Application Note 47

The Challenge of Making Reliable Solar Cell Measurements

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Photovoltaics is normally associated with images of rooftop mounted solar panels or a vast expanse of solar panel arrays spread out over a desert floor probably because so much emphasis is placed on photovoltaics as an alternative way to generate electrical power. Solar cells generate little electrical power, but do generate information of great interest for the photovoltaic researcher.

Solar cells are the smallest photovoltaic devices and are used either as irradiance sensors or as samples for studying new photovoltaic materials and or processes. Solar cells range in size from a few square millimeters up to 156 mm square or more for a silicon wafer. A research or prototype solar cell can have a rather crude looking construction compared to the sleek panels on display at any solar energy convention. It may simply be a thin film of photovoltaic material sandwiched between two glass microscope slides with silver paint for contacting. A research solar cell usually requires probing and typically lacks the encapsulation so important for protecting solar modules from the degrading atmospheric and weather effects.

A solar reference cell is simply a small area (2 cm x 2 cm) solar cell packaged in a metal housing under a glass window intended for use indoors to set simulated sunlight levels. A solar reference cell can be framed in such a way that it resembles a miniature version of its associated solar panel and, in place of a pyranometer, can be used outdoors for use as an accurate irradiance sensor with the same spectral and angle of incidence responses as the panel.

There are five electrical performance parameters to be discussed below that are used to characterize any solar cell and to compare it to other solar cells of the same or different material. The challenge to making reliable electrical performance parameter measurements is setting up standard testing conditions, knowing what the actual test conditions are, and accounting for all sources of error in order to express these parameters with associated measurement uncertainties.

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

1. temperature of the device under test (DUT) must be 25 ± 1 °C,

2. spectral distribution of the light must be AM1.5 ± 25%,

3. irradiance measured at the plane of the solar cell must be 1 Sun ± 2%.

The Sun is a unit of irradiance, one of which is equivalent to 1000 W/m^2 or 100 mW/cm^2. 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. In a given day, AM is minimum when the sun is at its zenith and largest near the horizons. The test condition 1 Sun of AM1.5 represents the average situation for the United States, but for some combinations of locations and dates 1 Sun of AM1.5 may not occur. Given an AM of 1.5, testing outdoors may proceed only under a clear sky, i.e., when there are no clouds within an angle of 30° around the sun. A practical alternative method is to perform the photovoltaic measurements indoors using an I-V Test Station. This is based on Newport's Oriel® Sol3A™ Class AAA solar simulator, which collimates light produced by an intense Xenon source into various beam sizes from 2 to 12 inches square for testing purposes. Standard practice is to place a calibrated reference solar cell in the simulator beam at the simulator's working plane and adjust the current to the Xenon bulb until the short-circuit current produced by the reference cell matches the value published in its calibration certificate. The light at the working plane can be made "sun-like" by passing it through an aptly named Air Mass (AM) filter. This simulates the extended path length effect on the sunlight passing through the atmosphere at an obtuse angle of incidence. This ensures the spectral distribution at the working plane resembles the AM1.5 spectrum as referenced in tables like the international standard IEC 60904-3.

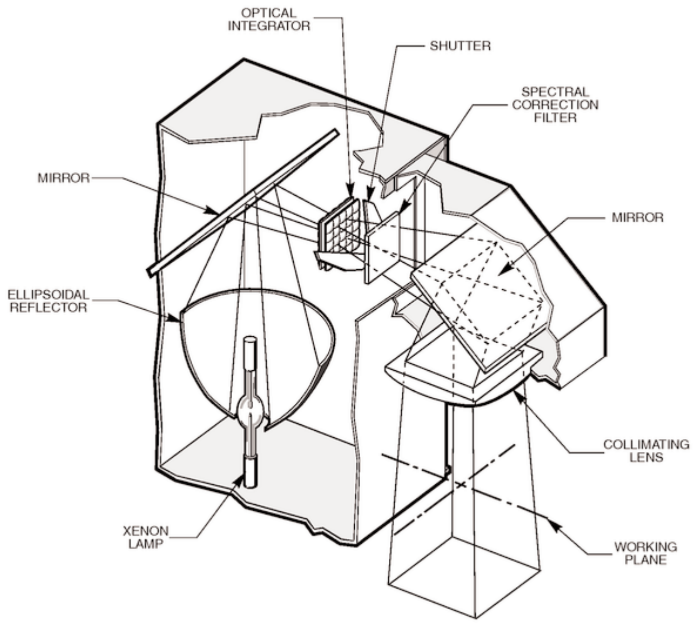

Figure 1. Schematic of an Oriel Sol3A Class AAA solar simulator.

Standard practice is to mount a solar reference cell on a temperature controlled chuck and illuminate 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 is more often a programmable precision power supply. When the measured photocurrent is plotted against the bias voltage the result is a characteristic "I-V curve" for the solar cell.

Three of the five performance parameters, the short-circuit current I_{sc}, the open-circuit voltage V_{oc}, the maximum power point P_m, are derived from mathematical fits to different portions of the I-V curve. The parameters V_{oc} and I_{sc} are the intercepts of least-square fitted lines. P_m is the point at which the derivative with respect to voltage is zero, for a fifth-order polynomial fit to power, the product of current and voltage. Fitting helps to reduce measurement noise, and the Oriel I-V Test software automatically performs this fitting and analysis. The parameters, I_{sc}, V_{oc}, and P_m are then used to calculate 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 or fill factor is the ratio of the area determined by P_m to the area determined by V_{oc} and I_{sc}. Power Conversion Efficiency is calculated by the following formula:

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

where E_m is the measured irradiance at the working plane of the solar cell, and Area is the area of the cell. For research and early stage solar cells the PCE is the parameter of interest, but for solar cells intended to be used as irradiance sensors the short-circuit current is what matters most.

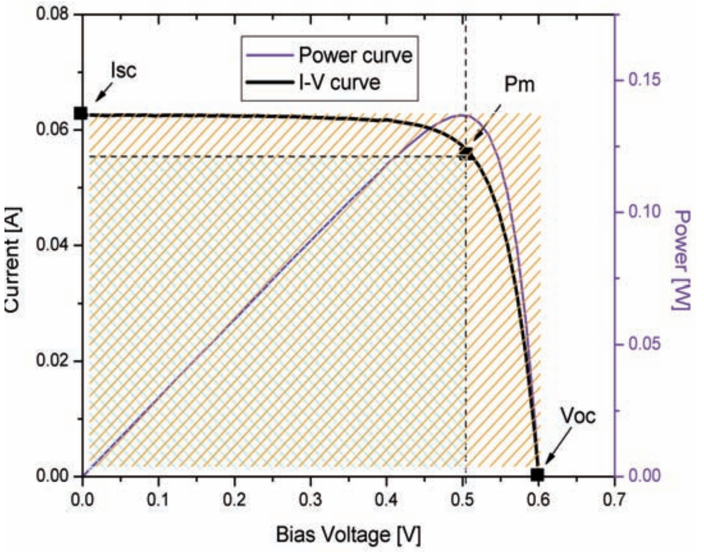

Figure 2. I-V curve showing I_{sc}, V_{oc}, and P_m. FF is the ratio of the blue to orange areas.

Measurements of photovoltaic devices 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 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. The measured current I_m can be corrected for

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

each off-nominal condition according to:

where αI_{sc} is the normalized temperature coefficient for I_{sc}, M is the spectral mismatch factor, 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) is corrected since voltage is imposed across the cell by a power supply in sweep mode. The factor (E_o/E_m) corrects the raw current data for the actual measured total irradiance during the time of test. It is recommended that E_m is measured just before or just after an I-V sweep to achieve maximum accuracy.

The spectral mismatch factor (M) corrects the measured current for spectral mismatch error, which will arise when the respective spectral responses and test spectra for the DUT and the solar reference cell do not match. Calculation of M requires four sets of data: the respective spectral responses and spectral irradiances for both the DUT and the reference cell[1]. The Oriel IQE-200™ is a multi-beam instrument that measures the spectral response or QE of a cell. If the DUT and reference cell share either common spectral responses or spectral irradiances, then the spectral mismatch error will be zero, but in general this is never the case. In order to minimize the spectral error, M should be 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 making the spectral distribution of the simulated light resemble the reference spectral distribution. For example, a GaAs solar cell should be calibrated with a GaAs reference cell, or dissimilar devices like an organic solar cell and a m-Si reference cell are made a good match by adding a KG5 window to the reference cell. A rule of thumb is that if the spectral error exceeds 2%, a better matching solar reference cell must be found since a conservative estimate for the error in M is 20% of the absolute difference between M and unity[2]. Oriel offers solar reference cells for sale. The reference cells can be equipped and calibrated with various colored glass filters.

Another correctable error encountered in photovoltaic 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 (Figure 3), the height of which can be used as a metric for spatial non-uniformity. Class AAA solar simulators like the Oriel Sol3A minimize spatial non-uniformity under 2%. Residual spatial non-uniformity causes irradiance error proportional to the relative areas of the solar reference cell and device under test and also the relative locations of the two. A factor (analogous to the spectral mismatch factor) can be calculated and applied to correct for this error.

Some errors associated with characterizing PV cells are

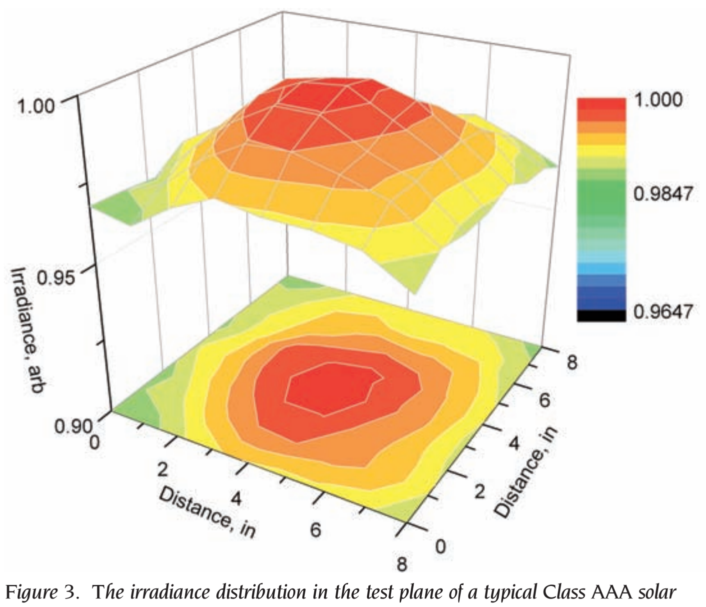

Figure 3. The irradiance distribution in the test plane of a typical Class AAA solar simulator, showing less than 2% spatial non-uniformity.

unavoidable and 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. One unavoidable error source is associated with the calibration of the solar reference cell used to calibrate the cell under test. Currently the National Renewable Energy Laboratory (NREL) reports short-circuit current with an accuracy of 1.3% which represents the lower bound on subsequent calibrations. Another unavoidable error source comes from the uncertainty in T_{cell} which should be the temperature at the space charge region of the cell. A solar cell's temperature is normally measured with either thermocouples or resistive temperature detectors (RTDs) which can either be attached to the surface in shadow (back) or to the exposed surface (front) of the cell. Temperature measured with a sensor attached to the back of the cell will be artificially low because the sensor itself tends to act like a heat sink. This effect is known as thermal shunting and can be minimized by choosing a temperature sensor with as little mass as possible to cut down on heat transfer between the cell and the sensor. Thermal shunting can also occur when the temperature sensor is attached to the front surface and shadows the cell, so that the temperature it measures will be artificially lower than that of the surrounding exposed cell area. Attachment of the temperature sensor to the back of the cell is preferable to attaching it to the front of the cell to avoid the additional error from shadowing the cell.

A further challenge to knowing T_{cell} accurately comes from the light induced temperature gradient in the cell because one side is exposed to light and the other is not. This effect is aggravated if the solar cell is mounted onto a temperature controlled chuck which cools the back of the cell by conduction more efficiently than the exposed surface of the cell exchanges heat with the surrounding air by convection. The result is that the surface in shadow is typically a few degrees C cooler than the exposed surface of the cell. The resulting uncertainty in T_{cell} translates into uncertainty in the performance parameters. The temperature gradient is apparent (Figure 4) when the parameter V_{OC} is plotted against temperature (at the back of the cell) when the cell is heated or cooled. As the best estimate of the open circuit voltage, the two lines in Figure 4 can be extrapolated to

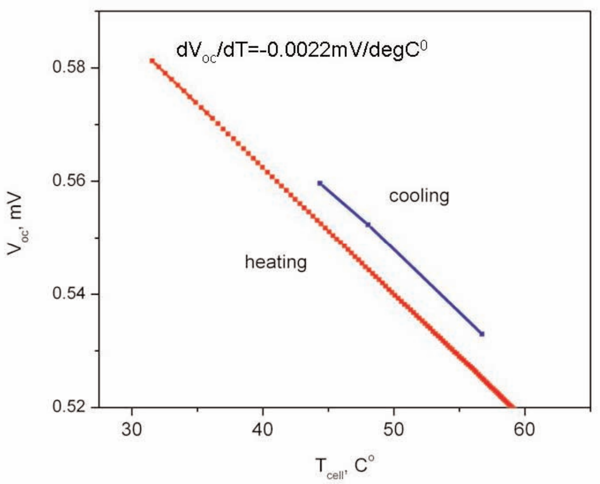

Figure 4. Open-circuit voltage plotted against temperature yields the respective temperature coefficients and exhibits hysteresis with temperature.

25 ˚C using the temperature coefficient, and the mid-point of the two V_{OC} intercepts at 25 ˚C can be calculated.

In practice, guaranteeing that I-V data is collected at 25 ˚C can be the greatest challenge in producing reliable photovoltaic measurements. Table 1 displays a set of four possible measurement scenarios depending on one's knowledge of and ability to control the cell temperature and an associated relative measurement uncertainty.

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

Table 1. Four temperature based measurement scenarios.

The first scenario is the ideal case and is the scenario prescribed in the PV standards. Calibration of solar reference cells fall into this category since a temperature sensor is built into the reference cell package and it can easily be mounted to a temperature controlled chuck. Illuminating the cell only during the I-V scan will perturb the cell temperature from the nominal 25 ˚C (Figure 4). Therefore, the bias voltage should be swept from V_{OC} to 0 Volts rather than the other way around since

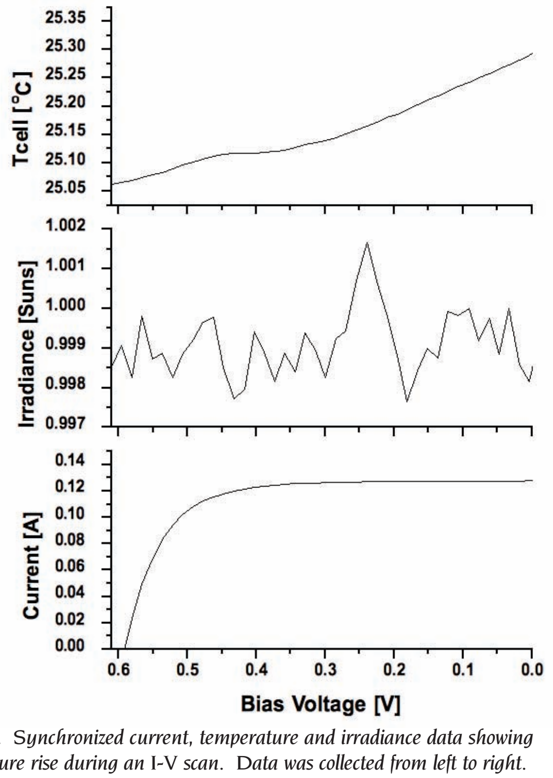

Figure 5. Synchronized current, temperature and irradiance data showing temperature rise during an I-V scan. Data was collected from left to right.

V_{OC} is more sensitive than I_{SC} to the slight increase in temperature during the I-V scan (Figure 5). The short-circuit current I_{SC} should then be collected after collecting V_{OC}.

The temperature drift during the I-V sweep can be eliminated by soaking the cell in 1 Sun of AM1.5 for several minutes.

Eventually the cell temperature will reach equilibrium with the temperature controlled chuck. The temperature of the chuck can be set such that the cell equilibrates to 25 °C, and the I-V sweep can then be performed without disturbing the temperature of the cell. This is the technique used in the TAC PV Lab, an ISO Certified calibration lab. The advantage of this method is twofold: not having to temperature correct the measured current (to 25 °C) and avoiding separately measuring the temperature coefficient for the normalized short-circuit current α_{Isc}.

Characterizing experimental solar cells often falls into the last scenario where there is no direct control or knowledge of the temperature. Due to their delicate construction, attaching a temperature sensor to the cell might cause permanent damage and precludes the ability to attach a temperature sensor. Bottom contacts (for the anode and cathode) require that the cell be probed from the bottom preventing mounting to a temperature controlled chuck, so the DUT is essentially suspended in air during testing. The best one can do in this situation is to blow temperature controlled air over the DUT and/or store the sample for several hours in a laboratory held to an average temperature of 25 °C before collecting the I-V curve

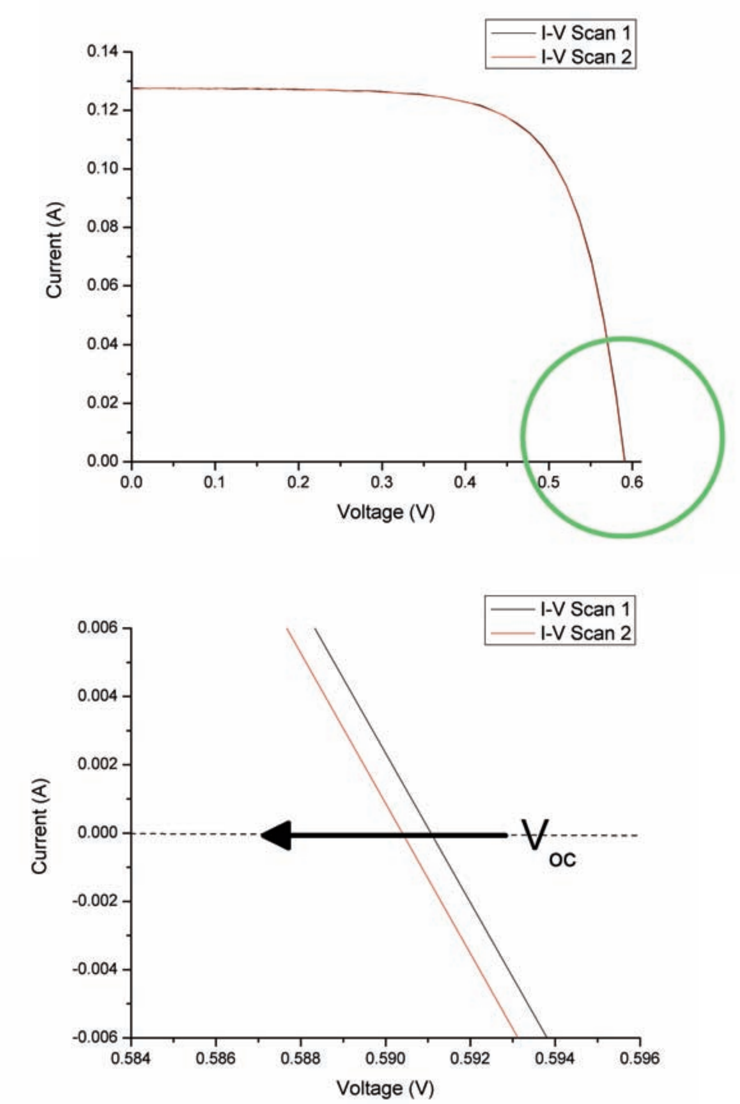

Figure 6. Plot area on the lower plot is encircled in the upper plot. Two successive I-V curves are superimposed in the upper plot. The lower plot shows shifting of successive V_{oc} values to the left due to cumulative heating during successive scans.

with a solar simulator equipped with a fast shutter. The fast shutter makes it possible to illuminate the cell briefly (< 1 s) and avoid heating the cell appreciably to capture V_{oc} at 25 °C. This process can be repeated to generate the entire I-V curve by stepping down the bias voltage from V_{oc} and measuring the current in response to momentary illumination. The cell should be allowed to sit at room temperature for several minutes before stepping the voltage down. A more practical method is to take successive (at least two) fast I-V curves. If the V_{oc} corresponding to the second scan differs little from the V_{oc} from the first scan, the cell was not perturbed significantly from 25 °C during the brief exposure to light (Figure 6). In a similar manner, the respective maximum power points of the two scans can be compared for an estimate of STC temperature related error in P_m and in PCE. Care must be taken that the bias rate (or sweep rate) is not so fast that the cell can't respond. This can be checked by comparing the FF from two scans taken with different bias rates.

The second scenario is dealt with by applying the temperature correction as in Eq. 1 to the I-V data. The uncertainty of the corrected results will depend on the uncertainty of T_{cell}. In the third scenario, the DUT is allowed to equilibrate with the chuck maintained at 25 °C. Temperature and temperature related effects can be inferred from monitoring V_{oc} as is done in the fourth scenario.

The small area solar cell is indispensable for the small scale study and optimization of new photovoltaic materials and processes, before scaling up to manufactured solar panels. The national ASTM and international IEC standards for measuring the electrical performance parameters of photovoltaic cells allow for the calibration of solar reference cells or for comparing cells made from differing materials and/or processes. Photovoltaic cell measurements are to be performed under Standard Testing Conditions (STC). Newport Oriel equipment designed to reproduce these STC conditions in the laboratory and for characterizing photovoltaic cells has been discussed. Reported results for the electrical performance parameters of a solar cell will be erroneous if the conditions during measurement deviated significantly from STC. Fortunately these can be corrected. Error sources that are not correctable are the main contributors to measurement uncertainty. Finally, a set of four possible measurement scenarios, depending on one's knowledge and ability to control the cell temperature, was presented with some ways to minimize measurement uncertainty for each scenario.

References

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