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Global horizontal spectral irradiance and module spectral response measurements: an open dataset for PV research

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ABSTRACT

This report describes the creation process and final content of a spectral irradiance dataset for Albuquerque, New Mexico accompanied by a set of spectral response measurements for modules deployed at the same location. The spectral irradiance measurements were made using horizontally mounted spectroradiometers; therefore, they represent global horizontal irradiance. The dataset combines non-continuous spectroradiometer and weather measurements from a two-year period into a single calendar year. The data files are accompanied by extensive metadata as well as example calculations and graphs to demonstrate the potential uses of this database. The spectral response measurements were carried out by the National Renewable Energy Laboratory using 12 commercial silicon modules types that are undergoing long-term evaluation at Sandia National Laboratories in Albuquerque.

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ACRONYMS AND DEFINITIONS

Abbreviation	Definition
DHI	Diffuse horizontal irradiance
DNI	Direct normal irradiance
GHI	Global horizontal irradiance
GNI	Global normal irradiance
NetCDF	Network Common Data Form
NREL	National Renewable Energy Laboratory
PSEL	Photovoltaic Systems Evaluation Laboratory
QE	Quantum Efficiency
SNL	Sandia National Laboratories
TMY	Typical Meteorological Year

1. INTRODUCTION

The Photovoltaic Systems Evaluation Laboratory (PSEL) at Sandia National Laboratories (SNL) in Albuquerque, NM has measured global horizontal spectral irradiance nearly continuously from September 2019 to March 2022. During this time other broadband irradiance measurements (global horizontal, direct normal, diffuse horizontal and global normal) and weather variables were also recorded. For this dataset PV Performance Labs has pulled together data from both sources to assemble a partial calendar year spectral dataset for use in photovoltaic research. It is composed of twelve segments of 15 days each (180 days total), evenly distributed throughout the calendar year, but taken from different years (2019, 2020 and 2021).

To support evaluation and investigation of the influence of spectrum on PV module performance, either at SNL or at other sites where spectral irradiance is measured, SNL has obtained the assistance of the National Renewable Energy Laboratory (NREL) to measure the spectral responses of 12 commercial Silicon based PV modules. These measurements are distributed as part of the dataset.

2. SPECTRAL IRRADIANCE

2.1. Instruments and measurements

The PSEL facility has a comprehensive set of instruments to record irradiance and other weather parameters. These are located on a building roof at 35.0545° N, 106.5401° W and elevation 1660 m. These instruments include a pair of spectroradiometers, EKO MS710 and EKO MS712 (see Figure 1) which have been operated in a horizontal position since September 2019. Spectra were recorded at 5-minute intervals from shortly before sunrise to shortly after sunset, whereas the remaining instruments were scanned and recorded at 1-second intervals.

Figure 1. Pair of spectroradiometers mounted horizontally at the PSEL facility.

Table 1: Summary of instruments and parameters

Parameter	Orientation/Position	Manufacturer	Model	Additional details
Spectral irradiance	Global horizontal (GHI)	Eko instruments	MS710	~350-925 nm
			MS712	~925-1700 nm
Broadband irradiance	Global normal (GNI)	Kipp & Zonen		
	Global horizontal (GHI)	Kipp & Zonen		Using Sandia zenith correction
	Diffuse horizontal (DHI)	Kipp & Zonen		On separate tracker
	Direct normal (DNI)	Kipp & Zonen	CHP1	Using Sandia temperature correction
Temperature	Inside aspirated shield	Climatronics	100093	Accuracy: ±0.1°C
Humidity		Climatronics	102273	Accuracy: ±1%
Wind speed	10 m height	Climatronics	102083	Accuracy: ±0.11 m/s

2.1.1. Calibrations

The pair of spectroradiometers was newly installed in 2013 and calibrated by the manufacturer. They were subsequently calibrated at NREL in early 2022 and deviations from the original calibrations were determined to be only minor, indicating excellent stability over the long period of continuous deployment.

The pyranometers and pyrheliometer were calibrated annually at Sandia Labs with traceability to the World Radiation Reference (WRR) through two absolute cavity radiometers (ACR). For the GHI measurements, a zenith angle dependent responsivity function was used, and the DNI measurements were corrected for temperature. Both of these adjustments were derived from the calibration procedure at Sandia.

The remaining weather instruments relied on factory calibrations and were not recalibrated during the two-year period used for this dataset.

2.2. Data processing

2.2.1. Spectrum selection

Despite best efforts, the spectroradiometer data collection was not free of gaps during the measurement period. Sometimes just one or two spectra were missed in a day, whereas other times the instruments were offline for several days in a row. As a result, it was not possible to assemble a complete calendar year, even by selecting different days from different years. Instead, a partial calendar year was assembled by collating 12 evenly spaced 15-day periods beginning with Jan 1-15 and ending with Dec 1-15. Thus 180 days are available covering the full range of sun positions and seasonal conditions.

This assembly of segments resembles a typical meteorological year (TMY), which uses 12 fixed duration segments (calendar months). However, unlike the TMY, the available data did not span a long period and actual weather conditions did not influence the selection process, therefore this spectral year cannot be deemed typical.

2.2.2. Spectrum reduction

The raw spectral measurements are recorded at 1246 unevenly spaced wavelengths beginning with 349.419 nm and ending with 1700.3093 nm. With spacing between 0.7 and 1.9 nm the recorded spectra are somewhat oversampled with respect to optical resolution, which can be represented by a Gaussian window with a full-width-half maximum (FWHM) specification of 7 to 8 nm. (See Figure 2.) Thus the spectra could be resampled with fewer points without losing information.

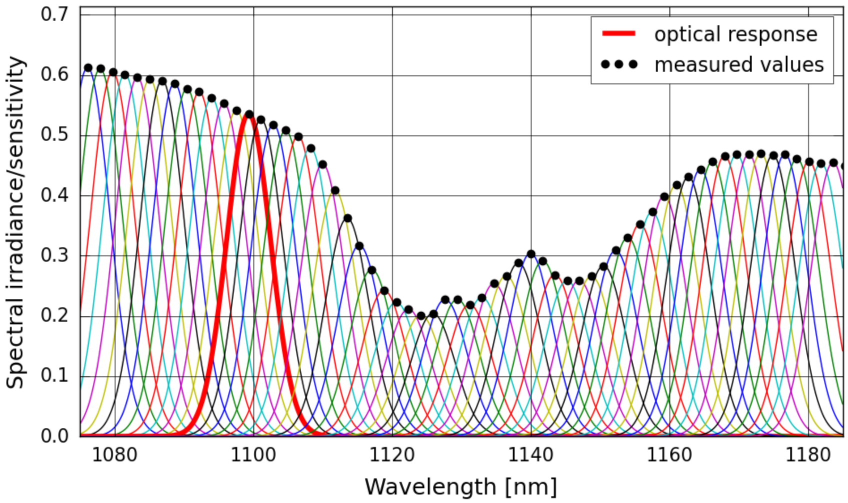

Figure 2. Illustration of the optical resolution of the spectroradiometer in relation to the wavelength interval of the measurements.

A second observation is that there are some fluctuations between adjacent wavelengths in the measurements especially near the lower end of the range of each instrument. Since these are beyond the resolution of the optics, they are clearly measurement noise. This should be filtered out, if possible.

The potential choices for resampling and filtering are many, but we must also consider the intended application: photovoltaic studies (as opposed to analysis of atmospheric conditions). This means that the spectral irradiance will be multiplied by the spectral response of photovoltaic devices and integrated over wavelength in order to calculate total photo-current or spectral mismatch factors. Random noise is automatically attenuated in this process; and since spectral response of PV devices have few if any high-resolution features and are typically measured at lower wavelength resolutions, high-resolution features of the spectral irradiance do not influence the integrated values either. The most important feature of the spectral response is the rapid drop around the band-gap energy, which is still gradual enough that it spans a range of 100 to 300 nm.

Thus, it is possible to reduce the wavelength resolution without undermining the objectives for the dataset. The motivation for creating this dataset is to make spectral irradiance data more widely accessible. Accessibility includes ease of use; therefore both resampling to uniformly spaced wavelengths and reduction of file size are desirable.

The chosen wavelength interval is 5 nm, which corresponds to the highest resolution photovoltaic cell spectral response measurements that we are aware of, from the German national metrology laboratory PTB. As such, the final spectra have 271 wavelengths from 350 to 1700 nm. In the process of down sampling, a Gaussian smoothing kernel with FWHM 6.6 nm was used so that the final data correspond to what would have been measured with an instrument having an optical resolution of 10 nm and sampling interval of 5 nm (See Figure 3). Figure 4 shows the processed spectra over the course of a sunny day.

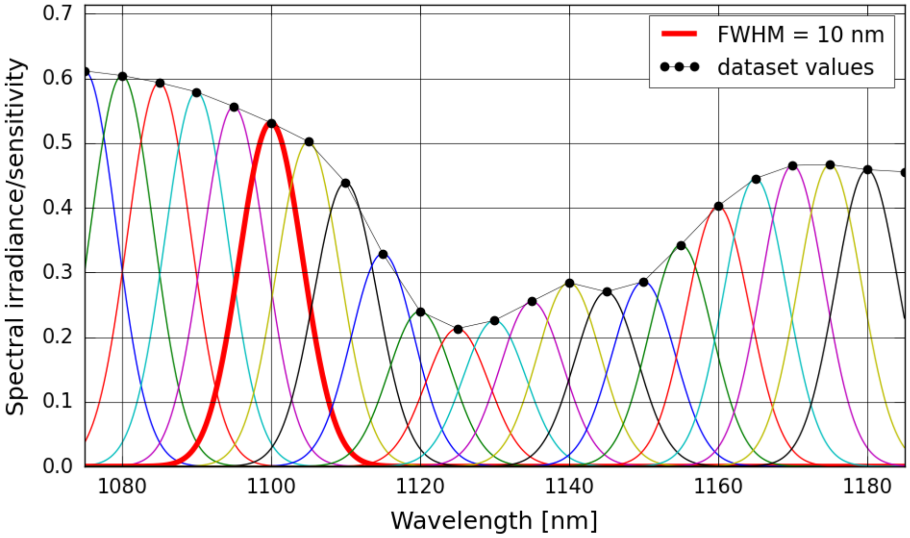

Figure 3. Illustration of the effective resolution in relation to the wavelength interval for the dataset.

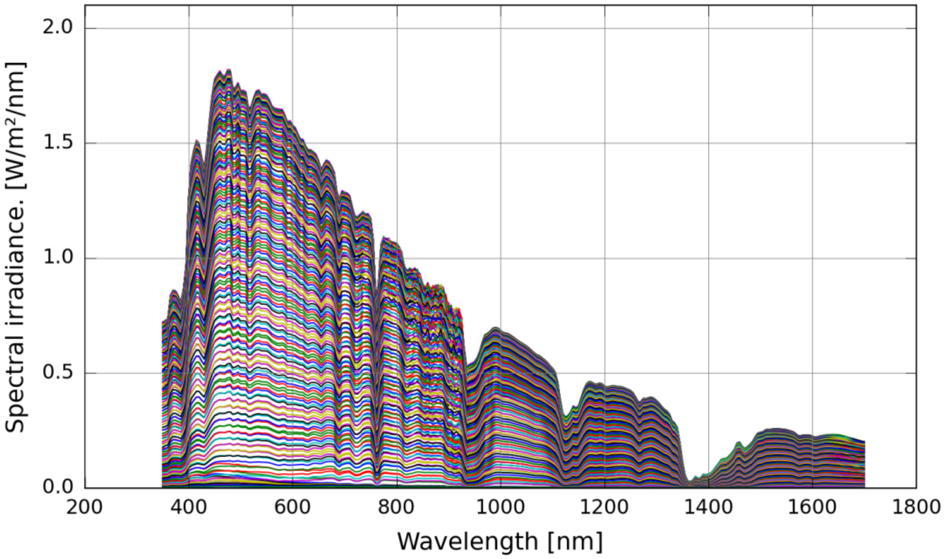

Figure 4. Spectral irradiance over the course of a sunny day (June 11, 2021).

2.2.3. Corresponding broadband irradiance

As the spectra are recorded precisely every 5 minutes, it is most useful to provide broadband values taken simultaneously rather than one- or five-minute averages. The broadband irradiance was measured nominally every second, so these simultaneous values are usually available. Gaps shorter than 15 seconds are filled using monotonic polynomial interpolation, whereas gaps of longer duration are considered missing, and these records are excluded from the dataset.

This approach takes care of providing synchronized measurements but does not alleviate the problem that the response times of the broadband thermopile instruments are slower than that of the spectroradiometer. Thus, under rapidly changing conditions, the integrated spectral irradiance will deviate further from the broadband measurements. Such conditions can be identified with a stability indicator, which is explained in the following section.

2.2.4. Stability indicator

Under windy and partly cloudy conditions, irradiance levels can change so rapidly that a single recorded spectrum no longer represents a stable condition and broadband instrument values are inconsistent with each other because their response times differ. To rate the stability of the measurement conditions, therefore, an additional irradiance value is calculated, *dni_range*. This records the difference between the maximum and minimum DNI in a 15 s window surrounding each spectral measurement. We have observed that a threshold of 10 W/m^2 is a good starting point for separating the stable times from the unstable in this data set. Note that even in overall stormy weather a brief, well-timed break in the clouds will be identified as stable: it is an indicator for the measurement stability, not the overall weather stability.

3. MODULE SPECTRAL RESPONSE

The calculation of spectral mismatch requires not only measured spectral irradiance, but also a reference spectrum and of course the spectral response of a PV cell or module. This dataset includes 12 spectral response curves for 12 commercial silicon module types that are deployed at SNL in Albuquerque.

3.1. Modules and measurements

The modules chosen for evaluation were originally purchased by SNL for the PV Lifetime project (renamed to Systems Long-Term Evaluation [SLTE]). The majority of those modules are deployed outdoors for long-term evaluation, but several modules of each type were placed in storage for future comparison purposes. One stored module of each type was sent to NREL for the spectral response measurements (Table 2).

Table 2: List of module types for which spectral responses were measured

Manufacturer	Model	Type
Canadian Solar	CS6K-275M	mono-Si
Canadian Solar	CS6K-270P	poly-Si
Itek Energy	IT-360-SE72	mono-Si PERC
Jinko Solar	JKM260P-60	poly-Si
LG	LG400Q1C-A6	mono-Si N-type IBC
LG	LG320N1K-A5	mono-Si N-type PERT
Mission Solar	MSE300SQ5T	mono-Si PERC
Panasonic	VBHN325SA 16	mono-Si HIT
Qcells	Q.PLUS BFR-G4.1 280	poly-Si PERC
QCells	Q.PEAK-G4.1 300	mono-Si PERC
Solaria	400R-PM	mono-Si shingle
Trina Solar	TSM-PD05.08	poly-Si

NREL used the recently developed Module Quantum Efficiency (QE) test bed, which is described by Kopidakis et al. [1]. What makes this system unique is that it scans the entire module automatically, taking one or more measurements on each cell. Using the mean of these measurements at each wavelength leads to improvements in spectral mismatch correction and module power measurements according to Kopidakis et al. [1] but having the individual measurements also makes it possible to identify outlier cells, which could be useful for investigating underperforming modules. All measurements were performed nominally at 25°C.

3.2. Data and processing

The data obtained from NREL for each module consist of a grid of QE values indexed by measurement position and wavelength. The number of wavelengths is fixed at 40 in the range 310 to 1195 nm whereas the number of measurement locations varied from 60 to 384 per module. The normalized QE data for one of the modules are plotted in Figure 5 showing moderate variation between cells. The standard deviation in the infrared region is about 0.04 in this example, whereas it ranges between 0.014 and 0.19 for the other modules.

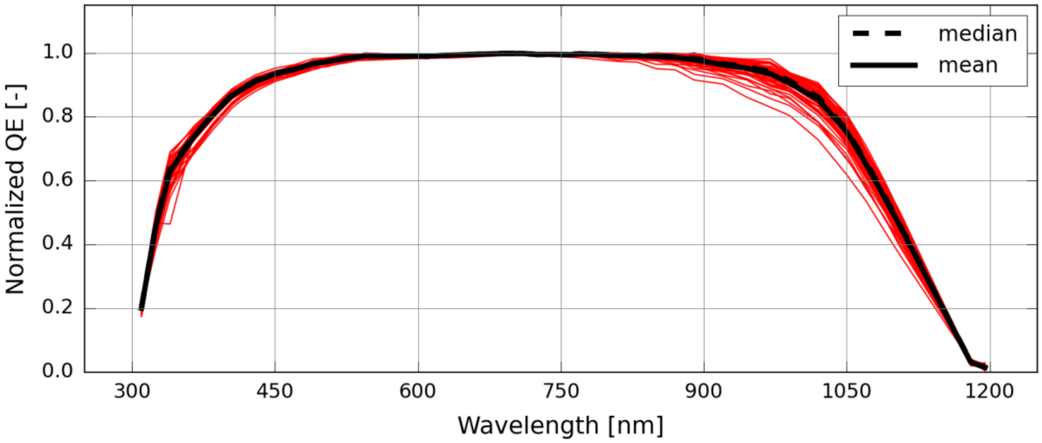

Figure 5. Quantum efficiencies of 60 cells in a module showing moderate variations between cells.

While NREL uses the *mean* QE values in spectral mismatch calculations for a specific module, we take the *median* QE values instead to produce a representative QE curve for the module type. This has the advantage of being less susceptible to outliers; however, for most of these modules the differences between mean and median are below 1%.

The median QE values are then converted to spectral response (multiplied by wavelength) and normalized. Endpoints with zero values are added at 300 nm and 1200 nm to remove potential ambiguity when calculating integrals, and finally, spectral response values are calculated at regular 5 nm intervals using monotonic cubic interpolation of the measurements. This provides consistency with the spectral irradiance data and facilitates multiplication of the two. Figure 6 shows the 12 median spectral response curves with clearly apparent technology trends.

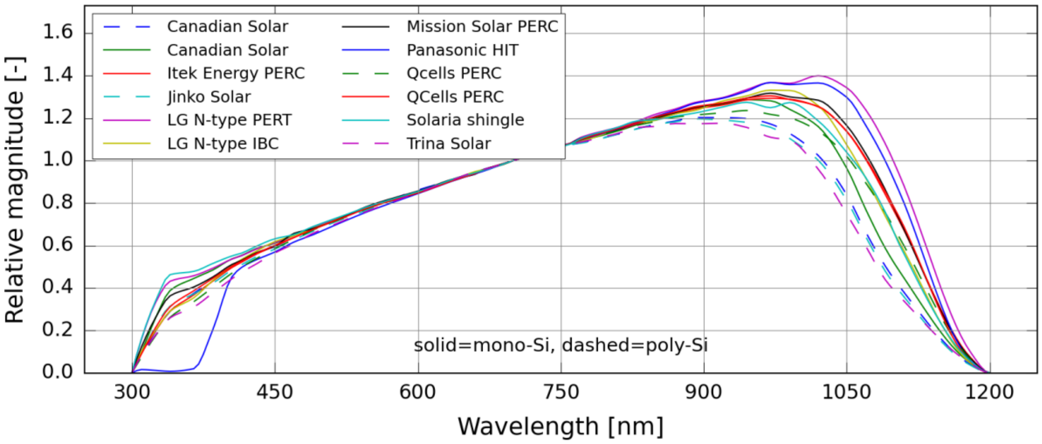

Figure 6. Spectral responses of 12 modules showing comparatively weak infra-red response in poly-Si modules and strongest infra-red response in newer mono-Si variations. Each curve represents the median SR of all solar cells within a module.

4. PRACTICAL DETAILS

4.1. File structure

Both spectral irradiance and spectral response data are made available in NetCDF format. This file format is space efficient and can accommodate multidimensional data as well as associated metadata. Libraries are available for many high-level programming languages to facilitate access to the data and metadata.

4.2. Download locations

There are two primary download locations. The first is on the website of the PV Performance Modelling Collaborative at https://pvpmc.sandia.gov/ [2]. The second is on the Duramat Datahub at https://datahub.duramat.org/project/about/spectral-irradiance-data-and-resources [3].

5. AUTHOR CONTRIBUTIONS

Anton Driesse: Conceptualization, methodology, data curation, software, visualization, writing – original draft. Marios Theristis: project administration, supervision, writing – review and editing Joshua Stein: Conceptualization, funding acquisition, resources, project administration, supervision, writing – review and editing.

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