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 four facilities in the world that are certified to calibrate reference cells in accordance with the world photovoltaic scale.

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 assure 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 and errors due to spectral correction.

NREL has unique capabilities to calibrate reference cells. Part of the calibration process involves concurrently measuring spectral irradiance, total irradiance, and a cell's short-circuit current under outdoor conditions.

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. The resultant calibrated cell is equally applicable to global, direct, and AM0 reference spectra.

Because the measurement of spectral irradiance does not encompass the limits of the reference spectrum, we use a computerized atmospheric transmission model and extraterrestrial spectra to extend the measured spectrum to cover the range of the reference spectrum (300-4000 nm).

We compute the calibration value at least 20 times for at least 3 separate days to arrive at a single calibration value. To ensure that the calibration uncertainty is within ±1%, we perform uncertainty analyses and compare our results and methods with those of other agencies.

We periodically recalibrate our cells and make intercomparisons. Those cells that do not meet the stability requirements (±1% change per year in short-circuit current) are discarded as reference cells.

NREL

National Renewable Energy Laboratory
1617 Cole Blvd., Golden, CO 80401

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Measurements and Characterization is a division of the National Center for Photovoltaics at NREL
Web site: www.nrel.gov/measurements
Phone: (303) 384-6675
Fax: (303) 384-6604

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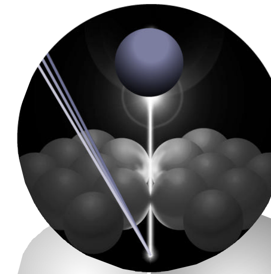


Measurements and Characterization

Device Performance

This system uses a 1000-W xenon arc lamp and 61 band-pass filters to measure the spectral response of cells and modules. (Jim Yost Photography/PIX02044.)

We measure the performance of PV cells and modules with respect to standard reporting conditions — defined as a reference temperature, total irradiance, and spectral irradiance distribution. Typically, these are *"global" reference* conditions, but we can measure with respect to any reference set (e.g., direct normal, AM0, etc.).

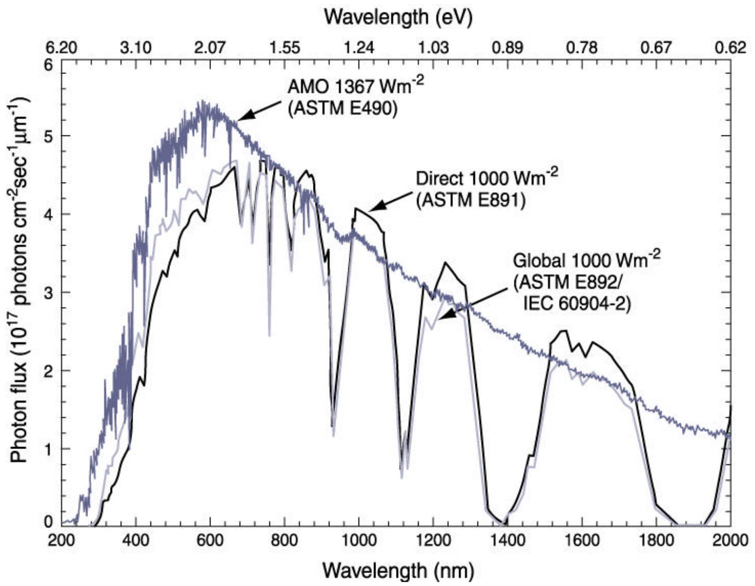
To determine device performance, we conduct two general categories of measurements: *spectral responsivity (SR)* and *current versus voltage (I-V)*. We usually perform these measurements using standard procedures. But we often use special procedures and extend the capabilities of our measurement systems to meet a client's distinct requirements.

We do more than measure and report cell and module performances. 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, measurement procedures, and anomalous results. And we collaborate with researchers to analyze devices and materials.

Our facility for *calibrating primary reference cells* is one of four facilities that are certified in accordance with the world photovoltaic scale and that cooperate internationally to provide the PV community with a path of traceability to standards. Plus, we help develop consensus U.S. and international PV standards.

Typical Measurement Flows

For devices that come to our team for measurement, we typically follow a procedure that ensures quality measurement and follow up. After first logging in the device, we measure its area, which is crucial for determining its efficiency. We then obtain its spectral responsivity. For cells, this entails measuring the spectral responsivity with one of three systems. For modules, however, spectral responsivity is generally provided to us by the manufacturer; if not, we can measure it with our filter spectral responsivity system.



Three representative standard reference spectra under which we measure the performance of PV cells and modules — global, direct normal, and AMO.

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.

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 reported in terms of *quantum efficiency (QE)* — a measure of how efficiently a device converts incoming photons to charge carriers in an external circuit.

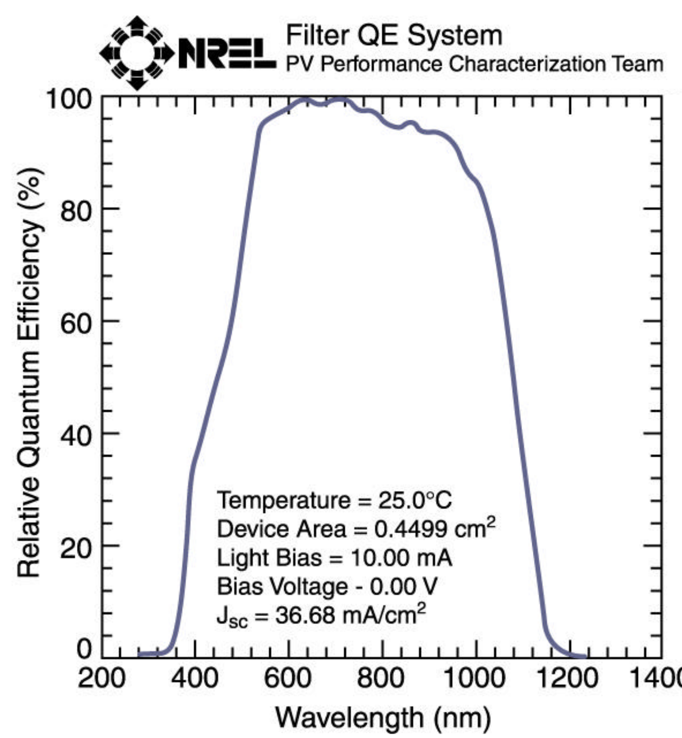
We use three SR systems — two grating systems and a filter system. One grating system is used for special cells, including thermophotovoltaic (TPV) cells. The other grating system provides high-resolution responsivity data in the ultraviolet (UV) region. The filter system is used for solar cells and modules. Although these are their typical uses, we cross-check the systems — sometimes using the TPV grating system for solar cells and the filter system for testing TPV cells under a large light-bias.

Whereas there are important differences among the three 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.

The intensity of the spectral beam is measured with a pyroelectric radiometer or a NIST-calibrated semiconductor detector. Typically, a device is measured over the range of wavelengths to which it responds. The QE of each band is calculated from the *spectral responsivity* — the light-induced current divided by the power of the incident light. Although not part of the measurement process, the product of the spectral responsivity and the spectral irradiance may be integrated to determine the cell's current density for a given reference spectrum.

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, and calculates QE.

Each system also uses a vacuum chuck and thermoelectric heat pump on the sample stage to control sample temperature between 5°C and 80°C. This allows for more accurate measurements and enables measurements to be conducted under standard conditions or as a function of temperature.



Typical output provided for spectral responsivity measurements. In this case, in which measurements were made on a world-record-efficient copper indium gallium diselenide device, the quantum efficiency is extremely high over almost the entire response range of the device.

to provide a filtered light source to simulate the AM1.5 global spectrum (ASTM E927 Class A). It is housed in a special room to permit modules as large as 152 cm x 122 cm to be measured with spatial uniformity of ±3%. Sample temperature is measured with a spring-loaded, type T thermocouple at the back of the module.

Features/Advantages

- Dark I-V measurements. Custom software enables this system to be routinely used for dark I-V measurements, for determining series and shunt resistances, and diode parameters.
- Continuous light source. Because some materials do not respond well or "truly" to pulsed solar simulation, testing a module with LACSS under continuous radiation helps to reveal false readings that may occur on other systems that measure the I-V data in less than one second.
- Temperature-controlled test bed. The system has a custom temperature-controlled bed that enables the operator to set and control temperature at any desired value. The controlled test bed also gives the system the ability to determine temperature coefficients.
- User-controlled bias conditions. The user can set conditions, such as the range and polarity of the voltage, and then test the module I-V characteristics over an extended range, under reverse or forward bias, and more.

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 W/m^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 measures the I-V characteristics, the temperature (using a thermocouple at the back of the module), and calculates other performance characteristics.

Features/Advantages

- Two-axis positioning. The system uses a custom-designed test bed that can be rotated or tilted to the desired position.
- Meteorological parameters. Wind speed, wind direction, direct and diffuse irradiance, air temperature, and barometric pressure are monitored and recorded on-site continuously.
- User-controlled bias conditions. The user can set conditions, such as the range and polarity of the voltage, and then test the module I-V characteristics over an extended range, under reverse or forward bias, and more.
- Reference-cell calibration. This system is also used with the primary reference-cell calibration facility to evaluate concentrator modules.

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 it is typically used only when the sample is too cumbersome or impractical to disassemble and remount on the SOMS test bed. The total irradiance is measured using a pyranometer mounted in the same plane as the sample.

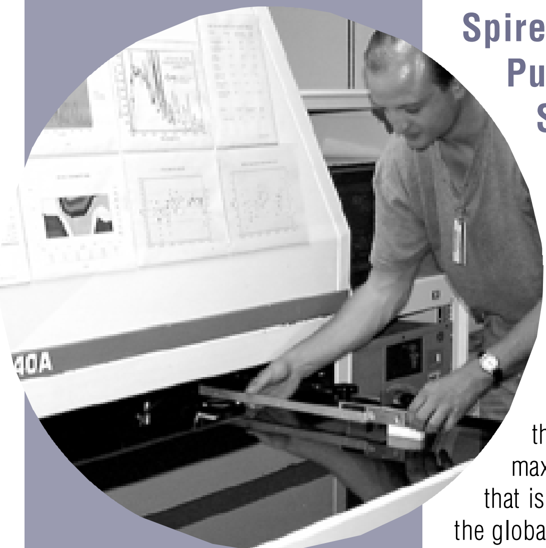
Features/Advantages

- Portable. This provides us with the capability of going to the sample and measuring in place.
- Line or battery powered. May be powered either with a 120 V_{ac} line or with a 12 V_{dc} battery.

The Daystar DS-10/125 Portable I-V Curve Tracer is being set up to measure I-V characteristics of large-area silicon modules mounted at the NREL outdoor test facility.

Light Source	Test Bed	Voltage Resolution/Limit	Current Resolution/Limit
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
2 Xe flash lamps, 30 cm long; 0.5 to 5 suns	200 cm x 200 cm	0.1 mV to 100 V	500 µA to 50 A
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
Sunlight	200 cm x 300 cm	5 µV to ±300 V	±1 µA to ±60 A
Sunlight	unlimited	12 mV to 600 V	5 mA to 125 A

Spire 240A Pulsed Solar Simulator



We use a modified Spire 240A pulsed solar simulator to measure the I-V characteristics of modules as large as 61 cm x 122 cm.

This system is used to measure module I-V characteristics over a temperature range of 20°C to 60°C. It uses a long-arc pulsed xenon lamp that is flashed at a maximum rate of 15 Hz, that is filtered to simulate the global reference spectrum, and whose irradiance has a spatial uniformity of ±3% over an area of 61 cm x 122 cm. To measure the I-V characteristics of a module, the xenon lamp flashes 200 or more times. During each pulse, a data point is taken, for a total of more than 200 points of data per sample. Temperature measurements are made with a spring-loaded thermocouple in contact with the back of the module. The original software has been modified slightly to store data in a database format for improved data analysis and retrieval.

Features/Advantages

- Commercial system. This is a commercially available system that we have maintained close to stock to provide concurrence with customers who may have such a system. Nonetheless, to provide better measurements and a greater range, we have modified the system as follows:
  - Temperature coefficients. We have added a removable and adjustable heating blanket that enables us to measure temperature coefficients.
  - Customized bed. We have modified the drawer that holds modules so that the reference cell is placed in a position for optimal readings. The drawer accommodates modules as large as 61 cm x 122 cm.
  - Screen filters. We have added screen filters to increase the range of the lamp intensity to 0.15 – 1.3 suns.
  - Extended current range. By installing a low (200 mA) current range, we have extended the system's current-measuring capabilities.

Large-Area Pulsed Solar Simulator (LAPSS)

This is a commercial system that has been customized to measure the I-V characteristics of modules as large as 200 cm x 200 cm. The system, which uses two xenon arc lamps operating between 1200 V and 3200 V, employs a large capacitor bank that charges up quickly. Upon discharge, the lamps flash for one millisecond, during which time the system acquires 30 to 120 data points. It uses these data points to plot the I-V curve and to calculate the performance characteristics of the module.

Features/Advantages

- Fast. All required data can be acquired during a single 1-msec flash.
- Minimal heating. Because of the quick data collection, a sample will experience minimal heating.
- Spatial uniformity. The flash arc lamps irradiate the sample with a uniformity of ±1% over the entire 200 cm x 200 cm test bed.
- Spectrally adjustable. Like the X-25 system, the LAPSS will receive a custom attachment with individually adjustable filters that may be used to modify the spectrum; this will allow more accurate I-V measurements of multijunction modules.
- Temperature-controlled test bed. A custom temperature-controlled test bed, currently being assembled, will enable us to make I-V measurements over a temperature range of 15°C to 75°C. This will result in more accurate measurements of temperature coefficients.

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 X200 continuous 20-kW xenon short-arc lamp with a water-cooled collector

MAJOR INSTRUMENTATION FOR MODULE I–V MEASUREMENTS

System	Typical Applications	Special Features
Spire 240A pulsed solar simulator	I-V measurements (1-sun modules) under simulated conditions	Commercial system; 25°C (20°C to 60°C possible)
Large-area pulsed solar simulator	I-V measurements (1-sun modules) under simulated conditions	Spectrally adjustable; ±1% spatial uniformity; minimal heating; 25°C
Large-area continuous solar simulator	I-V measurements (1-sun modules) under simulated conditions	User-controlled bias conditions
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 conditions
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

Each system employs light and voltage biasing. Light striking a PV cell changes the internal electric field, which affects SR. To simulate the internal electric field under sunlight conditions, we bias the sample with continuous light from a projector lamp.

Typically, we measure SR under conditions of zero voltage. Voltage biasing allows us to measure SR under power conditions, in which a voltage is present and in which SR can depend on voltage. Voltage biasing is also required for many multijunction PV technologies.

Grating Spectral Responsivity Systems

These systems are used for determining relative and absolute QEs in the wavelength range of 300 to 3000 nm. Because so much of the range is in the infrared (IR) region, these systems are effective for cells that have low bandgaps and that respond well to the IR region, such as TPV cells.

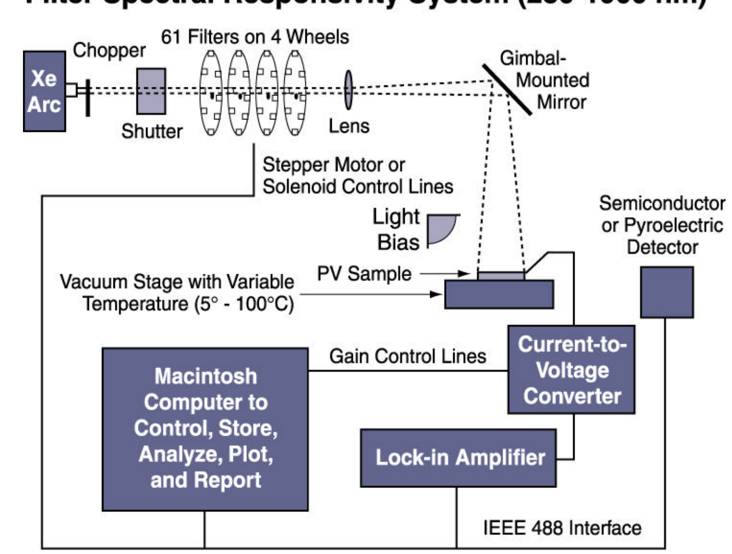
One system uses a 250-W tungsten lamp light source. The other system uses a 75-W xenon lamp or a 250-W tungsten lamp. All light sources are filtered to remove harmonics of first-order diffracted wavelengths. To produce the desired narrow spectral bands, each system employs a grating monochrometer — which uses three separate gratings — to produce monochromatic light.

The chopped monochromatic beam is reflected from mirrors to focus a spot as small as 1 mm x 3 mm on the sample.

Features/Advantages

- Broad wavelength range. These systems measure QEs in the wavelength range of 300 to 3000 nm.
- High signal-to-noise ratio. Enables the system to detect a weak signal embedded in a large amount of noise.
- Good wavelength resolution. Can resolve wavelengths to 1 nm.
- Large range of chopping frequencies. (Same feature capability as the filter SR system.)
- Light bias of up to 200 mA. (Same feature capability as the filter SR system.)

Filter Spectral Responsivity System (280-1900 nm)

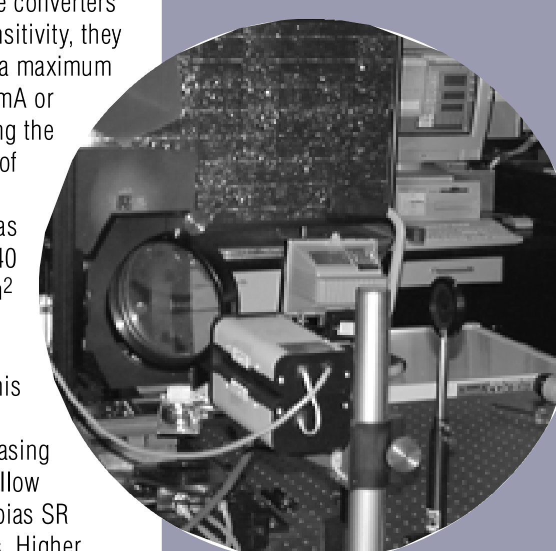


Filter Spectral Responsivity System

We use the filter SR system to measure the spectral response of cells and modules. The system uses a 1-kW xenon arc lamp and 61 narrow-band-pass filters mounted on four wheels. Each filter passes a narrow band of light approximately 10 nm wide (full width at half maximum — FWHM). The wavelength range represented by the filters extends from 280 nm at the UV end of the spectrum to 1900 nm at the IR end. (We have other filters available and can extend the range even further by using more filters.) Before we measure the spectral responsivity of a cell or module with this system, we calibrate the system to determine the beam intensity passed through each filter. The QE profile is normalized to 100% at its maximum for relative units of QE.

Features/Advantages

- High flux density. Provides a strong light and a strong signal that is easily detected in the presence of a large voltage or light bias.
- Variable beam size. Beam size can be adjusted from 10 cm to greater than 1 m; this allows SR measurements over a wide range of sample sizes — from the typical solar cell to modules.
- Large range of materials. Can measure the SR of PV devices made of crystalline silicon, amorphous silicon, cadmium telluride, copper indium diselenide, and more.
- Large range of chopping frequencies. Although the chopping frequency of this system typically operates between 15 and 100 Hz, the frequency range can be extended to as little as 4 Hz and as high as 2000 Hz. This allows us to produce a periodic light source that best suits the responsivity characteristics of specific devices, such as photoelectrochemical cells, for which a low chopping frequency is required.
- Module measurements. The spectral responsivity of individual cells in large modules can be measured.
- Light bias up to 200 mA. Although commercial current-to-voltage converters have good sensitivity, they are limited to a maximum current of 10 mA or less, preventing the measurement of the SR with a 1-sun light bias (typically 10-40 mA for a 1-cm^2 solar cell). Consequently, we augment this system with a larger light-biasing capability to allow desired light-bias SR measurements. Higher light-bias levels are possible with increased noise.



The filter spectral response system is used to determine the quantum efficiencies not only of solar cells, but also of modules, as shown.

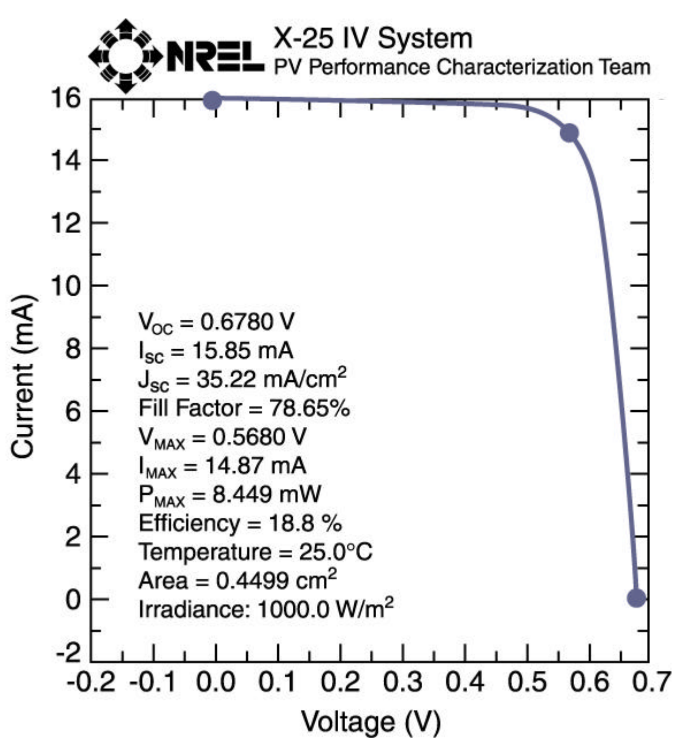
MAJOR INSTRUMENTATION FOR SPECTRAL RESPONSE MEASUREMENTS System	Typical Applications	Special Features	Light Source	Wavelength Range	Bandwidth	Voltage Bias	Light Bias
Grating spectral responsivity	SR measurements for small-area TPV cells	3 gratings for visible and IR; adjustable chopping frequency	250-W tungsten	400 to 3000 nm	>1 nm FWHM	±5 V	Up to 200 mA
Ultraviolet spectral responsivity	SR measurements for small areas on solar cells	3 gratings for UV, visible, and IR; adjustable chopping frequency	75-W Xe or 250-W tungsten	300 to 1900 nm	>1 nm FWHM	±5 V	Up to 8 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 1900 nm	10 nmFWHM	±40 V	Up to 200 mA

Current Versus Voltage (I-V) Systems

I-V measurement systems determine the output performance of devices. This includes the open-circuit voltage (V_{oc}) of the device, its short-circuit current (I_{sc}), its fill factor (FF), the maximum power output of the device (P_{max}), the voltage at maximum power (V_{max}), the current at maximum power (I_{max}), and the 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.

We use three I-V systems to measure the performance of cells: two systems for solar concentrator cells and TPV 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 five I-V systems. Three systems are used for measurements under simulated conditions: a *Spire 240A pulsed solar simulator, a large-area 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.*



Typical output provided for current-voltage measurements. This is the I-V output of a record-setting copper indium gallium diselenide device; it exhibited an 18.8% conversion efficiency under a simulated global irradiance of 1000 W/m^2

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 software optimized for PV measurements. This includes algorithms for calculating I-V characteristics and, for most systems, for making the spectral mismatch corrections. (For the Daystar and the standard outdoor measurement systems, mismatch corrections are made with separate software.) It also includes separate meters for measuring voltage and current; this allows us to make simultaneous measurements of voltage and current, rather than sequential ones in which errors due to fluctuations in light intensity may occur. To further minimize fluctuation errors, each system (with the exception of the continuous concentrator solar simulator) also employs monitor cells.

Continuous Illumination Concentrator

This system has two light sources, giving it the dual capability of measuring concentrator solar cells and 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 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.

Features/Advantages

- Good current/voltage ranges. The system can measure cells with output currents as high as ±10 A and output voltages as much as ±10 V.
- Accurate V_{oc} under high heat load. Under concentration, large temperature gradients can exist between the measurement plate and the cell junction. This makes it difficult to obtain the correct temperature reading, which can result in uncertainties in the V_{oc} and subsequent I-V measurements. This system employs a custom technique that enables accurate V_{oc} determination under concentration.

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 msec pulses of light with an intensity of up to 2 x 10^6 W/m^2 and a spatial uniformity of ±3% over the area of 17 cm x 3 cm. The beam is adjustable to provide concentrations of 1 to 2000 suns.

Features/Advantages

- Minimal heating. The 1 msec light duration minimally heats the sample, reducing temperature gradients and providing greater certainty for I-V measurements.
- Wide current/voltage ranges. The system can measure cells whose output current is as high as 50 A and whose output voltage is as much as 100 V.
- Planned upgrade. In the near future, the system will be equipped with filters for modifying the spectrum of the light source; this will allow the measurement of multijunction samples.

Spectrolab X-25 Solar Simulator

The light source for the Spectrolab X-25 uses a custom attachment with 19 separate, individually selectable filters to modify the spectrum. (Jim Yost Photography/PIX02043.)

The Spectrolab X-25 is used to measure I-V characteristics of PV cells with areas 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 (ASTM E927 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 system also uses a temperature-controlled monitor cell whose stage height and position are adjustable. This keeps the monitor (reference) cell and the test cell at the same distance from the light source (and hence, at the same light intensity), enabling accurate determination of temperature coefficients and short-circuit current.

Features/Advantages

- Spectrum modification. A custom attachment with 19 separate, individually selectable filters is used to modify the spectrum for measuring multijunction samples.
- Wide current/voltage ranges. The system can measure cells and modules with output currents as high as ±16 A and output voltages up to ±50 V.
- Good measurement uncertainty. The measurement uncertainty for device efficiency ranges from ±2% to ±5%, depending on sample size, geometry, and number of junctions. This takes into account the ±1% uncertainty of the reference cell, and the uncertainties in the spectra, intensity, spectral mismatch, and electronics.

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°C 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°C 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°C to 50°C	5 μV to ±50 V	±10 pA to ±16 A