Technical Notes

Issue 11 January 2013

Understanding Solar Module Specs and Testing

This Technical Note discusses how solar module performance characteristics relate to off-grid lighting systems and how to best assess module performance by measuring the current-voltage (I-V) performance curve.

The Information contained in this article builds on previous Technical Notes. See also: http://www.lightingafrica.org/resources/briefing-notes.html

Introduction

Solar modules are the heart of many off-grid lighting systems and are often among the most costly components. To maximize performance and provide good value to consumers, solar photovoltaic (PV) modules must perform as advertised and be properly matched to the electronic circuit or batteries they are powering. The best way to ensure good performance is to learn to use current-voltage (I-V) curve data effectively and, if needed, to measure your own I-V performance curves. This Technical Note describes how to interpret and use PV module specs and how to measure I-V curves using low-cost equipment.

Part 1: What is an I-V Curve?

An I-V curve shows the relationship between current and voltage for an electronic component or device. For a PV module, it shows all the possible operating points for a given combination of solar irradiance and temperature[1]. While this document focuses on I-V curves for PV modules, an I-V curve can be plotted for any electronic device or component.

An example of the typical shape for PV I-V curves is shown in Figure 1. There are two plots; the lower plot is the I-V ("current-voltage") curve and the upper plot shows the power as a function of voltage. Remember that power is equal to current times voltage.

I-V curves for PV modules typically have the following characteristics:

- At low voltages, the I-V curve is relatively flat, meaning that the current does not depend strongly on voltage and is generally similar to the current at zero volts ("short circuit"), denoted by I_{sc}.
- The peak power occurs at the "knee" of the I-V curve. This is generally the optimal operating point and is known as the maximum power point (MPP). It is common to specify PV power ratings at maximum power (P_{mp}) and to also specify the corresponding current and voltage (I_{mp} and V_{mp}).
- At voltages higher than the maximum power voltage, the current and power drop steeply. Operating in this region is not recommended if the goal is to maximize current or power.

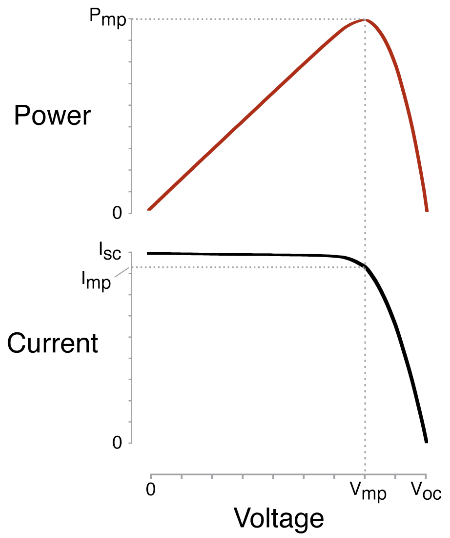

Figure 1: I-V curve (bottom) and power curve (top). The maximum power point (peak power, P_{mp}) lines up with the I-V curve "knee."

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[1] The I-V curves in this document show only positive current and voltage values (quadrant I). Operation also can occur in quadrant II (positive current, negative voltage) or quadrant IV (negative current, positive voltage); this operation is beyond the scope of this technical note.

The shape of a PV module I-V curve is described by the fill factor, the ratio of the maximum possible power (P_{mp}) to the product of V_{oc} and I_{sc}. Fill factor is a unitless number between 0 and 1; as the fill factor approaches 1, the knee of the curve becomes sharper. High-quality PV modules generally have higher fill factors than poor-quality modules, and crystalline silicon modules tend to have higher fill factors than thin-film (amorphous) modules.

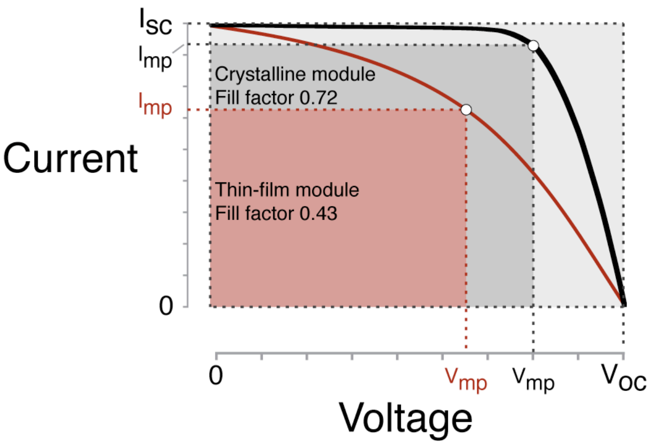

Figure 2: Fill factor for typical crystalline and thin-film PV module I-V curves. The fill factor is the ratio of the area of the inner rectangle to the area of the outer rectangle.

The shape of a PV module I-V curve also depends on the operating conditions, as shown in Figure 3. The main factors affecting performance at any given instant are temperature and solar irradiance. Open-circuit voltage is strongly dependent on the operating temperature of the PV module; at higher temperatures, V_{oc} decreases and the I-V curve shifts to the left. Temperature also has a small effect on short-circuit current, with I_{sc} increasing slightly at higher temperatures, but it is normally safe to assume that short-circuit current is constant with respect to temperature. On the other hand, short-circuit current is strongly dependent on solar irradiance; as irradiance increases, I_{sc} also increases, and the curve shifts upward.

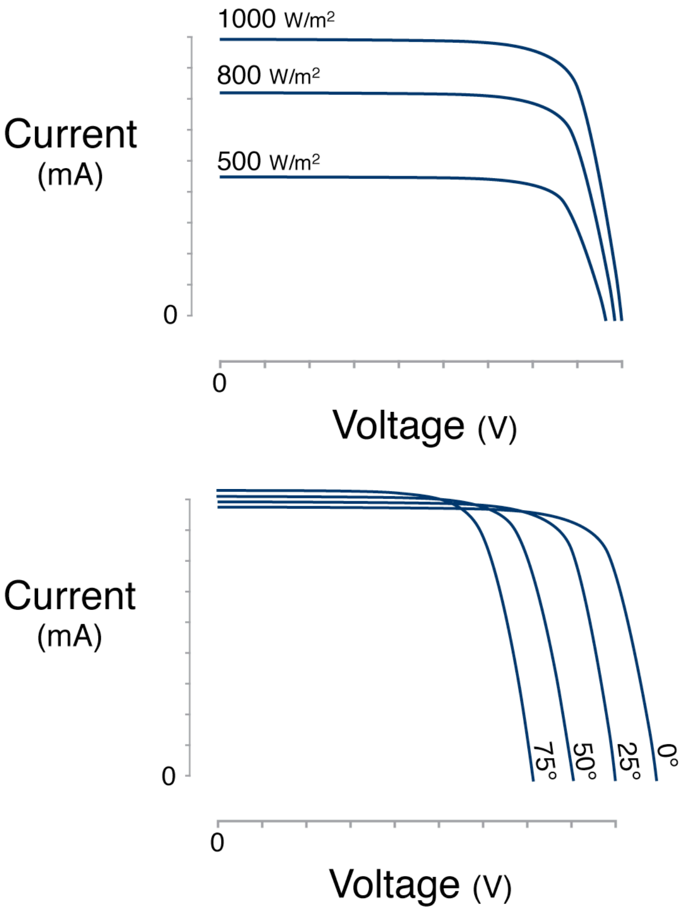

Figure 3: I-V curves showing the dependence of solar module performance on solar irradiance (top) and module operating temperature (bottom).

Standard Test Conditions

To allow fair comparison between PV modules, I-V curves are given for standard testing conditions (STC), which define a standard solar irradiance (1000 W/m^2), spectral characteristic (air mass 1.5), and solar module operating temperature (25°C).

Solar Module Specifications

The specifications like those found on the backs of PV modules come directly from I-V curves measured at STC. From these specs, it is possible to “rebuild” the basic shape of an I-V curve as shown in Figure 4 below.

Open Circuit Voltage (V_{oc}) – The peak voltage; occurs at zero current, with no connection between the terminals.

Short Circuit Current (I_{sc}) – The peak current; occurs at zero voltage, with short circuit (approximately 0 ohm resistance) connection between the terminals.

Maximum Power Voltage (V_{mp}) – The voltage at the maximum power (i.e., peak efficiency) operating point.

Maximum Power Current (I_{mp}) – The current at the maximum power operating point.

Maximum Power (P_{mp}) – The highest power operating point for given conditions, i.e., the best efficiency point; the product of Vmp and Imp.

Solar Radiometry Terms

Terms associated with measurement of solar radiation can be confusing; these are the terms used in this note:

Irradiance – The amount of radiated power per unit area incident on a surface (units of W/m^2).

Irradiation – The amount of radiated energy per unit area incident on a surface in a given time, often one day (units of Wh/m^2 or kWh/m^2).

Insolation – the same as “solar irradiation,” although often used to refer to solar irradiance as well.

Air mass – the ratio of sunlight’s path length through the atmosphere to the path length if the sun were directly overhead. Air mass is a function of latitude, time of year, and time of day, and determines the spectral characteristics of the solar radiation reaching the earth’s surface.

Pyranometer – an instrument to measure solar irradiance.

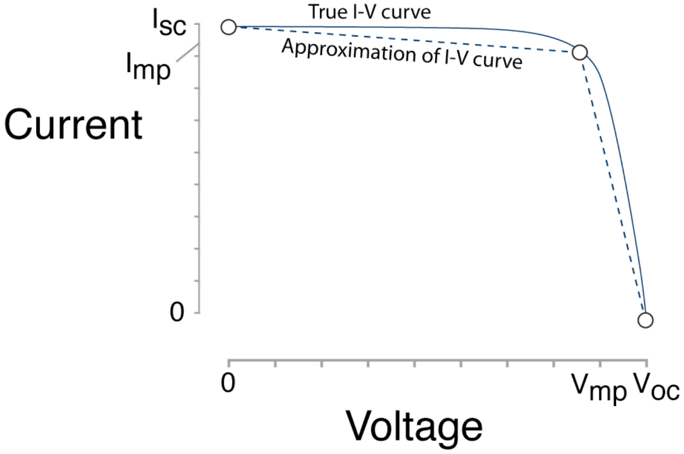

Figure 4: "Rebuilding" an I-V curve based on PV module specifications. The approximation of the curve with three anchor points can be good enough for engineering design.

Operating Point for Connected Devices

With a PV module I-V curve, you can predict the current and voltage that the module will provide to a given load. Any I-V curve represents the set of all possible operating points for each device under the given environmental conditions. When two devices are directly connected, the current and voltage of both are determined by the intersection of their two I-V curves, the only point where both can operate simultaneously.

Figure 5 shows the I-V curves of a PV module and a resistor—the simplest type of load. The I-V curve of a resistor with resistance R is a straight line with slope 1/R. When the resistor and PV module are connected, the only possible operating point is the intersection of the two curves, indicated by the white dot. If the PV module temperature or solar irradiance changes, the PV module I-V curve will change and the operating point will thus be different. Similarly, if the load resistance changes, the slope of the load I-V curve will change, also changing the operating point. For example, if the resistor in Figure 5 is increased from R_1 to R_2, the voltage will increase from V_1 to V_2 and the current will decrease from I_1 to I_2.

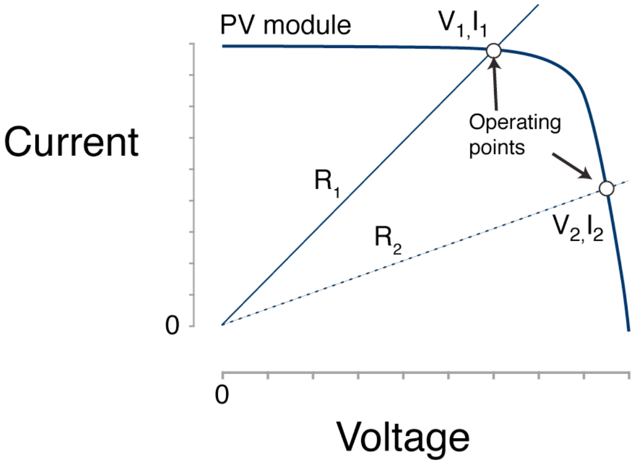

Figure 5: I-V curves for a typical PV module and two ideal resistors ($R_1 < R_2$). If the PV module and one of the resistors are connected, the operating point will be at the intersection of the I-V curves.

I-V Curves and Product Design:

There are two general rules for using I-V data to match PV modules:

1) **Match voltage:** Make sure the expected operating voltage of the battery charging circuit (accounting for any circuit losses between the PV module and battery) matches well with a good operating region for the PV module. In general, this means operating in the region directly to the "left" of the maximum power point. Make sure to account for the full range of expected solar irradiance, temperature, and load conditions.

2) **Predict performance:** Make sure that the PV module produces enough energy in a typical day to meet the expected load.

Voltage Matching

A PV module will operate near the maximum power point (where efficiency is maximized) when it is well matched with its load. Figure 6 shows how I-V curves can be used to match PV modules and batteries in terms of voltage. The I-V curve of a battery is approximately a vertical line, which shifts to the left as the battery discharges and to the right as the battery charges; the shaded region shows a hypothetical range of operation for a battery. The middle curve in Figure 6 is well matched to the battery. The maximum power point is slightly to the right of the fully charged battery voltage. If the maximum power point voltage is below the battery charging voltage, like the curve on the left, the battery will never fully charge since the current drops to zero as the battery voltage increases. On the other hand, if V_{mp} is too high, the module will not operate at peak efficiency; a better-matched module with the same maximum power could supply more current for a faster charge, or the same charging time could likely be achieved with a smaller, less expensive module.

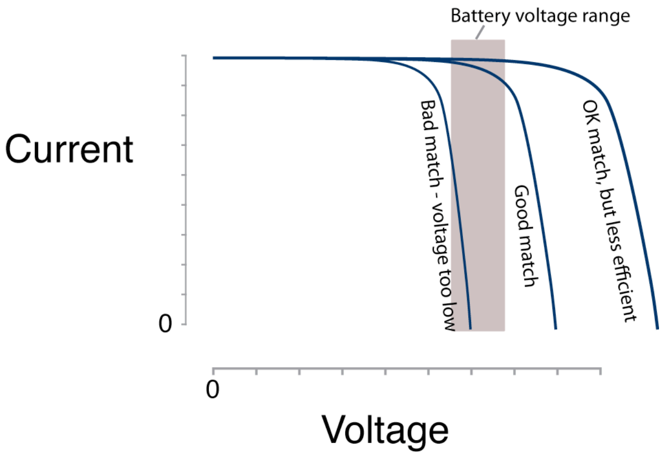

Figure 6: An illustration of voltage matching between PV modules and batteries.

Maximum Power Point Tracking

Instead of directly connecting the PV module and battery, a DC-DC converter[2] can also be used to step the PV module voltage up or down to match the battery voltage—in theory optimizing the performance

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[2] A DC-DC converter is an electronic circuit that converts DC power from one voltage to another; essentially, it serves the same purpose as a transformer in an AC circuit.

of an otherwise poorly matched system. Some DC-DC converters can also provide maximum power point tracking (MPPT), in which the PV module voltage is constantly adjusted in an attempt to operate the module at the maximum power point. Well-designed MPPT can improve charging efficiency, allowing a smaller PV module; unfortunately, including a DC-DC converter adds complexity and increases cost, and some power is lost due to inefficiency in the converter itself. A well-matched PV module and battery can provide results that are as good as or better than those from a DC-DC converter, especially in a low-cost product.

Accounting for High Temperature Operation

Since real products almost never operate at standard test conditions, it is important to also consider the influence of module operating temperature on voltage matching. Recall that higher temperatures mean lower operating voltages. In most places, 50°C is a good estimate for the operating temperature under full sun at moderate ambient temperatures; however, on very hot days, the module temperature may reach 70°C. Figure 7 shows how a product that performs well at moderate temperatures may have a much lower charging current (poor performance) in very hot places. In this case, the voltage of the PV module should be made higher by adding cells to the module if the product is intended for use in very hot areas. The best way to find the module temperature for a given product is to measure it in the expected conditions.

To estimate the expected performance of your own PV modules at various operating temperatures, you can use Equations 2-3 (Appendix A) to adjust each current and voltage measurement from the STC value to the value at the expected operating temperature. An alternative is to simply measure the curves at the temperatures of interest; low-cost measurement procedures are presented in Part 2 of this Technical Note.

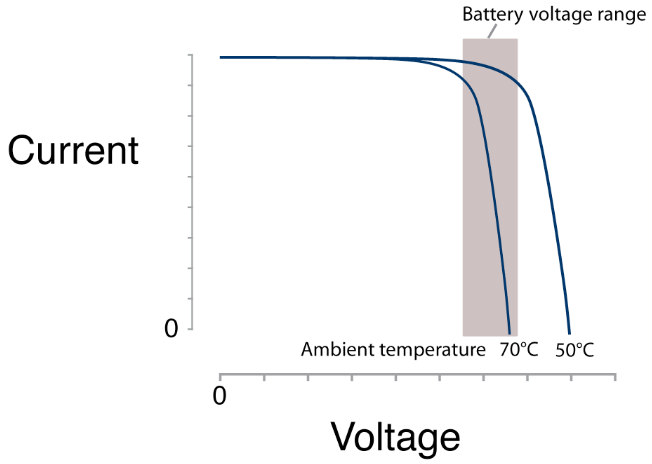

Figure 7: The influence of module temperature on voltage matching between PV modules and batteries. This combination of PV module and battery will work well at 50 °C, but the battery may not be fully charged at 70 °C.

Predicting Performance

Once you have a temperature-adjusted I-V curve it is possible to estimate the current (or power) that will be produced by the module during a day of charging. This determines how well a particular load (like an LED light) can be served by the PV module.

Estimating the daily charge (mAh) or energy (Wh) produced by a PV module is a three-step process:

1) ***Generate a temperature-adjusted I-V curve.*** This can be as easy as using a three-point approximation like in Figure 4 or measuring a detailed I-V curve (as is described in later sections). The temperature adjustment should convert from standard test conditions temperature (25°C) to the expected operating temperature (normally 50°C, but up to 70°C in hot areas).

2) ***Locate the expected operating point on the I-V curve*** based on the typical battery charging voltage and including any losses in the circuit

between the battery and PV module. Typically the losses are very small, but they can be large in some cases, such as when a linear voltage regulator or other inefficient DC-DC converter is used. (For example, if a blocking diode is used between the PV module and battery, add approximately 0.6 V to the battery voltage to find the PV operating voltage.) Note the current (mA) or power (W) at this operating point.

3) ***Estimate the daily charge or energy production using an estimate for the available solar resource at the location where the product will be used.***[3] Use an estimate of average daily solar irradiation (insolation), in units of kWh/m^2. Note that these units are also equal to “full sun hours”—the number of equivalent hours of sun at 1,000 W/m^2 (approximately the intensity of noontime sun). Since I-V curves are typically given for 1,000 W/m^2 solar irradiance, it is possible to simply multiply the full sun hours by the current or power at the expected operating point to find the daily charge (mAh) or energy (Wh).

Consider a hypothetical example 0.8 W PV module with an I-V curve shown below in Figure 8. It will be used to charge a lithium-ion battery in Nairobi, Kenya, where the temperature is moderate, so the I-V curve has been adjusted for an estimated operating temperature of 50°C. Based on the typical range of charging voltages for the battery, we expect a typical PV module operating point at 3.5 volts and 210 mA if the solar irradiance is at “full sun.” This is 0.74 W. Since Nairobi receives 5.3 kWh/m^2 on a typical day, we can estimate the daily energy production from the solar module will be 3.9 Wh—0.74 W times 5.3 sun-hours. Likewise, the total charge generated will be 1,100 mAh. If the lithium-ion battery capacity is 2,000 mAh, this means it can be recharged about halfway in one typical day of solar charging in Nairobi.

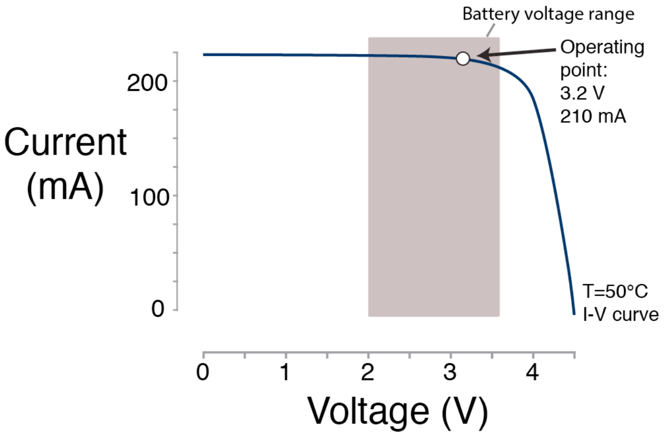

Figure 8: Hypothetical matching between a PV module operating at 50°C and a LiFePO$_4$ battery.

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[3] Solar radiation is highly variable, depending on location, season, weather, shading from nearby objects, and user behavior. Data resources for estimating the available solar radiation are listed in Appendix C, but it is important to remember that real operation on a day-to-day basis will rarely match the “typical day” exactly. For a typical sunny place, 5 full-sun hours (i.e., 5 kWh/m^2)—the standard solar day—is a reasonable estimate.

Part 2: Measuring I-V Curves

Before measuring an I-V curve it is important to first define the goals of the measurements. Do you want to check the consistency of PV modules in a batch? Are you interested in checking that a delivered PV module matches specs?

The outdoor test methods described in this note generally use inexpensive equipment, but require careful measurements that may not be fast and require a skilled and experienced technician. However, with careful measurement it is possible to get results that are nearly as accurate as those from national laboratories using high-tech (expensive—$50,000 and up) equipment. The equipment we describe can cost as little as $1,000.

The goal of our measurement is to generate an I-V curve that describes the PV module at standard test conditions. Those conditions can be simulated indoors with expensive equipment, but since they don't typically occur in real operation, the outdoor testing approach is to measure an I-V curve somewhere near the standard conditions and correct for deviations.

Equipment Snapshot

There are three main parts to an outdoor I-V curve measurement setup: a variable load, temperature and solar radiation sensors, and voltage and current measurement equipment.

Variable Load

It is quite easy to measure short-circuit current and open-circuit voltage; the challenge is measuring points between the two extremes by systematically varying the load. I-V curves can be measured using resistive or capacitive loads; resistors are easier to use with low-cost measuring equipment, but capacitors allow faster measurements. Only resistive loads are discussed here.

A variable resistor (also called a potentiometer or rheostat) for measuring I-V curves must be sized correctly to capture the full curve. The goal is to measure the maximum power point and several points around it to fully characterize the most "non-linear" section of the curve—the knee. Figure 9 below shows a well-matched variable resistor. Recall that a single resistance is a straight line on the plot with a slope equal to 1/R; a range of resistances will look like a triangle-shaped window on the I-V curve. Figure 10 shows how a well-matched potentiometer for one PV module may be a bad fit for another one. If you are measuring a wide range of PV modules you will probably need a range of variable resistors[4].

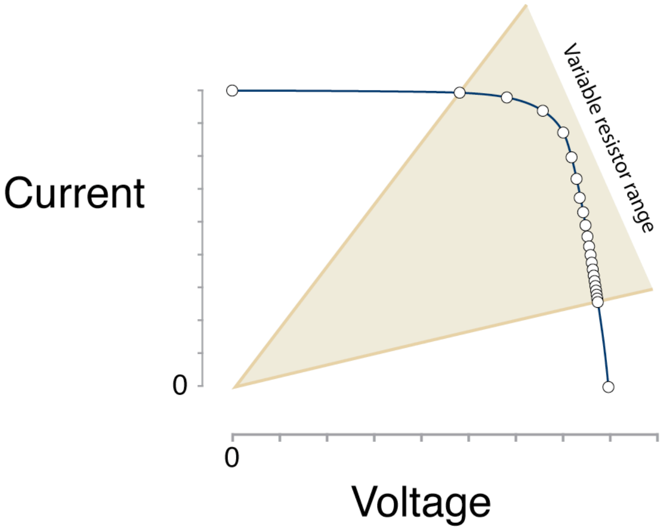

Figure 9: A well-matched variable resistor for measuring a given PV module I-V curve. The points that can be captured (white) give a good picture of the true I-V curve. The points shown correspond to equally spaced resistance values; short-circuit current and open-circuit voltage are measured without using the resistor.

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[4] Appendix D details a procedure for sizing resistors for I-V curve testing.

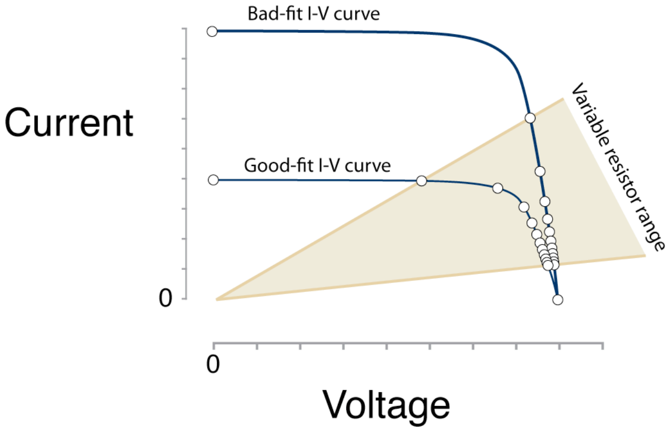

Figure 10: A variable resistor that is poorly matched for one PV module but OK for another. A lower-value resistor would be required to measure the "bad-fit" I-V curve.

In addition to having an appropriate resistance range and resolution, a variable resistor must be able to withstand the current produced by the PV module; if the current rating is exceeded, the variable resistor can be damaged. If the variable resistor has a current rating, it should be greater than I_{sc}. Some variable resistors have only a maximum power rating; in this case, find the current rating using Equation 1.

$$I_{max} = \sqrt{P_{max}/R} \qquad (1)$$

where:

I_{max} = Variable resistor current rating in amps
P_{max} = Full-scale power rating in watts
R = Full-scale resistance in ohms

Environmental Sensors

It is important to measure each aspect of the system that influences the I-V curve during the test; these are generally the PV module temperature and the solar irradiance. Note these are the same factors that are fixed by the standard test conditions and will be the factors that we correct for when converting real operating measurements to standard test conditions.

The module operating temperature can be measured with a surface-mounted thermocouple and a thermocouple reader. The thermocouple is generally attached to the back of the PV module, directly behind part of the active cell area.

A silicon-based pyranometer (solar irradiance measurement device) is the best type of solar irradiance sensor during an I-V curve test. They are lower cost and offer faster response times than the thermopile-based pyranometers that are typically used for long-term solar energy monitoring. Silicon pyranometers often have an output signal that is a scaled current or voltage; a good quality multimeter can be used to measure the output signal for conversion to solar irradiance using the calibration factor provided by the pyranometer manufacturer. Pyranometers should be periodically recalibrated to maintain their accuracy.

Electronic Measurements

Devices to measure the electrical performance of PV modules range from simple self-built setups to more sophisticated off-the-shelf or custom made analyzers. In this technical note, we present two low-cost, self-built setups and discuss more sophisticated options available on the market.

The most basic setup (Figure 11) consists of two multimeters: one to measure current and the other for voltage. Also shown are a temperature meter with thermocouple, a silicon photovoltaic pyranometer with multimeter, and a variable resistor, also called a rheostat or potentiometer. The multimeter used to measure current must be rated for a maximum current higher than I_{sc}. The estimated cost of the pyranometer and variable resistor is about \$300 US. Appendix A has step-by-step instructions on how to operate this basic I-V curve setup.

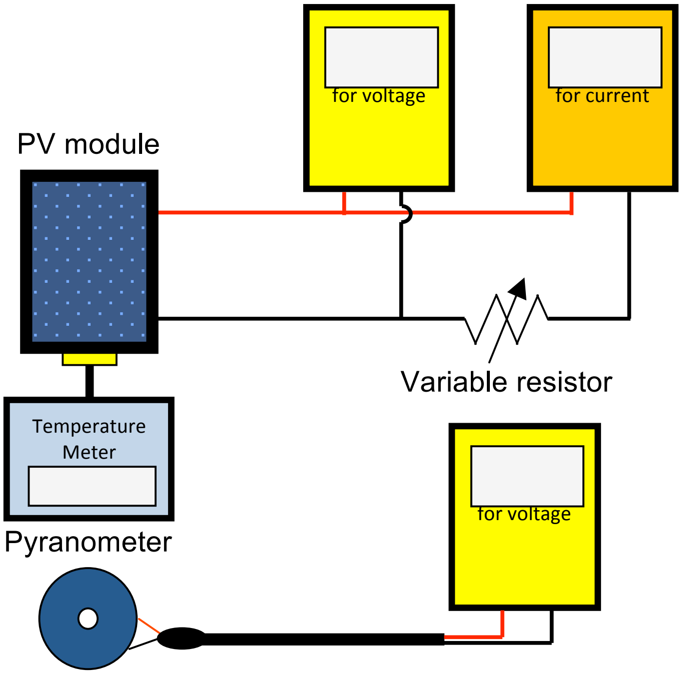

Figure 11: Basic I-V curve measurement setup. The pyranometer must be mounted in the same plane as the PV module (see Figure B1).

Incorporating data-logging capabilities with the measurement devices can simplify the I-V curve measurement procedure and improve the quality of results by allowing more points on the curve to be measured. To add data-logging capability, the multimeters in the basic setup are replaced (or complemented) by a data logger and current transducer. A current transducer produces a voltage proportional to the current passing through it; the data logger records this voltage. In Figure 12, the data logger reads three signals: the voltage across the PV module, the transducer voltage representing the current through the load, and the output signal from the pyranometer. The transducer and pyranometer signals typically need to be rescaled using the appropriate calibration factors; this can occur in post-processing of the data.

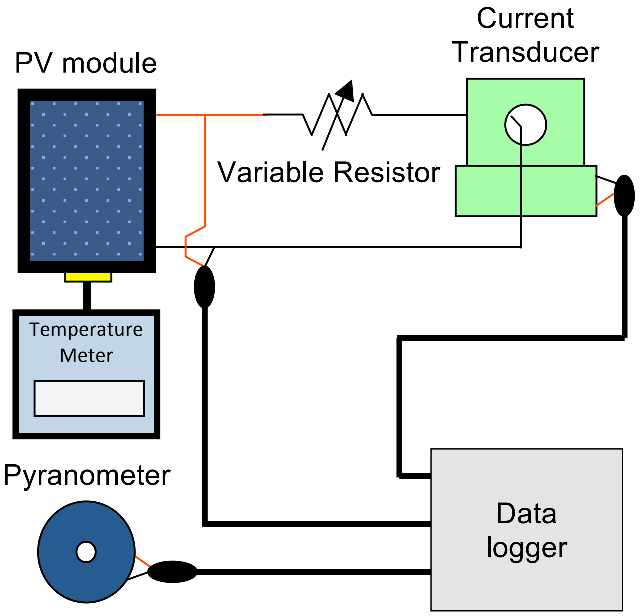

Figure 12: I-V curve measurement setup with data logger. The pyranometer must be mounted in the same plane as the PV module (see Figure B1).

General Rules for Outdoor I-V Testing

In general, the goal of outdoor testing is that conditions should be as close as possible to STC and, more importantly, should change as little as possible during the course of the test. Practically, the following general rules will help meet that goal:

- I-V curves should be measured under a completely clear sky as close as possible to solar noon. The air mass (the relative thickness of the atmosphere through which the light from the sun travels—which is based on the solar angle) should be less than or equal to 2. It is generally OK to make measurements between 10 AM and 2 PM, but this depends on the location and time of year. In high latitude locations, it may not be possible to make measurements during the extreme winter months.

- The PV module should be allowed to reach a stable operating temperature before the test.

In practice this means the temperature is changing less than 1 °C per minute.

- The pyranometer must be mounted in the same plane as the PV module; both should be directly perpendicular to the incoming solar radiation.

I-V Curve Analyzers

Sophisticated I-V curve analyzers are available on the market. These products often come with software to simplify data collection and analysis. In addition, they are often designed with conveniently integrated components, making the test setup and operation quicker and easier. When selecting an analyzer, pay careful attention to the analyzer's PV module size range, as most are designed for larger modules than are typically used for off-grid lighting products. I-V curve analyzers range from handheld devices for outdoor testing, which are relatively inexpensive ($3,000 US) but require skilled operators and clear skies, to indoor solar simulators, which provide repeatable results and allow testing at any time of day but can cost $50,000 or more. The solar simulators commonly used by PV manufacturers use a flash of light that lasts for only a fraction of a second without affecting the cell temperature, allowing direct measurement of performance at STC.

Appendix A. I-V curve adjustment equations

To generate a temperature-adjusted I-V curve, each current-voltage pair in the STC I-V curve should be adjusted using Equations 2-4 and the location-specific PV module temperature. If measured temperature coefficients are not available for the specific module of interest, use the values in Table A1. To estimate solar charging time, refer to Lighting Africa Quality Test Method section 2.8.1.

Equations 5-7 are used to convert a measured I-V curve to STC from the conditions during measurement. Use the solar irradiance value from the pyranometer and the module temperature and temperature coefficients measured during the test. Note that these equations neglect the dependence of voltage on irradiance and the dependence of current on temperature; these are generally reasonable approximations, especially when characterizing operation at voltages less than V_{mp}.

Table A1: Typical temperature correction coefficients for selected PV module types.

Module Type	$T_{c,voc}$ (1/°C)
Monocrystalline	-0.0043
Polycrystalline	-0.0035
Amorphous silicon	-0.0031
Copper indium selenide (CIS)	-0.0029
Cadmium telluride (CdTe)	-0.0025

Converting from STC:

$$I_2 = \frac{I_{stc}}{\left(\frac{G_{stc}}{G_2}\right)} \quad (2)$$

$$V_2 = \frac{V_{stc}}{\left(1 + T_{c,voc}\left(T_{stc} - T_2\right)\right)} \quad (3)$$

$$P_2 = I_2 V_2 \quad (4)$$

Converting to STC:

$$I_{stc} = I_2\left(\frac{G_{stc}}{G_2}\right) \quad (5)$$

$$V_{stc} = V_2\left(1 + T_{c,voc}\left(T_{stc} - T_2\right)\right) \quad (6)$$

$$P_{stc} = I_{stc} V_{stc} \quad (7)$$

where:

I = Current (A)
V = Voltage (V)
G = Solar irradiance (W/m^2); 1000 W/m^2 at STC
T = Temperature (°C); 25 °C at STC
$T_{c,voc}$ = Temperature coefficient of voltage (°C^{-1})

Subscript stc: value at standard test conditions.
Subscript 2: measured or location-specific value.

Appendix B: I-V curve test procedure

Follow these steps to measure an I-V curve using the basic test setup (Figure 11). For accurate results, take measurements under an absolutely clear sky and close to solar noon with an air mass value less than or equal to 2 (see General Rules for Outdoor I-V Testing on page 9). These conditions minimize the change in solar radiation parameters during testing.

Materials required: stand (see below), pyranometer, variable resistor, two multimeters, thermocouple, temperature meter, small piece of foil-backed foam tape for thermal insulation.

The solar module and pyranometer must be in the same plane, directly normal (perpendicular) to the incoming solar radiation. This can be accomplished using a stand consisting of a board with a sight tube perpendicular to the plane of the module and pyranometer (Figure B1). The board is then positioned so that the area illuminated through the tube is perfectly circular.

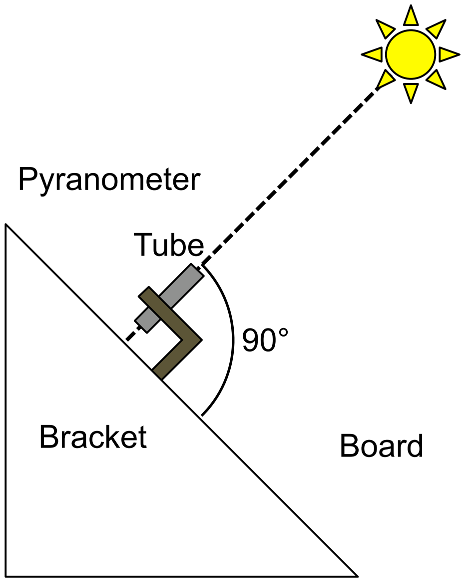

Figure B1: I-V curve testing rack.

Setup and temperature coefficient measurement

If the PV module is separate from the product or can be removed without damaging the active PV material:

1. Connect the voltage meter in parallel with the PV module. Keep the module in the shade until step 3.
2. Affix the thermocouple to the back of the PV module with thermal insulating tape. Connect the thermocouple to the temperature meter.
3. Position the testing stand so it is perpendicular to the sun and place the PV module on the stand. Immediately record the temperature (T_1) and open-circuit voltage ($V_{oc,1}$).
4. Leave the PV module on the stand and wait for the module to reach an equilibrium temperature (approximately 30 minutes, until the temperature is changing by less than 1 °C/min). Adjust the stand as needed to keep it perpendicular to the sun.
5. Connect the variable resistor and current meter as in Figure 11, but leave one terminal of the variable resistor disconnected to allow measurement of the open-circuit voltage. (You can do this while waiting for the module to reach equilibrium temperature.)
6. Perform the I-V curve measurement procedure below.
7. After the I-V curve measurement, measure and record the PV module temperature again (T_2).
8. Disconnect the variable resistor and measure the open-circuit voltage at T_2 ($V_{oc,2}$)

If the back of the module is inaccessible (for example, if the module is integrated into a product and cannot be removed without damaging it):

1. Connect the voltage meter in parallel with the PV module. Keep the module in the shade until step 3.

2. Affix the thermocouple to the front of the PV module over the active area with thermal insulating tape.
3. Position the testing stand so it is perpendicular to the sun and place the PV module on the stand. Immediately record the temperature (T_1), then quickly remove the thermocouple and insulating tape and measure the open-circuit voltage (V_1).
4. Reattach the thermocouple to the front of the module, in the same location as before.
5. Leave the PV module on the stand and wait for the module to reach an equilibrium temperature (approximately 30 minutes, until the temperature is changing by less than 1 °C/min). Adjust the stand as needed to keep it perpendicular to the sun.
6. Connect the variable resistor and current meter as in Figure 11, but leave one terminal of the variable resistor disconnected to allow measurement of the open-circuit voltage.
7. Remove the thermocouple from the PV module. Record the open-circuit voltage ($V_{oc,2}$). Immediately reattach the thermocouple in the same location as before and record the temperature (T_2).
8. Immediately remove the thermocouple again and immediately perform the IV curve measurement procedure below.

I-V curve measurement procedure

1. Ensure that the stand is still perpendicular to the sun before beginning the test.
2. Record the pyranometer output signal (either voltage or current) for later conversion into a solar irradiance value using the pyranometer's calibration factor.
3. With one terminal of the variable resistor still disconnected, record the voltage; this is the open-circuit voltage V_{oc}.
4. Set the variable resistor to its highest setting and reconnect it.
5. Slowly turn the variable resistor knob, pausing often to record the current-voltage pairs. For better accuracy, record the temperature (if the thermocouple is on the back of the module) and pyranometer output value along with each current and voltage measurement. Record more points near the knee of the curve. It may be helpful to sketch a plot of the I-V curve as the measurements are recorded, as long as this can be accomplished without slowing down the data collection. (For example, the data could be entered directly into a spreadsheet on a laptop computer.)
6. Continue until you reach zero resistance; this will measure the module's short-circuit current I_{sc}. To prevent damage to the equipment, avoid leaving the variable resistor at or near zero for longer than necessary.
7. Record the pyranometer output value again, verifying that it is within a reasonable tolerance[5] of the measurement at the start of the test. Use the average of the two values to compute the measured solar irradiance (G_2). (You can also use a multimeter with averaging functionality to measure the average irradiance over the entire test.) If the pyranometer output value has changed by more than a reasonable tolerance, repeat the test. If you recorded the pyranometer output value with each measurement, this step is unnecessary.

With a data logger, the procedure is the same, except that you do not need to pause to record measurements. Turn the variable resistor knob slowly, especially near the knee of the curve.

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[5] The definition of the reasonable tolerance for a change in irradiance will vary depending on the application of the test results, but will nearly always be <5%.

Calculations

1. Calculate the solar irradiance (G_2) from the pyranometer output signal using the pyranometer's calibration coefficient.
2. Convert all current measurements to STC using Equation 5. For the solar irradiance at STC (G_{stc}), use 1000 W/m^2.
3. Compute the temperature coefficient of voltage using Equation 8.

$$T_{c,voc} = \frac{\left(V_{oc,1} - V_{oc,2}\right)/V_{oc,2}}{T_1 - T_2} \qquad (8)$$

where

$T_{c,voc}$ = Temperature coefficient of voltage (1/°C)
T_1, T_2 = Measured temperatures (°C)
$V_{oc,1}$ = Open-circuit voltage at T_1 (V)
$V_{oc,2}$ = Open-circuit voltage at T_2 (V)

4. Convert all voltage measurements to STC using Equation 6. If the thermocouple was attached during the test, use the actual temperature values; otherwise use T_2.
5. Compute power by multiplying the STC values of current and voltage (Equation 7).
6. Plot current on the vertical axis and voltage on the horizontal axis to create the I-V curve. The point where current equals zero is the open-circuit voltage (V_{oc}); the point where voltage equals zero is the short-circuit current (I_{sc}).
7. Plot power on the vertical axis and voltage on the horizontal axis to create the P-V curve. The highest value on this curve is the maximum power point power (P_{mpp}). The maximum power point voltage (V_{mp}) is the voltage corresponding to P_{mp}; the maximum power point current (I_{mp}) is the current corresponding to this voltage on the I-V curve.

Appendix C: Solar radiation data and additional data sources

The following data and sources of data may be useful for estimating the solar radiation available at sites in Africa and elsewhere. Table C1 gives average daily solar irradiation values for selected locations in Africa.

Table C1. Average daily solar irradiation values calculated by Fraunhofer ISE.

Location (City, Country)	Daily solar Irradiation (Wh/m²)
Addis Ababa, Ethiopia	5,194
Accra, Ghana	4,912
Nairobi, Kenya	5,382
Lusaka, Zambia	5,170
Dodoma, Tanzania	5,618

Additional data sources

- USA NASA Surface Metrology and Solar Energy
  http://eosweb.larc.nasa.gov/sse/

  Model-based estimates of solar resource for any location on Earth.

- European Commission Joint Research Center Photovoltaic Geographical Information System (PVGIS)
  http://re.jrc.ec.europa.eu/pvgis/

  Model-based estimates of solar resource for locations in Europe and Africa. Clickable GIS interface and full-color maps.

- USA National Renewable Energy Laboratory Renewable Resource Data Center
  http://www.nrel.gov/rredc/solar_data.html

  Variety of model-based and measured solar resource data focused on USA but also with a dataset for India.

- United Nations Environment Program Solar and Wind Energy Resource Assessment (SWERA)
  http://swera.unep.net/

  Web clearinghouse for solar and wind data; references many of the sites above with some others.

Appendix D: Procedure for sizing resistors for I-V curve testing.

Consider the PV module with I-V curve shown in Figure D1 below. V_{oc} is about 4.5 V and I_{sc} is approximately 200 mA. At currents below 75 mA and voltages below 2 V, the curve is approximately linear, so it would be acceptable to take measurements only in the shaded area. The maximum resistance can be estimated by dividing V_{oc} (4.5 V) by the minimum desired current (75 mA), which gives 60 ohms. The minimum resistance can similarly be estimated by dividing the minimum desired voltage (2 V) by I_{sc} (200 mA) to get 10 ohms. Any resistor that can be adjusted between these values with sufficient resolution will capture the most important part of the I-V curve for this PV module.

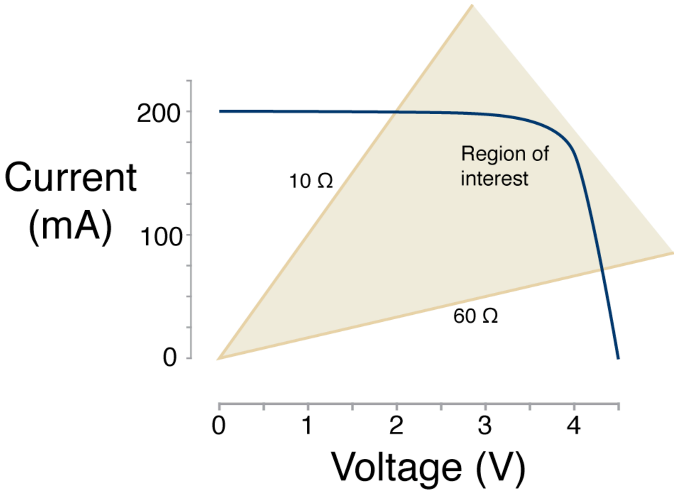

Figure D1: Variable resistor selection example. Varying the resistance from 10 to 60 ohms will capture the most important part of the I-V curve.

The resolution (i.e., the number of points one can sample on the curve) is a function of resistor design and operator technique. For a wirewound rheostat (a common design for high-power applications), the best achievable resolution can be estimated by dividing the total resistance by the number of turns in the resistor's winding. The spacing of points near short circuit can then be estimated by multiplying the resistance resolution by the short-circuit current. For example, if a 100-ohm rheostat with 200 turns is used to test the module the resistance resolution will be approximately 0.5 ohms and the minimum possible spacing of points near short circuit will be about 0.1 V (0.5 ohms times 200 mA). As the voltage approaches open-circuit, the spacing between points will decrease. Resolution can be improved by adding a small "fine-tuning" rheostat in series with a larger "coarse adjustment" rheostat.

Note that the above procedure for estimating the resistor values assumes some knowledge about the shape of the I-V curve. Some trial and error may be necessary to select the proper variable resistor for a previously untested module type. In general, the more the I-V curve deviates from the ideal silicon module behavior depicted here, the less accurate these methods will be.