
SAMSUNG

Field Applications for I-V Curve Tracers

By Paul Hernday

While indispensible to PV cell and module manufacturing processes, I-V curve tracers have historically held a limited role in the field. Now that the technology is more widely accessible, the role of curve tracers is expanding beyond the laboratory.

Courtesy Integrated Energy Systems, Pittsburg Unified School District, Sage Renewables, Solmetric, Stellar Energy Solutions

Silicon PV modules are highly reliable, but performance problems do arise, and the industry needs fast and accurate ways to detect them. The stakeholders in newly built systems want to verify that all the PV modules are of a consistent quality, that they were not damaged during shipment or assembly, and that the array is producing at the contracted capacity. These stakeholders would also like a permanent record of the as-built system performance, a benchmark for comparison as arrays age and degrade—particularly in cases where warranty negotiations are required. Later in the system's life cycle, operations and management (O&M) or asset management companies want to evaluate the health of older arrays and have the ability to efficiently locate an ailing module.

These are all potential applications for I-V curve tracers, which can provide both a qualitative visual representation and a quantitative measure of PV performance. Curve tracing equipment was developed for testing transistors and diodes in the semiconductor industry. Now it is a workhorse in PV R&D and manufacturing, for use with both individual cells and modules. It also has a long history of use in field testing of PV arrays, a use that is likely to increase in frequency as more affordable and user-friendly products become available.

In an effort to demystify I-V curve tracers, here I explain how these devices work and how they can be used to commission and troubleshoot PV arrays. The basic characteristics of a healthy I-V curve are described, as well as characteristics that indicate the most common classes of PV array performance impairments. I present rules of thumb for the successful use of I-V curve tracers in the field, which is inherently more challenging than taking measurements in controlled settings like a factory or laboratory. I also provide tips on how to avoid common measurement and data analysis mistakes. When properly attained and analyzed, I-V curve traces provide the most comprehensive measurement possible of PV module or array performance.

I-V Curve Measurements

I-V curves or *traces* are measured by sweeping the load on a PV source over a range of currents and voltages. Curve tracers accomplish this by loading a PV module or string at different points across its operating range between 0 V and Voc. At each point, the output current and voltage are measured simultaneously. The load presented by the curve tracer may be resistive, reactive (typically capacitive) or electronic. Field test gear uses resistive or capacitive loading, whereas reference I-V test systems at research facilities tend to use electronic loads. The I-V curve may be swept in either direction.

In field test equipment, the actual I-V measurement sweep typically requires less than a second. However, there is a sweep speed limit for certain cell types. High-efficiency cell technologies from Sanyo, SunPower and other manufacturers cannot be swept arbitrarily fast. Because these cells store considerably more charge, more time is required for the cells to reach steady-state operating conditions at each point in the curve. A rough guideline is that the sweep rate for high-efficiency cells should not exceed 10 V per second per cell.

I-V CURVE REFRESHER

I-V curves, which appear on every PV module datasheet, represent all of the combinations of current and voltage at which the module can be operated or loaded. Normally simple in shape, these curves actually provide the most complete measure of the health and capacity of a PV module or array, providing much more information than traditional electrical test methods.

A normal-shaped I-V curve is shown in Figure 1 (p. 78). The maximum power point (Pmp) of the I-V curve—the product of the maximum power current (Imp) and the

Courtesy Solmetric (3)

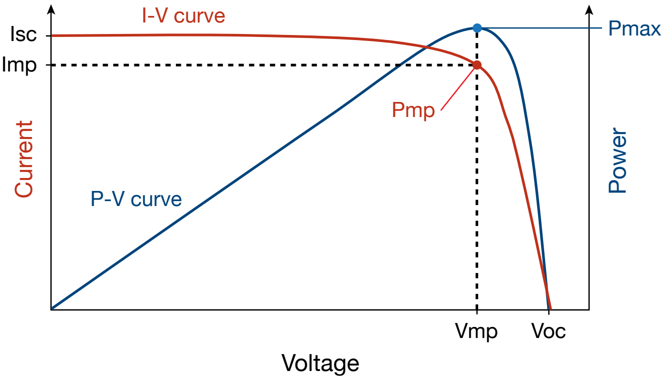


Figure 1 The normal I-V curve (red) and P-V curve (blue) shown here could represent any portion of a PV array—from a single cell, to a cell string or module, up through the array itself. The points making up this curve can be measured with a single connection and a single piece of equipment.

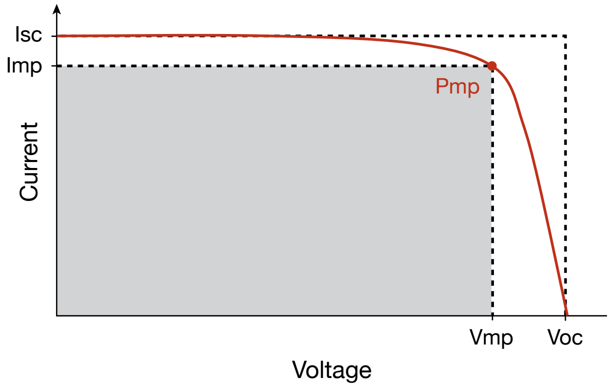


Figure 2 The outer rectangle represents an ideally square (but physically impossible) I-V curve; the shaded rectangle represents the actual measured I-V curve. The ratio of the smaller area to the larger area is the fill factor, a figure of merit for PV output capacity.

maximum power voltage (Vmp)—is located at the knee of the curve. At lower voltages, between the knee and the short-circuit current (Isc), the current is less dependent on voltage. At higher voltages, between the knee and open-circuit voltage (Voc), the current drops steeply with increasing voltage. The output current of a typical crystalline silicon PV module drops 65% in the upper 10% of its output voltage range. It is not uncommon for an I-V curve to be displayed with its associated power-voltage (P-V) curve, which is also shown in Figure 1. The value of power at each voltage point is calculated using the corresponding current from the I-V curve. The peak of the P-V curve (Pmax), of course, occurs at Vmp.

Fill factor. For given values of Isc and Voc, the power-generating capability of a PV module or array is related to the squareness of the I-V curve. The two rectangular areas in Figure 2 illustrate this relationship. The more square (or rectangular) the I-V curve, the closer Imp and Vmp approach Isc and Voc, and the higher the output power.

This relationship is also described by a figure of merit called the *fill factor,* expressed mathematically in Equation 1:

$$\text{FF} = (\text{Imp x Vmp}) / (\text{Isc x Voc}) \qquad (1)$$

A fill factor of 1.0 represents a perfectly square I-V curve, a physical impossibility but a useful reference shape. The two areas in Figure 2, and the numerator and denominator of Equation 1, are all products of current and voltage, with units of electrical power. Any physical effect that reduces the fill factor also reduces the output power of the PV module or string.

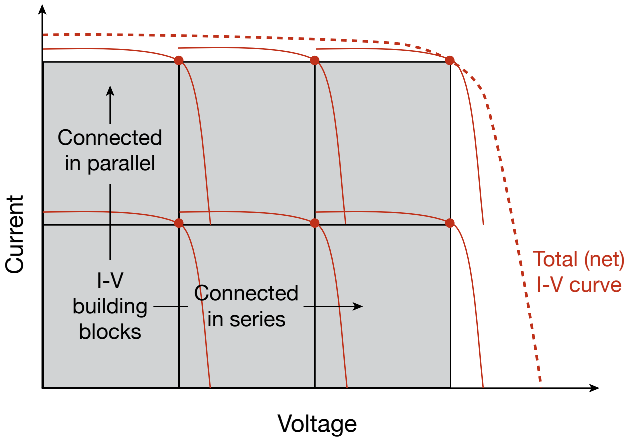
Modules with a given PV module part number should have very similar fill factors under similar environmental conditions. Fill factor does vary across cell technologies, ranging from 0.75 to 0.85 in crystalline silicon cells and from 0.55 to 0.75 for most thin-film cells. Fill factor can be also be reduced by several classes of PV impairments, which are described later.

Scaling curves. The I-V curve of a given PV module can be scaled to represent a string or array by simply rescaling the voltage and current axes. A building block analogy, as shown in Figure 3, is useful in troubleshooting PV arrays. When modules are placed in series, the curves are stacked horizontally by adding voltages for each value of current. When modules are placed in parallel, their curves are stacked vertically by adding currents for each value of voltage. The resulting overall I-V curve and max power point are the horizontal and vertical sum of the individual building blocks.

The building blocks can also represent cell strings within PV modules. This view is helpful in

CONTINUED ON PAGE 80

Figure 3 The I-V building blocks shown here could represent PV cells, cell strings or modules. The analogy of scaling up an I-V curve from more basic building blocks is useful when troubleshooting PV arrays.



troubleshooting situations because, although PV cells are the fundamental unit of production, string voltage tends to be lost in jumps that correspond to the loss of individual cell strings. A step down in an I-V curve may indicate the loss of a building block or at least a reduction in current of one of the building blocks. The width of the step is a clue to how many modules or cell strings are affected by shading, failed bypass diodes or other problems.

Benefits of Curve Tracing

The benefits of curve tracing are substantial. In addition to measuring Isc and Voc, curve tracing also captures all of the operating points in between these values, including the current and voltage of the MPP and thus the maximum power value itself. The overall shape of the I-V curve can be analyzed to give clues to performance issues in ways that traditional test methods cannot. Further, the maximum output-power rating for individual PV modules or strings can be obtained without an inverter or the attendant uncertainties of the individual inverter efficiency.

David King, PV consultant and founder of DK Solar Works, has extensive laboratory and field experience with I-V curve tracers. King worked for 31 years in the solar energy departments at Sandia National Laboratories, where he managed laboratories for testing PV cells, modules and high voltage arrays, as well as overseeing system performance characterization and modeling activities. Based on that experience, King concludes that I-V curve tracing is a fundamental, required measurement throughout the PV industry, both indoors in cell or module manufacturing environments, and outdoors for the testing of modules, module-strings and large arrays.

"I-V curve measurements provide direct performance characterization and verification, as well as a diagnostic tool for periodic PV system performance assessments," says King. "I-V curve tracing is the most informative measurement that can be performed on a PV module or array. The visual shape of the curve provides immediate diagnostic insight for a PV specialist. When coupled with the associated solar irradiance and temperature data, it provides a quantified comparison to expected performance."


Courtesy Daystar

Daystar DS-100C Designed for field use, this I-V curve tracer from Daystar is rugged and portable. It is capable of tracing subarrays of up to 50 kW in capacity.

Though no other diagnostic tool can provide as much relevant information about PV component or system health, today's commissioning agents and O&M technicians do not often use I-V curve tracers for their periodic performance assessments. According to Andrew Rosenthal, director of the Southwest Technology Development Institute (SWTDI) at New Mexico State University, the high cost of these tools has limited their use in the field.

"Curve tracing has not been more widely used in the industry because of the prohibitively high cost of most curve tracers," Rosenthal says. He explains that one of the common field applications for curve tracing in R&D is to accurately determine the dc power rating for a PV system. "I-V curve tracing is a valuable tool when an accurate system rating is required," says Rosenthal. "It is also a valuable tool for system troubleshooting when string or array performance is less than expected."

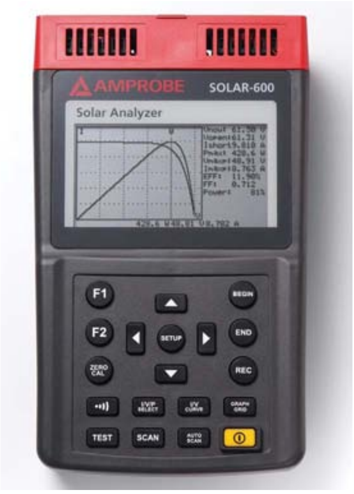
Specialists engaged in PV system troubleshooting activities have long required access to I-V curve tracers, regardless of the cost. For example, Bill Brooks, principal at Brooks Engineering, first used an I-V curve tracer in 1988 and purchased a tracer of his own in the early 1990s. Brooks believes that the educational benefits of working with a curve tracer are hard to overstate. "I had the great fortune of learning about PV through the eyes of an I-V curve tracer," he says. "I consider that education a critical part of my success in understanding and troubleshooting how PV systems operate."

This educational component is one of the reasons Brooks is excited about the increasing availability of affordable and portable products. Companies like Amprobe, Daystar, EKO, HT-Italia and Solmetric all have curve tracers available in North America that are specifically intended for field-testing applications like PV system commissioning and troubleshooting; even more products are available in Europe.

"Now that these devices are so much more affordable, there is no good reason not to get one," says Brooks. "For example, the cost for the PVA-600 PV Analyzer from Solmetric is in a range that makes it attractive to any company with a dozen or more employees. Unlike a new truck that depreciates the second it is driven off the lot, a curve tracer is an investment that helps the employees of that company understand their trade better and eventually become experts in their field."

Isaac Opalinsky, technical trainer at SunPower,

CONTINUED ON PAGE 82



Courtesy Amprobe

Amprobe Solar-600 This handheld solar analyzer from Amprobe is capable of tracing I-V curves for individual modules rated at up to 60 V and 12 A. The internal memory stores up to 99 measurements.

Courtesy Solmetric

Solmetric PVA-600 The PV analyzer from Solmetric, which has a measurement range of 600 V and 20 A, is designed specifically for field testing PV systems. An optional wireless sensor kit is also available.

has long used curve tracers in training programs as an educational tool to help students understand how real-world effects, such as temperature, irradiance, shading and mismatch, impact system performance.

"Recently, we have been able to measure some of the I-V curves that had previously only been modeled, including scenarios with multiple strings, shading and intentional mismatch, for instance multiple orientations," says Opalinsky. "It is satisfying for students to see how the things we discuss in the classroom are validated and replicated with real-world measurements. Even if the students are not the technicians who are likely to be performing O&M tasks in the field, an I-V curve tracer that can be used directly by the students can help create the 'ah-ha!' moments where abstract concepts are synthesized."

While it is possible for technicians in the field to get a basic snapshot of system performance and diagnose many field failures using affordable and widely available tools like digital multimeters and clamp meters, Opalinsky notes that I-V curve tracers have two unique advantages. First, I-V curve tracers make it easier and safer to take Isc measurements. Second, curve tracers can reveal what happens to an array under load.

"The four key measurements that can be performed with a digital multimeter (Voc, Vmp, Imp, Isc) are inadequate if we want to get a picture of how the PV system responds to a varying load," states Opalinsky. "Without disassembling an array, it can be difficult to determine if a perceived problem is just a function of varying environmental conditions, a single bypass diode that has failed or high resistance in a corroded connector."

PV Array Performance Impairments

In order to identify potential problems using an I-V curve tracer, technicians need to be trained to understand the different classes of performance impairments, as well as the associated curve signature for each. There are five basic classes of PV array performance impairments: series losses, shunt losses, mismatch losses, reduced current and reduced voltage.

Series losses. Losses due to excess series resistance show up in the I-V curve as a decreased slope, or inward tilt, of the curve near Voc. An example is shown in Figure 4 (p. 84). Series resistance effects are equivalent to adding a single external resistor in series with the PV module. The voltage drop across this resistor increases linearly with output current, reducing the output voltage. Since the current change relative to voltage in the I-V curve is much

CONTINUED ON PAGE 84

> "As our industry matures, we should not be selling PV as a 'maintenance-free' energy solution. At a minimum, we should be inspecting all PV systems on a regular basis. If using a digital multimeter is like measuring a patient's blood pressure and heart rhythm, using an I-V curve tracer is like administering an MRI. Rather than being EMTs responding to an emergency, we should be physicians helping to keep our patients healthy through preventative maintenance and regular screening."
>
> —Isaac Opalinsky, SunPower

more pronounced near Voc, the decreased slope due to increased series resistance is most apparent at these higher voltages, near Voc.

Series resistance losses can be located internally, inside a PV module, or externally, in the array wiring and switchgear. Dr. Sarah Kurtz, principal scientist and reliability group manager at the National Renewable Energy Laboratory (NREL), notes that the most common cause of PV performance problems is probably increased series resistance. "This is often caused by internal interconnections beginning to crack or break entirely," she explains. "Most of today's modules have redundant wiring so that a single break doesn't stop the current flow, but it still increases the series resistance." Corroded or poorly connected array wiring can be an external cause of increased series resistance.

A solar module is typically divided into cell strings, each of which is shunted by a bypass diode. If series resistance in a module is very large, sufficient voltage can be developed across the series resistance so that the bypass diode turns on. An example of this effect can be observed when part of a module is shaded. In this case, the shaded cells are no longer predominantly current generators, but instead act as a dissipative resistive element. The bypass diode then shunts the current around the resistive cells, at the price of reduced string voltage and power in the partially shaded string.

Both series and shunt (or parallel) resistances degrade system efficiency by dissipating power. Since power dissipation can occur in a localized region, "hot spots" can develop. This can lead to thermal runaway where the high temperatures lead to greater power dissipation and, in some cases, damage to a PV module. If functioning properly, the bypass diodes help mitigate series resistance effects.

Shunt losses. Losses due to shunt resistance show up in the I-V curve as an increased slope, or downward tilt, of the curve near Isc. This is a region where the I-V curve is ordinarily very flat, if no shunt resistance is present. Shunt resistance effects are equivalent to connecting resistors across PV cells. As the cell voltage increases, the current through this shunt resistor also increases, reducing the module's output current and power correspondingly.

Shunt losses are located mostly within PV modules and are caused by resistive paths between the cell's front and back faces. Imperfections in cell material and faulty edge isolation can cause shunt losses. Cells that are cracked or damaged—sometimes when the metallization is added—can also cause leakage.

Mismatch losses. Substantial mismatch effects show up as notches or kinks in the I-V curve, as shown in Figure 5. More moderate effects show up as slope changes in the Isc leg of the I-V curve. The many possible causes include shading, uneven soiling, cracked PV cells, shorted bypass diodes and mismatched modules. Module mismatch can be due to differential aging effects, manufacturing tolerances or the mixing of different modules in the same string. It can also arise from one or more cell strings cutting out due to shading, bypass diode failure or the triggering of bypass diodes by other module level issues.

Reduced current. Reduction in the height of the I-V curve can be caused by uniform soiling, edge soiling (common in low-tilt, portrait-mode arrays), PV module degradation or weather conditions that reduce the input irradiance. Soiling directly impacts the height of the curve because it reduces the incident irradiance.

Figure 4 The I-V curve signature for a cell string with excess series resistance (in red) is compared here to the curve for a healthy cell string (in green).

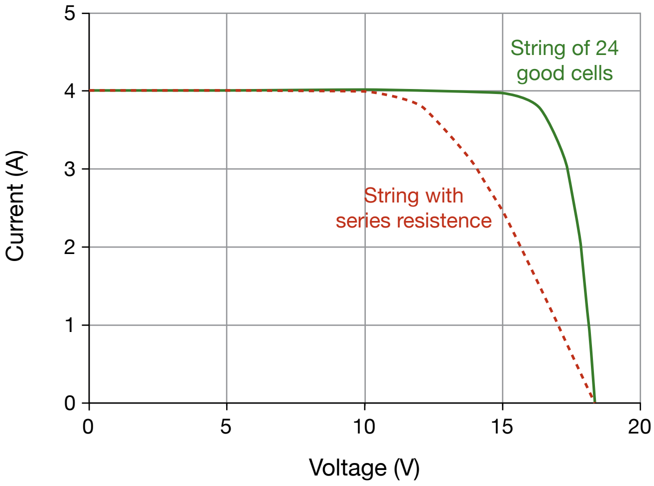
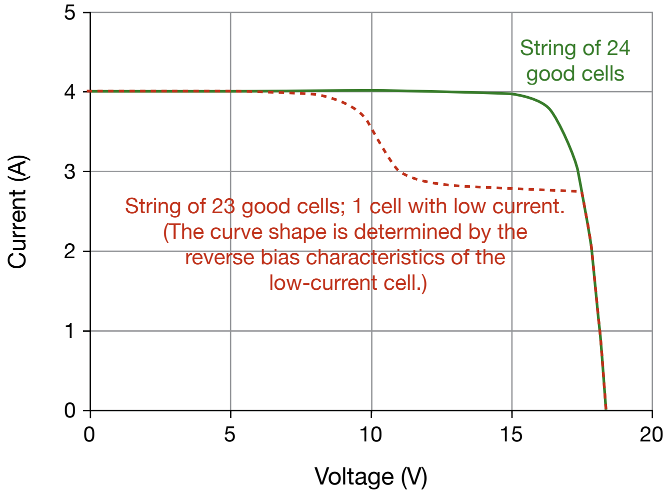


Figure 5 Reduced current from a single PV cell in a string of cells can produce the notched I-V curve signature (in red) typical of a PV source with mismatch losses.



Courtesy NREL (2)

Reduced voltage. The width of the I-V curve is affected by module temperature. Poor air circulation, for example, can raise the module temperature and substantially reduce Voc and Vmp. Module degradation, shorted bypass diodes and other system problems can also reduce Voc and Vmp. The width of the I-V curve is relatively insensitive to normal soiling.

IMPAIRMENT SIGNATURES

Each of the impairment classes described has a characteristic I-V curve signature, as summarized in Figure 6 (p. 86). The reduced current and reduced voltage impairment classes affect the height and width of the I-V curve. The other three impairment classes affect the overall shape of the I-V curve. Excess series resistance, decreased shunt resistance, and mismatch cannot be detected by simple open-circuit voltage measurements or clamp meter current measurements of individual strings. I-V curve tracers, however, provide a window into these failure modes that allows the PV technician to verify performance quickly and spot problems early.

"Some failure or degradation mechanisms cause internal changes to cells that cannot be seen with the naked eye," explains NREL's Kurtz. However, it may be possible to see the effects of these changes in I-V curve traces. She continues, "These changes may increase the series resistance, decrease the voltage and/or current, or may cause some shunting that makes the flat part of the I-V curve slope somewhat, decreasing the height of the knee, and, therefore, the output power."

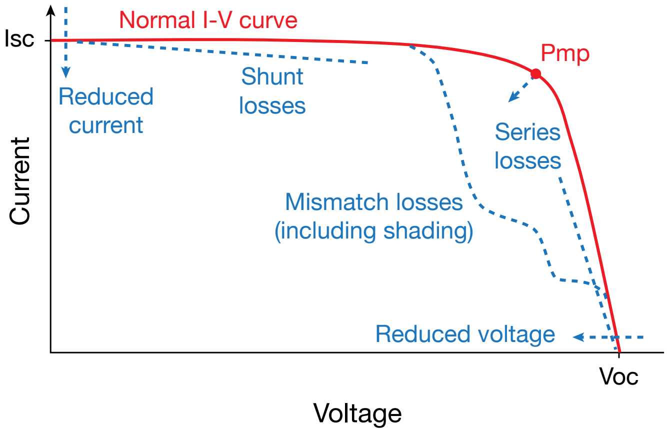
PV Performance Verification Process

Because field testing PV arrays requires working on or around energized circuits, personal protective equipment is required. It is also necessary to observe proper safety procedures, such as lockout-tagout. Read and follow NFPA-70E, *Electrical Safety in the Workplace,* for more information (See Resources).

The process of isolating circuits for measurement varies depending on the details and scale of the installation.

Residential systems. In residential systems, the PV output conductors may land on terminal blocks in an inverter-integrated disconnect switch or in the inverter itself. While curve tracers can be connected to live PV strings as long as the measurement process is disabled, lifting live PV circuit conductors can be dangerous. It is advisable that residential system designs always include either fuses or dc disconnects that enable the isolation of individual strings from the inverter and from each other. PV systems require checkups and servicing as they age, so it makes sense for system components to include the means for isolating and connecting to individual PV strings quickly and safely. Some inverters, particularly those with fused dc inputs, already provide this capability.

Figure 6 I-V curve signatures for each of the five classes of PV performance impairments are summarized here. Two classes affect the height or width of the curve. The remaining three classes affect the shape of the curve.



Commercial systems. In commercial PV systems, curve tracer measurements are performed at the combiner box, as shown in the photo to the right. The combiner is isolated from the rest of the array and the inverter by opening its dc disconnect switch. Then the combiner box is opened and all the touch-safe fuses are lifted. Once the busbars are de-energized, the curve tracer's test leads are clipped onto the busbars. Fuses are inserted one at a time for measurement of individual strings. Once an I-V curve is captured, it can be saved electronically. Some I-V curve tracers, like the Solmetric PVA-600, also allow the measured I-V curve to be compared via integrated software to a model I-V curve. The entire process typically takes 10–15 seconds per string.

PERFORMANCE STANDARDS

Verifying PV array capacity requires a standard of comparison, regardless of the testing equipment used. The standard of comparison may be a contracted power value or the prediction result from a PV array model. In the case of commercial-scale PV systems, performance verification test limits and even the test equipment itself are often specified in the performance guarantee contract. In troubleshooting situations, the standard for comparison is often a neighboring PV string.

The most common standard for performance verification measurements in the field is the nameplate specifications for the PV module. Since these apply at STC, measured I-V parameters must be translated to an irradiance of 1,000 W/m^2 and a cell temperature of 25°C. Curve-tracing instruments, however, can use PV models to predict the expected I-V curve shape. This allows the user to instantly verify performance or diagnose problems by looking for deviations between the measured curve and the expected curve predicted by the PV model or models.

Several types of PV performance models are commonly used for estimating array capacity. These models describe the performance of PV modules, strings and arrays. The three performance models most often used in the PV industry are (in order of most to least detailed): the Sandia PV array performance model, the 5-parameter model and the single-point efficiency model. These models are provided in NREL's Solar Advisor Model (SAM) simulation software. Assuming data for a PV module is available, the first two of these models can be used to generate a predicted I-V curve, given sufficient detail about system components, array orientation and environmental conditions. This makes them ideal candidates for predictive models built into curve tracing equipment. The third model predicts the maximum

CONTINUED ON PAGE 88

Courtesy Solmetric (2)

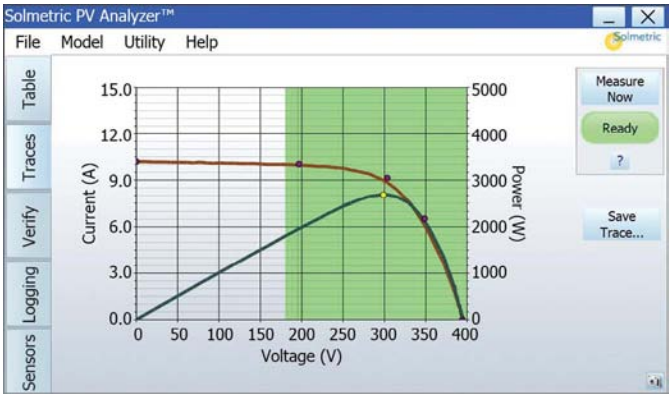
Field measurements After electrically isolating the ungrounded busbar in the combiner box, test leads to the I-V curve tracer are clamped in place. Individual source circuits can then be curve-traced by closing the series fuses one at a time, as shown here.

power value and is a good backup when a PV module is not represented in either the Sandia or 5-parameter model databases.

Sandia model. The Sandia PV array performance model was developed by David King and his co-workers at Sandia National Laboratories in Albuquerque, New Mexico, and features over 30 parameters representing irradiance and temperature dependence, spectral response, angle of incidence and other effects (see Resources). It is the most descriptive of the three PV performance models and has the greatest potential to benefit the PV industry. According to Richard Bozicevich, VP of business development for TÜV Rheinland PTL in Pheonix, Arizona: "Applications for the Sandia model include system design and sizing, translation of field performance measurements to standard reporting conditions, system performance optimization and real-time comparison of measured versus expected system performance."

The Sandia model database now contains parameters for more than 500 PV module model numbers. Under contract with Sandia and the US Department of Energy, TÜV Rheinland PTL has developed the in-house capability for measuring Sandia model parameters. Regarding the status of the technology transfer, Bozicevich reports that model validation is completed, and TUV Rheinland PTL has full capabilities to execute testing to the model for client samples.

Model behavior This screen capture shows the I-V and P-V curve traces for two paralleled PV source circuits, each consisting of 10 modules, taken using the Solmetric PVA-600 PV Analyzer. The five black dots show the shape of the I-V curve predicted by the onboard PV models.



Courtesy Solmetric

"Top-tier manufacturers are starting to request the testing and are using the data to

CONTINUED ON PAGE 90

analyze their module performance," according to Bozicevich. "However, the likelihood that these manufacturers will release the parameters to the Sandia database remains an open question."

5-parameter model. The 5-parameter PV performance model was developed at the University of Wisconsin Solar Energy Laboratory. It is used by the California Energy Commission (CEC) to simulate PV system performance for its New Solar Homes Partnership. Patrick Saxton, senior electrical engineer at the CEC, reports that as of May 12, 2011, the CEC 5-parameter model database contains parameters for more than 4,900 PV module model numbers.

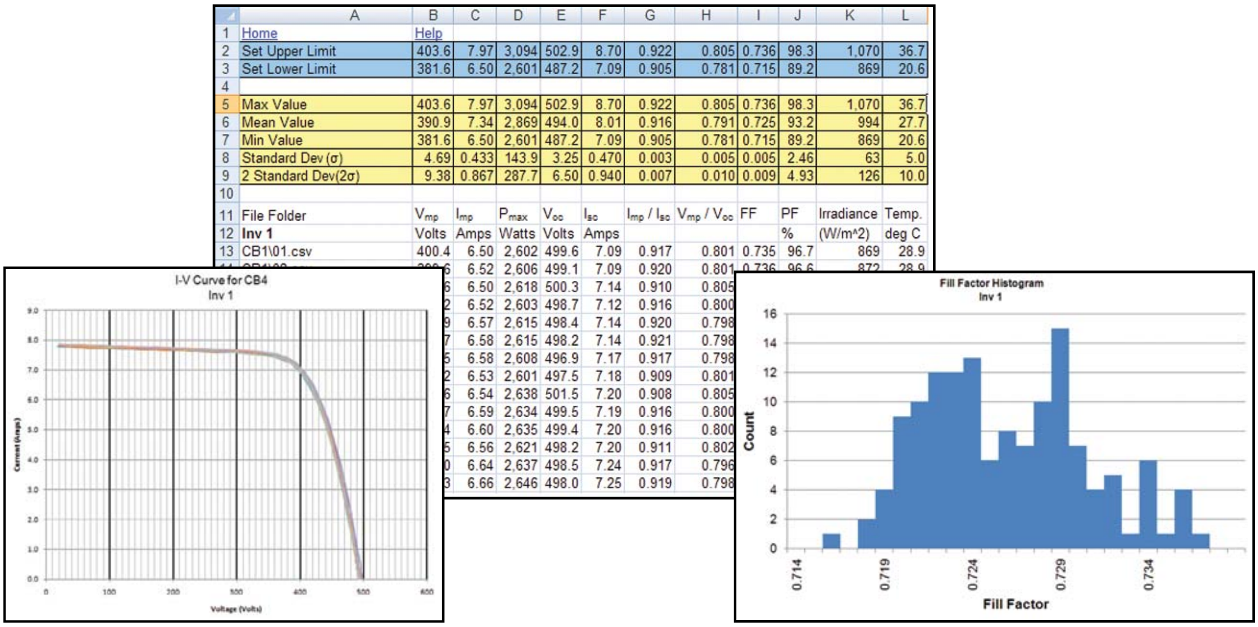
"The database has been growing at the rate of 300-400 new model numbers a month for at least the last year," Saxton says. "Some fraction of these may be repeat entries for private labels. Model parameters are generated at third-party testing facilities using a single sample module, often at the time of UL 1703 certification."

Single-point model. The single-point efficiency model predicts the maximum power value based on parameters normally listed in the PV module datasheet. The calculations for this method are familiar to installers who have used datasheet parameters to translate the maximum power value of a PV system to standard test conditions, or vice versa. (For more details on I-V parameter translation, see "PV System Commissioning," October/November, 2009, *SolarPro* magazine.)

Translation of measured I-V curve data to STC conditions always introduces error. The magnitude of the error increases with the difference in CONTINUED ON PAGE 92

> "I often tell students in my classes to **learn to think like a PV array.** Thinking like a PV array requires understanding the I-V curve and how it changes based on ambient conditions and array problems. An I-V curve tracer is the best way to gain an understanding of these changes, since it provides a graphical representation of the array operating characteristics."
>
> —Bill Brooks, Brooks Engineering

Figure 7a



	A	B	C	D	E	F	G	H	I	J	K	L
1	Home	Help										
2	Set Upper Limit	403.6	7.97	3,094	502.9	8.70	0.922	0.805	0.736	98.3	1,070	36.7
3	Set Lower Limit	381.6	6.50	2,601	487.2	7.09	0.905	0.781	0.715	89.2	869	20.6
4												
5	Max Value	403.6	7.97	3,094	502.9	8.70	0.922	0.805	0.736	98.3	1,070	36.7
6	Mean Value	390.9	7.34	2,869	494.0	8.01	0.916	0.791	0.725	93.2	994	27.7
7	Min Value	381.6	6.50	2,601	487.2	7.09	0.905	0.781	0.715	89.2	869	20.6
8	Standard Dev (σ)	4.69	0.433	143.9	3.25	0.470	0.003	0.005	0.005	2.46	63	5.0
9	2 Standard Dev(2σ)	9.38	0.867	287.7	6.50	0.940	0.007	0.010	0.009	4.93	126	10.0
10												
11	File Folder	V_{mp}	I_{mp}	P_{max}	V_{oc}	I_{sc}	I_{mp} / I_{sc}	V_{mp} / V_{oc}	FF	PF	Irradiance	Temp.
12	**Inv 1**	Volts	Amps	Watts	Volts	Amps				%	(W/m^2)	deg C
13	CB1\01.csv	400.4	6.50	2,602	499.6	7.09	0.917	0.801	0.735	96.7	869	28.9
			6.52	2,606	499.1	7.09	0.920	0.801	0.736	96.6	872	28.9
			6.50	2,618	500.3	7.14	0.910	0.805				
			6.52	2,603	498.7	7.12	0.916	0.800				
			6.57	2,615	498.4	7.14	0.920	0.798				
			6.58	2,615	498.2	7.14	0.921	0.798				
			6.58	2,608	496.9	7.17	0.917	0.798				
			6.53	2,601	497.5	7.18	0.909	0.801				
			6.54	2,638	501.5	7.20	0.908	0.805				
			6.59	2,634	499.5	7.19	0.916	0.800				
			6.60	2,635	499.4	7.20	0.916	0.800				
			6.56	2,621	498.2	7.20	0.911	0.802				
			6.64	2,637	498.5	7.24	0.917	0.796				
			6.66	2,646	498.0	7.25	0.919	0.798				

Courtesy Solmetric (3)

Figure 7b

Figure 7c

Figures 7a, 7b and 7c Curve traces for a commercial PV array taken with the Solmetric PVA-600 yield a large amount of data. Automated data analysis tools, like summary tables (7a), I-V curve overlays (7b) and data distribution plots (7c), make it easy to spot strings that have performance problems.

irradiance or temperature that is measured versus the STC conditions. A way around this limitation is to use the Sandia model to predict the shape of the I-V curve and the values of the key performance parameters, taking into account instantaneous irradiance and temperature. This approach allows for immediate, high-quality assessments of string performance in the field.

DATA ANALYSIS

Analyzing PV array performance data always involves comparison of the results with a specification or model, and may involve detailed analysis of variations of I-V curves across the population of strings. The shape of a measured I-V curve gives important clues to the causes of performance problems. Combined with a predictive PV performance model, I-V curve traces provide the most complete picture of the electrical health of a PV module, string or array.

While commercial-scale PV arrays yield huge amounts of string-level performance data, automated measurement, data collection and analysis can be employed to increase throughput and reduce operator fatigue and data recording errors. Further, automated analysis tools quickly summarize results and make it easy to spot nonconforming strings.

Figures 7a, 7b and 7c show three automated analysis tools for a particular array. The table view, shown in Figure 7a, lists the key performance parameters extracted from the measured I-V traces. These include the familiar Isc, Imp, Vmp, Voc and Pmax values, and also fill factor and the current and voltage ratios that represent the slopes of the lower and upper voltage legs of the I-V curve. If a fill-factor value is out of line, the current and voltage ratios give hints as to whether series or shunt resistance effects may be involved. Statistics for each column are indicated, including the spread of the values. The user can define the acceptable range of values; out-of-range cells in the table are shaded yellow to identify the outlying string.

The I-V curve overlay graph, Figure 7b, gives a quick visual indication of the I-V curve consistency across strings. Figure 7c shows distribution plots or histograms that provide insight that simple statistical parameters such as max, min, mean and standard deviation do not. The shape of the distribution plot can indicate whether the spread or deviation measured is the result of random module performance or environment-sensing variations, a problem with the measurement setup, or even the outcome of more systematic effects. For example, the performance verification data for one commercial rooftop array showed an unusual distribution of string Voc data. Further analysis led to the discovery of a large temperature differential between strings at the edge of the array compared to strings located away from the edges where air circulation was limited. This is common in large rooftop arrays where modules are packed in a tight formation.

CONTINUED ON PAGE 94

> "The best way to derive a dc system rating is with an I-V curve and using the performance coefficients provided by the module manufacturer to correct from actual conditions of irradiance and temperature to standard conditions. Energy modeling using TMY or other data can provide an estimated annual energy rating, but it all starts with an accurate power rating."
>
> —Andrew Rosenthal,
> Southwest Technology Development Institute

Field Applications for I-V Curve Tracers

The main field-testing applications for I-V curve tracers are system commissioning, routine operations and maintenance, and troubleshooting performance problems. Benchmarking system performance is an important aspect of system commissioning and acceptance, and it is valuable whenever PV performance guarantees are used. Once a performance benchmark is established, taking routine I-V curve traces can make preventative maintenance activities more meaningful for array operators. In the event that unscheduled maintenance is required, I-V curve collection and analysis can help to quickly pinpoint problems.

SunPower's Opalinsky believes that companies engaged in these activities should consider taking curve traces. "Anybody involved in the commissioning of PV systems—either as system owner, integrator or third-party commissioning agent—should consider I-V curve traces as a method of benchmarking system performance at the time of startup and for verifying performance in the future," Opalinsky says. "Companies involved in maintaining and operating PV systems should consider having at least one person on staff who is trained to use an I-V curve tracer and interpret the results."

COMMISSIONING PV ARRAYS

Developers, PPA financiers, engineering, procurement and construction (EPC) contractors, and providers of O&M services all have a strong interest in verifying and optimizing the performance of a solar asset. Each stakeholder stands to benefit from a test measurement method that provides deep insight into PV system operation and potential problems.

By employing proper performance measurements in solar PPA projects, financial risk can be reduced and ROI increased. When the developer and PPA financiers want to be sure that a system is fully functional and operating optimally, they can require a complete commissioning report that includes the measurement of I-V curves for every string. Any deviations of actual performance from expected performance beyond some agreed threshold are then corrected before funds are released to the EPC contractor.

For its part, the EPC contractor establishes a baseline of data that can be used in the future if performance questions or contract disputes arise. By curve tracing each string and demonstrating that the system is fully functional at the time of commission, the EPC contractor can prove that it has met the installation electrical performance verification portion of its contractual obligations. The

CONTINUED ON PAGE 96

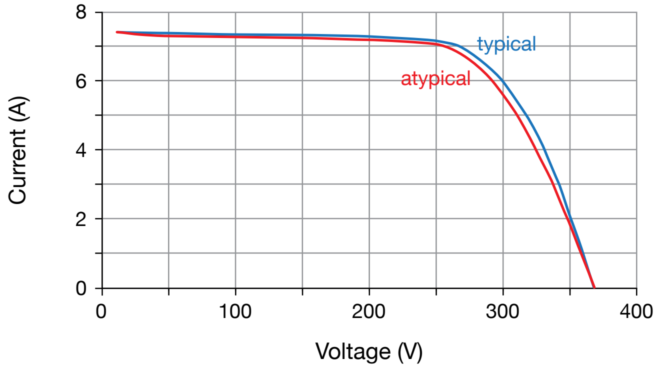


Figure 8a

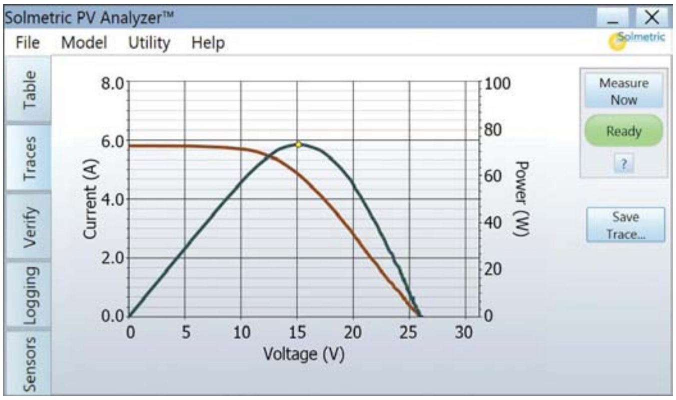
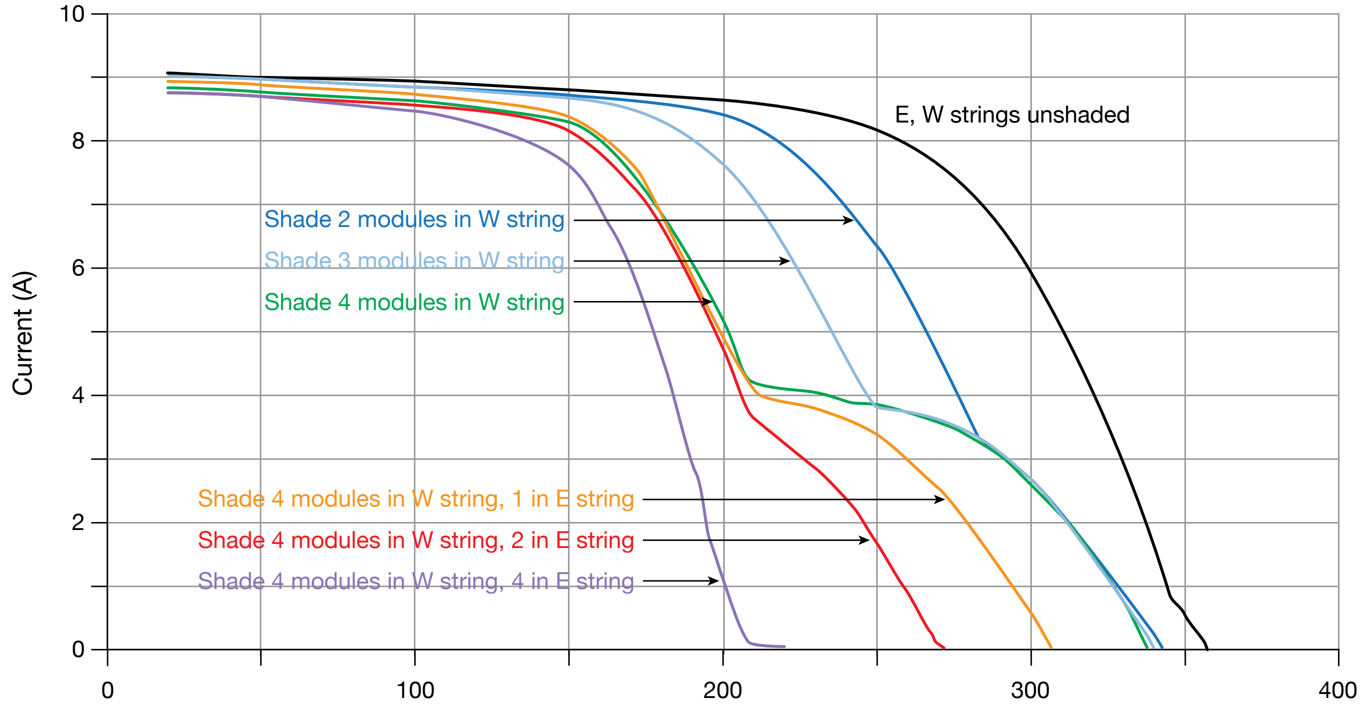


Figure 8b

Courtesy Solmetric (2)

Figures 8a and 8b After an atypical string was spotted in an overlay of I-V curve traces (8a), the underperforming string was analyzed in more detail. This led to the discovery of a single module with excess series resistance (8b). Small burn marks were subsequently observed on several cells within the module.



Figures 9a (above) and 9b (at right) The stepped I-V curve shapes (9a) caused by shading various combinations of modules in two paralleled strings are measured at a site provided by the solar division of Harmony Farm Supply (9b).

Courtesy Solmetric (2)

archived data is then referenced if there are performance issues in the future.

Performance verification is typically required by contract as part of the commissioning of new commercial systems, and it is likely to become commonplace for systems of any size, including residential, in the future. Recommissioning is appropriate at other points in the PV system's life cycle, including a change of ownership, a trauma to the PV system (lightning strike, extreme wind, theft and so on) and array removal and replacement for reroofing.

Traditionally, performance verification of commercial-scale arrays involves measuring and recording the string open-circuit voltages, as well as the string operating currents at the overall system MPP as determined by the inverter. The short-circuit current may also be measured. The drawbacks to this traditional approach are that the individual measurements and data recording take considerable time; they are limited in the performance issues they can identify; and they do not make independent maximum power measurements of each string.

I-V curve tracers overcome these limitations by integrating and automating the measurements and data recording, and by revealing all the performance issues. For example, open-circuit voltage measurements and clamp meter current measurements cannot detect excess series or shunt resistance, or module mismatch in a string, whereas curve traces can.

TROUBLESHOOTING PV ARRAYS

Troubleshooting may be triggered by a system owner's complaint of poor production, an alarm thrown by a monitoring system or by observations made during a routine checkup. The technician may turn to an I-V curve tracer after reading the inverter display and checking dc voltages and currents with a digital multimeter (DMM) and clamp meter. In troubleshooting situations, compared to using a DMM or clamp meter, an I-V curve tracer can provide far greater detail in the data that it reveals and the records it keeps of performance before and after the repair. If a module warranty return is in order, curve tracing provides the most complete documentation.

The first step in troubleshooting with a curve tracer requires no PV model or reference standard, but only the measurement of a string's I-V curve. Once the trace is complete, consider whether the curve has a normal shape. If it

CONTINUED ON PAGE 98

does not—if there are steps or notches in the curve—consider the following:

- Is any of the string shaded, even a fraction of a cell?
- Is substantial, uneven soiling from birds, dirt dams, lichens or tree litter present?
- Are there burn marks on the front or back faces of the modules?

Comparing the curves of two or more strings is a good way to spot more subtle effects, like a softer knee in an I-V curve or reduced short-circuit current or open-circuit voltage. For a more objective test, translate the I-V curve to STC and compare key parameter values to the specifications on the modules' product data sheet. For the most reliable and accurate test, compare the shape of the trace with the predictions of an onboard PV performance model such as the Sandia model or 5-parameter model.

Fill factor is an effective initial screen for any performance problems that show up as subtle changes in the slopes or softness of the knee in an otherwise normal looking I-V curve. If the fill factor is low, check the Imp/Isc and Vmp/Voc ratios relative to neighboring strings or the predictions of the PV model.

Series resistance signature. Reduced Vmp/Voc may indicate increased series resistance. The I-V curve signature for series resistance is a reduced slope or inward tilt in the leg of the curve between Vmp and Voc. Figure 8 (p. 94) shows an example of this condition. I-V curves taken for two adjacent strings showed a noticeable difference in series resistance. Further investigation showed that the source of the extra resistance was a single module that had several fingerprint-sized burn marks scattered along several cells.

Increased series resistance does not always show physical signs on the module face or backsheet. Therefore, it may be necessary to successively break the string in two, using the *half-splitting* method to zero in on the damaged or degraded module. In this technique, a poor performing string is split into two substrings, and each substring is measured. Then the poor performing substring is again split and measured until the problem becomes obvious or the substring is reduced to an individual module.

Shunt resistance signature. Shunt resistance effects show up as increases in the slope of the leg of the I-V curve near Isc, but shunt resistance is not the only possible cause of this increased tilt. Tapered edge soiling (dirt dams) or slight shading that tapers gradually across a row of modules can produce a similar change in slope with no apparent bypass diode action.

Reduced current signature. If the I-V curve has a normal shape and width, but the Isc is lower than predicted by the PV model, check first for uniform soiling. Depending on the purpose of the testing, you may need to clean the array.

An accurate way to demonstrate the impact of uniform soiling is to measure the I-V curve before and after cleaning and compare the maximum power values. Do the test under clear sky conditions close to solar noon, so that the irradiance is constant. Measure I-V curves for two neighboring strings. One of these strings will be cleaned as part of the test; the other serves as a control to remove the effect of any irradiance changes. After cleaning one string, measure I-V curves for both strings again and observe how much the cleaning affected Isc and Pmax in the test string. If the control string showed changes as well, use these changes to correct the before and after results in the test string for a more accurate comparison.

Certain module failure modes may also reduce module current. NREL's Kurtz describes two examples: "Especially for older modules deployed in hot, humid locations, some browning of the encapsulant may be visible, causing a somewhat decreased current but probably an undetectable change to the voltage. In addition, delamination can slightly decrease the current because of the reduced coupling of the light into the cell; in the long term, however, delamination can lead to corrosion and, eventually, catastrophic failure."

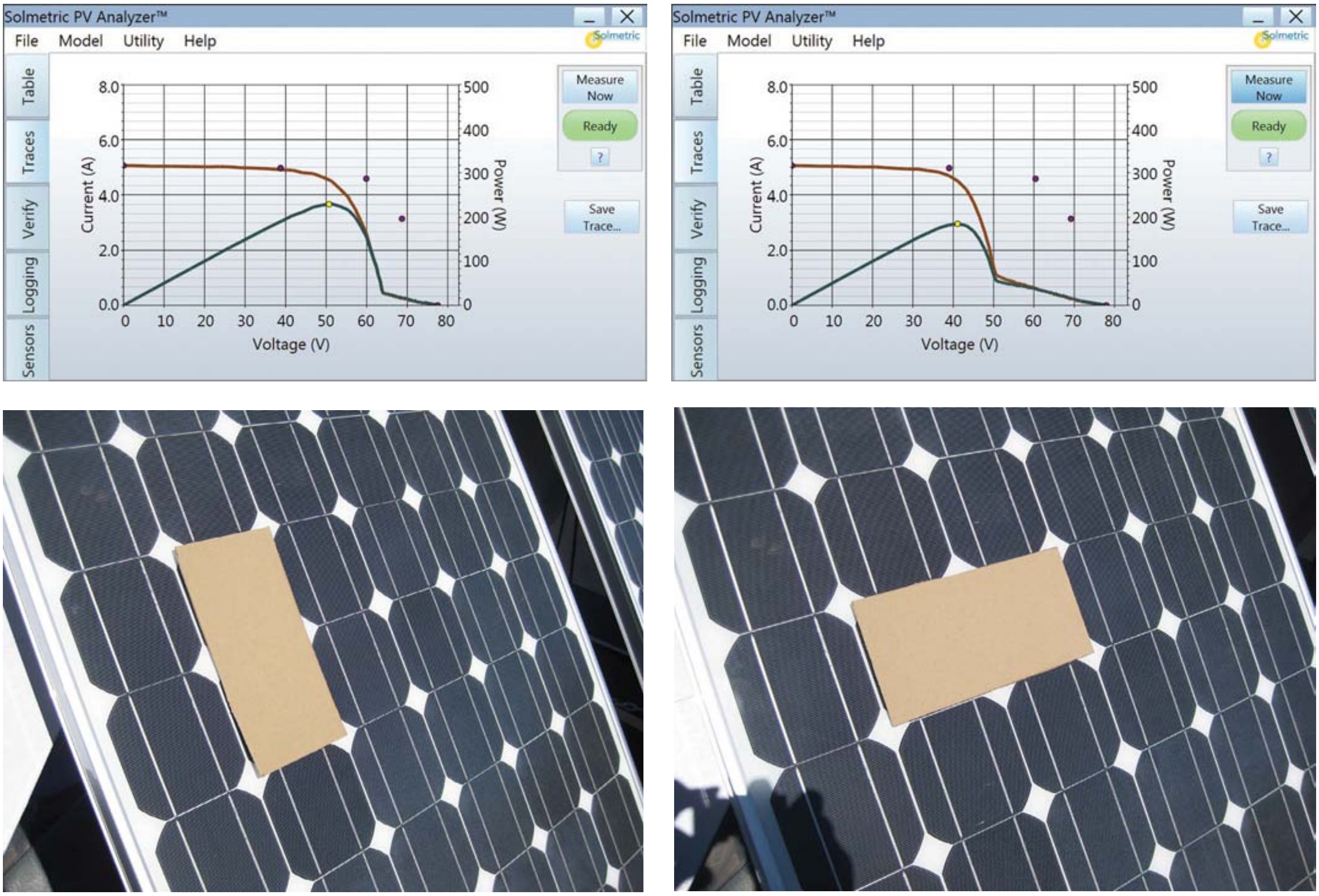
Reduced voltage signature. If the I-V curve of a single string has a normal shape and height, but the Voc value appears to be low, calculate the difference between the measured and expected Voc or translate to STC. Note that this comparison is done automatically when a curve tracer with an integrated PV model is used. If the difference happens to be close to the Voc of a single module, then a module may be missing from the source circuit—perhaps bypassed or not wired in. If the difference is smaller than the Voc for a single module, one or more cell strings within the modules may be bypassed or not functioning properly.

Bypass diodes sometimes play a role in PV module failures, particularly when modules are designed using inexpensive or undersized bypass diodes. "Frequent partial shading can cause a bypass diode to operate constantly, shortening its life," Kurtz observes. She notes that shade prone rooftop applications are particularly troubling in this regard. "The bypass diodes are stressed most when the module is partially shaded," she adds. "If they overheat, they may burn out."

Array installation methods, such as direct installation on a roof, can also cause overheating.

Mismatch signature. Shading, although not a problem caused by the array hardware, provides a good example of mismatch behavior. The shaded cell produces less current. If the shading is severe enough, the bypass diode spanning that cell string turns on and shunts current around it. The I-V curve shows a step on its falling slope, the width of which corresponds to that cell

CONTINUED ON PAGE 100



Courtesy Solmetric (4)

Shading lab The impact of shade on PV performance depends as much on pattern of the shade as on its area. In the first example, two cells are shaded in the same cell string. In the second example, the area of the shading is the same, but two cell strings are impacted. These are typical 72-cell modules with three bypass diodes and cell strings.

string's open-circuit voltage. The reduction of current at the step is proportional to the cell area that is being bypassed. Figure 9 (p. 96) illustrates the shading of different numbers of modules in two parallel strings. The normal-shaped curves correspond to no shading or to equal numbers of modules shaded in each string.

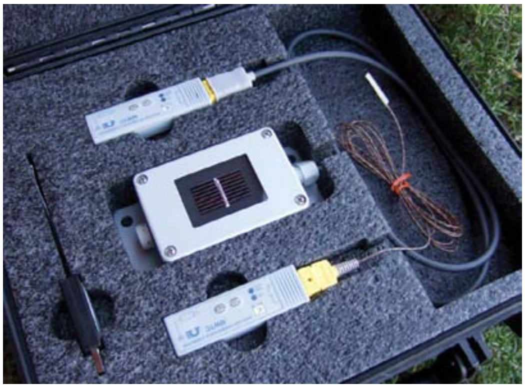
Unlike solar thermal collectors, the dependence of PV production on the actual pattern of shade is very nonlinear. A simple outdoor lab setup demonstrates this. A source circuit consisting of two PV modules is shaded with a rectangular piece of cardboard large enough to cover two adjacent cells, as shown in the photos above. The modules have 72 cells each, split across three bypass diodes. The setup and results are shown in the photos and associated I-V curves. In the first example, the cardboard covers two cells in the same cell string, causing its bypass diode to conduct and dropping the string's voltage and output power by roughly one-sixth. In the second example, the cardboard is rotated to cover one cell in each of two adjacent cell strings, dropping the voltage and output power by twice that amount.

Taking Environmental Measurements

Accurate array performance verification requires careful selection and measurement of environmental conditions. The shape of an I-V curve taken in the field is determined in part by the irradiance in the plane of the array (POA) and the cell temperature at the time of measurement. Therefore, POA irradiance and cell temperature are often collected simultaneously with I-V curve measurements in the field. No measurement is exact. Random variations and systematic bias combine to create some level of uncertainty. This uncertainty is a function of the test equipment, the environmental conditions and the user's measurement technique. However, through the proper use of appropriate irradiance and temperature sensors and careful screening

CONTINUED ON PAGE 102

Using the Array as a Sensor



Sensor kit While I-V curve tracers include inputs for irradiance and temperature sensors—like those in this wireless sensor kit from Solmetric—using the array as a sensor can reduce measurement time and complexity.

Courtesy Solmetric

Array performance verification measurements, such as those taken during system commissioning, normally require the use of irradiance and temperature sensors so that these parameters can be recorded along with the I-V curves. However, much of the diagnostic testing can be done without use of external sensors. Another option is to calculate the temperature and irradiance from the measured I-V curve itself, using the array as a sensor. The mathematical basis for this feature combines formulas from the Sandia PV Array Model and the IEC 60904-5 standard on determining equivalent cell temperature (see Resources). The translation method relies on knowing the dependence of Isc and Voc on irradiance and temperature. Irradiance is calculated from Isc with a slight correction from Voc. Temperature is calculated from Voc with a slight correction from Isc.

"Array as sensor" is an optional operating mode in the Solmetric PVA-600 that can simplify the process and save time when readings from external sensors are not required. When the array-as-sensor method is used to provide irradiance and temperature values to a PV model, the predicted I-V curve is forced to align with the measured curve at Isc and Voc. Thus, the array-as-sensor approach is blind to the effects of uniform soiling and to degradation in Isc or Voc. However, the method is very helpful when examining the shape of the I-V curves. Since the endpoints of the predicted and measured I-V curves coincide, any deviation in the shapes of the curves is very easy to spot. The sensor values are effectively measured at the same time as the I-V curve, so comparing measured and predicted curve shapes is much less affected by wind and by rapid changes in irradiance. The determined temperature also represents the string as a whole, not just the temperature at the edge of the array where an actual sensor would be attached.

The temperature across a string can vary ±15°C because of different exposure to wind, reflections and racking. In many cases, therefore, it is actually more accurate to use the array-as-sensor mode to determine the temperature because it measures the average cell junction temperature across the entire string rather than one specific spot measurement on the back of a single module.

The array-as-sensor mode is also useful for checking the I-V curve shape of basic functional modules, particularly when deploying a full sensor kit is not practical. The user can also mix sensor modes, using the array-as-sensor mode to determine temperature, while capturing irradiance with an external sensor mounted in any open area at the same orientation as the array. The temperature will be reasonably accurate as long as all of the modules and cell strings are operating. This can be assured by checking that Voc is roughly consistent across strings. ●

---

of sky conditions, both random and systematic errors can be reduced.

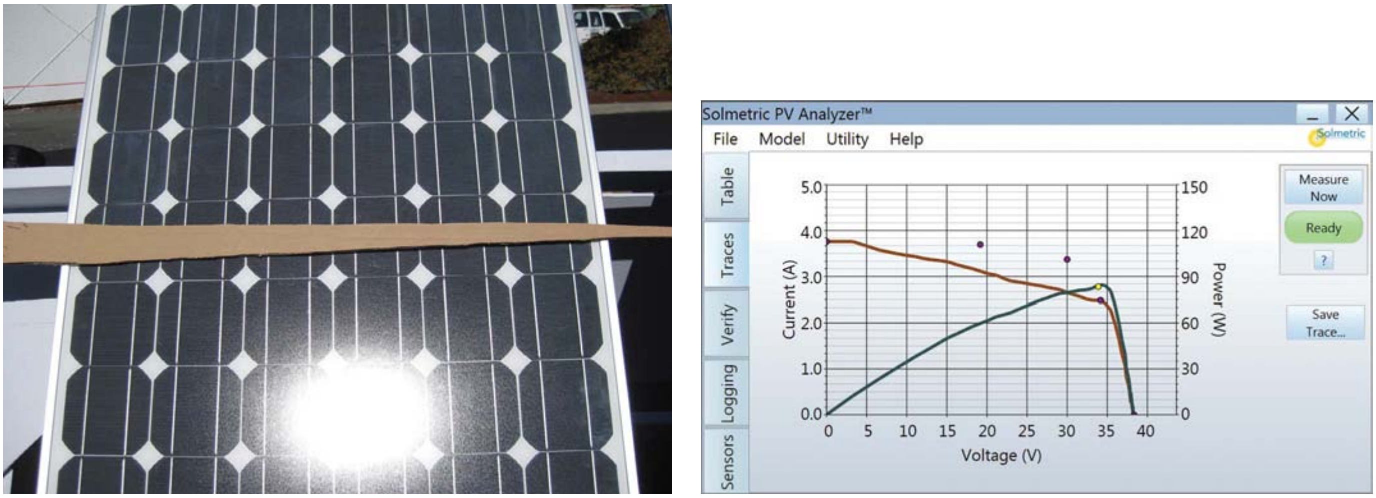
Irradiance measurement. This measurement is used to determine the irradiance in the plane of the array at the time of the trace. Good irradiance measurements can be obtained by selecting a high-quality sensor that uses a technology similar to that of the array being tested and is designed for backside mounting. To ensure that the sensor is mounted in the plane of the array, attach the sensor to a bar that is in turn clamped to the frame of a PV module.

If the irradiance sensor is not mounted in the plane of the array, it presents a different area to the sun; this is a key source of irradiance measurement error. Reflected light is another potential source of measurement error. Be aware of possible sources of reflected light and try to locate the irradiance sensor at a location that is representative of normal operating conditions for the array.

While handheld irradiance sensors can be used in I-V curve testing, they are usually difficult to accurately position in the plane of the array. In addition, the sensor technology and packaging are often quite different from the PV modules themselves. This can introduce spectral and angle of incidence errors. The angle of incidence is the angle between an incident light ray and a line that is normal (perpendicular) to the PV module. The angle of incidence response of the irradiance sensor and the PV modules under test should be reasonably well matched.

Changing irradiance conditions is another potential source of error. Using an I-V curve tracer

CONTINUED ON PAGE 104



Courtesy Solmetric (2)

Tapered shading As shown in this photo and associated I-V curve, tapered shading or soiling can result in a shunt resistance I-V curve signature, with an increased slope above Isc. This effect can be produced by shading from adjacent tilt-up arrays, by shading from building features such as parapet walls, or by dirt buildup along the edges of PV modules mounted at low tilt angles.

capable of making rapid curve sweeps can minimize these errors. Many curve tracers also offer optional sensor kits. When these kits are used, the curve tracer logs the irradiance measurement simultaneously with the I-V curve. Manual measurement and recording of irradiance and temperature can more than double I-V curve measurement time, and the delay between sensor readings and the I-V sweep can introduce significant random error. The preferred technique is to use a curve tracer with sensors that are triggered and recorded at the same time as the I-V curve sweep.

Temperature measurements. Temperature measurement for performance verification usually involves a thermocouple or resistive temperature device taped to the backside of the PV module. The sensor should be placed toward the center of the module, as the edges tend to run cooler than the rest of the array. High-temperature tape, applied with firm pressure, assures good thermal contact between the sensor element and the module backsheet.

Digital infrared (IR) thermometers are sometimes used for this purpose, but their accuracy is very dependent on the emissivity of the surface. Calibration of the IR thermometer can be accomplished using a side-by-side measurement of the same PV cell using the IR and thermocouple methods. The emissivity control on the IR device can then be adjusted to make the two temperature readings match. IR temperature measurements are typically less accurate when taken through the face of the module than when taken off the backsheet.

ENVIRONMENTAL CONDITIONS

Because a PV source responds to changing environmental conditions, verifying PV performance in the field is potentially challenging. DK Solar Works' King explains, "PV module and array performance in outdoor conditions is continuously changing due to a large number of factors, including variations in solar irradiance level and spectral content, ambient temperature, wind speed, thermal heat capacitance of the modules themselves, module shading, soiling and so on." Taking performance verification measurements under the recommended environmental conditions helps give consistent results when remeasuring the same site at a later date.

The rule of thumb espoused by Dr. Jennifer Granata, technical lead of the PV Test, Evaluation and Characterization group in the Photovoltaic and Grid Integration Department at Sandia National Laboratories, is to gather performance test data in a stable environment. "The ideal is to test during clear sky conditions with a stable irradiance level, stable spectrum and stable temperature, including wind effects," she states. "This usually occurs in the 4-hour window centered at solar noon."

Determination of irradiance typically has the most significant impact on the accuracy of PV performance measurements. The direct radiation component of sunlight is larger during the 4-hour window around solar noon. Since direct radiation measurements tend to be more repeatable than measurements of the diffuse radiation component, test results during this window tend to be more accurate and repeatable. The proportion of diffuse radiation is lower around solar noon than it is at other times of the day.

Temperature measurement errors also affect the results. Windy conditions cause rapid variation of array temperature. More importantly, wind—even a steady wind—can change the pattern of temperature across the array, making measured string performance look less consistent.

CONTINUED ON PAGE 106

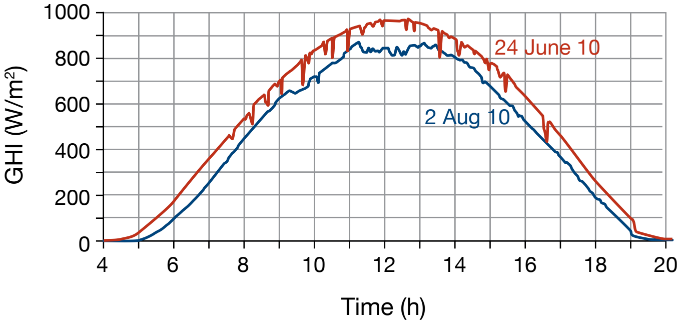
Testing in a wind speed of 2 mph or less is a good guideline for PV performance measurements.

Brooks agrees with the necessity for stable conditions. He states: "Ideally we always want a cloudless sky with no variations or jet contrails. This is rare for most of the US, so we normally have to compromise. It seems like clouds follow curve tracers, but the key is to take I-V curves when both the irradiance and module temperature are stable. If either one is moving at the time of the I-V curve, the data is going to be dubious. If we are just trying to get a ballpark shot for simple commissioning purposes, slight changes are okay. Temperature changes, since they tend to be much slower than irradiance changes, are more tolerable. Also, temperature changes have a much smaller impact on the curve, so the data error may be small. Irradiance changes of more than 1% or 2% while the curve tracer is measuring the data results in bad data. A 10% change results in a curve that looks like a major malfunction is present on a perfectly operating array."

While it is not always possible to avoid clouds, some clouds are worse than others. Large, slow-moving clouds located a significant angle from the sun in an otherwise clear sky contribute some additional irradiance from cloud effect, but this variation may be slow enough to be corrected for by the sensors. According to Bill Sekulic, master research technician at NREL's PV Performance and Reliability R&D group, "Large or spotty cumulus clouds located at fairly large distances from the sun are generally not an issue while taking curves." However, if there are fast-moving clouds near the sun, performance measurements should be postponed. Cirrus cloud cover is another showstopper, reports Sekulic. "Cirrus clouds cause irregular variations in irradiance, as well as a magnification of irradiance called cloud effect," he says. "Because cirrus clouds usually occur at high altitude, they can give an appearance of clear sky conditions that masks irradiance irregularities and cloud effect magnification."

Air mass (AM) 1.5 is one of the standard test conditions under which PV modules are specified. The earth's atmosphere affects the power spectrum of sunlight, and at AM 1.5 the atmospheric path length is 1.5 times more than it would be at sea level with the sun directly overhead. Sandia National Laboratories' Granata warns: "Although modules and arrays are rated under the AM 1.5 spectrum, the spectrum and irradiance can change rapidly as the sun moves through the AM 1.5 position, depending on location and time of year."

It is also important to recognize that PV module I-V curves change shape as light levels change. It is difficult to accurately extrapolate an I-V curve at STC from a trace taken at low irradiance levels. Granata recommends taking field measurements under conditions that are close to the reference condition: "Another aspect of choosing the conditions for testing an array is how one intends to normalize the data. If normalizing to standard reporting conditions or PTC, being as close to those conditions as possible is recommended to minimize uncertainties when translating the data." ⏚



Courtesy University of Oregon

Variable input These global horizontal irradiance curves for Eugene, OR, were captured by Dr. Frank Vignola of the University of Oregon in 2010. The results illustrate that irradiance can vary substantially even on relatively clear days.

» CONTACT

Paul Hernday / Solmetric / Sebastopol, CA / solmetric.com / paul@solmetric.com

Resources

California Energy Commission, New Solar Homes Partnership / gosolarcalifornia.org/nshp

National Renewable Energy Laboratory Solar Advisor Model / nrel.gov/analysis/sam/

NFPA-70E, Electrical Safety in the Workplace, National Fire Protection Association / nfpa.org

Publications

"Photovoltaic Array Performance Model," D.L. King, W.E. Boyson, J.A. Kratochvil, Sandia Report: SANDIA2004—3535, 2004

"Photovoltaic Devices—Part 5: Determination of the equivalent cell temperature (ECT) of photovoltaic (PV) devices by the open-circuit voltage method," International Electrochemical Commission, International Standard: IEC 60904-5, 1993

Manufacturers

Amprobe / 877.267.7623 / amprobe.com

Daystar / 575.522.4943 / daystarpv.com

EKO / 408.977.7751 / eko-usa.com

HT-Italia (US distribution by Hukseflux) / 631.251.6963 / hukseflux usa.com

Solmetric / 877.263.5026 / solmetric.com