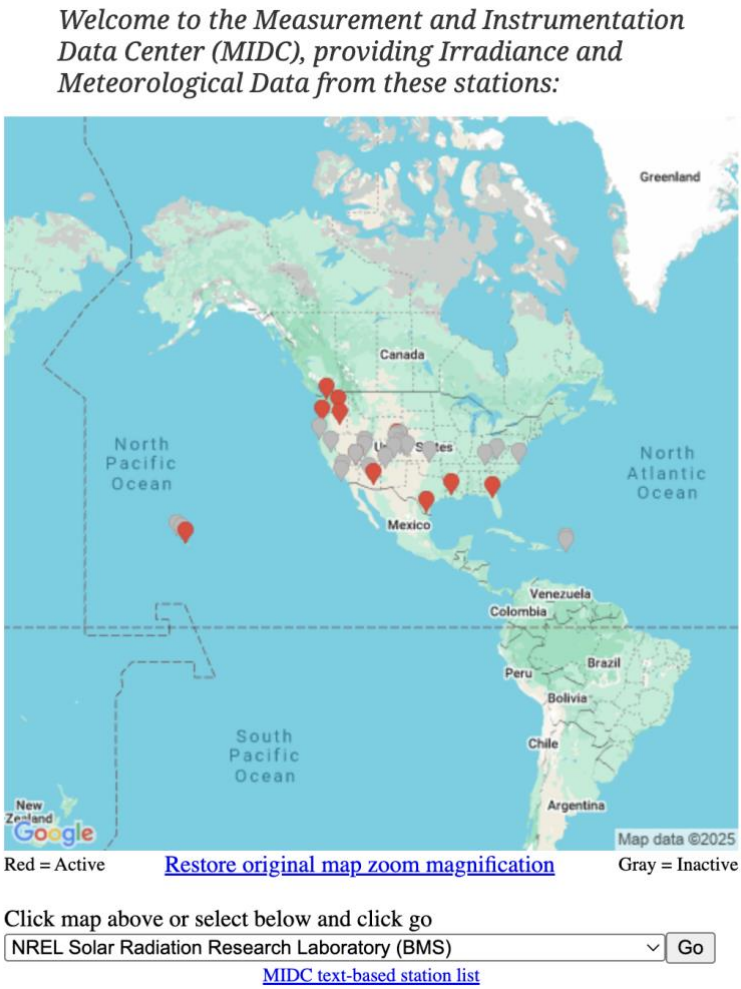

Figure 10. Sites where current and historical data are available on the MIDC website

Figure 11 provides the flowchart of the MIDC platform that allows SRRL to collect, store, and provide solar resource measurements and other meteorological/ancillary information to many stakeholders with a diverse set of needs. Through the MIDC's web portal, SRRL disseminates—in near real time—quality-controlled, traceable measurements collected from the SRRL and other partner sites around the United States (Figure 10) that take high-quality solar radiation measurements.

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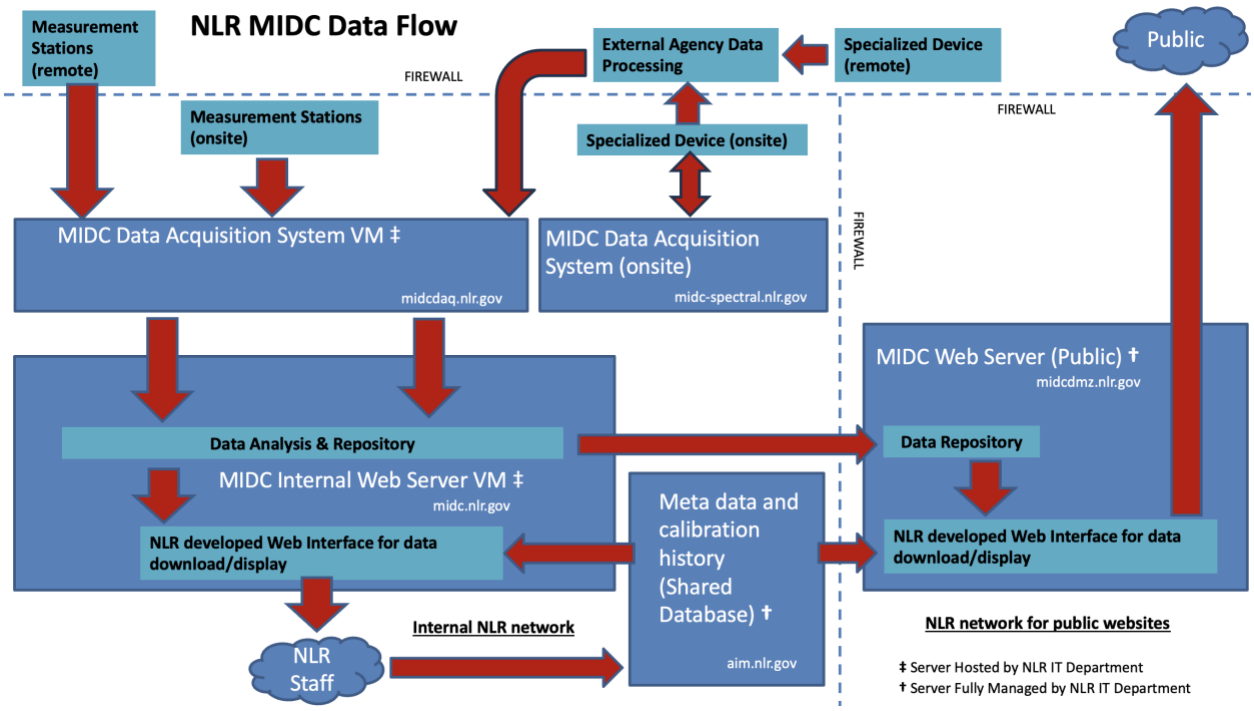

Figure 11. Flowchart of the MIDC infrastructure

3.2 Task 2: Standards Development and Knowledge Sharing

The knowledge and experience gained through 40 years of operating the SRRL has allowed NLR to develop the tools and best practices needed for solar resource assessment and their applications to solar energy systems.

SRRL shares this knowledge by contributing to the development of international consensus-based standards, e.g., for radiometer calibration, measurement evaluation, model development, reference data, and data processing. The standardization of datasets and models enables industry to develop widely accepted protocols for various stages of solar project development and operations. This reduces barriers to financing and reduces warranty costs. SRRL developed and regularly updates the *Best Practices Handbook for the Collection and Use of Solar Resource Data for Solar Energy Applications*. This task supports SRRL leadership in standards and best practices and their timely dissemination to the U.S. solar energy industry, including manufacturers and developers. The BMS data are unique because of their long duration and high quality, so they are heavily used to develop new ASTM, ISO, and IEC standards.

International standards for solar resource assessments provide assurance for traceable measurements associated with a low uncertainty. This benefits the solar energy industry by reducing the investment risks through heightened confidence in the solar resource information. SRRL, in collaboration with international organizations, such as subcommittees G03.09 of ASTM (Radiometry) and ISO/TC180/SC1 (Climate measurement and data), recently revised some standards that are widely used by the solar industry. These include radiometric standards that assist in (1) maintaining calibration traceability, (2) uncertainty analysis, (3) measurement quality assurance, and (4) establishing reference spectral irradiance distributions. The latter are widely used by the solar community to evaluate the actual absorptance, reflectance, and

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transmittance of solar energy materials, or the performance of solar energy devices and systems, relative to standard conditions.

3.2.1 Develop, Update, and Disseminate Standards

The ISO/TC180/SC1 subcommittee already updated and/or is in the process of updating a few standards. Similarly, the ASTM G03.09 subcommittee developed and/or updated multiple standards. The following subsections summarize recently updated standards.

The international radiometric standards, as illustrated in Figure 12, are essential for accurate and comparable solar irradiance measurement. Their contributions to maintaining traceability, uncertainty analysis, and measurement data quality assurance ultimately support the solar energy industry. Many standards were reapproved, updated, and balloted during this project cycle (ASTM 2017, 2021b, 2021a, 2023b, 2023e, 2023a, 2023d, 2023c; ISO 2023).

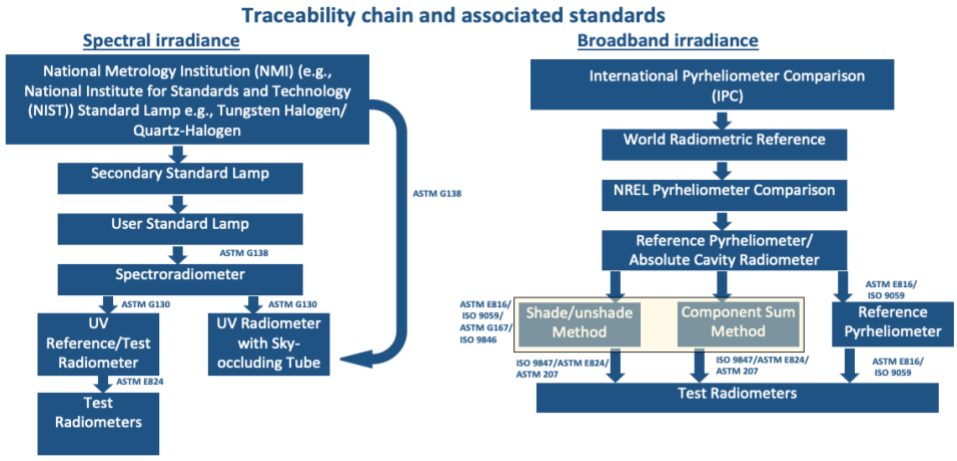

Figure 12. Example of radiometric standards calibration traceability chain for both spectral and broadband irradiance, and for use cases in solar energy applications

3.2.1.1 ASTM G173 – Standard Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface

The revised G173 standard includes recent advancements in science and knowledge, resulting in new tables and figures based on the Simple Model of the Atmospheric Radiative Transfer of Sunshine (SMARTS) software, which was recently updated (Gueymard 2019). The most recent version (v2.9.9) includes significant improvements over v2.9.2, which was used to define the reference solar spectra in the current G173 standard, initially promulgated in 2003. The revised standard based on this SMARTS revision also includes recommended editorial and technical changes as well as updated references for the SMARTS model and its inputs. Overall, the standard's revision benefits from these improvements:

- New solar constant: Based on a 42-year time series of recalibrated irradiance data, a revised solar constant of 1361.1 $W \cdot m^{-2}$ was recently accepted as part of standard ASTM E490-22 (see (ASTM 2022) for details). This value contrasts with the older WMO value of 1367 $W \cdot m^{-2}$, which was embedded in the original version of G173.
- New revised extraterrestrial spectrum: This is now based on a recalibration and merging of various sources of spaceborne extraterrestrial spectrum observations (ASTM 2022)

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and is included in SMARTS v2.9.9. This new extraterrestrial spectrum distribution forms the basis of standard E490-22 (ASTM 2022) and differs by up to a few percent (depending on the spectral band) compared to the earlier extraterrestrial spectrum used for the original version of G173 (ASTM 2023c). This particularly affects the UV and visible spectral bands of the resulting modeled terrestrial spectra.

- Various model improvements in the spectral calculation of atmospheric effects, particularly affecting the UV.

These various modifications are documented in (Gueymard 2018a, 2018b, 2019) and are expected to improve the experimental realization of reference modeled spectra, as suggested by Figure 13. The standard was published by ASTM in 2023.

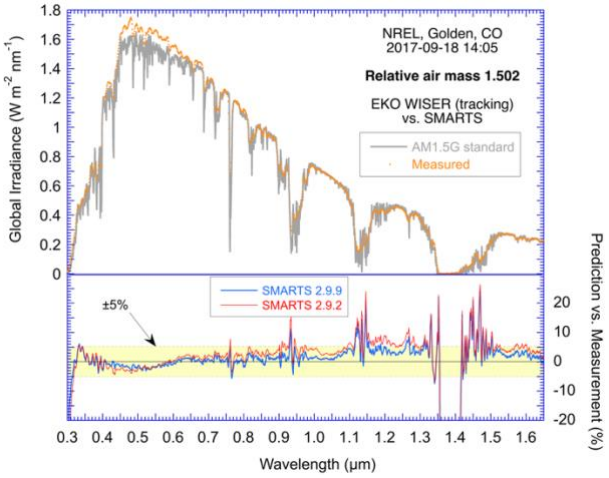

Figure 13. Experimental realization of the AM1.5G standard reference spectrum at Golden on Sept. 18, 2017.

Top panel: Comparison between AM1.5G and the spectroradiometer measurement of global normal irradiance. Bottom panel: Percent difference between the observations and predictions from SMARTS v2.9.9 and v2.9.2

3.2.1.2 ASTM G222-21 – Standard Practice for Estimation of UV Irradiance Received by Field-Exposed Products as a Function of Location

The ASTM G03 subcommittee recently published a new standard on methods to estimate the total UV irradiance based on an empirically derived model that assumes that measured or modeled data of GHI are available. This standard is expected to help understand the degradation of materials exposed outdoors. In particular, the UV irradiance is a key input to obtain reliable assessments of the service life of many products. Unfortunately, most of the locations that monitor and/or model solar irradiance only have instrumentation/models for GHI and thus completely lack information on UV irradiance. As a remedy, this standard promulgates a mathematical model that provides a simple way to estimate the contribution of UV to GHI through the UV/GHI ratio.

The model estimates the global UV irradiance in two widely used ranges (280–400 nm and 295–385 nm) from GHI (≈280–4000 nm). SMARTS is used to evaluate the UV/GHI ratio under a large variety of clear-sky conditions, and it examines the impacts of various atmospheric constituents—such as aerosols, precipitable water vapor, or ozone—and of the local surface characteristics (albedo) on the predicted UV. Using this large database of SMARTS predictions,

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the clear-sky UV/GHI model is created by fitting the predictions of this ratio to a fourth-order polynomial as a function of air mass only:

$$\frac{UV_{clear}}{GHI_{clear}} = \sum_{i=0}^{4} m_i \, AM^i$$

where:

- UV = extended global UV irradiance, W•m^{-2}
- GHI = global horizontal irradiance, W•m^{-2}
- m_i = location-specific numerical coefficient obtained from the fitting of SMARTS results
- AM = air mass coefficient.

This ratio is then applied to calculate the global all-sky horizontal UV from measured or modeled all-sky GHI:

$$UV_{mod_all_sky} = GHI_{all\ sky} * \frac{UV_{clear}}{GHI_{clear}}$$

The model was validated at multiple locations; Figure 14 shows one example result of the modeled versus ground-measured data for the SRRL station in Golden, Colorado for one year. Considering multiple sites, the overall mean absolute error of the model is within 8%, and the details about the accuracy are stated in (ASTM 2021b; A. Habte et al. 2019).

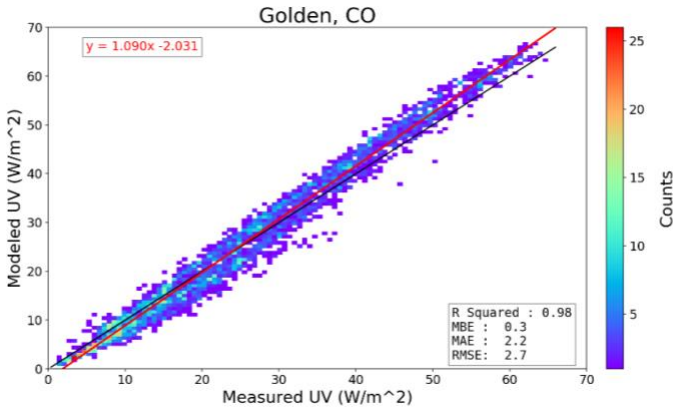

Figure 14. Scatterplot of modeled and measured global UV (280–400 nm) at SRRL location

3.2.1.3 ISO/TR 9901:2021 — Solar Energy — Pyranometers — Recommended practice for use (ISO/TR 9901:2021 Solar energy — Pyranometers — Recommended practice for use 2021)

Parallel to the work conducted at ASTM, the ISO/TC180/SC1 committee revised the following standard. After a significant revision, this standard was published in 2021. The summary of the updates includes consideration of recommended practices for the use of modern digital pyranometers equipped with internal diagnostic techniques. Further, the standard provides recommended practices for the use of pyranometers to measure two quantities of importance for the PV community: plane-of-array irradiance and ground-reflected radiation.

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3.2.1.4 ISO 9847: 2023 — Solar energy — Calibration of Pyranometers by Comparison to a Reference Pyranometer (ISO 2023)

This standard underwent significant updates compared to the previous version. The main changes consist of a new section on indoor calibration, which is now used by manufacturers and calibration service providers. The terms and definitions are updated and harmonized with published standards, such as ISO 9060:2018 (ISO 2018) and ISO Guide 99 (IEC 2012).

3.2.1.5 ISO 9845: 2022 — Solar energy — Reference Solar Spectral Irradiance at the Ground at Different Receiving Conditions — Part 1: Direct Normal and Hemispherical Solar Irradiance for Air Mass 1.5 (ISO 2022)

This standard was thoroughly revised and published in 2022. The revision includes the implementation of the SMARTS model to generate additional reference spectral irradiance distributions. Most notably, 171 subordinate spectra for hemispherical tilted irradiance are provided for a variety of atmospheric conditions and receiver geometries.

3.2.2 IEA Task 16 PVPS Collaboration

In collaboration with international partners within the IEA, the *Best Practices Handbook for the Collection and Use of Solar Resource Data for Solar Energy Applications: Fourth Edition* was published.[4]

The fourth edition (Sengupta et al. 2024) of the widely used *Best Practices Handbook* includes current progress in solar resource measurement and modeling, solar forecasting, and solar energy applications. Two new chapters were added, and many chapters were significantly revised to represent the advancement in the state of the art.

Since the first edition, released in 2015, the *Best Practices Handbook* has constituted an essential reference guide for solar energy practitioners seeking information about both the fundamentals and the state of the art in solar resource measurement, modeling, and forecasting. With collaboration of SRRL and the IEA PVPS Task 16 and enriched by the insights of 51 experts from 15 countries, the current handbook conveys a wealth of knowledge and experience from industry leaders, and it is published both as an IEA PVPS Task 16 report[5] and as an NLR report. Like the previous editions, this handbook is freely available for download through both the IEA and NLR publication websites. As the field of solar energy is evolving quickly, so is the knowledge of solar resource; thus, the fourth edition was significantly revised. This is reflected in the significant updates made to all existing chapters and the addition of two new chapters, for a total of 12 chapters. The solar resource is foundational to solar energy applications, and the fourth edition provides access to information that could reduce the cost and accelerate the pace of solar deployment.

The 12 chapters are summarized as follows. Chapters 4 and 6 are new, reflecting the significant importance of those topics as identified by the solar energy community:

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[4] See https://www.nlr.gov/docs/fy24osti/88300.pdf.
[5] See https://iea-pvps.org/wp-content/uploads/2024/09/Best-Practices-Handbook-for-the-Collection-and-Use-of-Solar-Resource-Data-for-Solar-Energy-Applications-Fourth-Edition-.pdf.

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- Chapter 1 provides an overview of the contents of the handbook and the rationale behind the chapters contained in the handbook.
- Chapter 2 introduces solar radiation concepts that are essential for understanding the characteristics and radiative properties of sunlight.
- Chapter 3 discusses the measurement of solar radiation and the best practices that need to be followed to acquire high-quality solar measurements.
- Chapter 4 provides users with information about how to perform the quality control of measurements and how to assess the quality after measurements have been taken.
- Chapter 5 provides users with information on the various meteorological quantities that are needed for the detailed modeling of solar energy production and PV reliability.
- Chapter 6 provides information about the variability of solar radiation at various spatiotemporal scales. As solar radiation is inherently variable, this chapter is important for those who seek to develop methods to balance grid operations.
- Chapter 7 provides users with information about solar radiation modeling, including how satellite data can be used to estimate solar radiation and how the incident solar radiation can be modeled for the various possible geometries of solar installations.
- Chapter 8 provides detailed information about various sources of solar data and models. This chapter is a useful repository of links for users looking for either measured or modeled datasets to manipulate solar data for their applications.
- Chapter 9 covers solar forecasting at various timescales and is important for grid operators seeking to reduce the cost of grid operations under the fast-growing deployment of solar energy.
- Chapter 10 provides users with an understanding of uncertainty in solar measurements and modeled solar data, both historical and forecast.
- Chapter 11 contains information about how to use both measured and modeled solar data for solar energy applications during the development and operation of solar energy plants. Moreover, the chapter summarizes the solar radiation needs at different steps of a hypothetical project (see Table 4). The information provided in the table is applicable to large solar energy projects, mainly PV and concentrating solar thermal, and to building energy performance evaluations.
- Chapter 12 provides users with an outlook on the horizon for IEA PVPS Task 16, primarily based on challenges and gaps that have been identified by experts.

Overall, the handbook covers the most relevant topics related to the solar resource that are of importance to stakeholders in the field of solar energy. This update, which contains the latest development in a fast-moving field, is expected to serve as an important reference within the whole solar industry, as the previous editions did in the past.

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Table 4. Solar Resource Data Needs for Different Stages of a Hypothetical Project

	System Size	Small	Medium	Large
Phase	1. Prefeasibility and planning	Long-term averages Monthly data Solar cadastres/ maps Simple shading analysis	Typical meteorological year Hourly data Shading analysis	Long-term satellite data Hourly data
	2. Feasibility			Satellite data Time series (>10 years) Ground measurements (>1 year) Shading analysis Further site- and technology-specific meteorological parameters (e.g., albedo, soiling)
	3. Due diligence and finance		Satellite data Time series (>10 years) Minutely data Shading analysis Further site- and technology-specific meteorological parameters (e.g., albedo, soiling)	Satellite data Time series (>10 years) Ground measurements (>1 year) Minutely data Shading analysis Further site- and technology-specific meteorological parameters (e.g., albedo, soiling)
	4. Operations and maintenance	Simple (inverter) monitoring	Local measurements Forecasts	Local measurements Forecasts

3.3 Task 3. Development of State-of-the-Art Instrumentation and Techniques

3.3.1 Toward Developing Accurate Long-term Solar Irradiance Data

Long-term solar irradiance data play an essential role in the risk analysis and decision-making processes for all phases of the development of solar energy projects, including rooftop to utility-scale PV. Long-term solar irradiance dataset represents the solar irradiance phenomenon over years (Sengupta et al. 2024; WMO 2018). Many studies demonstrate the long-term changes in solar radiation and how varying solar radiation can impact solar energy systems (Müller et al. 2014). The question that many researchers attempt to answer is: How do the long-term solar radiation changes affect solar energy systems? In addressing this question, many studies have examined the effects of the long-term solar radiation changes on solar energy. This ongoing study seeks to investigate this question. Solar radiation measurements are susceptible to various sources of uncertainties. These uncertainties can arise from the method of calibration employed on the radiometers, the type of instrument used, and the operations and maintenance method; therefore, solar radiation collected from a site needs to be checked through examining the instruments for consistency across neighboring locations and/or using redundant instrumentation.

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In the above context, SRRL team investigated the calibration bias of the radiometric data collected at the SRRL since mid-1985 to the present by comparing the data to a newer standard reference for DHI. This is established by determining the difference between the output of older radiometers measuring DHI and the newer standard used for calibration. Figure 15 demonstrates the process of the method and the ultimate bias correction method.

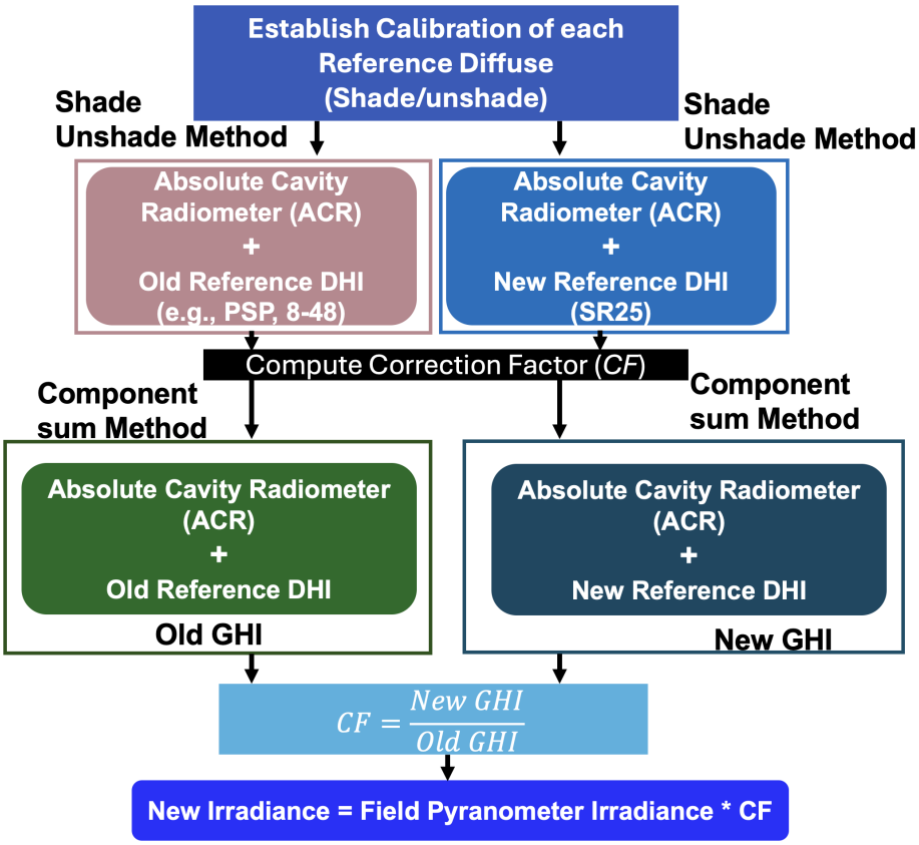

Figure 15. Flowchart demonstrating the process of correcting the bias in the reference diffuse measurements

Each year, the BORCAL method is employed for calibrating pyranometers. This involves using the shade and unshade method for reference DHI instruments, along with the component sum method utilizing the reference DNI obtained from an Eppley Laboratory Inc. Model AHF windowed cavity radiometer and a shaded reference pyranometer, which has been calibrated using the shade and unshade approach. Moreover, test pyrheliometers are calibrated directly against the AHF cavity.

By design, the sensitivity of the reference cavity radiometer does not significantly change from one year to another. Additionally, thorough characterizations of this instrument are carried out through the NPC and the International Pyrheliometer Intercomparison procedures. (See (Finsterle 2023; Reda et al. 2024b, 2024a) for details about these methods.)

In contrast, the reference DHI instrument in BORCAL has changed from one model of pyranometer to another during various periods, as detailed in Table 5. The reason for these changes is detailed in (Reda and Andreas 2017; Myers et al. 2000). These changes in the

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reference DHI instrument can cause artifacts (up or down shifts) in the long-term data. As illustrated in Figure 15, the process of correcting the reference DHI starts by calibrating the various types of pyranometers used as DHI references through time to the current standard reference, Hukesflux model SR25; consequently, the older DHI data was adjusted utilizing the current SR25 reference pyranometer (Table 5).

Table 5. Reference DHI Used Through Time

Model	Manufacturer	Variable	Date of Use
PSP	Eppley Lab	DHI	1985–1999
8-48	Eppley Lab	DHI	2000–2017
SR25	Hukseflux Inc.	DHI	2018–present

Figure 16 shows the correction that is proposed, which is based on the shade and unshade calibration process that was carried out in 2023. The shade and unshade exercise encompassed the three diffuse instruments described in Table 5 where the calibration was carried out sequentially for the three pyranometers. As mentioned, the process was to identify any biases in the data from the older reference DHI (Precision Spectral Pyranometer (PSP) and 8-48) compared to the SR25.

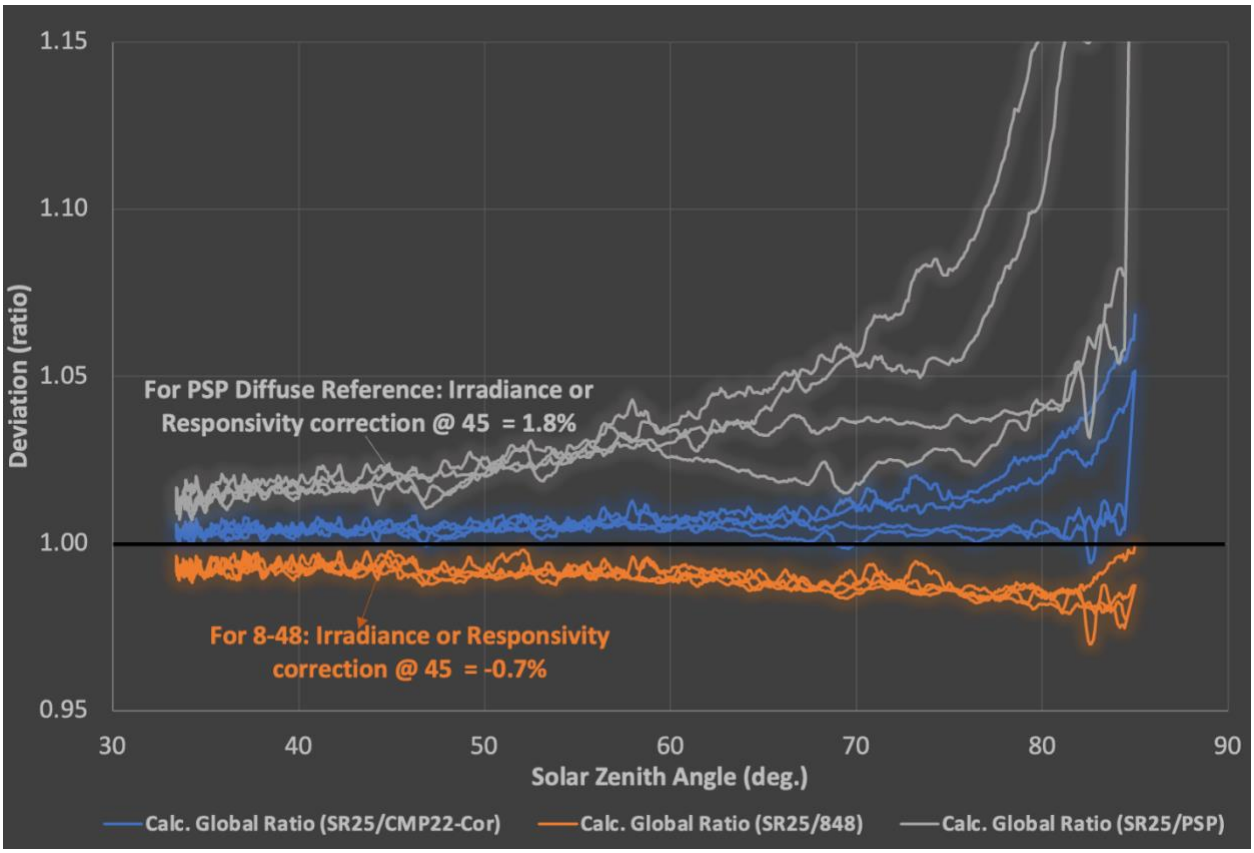

Figure 16. Correction factor proposed to align older data with the present reference DHI

The study focuses on how to prepare long-term solar irradiance data for solar energy applications. The SRRL team demonstrated the method on how to account for and correct biases

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in the historical data. The results showed that model 8-48 had a bias of -0.7% compared to the new pyranometer Hukseflux model SR25, and the Eppley Precision Spectral Pyranometer had a bias of 1.8%. These factors will be used to correct the long-term DHI and GHI dataset.

3.3.2 Data Quality and Uncertainty Integration

SRRL developed the Solar Uncertainty Integrator (SUNI) software, which adheres to the internationally accepted Guide to the Expression of Uncertainty in Measurement (GUM). The SUNI software, which is described below, has been specifically designed to integrate data quality analyses and radiometer measurement uncertainty estimates for GHI, DNI, and DHI.

As the global demand for solar energy sources continues to increase, accurate and reliable solar irradiance data have become increasingly essential for the successful implementation and optimization of solar energy systems. From evaluating project feasibility to monitoring system performance, precise measurements of solar radiation play an essential role in both research and practical applications. Numerous high-quality solar measurement networks, such as the Baseline Surface Radiation Network[6] (BSRN) and the Atmospheric Radiation Measurement[7] (ARM) network operated by DOE, provide valuable radiometric data. These networks are known for providing high-quality radiometric data collected using sophisticated instrumentation and rigorous quality control protocols. But despite the high standards maintained by such networks, the integrity and reliability of solar irradiance measurements remain susceptible to various sources of uncertainty. These include, but are not limited to, the type and condition of the radiometers used, the frequency and accuracy of the calibration, environmental and installation factors (e.g., shading, tilt, and orientation), and ongoing operational maintenance. These variables can significantly influence the uncertainty of the collected data and, consequently, the decisions made based on it.

Given the potential impact of these uncertainties on both research outcomes and real-world energy system performance, the quantification and transparent reporting of measurement uncertainty is a critical component of solar resource assessment. Recognizing this need, SRRL developed SUNI (Wilcox et al. 2025), a Python-based software tool designed to systematically estimate the measurement uncertainty in accordance with the internationally accepted GUM. SUNI enables users to evaluate uncertainty in GHI, DNI, and DHI at time intervals ranging from 1 minute to 1 hour, making it suitable for a wide array of applications and datasets.

The SUNI software package provides a method to assign expanded uncertainty estimates to three-component solar radiation measurements (Wilcox et al. 2025). The system merges static uncertainty information about radiometer performance with the dynamic operational uncertainty information extracted from the data quality assessment (Maxwell, Wilcox, and Rymes 1994). As shown in Figure 17, the SUNI software handles three-component datasets for GHI, DNI, and DHI. These three components are then assessed for data quality to identify a reasonable dataset using the SERI-QC software. The SERI-QC software is a well-established automated data quality assessment tool based on the fraction of incident extraterrestrial irradiance (Maxwell, Wilcox, and Rymes 1994) and the three irradiance components to estimate the clearness index.

[6] See https://bsrn.awi.de/.
[7] See https://armgov.svcs.arm.gov/.

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Similarly, the system uncertainty is estimated using the closure equation of the clearness index, namely, *Kt* for GHI, *Kn* for DNI, and *Kd* for DHI. A ratio based on this closure equation is considered a system uncertainty, as described in Figure 17.

Instrument uncertainty is a key in the SUNI process. Instrument uncertainty is an inherent radiometer uncertainty derived from the radiometer specification. These specifications can be obtained from the manufacturer and/or from ISO 9060 (ISO 2018). Moreover, the inherent uncertainty is estimated by following the GUM. The application of the GUM method is documented in (Reda 2011; ASTM 2017; Aron Habte et al. 2014; Konings and Habte 2016). Similarly, operational uncertainty, also known as field uncertainty (*U_o Field*), is calculated from the system uncertainty (*U_o SYS*) and the inherent radiometer uncertainty, as shown in Figure 17. The inherent radiometer uncertainty (*Ur*) for the three-component dataset is defined as:

- Uncertainty of GHI: *U_rGHI*
- Uncertainty of DNI: *U_rDNI*
- Uncertainty of DHI: *U_rDHI*.

To separate the field uncertainty from the radiometer expanded uncertainties, the method first establishes the collective expanded uncertainty for the radiometers (*U_{RADS}*) by combining the three radiometer uncertainties in quadrature:

$$U_{RADS} = 2 \cdot \sqrt{\left(\frac{UrGHI}{2}\right)^2 + \left(\frac{UrDNI}{2}\right)^2 + \left(\frac{UrDHI}{2}\right)^2}$$

U_o Field, the uncertainty attributable to environmental and operational effects, is then the difference between the absolute value of *U_o SYS* and U_{RADS}:

$$U_oField = MAX\ [|U_oSYS| - U_{RADS}, 0]$$

The MAX function in the field uncertainty calculation sets negative values of *U_o Field* to zero. In this arrangement, *U_o Field* represents the uncertainty in *U_o SYS* beyond that of the radiometer uncertainties. Combining *U_o Field* with each radiometer uncertainty in turn, the method estimates of the expanded uncertainty for each of the three measured irradiance components:

$$U_{95}GHI = 2 \cdot \sqrt{\left(\frac{UrGHI}{2}\right)^2 + \left(\frac{UoField}{2}\right)^2}$$

$$U_{95}DNI = 2 \cdot \sqrt{\left(\frac{UrDNI}{2}\right)^2 + \left(\frac{UoField}{2}\right)^2}$$

$$U_{95}DHI = 2 \cdot \sqrt{\left(\frac{UrDHI}{2}\right)^2 + \left(\frac{UoField}{2}\right)^2}$$

The overall radiometer uncertainty is calculated by following the GUM method of implementing the root-sum-square method. Details about the method are documented in (Wilcox and Stoffel 2024; Wilcox et al. 2025).

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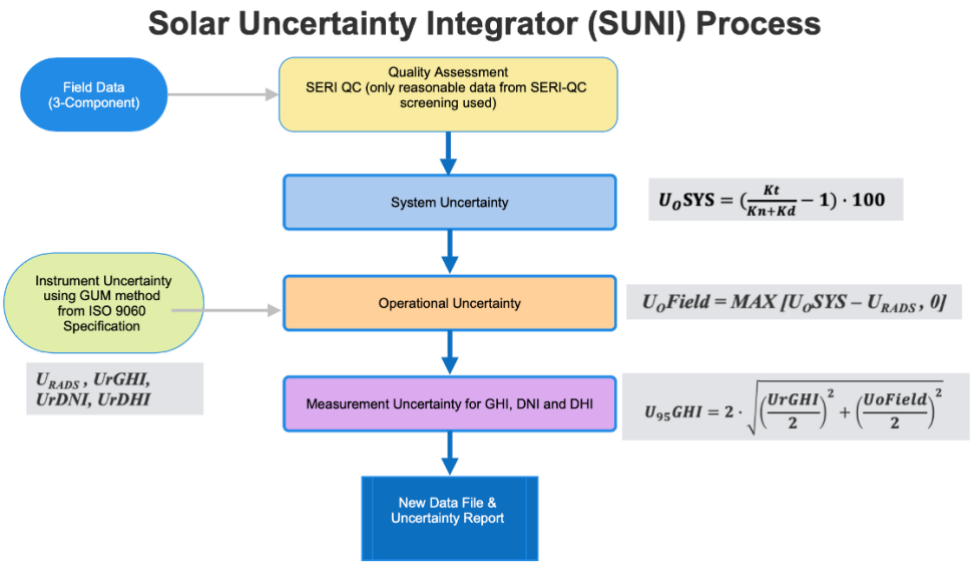

Figure 17. Flowchart of the SUNI process

An analysis using SUNI was conducted for 11 BSRN and 11 ARM three-component 1-minute irradiance datasets for 2017 and 2024, respectively. The year selection is based on the availability of data from all stations. Figure 18 and Table 6 show the results for the ARM stations. Some observations from the results in Figure 18 are as follows:

- The ARM's Southern Great Plains (SGP) BRS, E13, and S01 are collocated stations, but E13 is equipped with Eppley radiometers that demonstrate relatively higher overall uncertainty than S01, which is equipped with Hukseflux radiometers, and BRS, which is equipped with Kipp & Zonen radiometers.
- Similar to E13, the remaining ARM's SGP extended facilities—such as E12, E32, E33, E37, and E39—are equipped with Eppley radiometers. Like the ARM's SGP S01 site, the ARM's Eastern North Atlantic (ENA), North Slope of Alaska (NSA), and Kennaook/Cape Grim, Tasmania, Australia (KCG) are equipped with Hukseflux radiometers.
- The atmospheric and environmental conditions at the KCG location are difficult for collecting high-quality radiometric data. This is clearly illustrated in the scatter plot. The uncertainty is higher compared to other locations with the same type of Hukseflux radiometers. NSA has a limited amount of data after the radiometer upgrade.

Similarly, results from the BSRN station are shown in Table 7.

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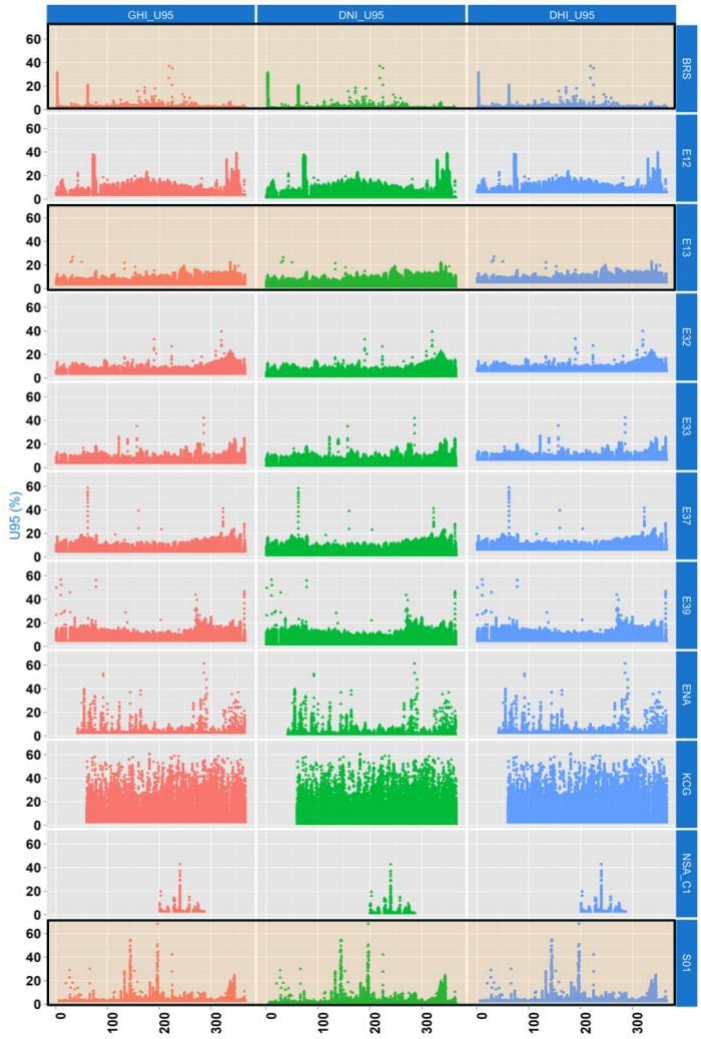

Figure 18. Field measurement uncertainty for the 11 active ARM stations using the 2024 dataset.

Note: The x-axis is the day of the year.

Table 6. ARM Summary Statistics for Parameters in the SUNI Process and the Final U_{95} GHI Values using the 2024

Stations	U_R GHI (Instrument Uncertainty) (%)	Mean U_{95} GHI (Instrument Uncertainty + Operational Uncertainty) (%)	Proportion of Data Where U_{95} GHI Exceeds U_R GHI (%)	Instrument Manufacturer
BRS	2.4	2.43	1.6	Kipp & Zonen
E13	3.7	4.24	32	Eppley
S01	2.9	2.98	4.7	Hukseflux
E12	3.7	4.35	21	Eppley
E32	3.7	4.37	37.8	Eppley
E33	4	4.52	28.6	Eppley
E37	4.7	5.28	25.9	Eppley
E39	4.9	5.67	32.7	Eppley
ENA	2.7	2.83	8	Hukseflux
KCG	2.8	10.86	76.7	Hukseflux
NSA C1	2.8	3	9.6	Hukseflux

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Table 6 and Table 7 provide insights about the overall uncertainties of the sites. These uncertainties are dependent on the instrument type, environmental conditions, and instrumentation performance at each site.

Table 7. BSRN Summary Statistics for Parameters in the SUNI Process and the Final U_{95} GHI Values using the 2017

	U_R GHI (Instrument Uncertainty) (%)	Mean U_{95} GHI (Instrument Uncertainty + Operational Uncertainty) (%)	U_{95} GHI Exceeds U_R GHI (%)	Instrument Manufacturer
CAB	**2.90**	2.90	0.82	Kipp & Zonen
CAM	**2.90**	3.71	41.19	---
CAR	**2.90**	3.51	0.17	Kipp & Zonen
CNR	**2.90**	3.55	0.56	Kipp & Zonen
IZA	**2.90**	3.42	3.34	EKO
LER	**2.90**	3.79	20.40	Kipp & Zonen
LIN	**2.90**	3.67	2.01	Kipp & Zonen
NYA	**2.90**	3.65	15.74	Kipp & Zonen
PAL	**2.90**	3.67	0.74	Kipp & Zonen
PAY	**2.90**	3.59	1.56	Kipp & Zonen
SON	**2.90**	3.65	13.89	Kipp & Zonen/Hukseflux
TOR	**2.90**	3.64	5.29	Kipp & Zonen

The distinction between the ARM and the BSRN datasets in calculating the inherent radiometer uncertainty (U_R) is summarized below. The inherent radiometer uncertainty for both the ARM and the BSRN stations is calculated using the specification provided for Class A radiometers in ISO 9060 (ISO 2018), whereas the ARM stations have documented calibration uncertainty. The calibration uncertainty, which is an integral part of the SUNI process in calculating the radiometer uncertainty, is only provided for the ARM stations; therefore, the SUNI software allows the use of a default calibration uncertainty for a radiometer class when actual values are not available, which is the case for the BSRN stations. This is shown in Table 7, where the radiometer uncertainty is the same for all stations containing Class A radiometers.

3.3.3 Reference Cell for PV Applications

In principle, a well-matched PV reference cell deployed near a PV plant in any geographic location provides an accurate measurement of the effective irradiance (the irradiance that generates current in the PV modules) over the full range of operating conditions: temperature, cloudiness, sun position, season, etc. This contrasts with broadband irradiance measurements from pyranometers, which must be processed using a variety of models to estimate the effective irradiance. Good reference cell measurements can eliminate these modeling steps and thereby remove the models' contribution to uncertainty in various project planning and evaluation activities.

The advantage of measuring effective irradiance as opposed to using models is particularly relevant for evaluating the contribution of the reflected radiation to the performance of bifacial modules and systems. Both directional and spectral distributions of reflected radiation strongly differ from the front-side irradiance, and there are currently no practical models to translate rear-side pyranometer measurements into rear-side effective irradiance.

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In practice, however, commercial PV reference cells and PV modules vary considerably in operating characteristics, and details about those characteristics are difficult to come by; therefore, it is impossible to choose a well-matched cell or to evaluate how well matched a given cell is. A poorly matched reference cell might still provide a more accurate measurement than a model using pyranometer measurements, but if the relevant characteristics are unknown, the uncertainty of using it remains needlessly high.

Two additional aspects are important for good reference cell measurements: accurate calibration and long-term stability. This is no different from any other measurement, but few studies have examined these qualities of commercial reference cells.

During this cycle, SRRL team and PV Performance Labs published a report on PV reference cell performance, *Report on a Baseline Performance Reference for Irradiance in PV System Applications* (Driesse, Habte, and Sengupta 2024). This report is described in the following.

PV cells (and therefore modules and arrays) respond in a complex manner to the complex variables that define their operating environment. Irradiance has spatial and spectral dimensions that interact with the spectral-angular response of cells, which is, in turn, is modified by the 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 device characteristics.

PV reference cells for irradiance measurements 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 cells and the 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 the faults of such a module. But it is less useful for detecting faults in other module types or for comparing performance with different module types that have their own different matching reference cells. A more neutral common reference device is needed for such tasks.

Pyranometers are neutral and well-defined reference devices for irradiance measurements, but 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 fluctuate strongly. 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.

Thus, there is a need for a well-defined generic PV reference cell whose characteristics are close enough to most operational PV devices to make it possible to have stable performance indicators with low uncertainty, but whose characteristics are not necessarily identical to any of them.

Figure 19 illustrates the essence of this idea using relative distances to indicate magnitudes of differences. The blue flag represents the well-defined broadband 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, and the proposal is to plant a new flag on the right to serve as a new well-defined reference quantity for outdoor PV measurements, which is called the

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baseline performance reference (BPR). 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.

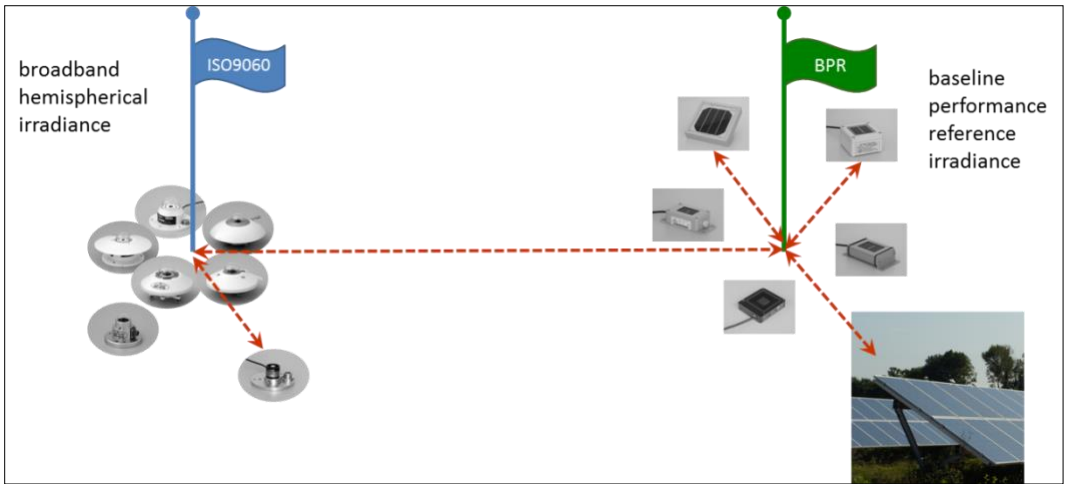

Figure 19. High-level view of the irradiance measurement landscape.

Photo by NLR

The distance separating different devices represents the differences in the operating characteristics. A well-defined broadband irradiance measurand is on the left (blue flag), and the BPR cell standard is 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.

An additional 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 time series of measurements to be quantified, like 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, 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.

Another report (Driesse et al. 2025) details observations about the stability of a set of 22 commercial reference cells that have been in continuous operation for a period of 4 years at the SRRL site. The 22 reference cells at the SRRL represent 10 different models from six manufacturers. They are divided into three sets or groups: one set mounted at a fixed 40° tilt facing south (S40), one set mounted on a single-axis tracker (TR1), and the third set mounted on a dual-axis tracker (TR2). Details are given in Table 8, and Figure 20 shows the physical arrangements.

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Table 8. PV Reference Cells Under Evaluation at the SRRL

Company	Model	Cell Type	Short ID	Fixed Tilt (S40)	Single Axis (TR1)	Dual Axis (TR2)
Atonometrics	810226-02	Mono	RC18	Yes	Yes	Yes
Atonometrics	810226-03	Mono (filtered)	RC18-F	Yes		Yes
EETS	RC01	Mono	RC01	Yes	Yes	Yes
Fraunhofer ISE	511311102	Mono	WPVS	Yes		Yes
IKS Photovoltaik	ISET	Mono	ISET	Yes	Yes	Yes
IKS Photovoltaik	ISET-poly	Poly	ISET-P	Yes		
IKS Photovoltaik	ISET-amorphous	Amorphous	ISET-A	Yes		
IMT	Si-mV-85-PT1000	Mono	Si2	Yes	Yes	Yes
NES	SOZ-03	Mono	SOZ-03	Yes	Yes	Yes
NES	SOZ-03-P	Poly	SOZ-03-P	Yes		

Figure 20. Reference cells installed for field observations at the SRRL.

Photos by NLR

The 22 reference cells deployed at SRRL exhibited varying degrees of stability over 4 years of continuous observation. Differences in stability were not random, but rather clearly associated with different products and manufacturers. The three units of the three most stable products drifted apart by no more than ±0.04%/year during the 4-year period, whereas the least stable unit degraded by more than −0.4%/year (Figure 21 shows an example of the result). Despite the clearly noticeable differences between products, all specimens meet the requirements of ISO 9060 Class A pyranometers.

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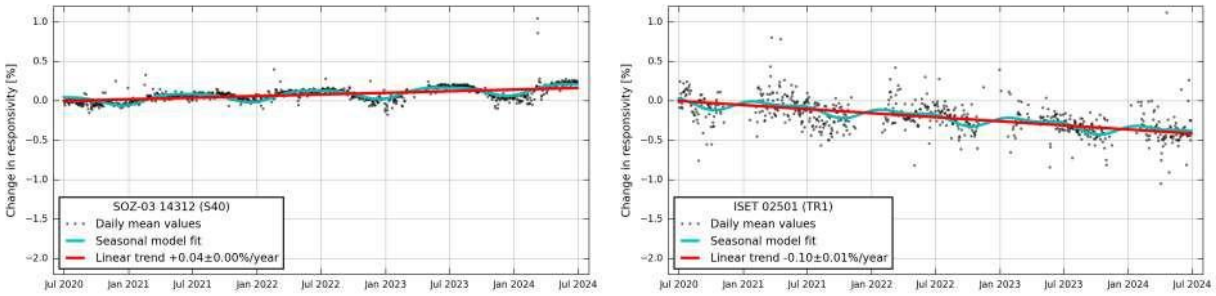

Figure 21. Example stability charts for two PV reference cells

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