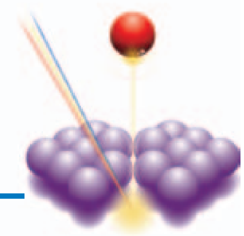
Measurements & Characterization • National Center for Photovoltaics

Device Performance



We measure the performance of PV cells and modules with respect to standard reporting conditions—defined as a reference temperature (25°C), total irradiance (1000 Wm^{-2}), and spectral irradiance distribution (IEC standard 60904-3). Typically, these are "global" reference conditions, but we can measure with respect to any reference set.

To determine device performance, we conduct two general categories of measurements: spectral responsivity (SR) and current versus voltage (I-V). We usually perform these measurements using standard procedures, but we develop new procedures when required by new technologies.

We also serve as an independent facility for verifying device performance for the entire PV community. We help the PV community solve its special measurement problems, giving advice on solar simulation, instrumentation for I-V measurements, reference cells, measurement procedures, and anomalous results. And we collaborate with researchers to analyze devices and materials.

A2LA ACCREDITED

certificate number 2236.01
Accredited for primary reference cell, secondary reference cell, and secondary module calibration

Our facility for calibrating primary reference cells is one of four facilities certified in accordance with the world photovoltaic scale and that cooperates internationally to provide the PV community with a path of traceability to standards. We are accredited by the American Association for Laboratory Accreditation (A2LA) to ISO-17025 standards for primary reference cell, secondary reference cell, and secondary module calibrations for samples that meet the requirements. We help develop consensus U.S. and international PV standards through participation in ASTM and IEC standards groups.

TYPICAL MEASUREMENT FLOWS

For devices that come to us for measurement, we typically follow a procedure that ensures quality measurement and follow up. After logging in the device based on information from a cover letter or request form, we measure its area, which is crucial for determining its efficiency. We then obtain its spectral responsivity. For cells, we measure the spectral responsivity with one of two systems. For modules, however, spectral responsivity is generally provided to us by the manufacturer or we measure it on a representative cell.

Next, we use the information on spectral responsivity to calculate the spectral mismatch between the test device and a primary reference cell for the simulator that will be used for the subsequent I-V measurement. This is done because the intensity of the light source in a simulator system is set with a reference cell; and the correction factor for the spectral mismatch enables measurement of the sample's performance with respect to a reference spectrum.

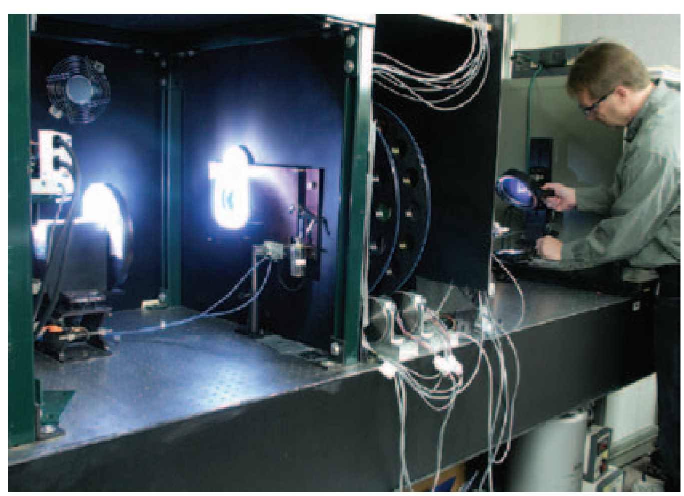
We then measure the I-V characteristics of the device under simulated conditions. For modules, we also measure I-V performance under natural sunlight, which enables us to determine module response under "real" conditions. After measurement, the results are translated to standard conditions. For concentrator cells, we measure the I-V characteristics as a function of light level. We can also adjust the spectrum to a limited extent for multijunction concentrators to make the current matching as close as possible to reference conditions.

After all measurements have been made, we carefully review the results for anomalies or procedural errors. Finally, we prepare a report for the client—which can be as simple as a presentation of data tables or as involved as a document that contains description, analysis, data, and recommendations.

SPECTRAL RESPONSIVITY (SR) SYSTEMS

Spectral responsivity systems measure how a device responds to selected narrow (spectral) bands of irradiance. Responsivity is measured in units of AW^{-1} versus wavelength and reported in terms of quantum efficiency (QE)—a measure of how efficiently a device converts incoming photons to charge carriers in an external circuit. These systems measure the spectral response at different temperatures (10° to 80°C) voltages (±15 V), light levels (0 to few suns), and different chopping frequencies (<0.2 to 400 Hz).

We use two SR systems—a grating system and a filter system. The grating system is used for applications where a narrow bandwidth and wavelength interval is required. The grating system has a typical minimum beam size of 1 mm x 3 mm, making it ideal for absolute spectral responsivity measurements. The filter system is used for solar cells and modules and has much more power in the beam, with a 10-nm typical bandwidth, but has a 20- to 50-nm wavelength interval from 290 to 2000 nm.



Mike Linenberger/PIX14476

Spectral responsivity measurement system using 10-nm-bandwidth interference filters

MAJOR INSTRUMENTATION FOR SPECTRAL RESPONSE MEASUREMENTS

System	Typical Applications	Special Features	Light Source	Wavelength Range	Bandwidth	Voltage Bias	Light Bias
Grating spectral responsivity	SR measurements for small-area TPV cells	3 gratings for visible and IR; adjustable chopping frequency	250-W tungsten	400 to 3,000 nm	>1 nm FWHM	±5 V	Up to 200 mA
Filter spectral responsivity	SR measurements for solar cells and modules	High flux density; variable beam size; 61 filters on four filter wheels; adjustable chopping frequency	1-kW Xe	280 to 1,900 nm	10 nm FWHM	±40 V	Up to 200 mA

Although important differences exist between the two systems, the basic procedures are similar: A wide-spectrum light source is chopped and filtered or diffracted into a discrete succession of narrow spectral bands, each of which is directed onto the test device. The device current produced from the monochromatic light is converted to an ac voltage signal. A lock-in amplifier locks into the chopper frequency of the light signal and measures the corresponding ac voltage produced by the light. Using a time-periodic light signal and a lock-in amplifier allows us to distinguish signals produced by the relevant spectral band from those that may be produced by other light sources.

Each system is controlled by a computer. Once the operator sets the parameters, the computer does the rest—runs the procedure through the selected wavelength range, acquires the data, calculates QE, saves the data, and updates the directory in a standardized manner as a tab-delimited text file.

CURRENT VERSUS VOLTAGE (I-V) SYSTEMS

I-V measurement systems determine the output performance of devices, including: open-circuit voltage (V_{oc}), short-circuit current (I_{sc}), fill factor (FF), maximum power output of the device (P_{max}), voltage at maximum power (V_{max}), current at maximum power (I_{max}), and conversion efficiency of the device (η). Some I-V systems may also be used to perform dark I-V measurements to determine diode properties and series and shunt resistances.

For cells, we use three I-V systems to measure performance: two systems for solar concentrator cells—a continuous-illumination concentrator and a high-intensity pulsed solar simulator—and a Spectrolab X-25 solar simulator for non-concentrator solar cells and multijunction devices. The Spectrolab X-25 test stage also accommodates small modules.

For modules, we use four I-V systems. Two systems are used for measurements under simulated conditions: a Spire 240A pulsed solar simulator and a large-area continuous solar simulator. And two are used for measurements under outdoor conditions: the standard outdoor measurement system and the Daystar DS-10/125 portable I-V curve tracer.

All I-V measurements are made using 4-terminal Kelvin connections. This enables the use of separate channels for voltage and current measurements, which minimizes measurement errors by eliminating voltage-drop losses that could result from resistances due to cables, connections, and wiring.

All I-V systems use data acquisition systems and custom software for accurate standardized PV measurements. This includes algorithms developed by the group over the years for calculating I-V characteristics and, for most systems, for making the spectral-mismatch corrections. The custom I-V systems and flash simulators use separate meters for measuring voltage, current, and intensity; this allows us to correct the current for intensity fluctuations. The custom systems all have multiple current ranges, allowing dark I-V on cells and modules to be routinely measured.

The combined systems capabilities allow us to accurately measure the characteristics of any conceivable photovoltaic cell or module technology. The overlapping capabilities of many of the systems allow for cross checking and understanding the various error sources of the test beds.

Continuous Illumination Concentrator

This system has two light sources, giving it the dual capability of measuring concentrator solar cells and thermophotovoltaic (TPV) cells. For concentrator cells, it uses a 1-kW short-arc xenon lamp. The light from the xenon source is reflected off a mirror onto a concentrator lens mounted on a translation stage. The system can be adjusted to achieve concentration ratios of 0.1 to 200 suns over an area that ranges from 4 cm^2 to less than 0.1 cm^2.

For TPV measurements, the system uses a 3-kW tungsten light source. The high infrared (IR) range of this light source makes it suitable for TPV cells, which have low bandgaps and respond best to the IR portion of the spectrum.

MAJOR INSTRUMENTATION FOR CELL I-V MEASUREMENTS

System	Typical Applications	Special Features	Light Source	Test Bed	Voltage Resolution/Limit	Current Resolution/Limit
Continuous illumination concentrator	I-V measurements for concentrator and TPV cells	Spectrally adjustable; user-controlled bias conditions	1-kW Xe or 3-kW tungsten; 0.1 to 200 suns	~1-cm diameter for Xe, 5 cm x 10 cm for IR lamp; 5° to 80°C	5 µV to ±10 V	±1 µA to ±10 A
High-intensity pulsed solar simulator	I-V measurements for concentrator and TPV cells	Spectrally adjustable; minimal heating	2 Xe flash lamps 30 cm long with mirror; 1 to 2000 suns	10 cm x 10 cm; 5° to 80°C	0.1 mV to 100 V	500 µA to 50 A
Spectrolab X-25 solar simulator	1-sun I-V measurements for cells and small modules	Spectrally adjustable; wide current and voltage ranges	Spectrolab X-25 filtered 3-kW Xe; 0.2 to 10 suns	30 cm x 30 cm; 5° to 50°C	5 µV to ±50 V	±10 pA to ±16 A

MAJOR INSTRUMENTATION FOR MODULE I-V MEASUREMENTS

System	Typical Applications	Special Features	Light Source	Test Bed	Voltage Resolution/Limit	Current Resolution/Limit
Spire 240A pulsed solar simulator	I-V measurements (1-sun modules) under simulated conditions	Commercial system; 25°C (20° to 60°C possible)	Spire 240A Xe flash lamp; 0.15 to 1.3 suns; filtered to AM1.5 global spectrum	61 cm x 122 cm	0.1 mV to 100 V	0.5 mA to 20 A
Large-area continuous solar simulator	I-V measurements (1-sun modules) under simulated conditions	User-controlled bias conditions	Spectrolab X200 filtered 20-kW Xe lamp; 0.1 to 20 suns	152 cm x 122 cm	5 μV to ±300 V	±1 μA to ±60 A
Standard outdoor measurement system	Flat-plate and concentrator I-V measurements under outdoor conditions	2-axis positioning; meteorological parameters; spectral irradiance measured; user-controlled bias	Sunlight	200 cm x 300 cm	5 μV to ±300 V	±1 μA to ±60 A
Daystar DS-10/125 portable I-V curve tracer	I-V measurements under outdoor conditions	Portable; may be powered either with a 120 V_{ac} line or with a 12 V_{dc} battery	Sunlight	unlimited	12 mV to 600 V	5 mA to 125 A

High-Intensity Pulsed Solar Simulator (HIPSS)

The HIPSS is a commercial system with a temperature-controlled vacuum plate that has an electrically isolated voltage contact and that can accommodate 10 cm x 10 cm cells. The system is used to measure I-V characteristics of both concentrator solar cells and TPV cells. Its light source is two low-pressure xenon arc lamps that are adjusted between 1200 and 3200 V. They deliver 1-ms pulses of light with an intensity of up to 2 x 10^6 Wm^{-2} and a spatial nonuniformity of ±3% over the area of 17 cm x 3 cm. The beam is adjustable to provide concentrations of 1 to 2000 suns.

Spectrolab X-25 Solar Simulator

This test bed is used to measure the 1-sun I-V characteristics of all cells we evaluate. The Spectrolab X-25 measures I-V characteristics of PV cells as large as 30 cm x 30 cm. It uses a 3-kW xenon arc lamp filtered to provide a standard AM1.5 Global reference spectrum (IEC 60904-3 Class A). The irradiance is adjustable from 0.2 to 10 suns (for smaller areas) and has a spatial uniformity of ±3% at 1-sun (i.e., at a beam diameter of 30 cm x 30 cm). The spectral irradiance of the unit is adjustable with filters to achieve current matching for 2- and 3-junction cells. The test device and monitor cell temperatures are controlled separately.

Mike Linenberger/PIX14458

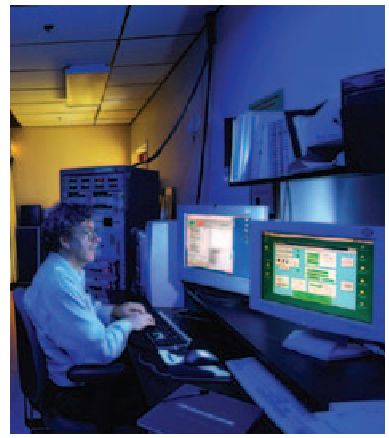
ISO 17025 accredited test bed for calibrating secondary reference cells

The measurement uncertainty for device efficiency ranges from ±2% to ±5%, depending on sample size, geometry, and number of junctions. This range takes into account the ±1% uncertainty of the reference cell, and the uncertainties in the spectra, intensity, spectral mismatch, and electronics.

Spire 240A Pulsed Solar Simulator

This simulator uses a long-arc pulsed xenon lamp, flashed at a maximum rate of 15 Hz, that is filtered to simulate the global reference spectrum (IEC60904-3, class A), and whose irradiance has a spatial nonuniformity of ±3% over an area of 61 cm x 122 cm. Temperature measurements are made with a spring-loaded thermocouple in contact with the back of the module. The original software has been modified to store data and update the directory in our standardized tab-delimited text format.

Temperature coefficients can be measured using an adjustable heating blanket. The I-V characteristics as a function of lamp intensity in the range of 0.15 to 1.3 suns can be measured using screen filters.



Jim Yost/PIX14091

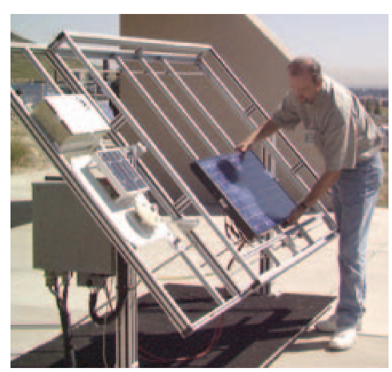
Large-area continuous solar simulator (LACSS)

Large-Area Continuous Solar Simulator (LACSS)

The large-area continuous solar simulator (LACSS) is a custom-designed system that is used for measuring module performance. It uses a Spectrolab model X200 continuous 20-kW xenon short-arc lamp to provide a filtered light source to simulate the global spectrum (IEC 60904-3, class A). It is capable of measuring modules as large as 152 cm x 122 cm with spatial nonuniformity of ±3%. Sample temperature is measured with a spring-loaded, type T thermocouple at the back of the module.

Standard Outdoor Measurement System (SOMS)

The standard outdoor measurement system is our principal system for measuring module performance under prevailing outdoor conditions. We attempt to make these measurements under a clear sky, with the irradiance between 950 and 1050 Wm^{-2}, and as close to 25°C as possible. For each measurement, we use a pyranometer and a silicon reference cell in a module package to determine the total irradiance, and a spectroradiometer to determine spectral content of the sunlight between 350 and 1100 nm. Once the parameters have been set by the operator, the system



Measurements and Characterization Team

Standard outdoor measurement system (SOMS) measures the I-V characteristics, the temperature (using a thermocouple at the back of the module), and calculates other performance characteristics.

Prototype Concentrator Evaluation Test Bed

We use this test bed to evaluate I-V characteristics throughout the day of prototype concentrator cells and modules. The site includes instruments to measure sample and air temperature, wind speed, and direct-beam irradiance. The system also records data from the RMIS meteorological station (see http://rmis.nrel.gov) with the individual module I-V curves. The data are analyzed for performance as a function of time, temperature, and light level. This test bed data set is also used to evaluate translation equations and energy rating methods.

James Kiehl/NREL

Prototype concentrator evaluation test bed contains prototype cell assemblies on right and variety of lens and mirror-based concentrator modules on left

Daystar DS-10/125 Portable I-V Curve Tracer

Like the SOMS, this system is used to make module I-V measurements under prevailing outdoor conditions. But typically, we only use it when the sample is too cumbersome or impractical to disassemble and remount on the SOMS test bed. Total irradiance is measured using a pyranometer mounted in the same plane as the sample.

SHORT-CIRCUIT CURRENT LINEARITY WITH IRRADIANCE

To rate photovoltaic devices, a reference detector is required whose response is linear with total irradiance. The detector determines the linearity of the short-circuit current (I_{sc}) versus the total irradiance (E_{tot}) by illuminating a reference cell with two lamps. The irradiance range is about 0.01-sun to several suns. A device is linear if the current measured with both lamps illuminating the cell is the same as the sum of the currents with each lamp illuminating the cell. The two-lamp method is insensitive to the light spectra or spatial nonuniformity changing with irradiance.

PRIMARY REFERENCE CELL CALIBRATION

We calibrate primary reference cells for in-house use, for use by other national laboratories, and to provide our clients and partners with a path for traceability to standards. Our laboratory is one of only four facilities in the world certified to calibrate reference cells in accordance with the world photovoltaic scale, and these measurements are accredited to ISO 17025 standards.

Most of the cells we select for calibration are obtained from organizations that have established reputations for making cells for reference and whose cells have a history of high quality and stability. When we make a reference cell for calibration, we carefully choose materials and structures. We then make the cell in accordance with stringent procedures that ensure quality and stability. Once we make or obtain a reference cell, we subject it to carefully devised calibration procedures that minimize errors due to measurement errors due to spectral correction.

To calibrate the cells, we concurrently measure short-circuit current, total irradiance, and spectral irradiance outdoors with the same field of view (5.0°). Total irradiance is measured with an Eppley HF primary absolute cavity radiometer. Spectral irradiance is measured with a LICOR LI-1800 spectroradiometer. From these measurements, we calculate an average uncorrected calibration value, which relates the cell's short-circuit current to total irradiance. The atmospheric parameters and cell temperature are also measured. Once a valid calibration value is obtained, the short-circuit current is corrected for temperature and spectrum to the standard conditions.

Jim Yost/PIX14100

Test bed for calibrating primary reference cells

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Innovation for Our Energy Future

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