Solar Industry®

Reprinted with permission from the March 2011 issue

How To Minimize Measurement Errors In Solar Cell Testing

Research using properly measured solar reference cells can be transferred to new technologies for full-scale modules.

Matthew O'Donnell & Dr. Ruben Zadoyan

With the increasing interest in photovoltaics as an alternative energy source, the solar sector is challenged to find more efficient and reliable electrical performance from PV cells, modules and vast solar panel arrays. Solar cells, the smallest of all photovoltaic devices, generate very little electrical power but are extremely useful in PV research that can be applied to devices of all sizes.

Cells, which range in size from 0.01 cm^2 to 6 inches in diameter, are used either as irradiance sensors or for studying new PV materials and processes. A research or prototype cell may simply be a thin film of photovoltaic material sandwiched between two glass microscope slides with silver paint for contacting.

A research cell usually requires probing and typically lacks the encapsulation that is so important for protecting solar modules from degrading atmospheric and weather effects. A solar reference cell is simply a small-area (2 cm x 2 cm) cell packaged in a metal housing under a glass window intended for setting simulated sunlight levels. A solar reference cell can resemble an associated solar module and, in place of a pyranometer, be used as an accurate irradiance sensor with rapid response to fluctuations in sunlight.

Five electrical performance parameters discussed below are used to characterize any solar cell and compare it to other solar cells of the same or different materials. This article will explore the challenges in making reliable electrical performance parameter measurements in solar cells, setting up standard testing conditions, monitoring the actual test conditions and accounting for all sources of error in order to express these parameters with associated measurement uncertainties.

By definition, one sun is a unit of irradiance and is taken to be 1,000 W/m^2/nm or 100 MW/cm^2/nm. The amount of atmosphere through which sunlight passes to reach a given location on Earth is called air mass (AM) and varies with that location's air pressure, elevation, latitude, date and time of day.

National ASTM standard E948 and IEC standard 60904-1 specify a set of common test conditions and methods for measuring the electrical performance parameters of photovoltaic cells. They are aptly named the Standard Testing Conditions (STC) and are as follows:

1. Temperature of the device under test (DUT) is to be 25° ± 1°C;
2. Spectral distribution of the light is to be AM1.5 ± 25%; and
3. Irradiance measured at the plane of the solar cell is to be 1 sun ± 2%.

Ruben Zadoyan

The test condition 1 sun of AM1.5 represents the average situation for the U.S., but for some combinations of locations and dates, this test condition may occur when the sun is too close to the horizon for making outdoor measurements. Given an AM of 1.5, testing outdoors may proceed only under a clear sky. A practical alternative is to perform PV measurements indoors using a solar simulator (see Figure 1).

Performance parameters

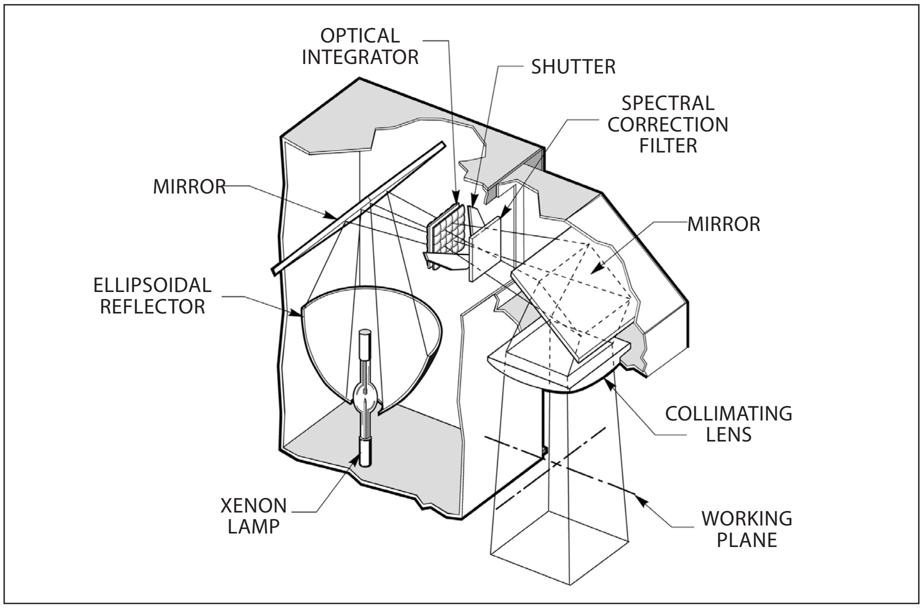
Standard practice is to place a calibrated reference cell at the working plane and adjust the simulator until the short-circuit current produced by the reference cell matches that which is published in its calibration certificate. The light at the working plane can be made "sun-like" by passing it through an AM1.5 filter that simulates the effect of Earth's atmosphere.

Matthew O'Donnell

Standard practice also includes mounting the solar cell on a temperature-controlled chuck and illuminating it with 1 sun of simulated AM1.5 sunlight. After the cell temperature equilibrates to 25°C, a variable electronic load placed across the cell is controlled such that the voltage across the cell is swept in small incremental steps.

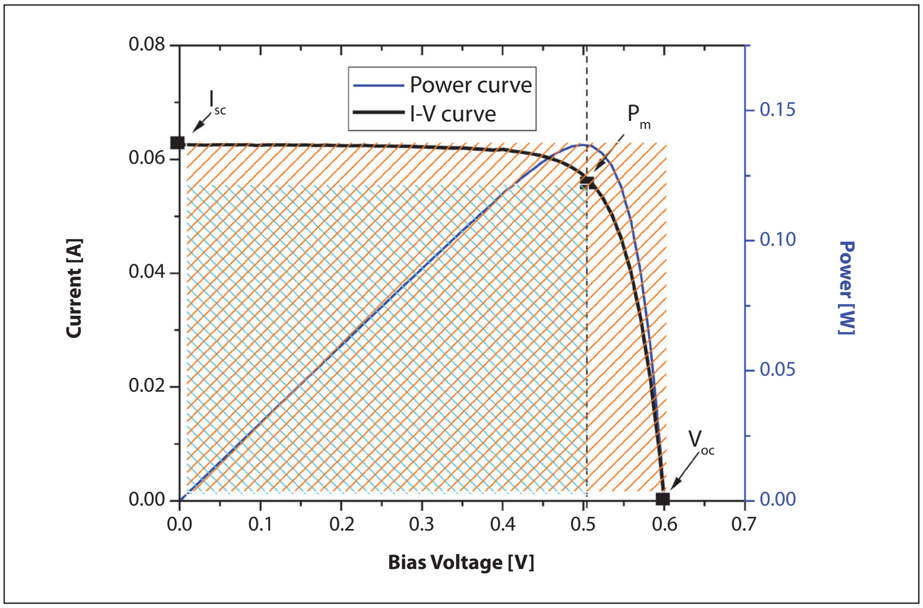
The electronic load can be a variable resistor, but it is more often a programmable precision power supply. When the measured photocurrent is plotted against the bias voltage, the

Figure 1: Schematic of a Solar Simulator



Source: Newport Corp.

Figure 2: I-V Curve



Source: Newport Corp.

FF=ratio of blue to orange areas

result is a characteristic curve called the I-V curve for the solar cell (see Figure 2).

Five performance parameters - the short-circuit current (I_{sc}), the open-circuit voltage (V_{oc}), the maximum power point (P_m), the power conversion efficiency (PCE) and the fill factor (FF) - are derived from the I-V curve. Three parameters - I_{sc}, V_{oc} and P_m - are derived from the I-V curve and then used to determine FF and PCE.

I_{sc} and V_{oc} are the intercepts where the I-V curve crosses the current and voltage axes, respectively, and the "knee" point at (V_m, I_m) is where the solar cell delivers maximum power - P_m. The FF is the ratio of the area determined by P_m to the area determined by V_{oc} and I_{sc}.

$$PCE=\frac{P_m}{E_m Area}$$

In the equation above, E_m is the measured irradiance at the working plane of the solar cell, and area is the area of the cell. For research cells, the PCE is the parameter of interest, but for solar cells intended to be used as irradiance sensors, the short-circuit current is most important.

Potential measurement errors

PV measurements are subject to a number of errors. Some correctable errors arise because measurement conditions deviate from the nominal STC during the I-V sweep. The STC are expressed as ranges of conditions centered on the nominal conditions, so the DUT temperature is allowed to be within 24-26°C, and irradiance may actually be between 0.98-1.02 sun.

Test conditions may be in tolerance, but the performance parameters derived from I-V data under those conditions will still be in error. Measured current I_m can be corrected for each off-nominal condition according to the following equation found in the ASTM standard E948.

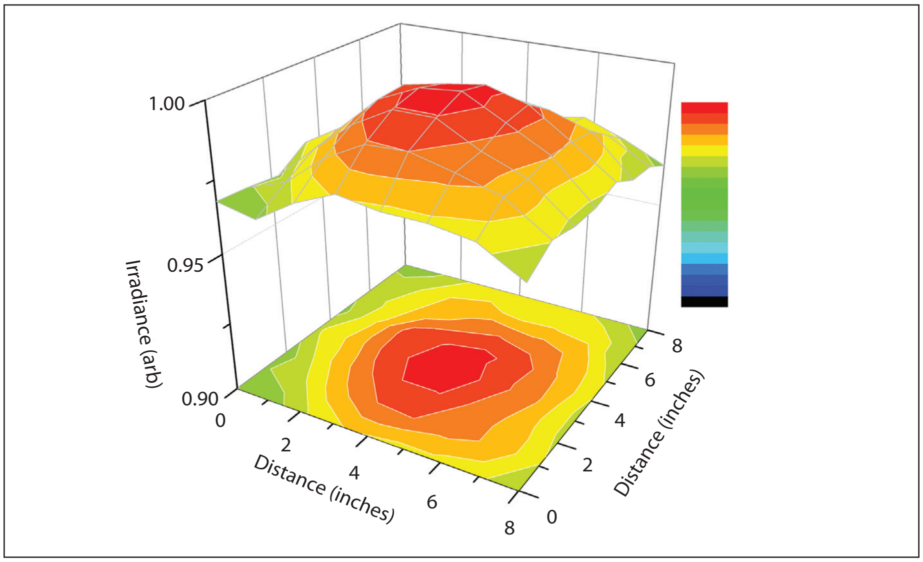
$$I_{corr}=I_m\left(\frac{E_o}{E_m}\right)\left(\frac{1}{M}\right)\left[\frac{1}{1-\alpha_{Isc}\left(T_{cell}-T_o\right)}\right]$$

In this equation, α_{Isc} is the temperature coefficient for I_{sc}, M is the spectral mismatch factor and E_m is the actual total irradiance measured with a solar reference cell. E_o and T_o are the nominal values for total irradiance 1 sun and temperature 25°C.

Only the measured current data (and not voltage data) are corrected, because voltage is imposed across the cell by a power supply in sweep mode. The factor (E_n/E_m) corrects the raw current data for the actual measured total irradiance during the time of test. It is recommended that E_m be measured just before or just after an I-V sweep, because even a Class AAA solar simulator can drift significantly (>0.1%) over a few hours of operation.

The spectral mismatch error is the difference between the spectral mismatch factor M and unity. The spectral

Figure 3: Irradiance Distribution



This figure represents the irradiance distribution in the test plane of a typical Class AAA solar simulator, showing less than 2% spatial non-uniformity.

Source: Newport Corp.

Figure 4: Measurement Scenarios and Associated Uncertainty

PV Measurement Scenario	Uncertainty
temp sensor, temp (direct) control	Lowest
temp sensor, no temp control	↓
no temp sensor, temp control	↓
no temp sensor, no temp control	Highest

Source: Newport Corp.

mismatch factor M corrects the measured current for errors that arise because of the different spectral responses of the DUT and the solar reference cell and also for errors that arise when the spectral distribution of light illuminating the DUT differs from that of the light that illuminated the solar reference cell during its calibration.

In order to minimize the spectral mismatch error, M should be made to as close to unity as possible by carefully choosing a reference cell with a spectral response that closely resembles that of the DUT and/or by making the spectral distribution of the simulated light resemble the reference spectral distribution. If the error exceeds 5%, a better-matching solar reference cell should be used.

Another correctable error encountered in PV measurements employing simulated sunlight is spatial non-uniformity in the solar simulator beam. Simulated sunlight is typically more concentrated in the center (around the optical axis) than at the edge of the illuminated area and maps into a domed surface (see Figure 3) - the height of which can be used as a metric for spatial non-uniformity.

Class AAA solar simulators minimize spatial non-uniformity (<2%). Residual spatial non-uniformity causes irradiance error proportional to the relative areas of the solar reference cell and DUT and the relative locations of the two. A factor (analogous to the spectral mismatch factor) can be calculated and applied to correct for this error.

Temp sensor influence

Some errors are extremely difficult - if not impossible - to correct. The combination of these types of errors represents a baseline limit to the accuracy with which the electrical performance parameters can be known. The most obvious source of these errors is associated with the calibration of the solar reference cell used to calibrate the cell under test.

Currently, the U.S. National Renewable Energy Laboratory reports short-circuit current with an accuracy of 1.3%, which represents the lower bound on subsequent calibrations. Another source of errors comes from the uncertainty in knowing the actual temperature (T_{cell}) at the space charge region of the cell.

Temperature is normally measured with either thermocouple or RTD temperature sensors attached to the surface in shadow (back) or the exposed surface (top) of the cell. Attachment to the back of the cell is preferred, as additional error from shadowing the cell is avoided, but there is always some unknown light-induced temperature gradient between the back and the space charge region of the cell, making T_{cell} uncertain.

A Class AAA solar simulator makes it easy to set up 1 sun of AM1.5 in the laboratory, but achieving 25°C is not so trivial. A set of four possible PV measurement scenarios depending on one's knowledge and ability to control the cell temperature is presented in Figure 4.

The first measurement scenario listed is the ideal case and is the scenario prescribed in the PV standards. Calibration of solar reference cells falls into this category, because a temperature sensor is built into the

Matthew O'Donnell, principal author, is lab manager at the Technology and Applications Center (TAC) - PV Lab at Newport Corp. He has worked at Newport for seven years and can be contacted at matthew.odonnell@newport.com. Dr. Ruben Zadoyan, corresponding author, is director of TAC at Newport Corp. His expertise is in nonlinear spectroscopy, nonlinear optics, ultrafast lasers, laser-matter interaction and ultrafast biomedical applications. Zadoyan can be contacted at ruben.zadoyan@newport.com.

package design and the cell's housing facilitates efficient heat exchange between the cell and the temperature-controlled chuck.

It should be noted that illuminating the cell during the scan will perturb the temperature of the cell from the 25°C nominal; therefore, the bias voltage should be swept from V_{oc} to 0 V rather than the other way around, because V_{oc} is more sensitive to temperature than I_{sc}.

An alternative is to soak the cell in AM1.5 and allow its temperature to equilibrate. The temperature of the chuck can be set such that the cell equilibrates to 25°C. The sweep can then be performed without disturbing the temperature of the cell. Thus, the temperature coefficient α_{Isc} is not needed.