Solmetric PVA-1000S
Startup Training

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Topics

- Introduction to the PVA-1000S PV Analyzer
- Using the software
- Making I-V curve measurements
- Measuring irradiance & temperature
- PV fundamentals for troubleshooting
- Troubleshooting PV arrays
- Using the I-V Data Analysis Tool (DAT)

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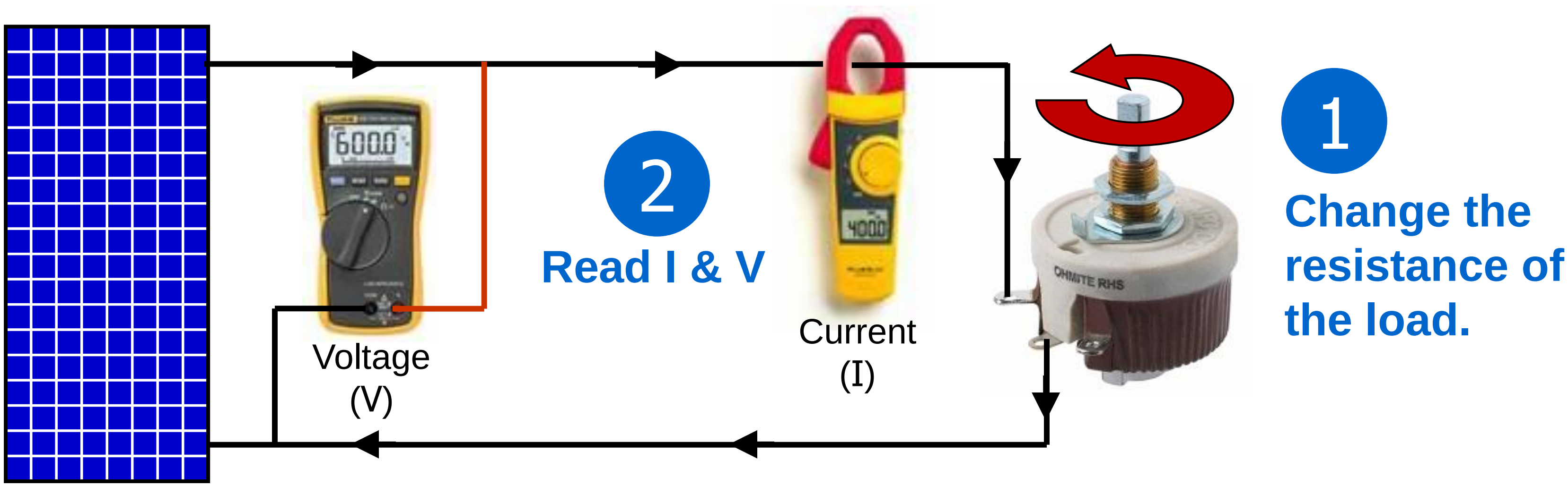
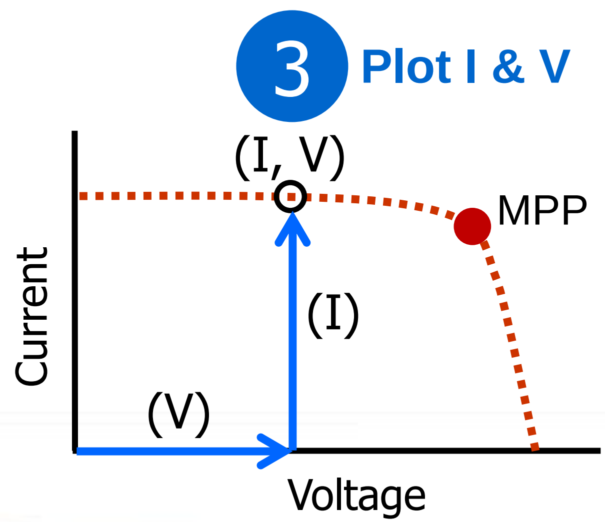
What is an I-V Curve?

Exercise from the outdoor PV training lab

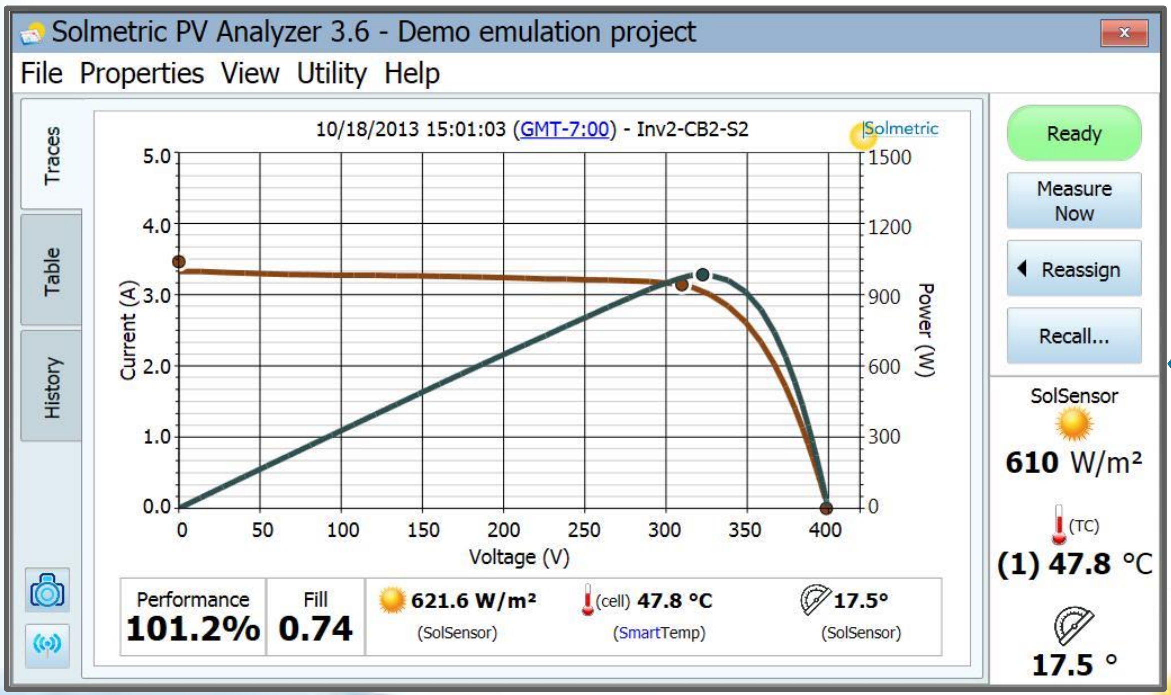




- Map of operating (load) points at current operating conditions
- Of greatest interest is the maximum power point (MPP)

PVA1000 PV Analyzer
Overview

- ✓ 1000V, 20A or 30A
- ✓ Measured vs. predicted (red dots)
- ✓ PC-based - large displays and 'touch' die speed
- ✓ Wireless interface
- ✓ 300 foot sensor wireless range (line of sight)



Your tablet
or notebook PC

PVA1000 PV Analyzer

Users include…

EPC's

System Integrators

Electrical contractors

Module Makers (Perf. Eng. & Warranty)

O&M and Asset Management

Inverter Makers (O&M)

Consultants & Commissioning Agents

PV Plane Insurers

Field Reliability Research

Training & Education

Laboratories NREL, TUV…

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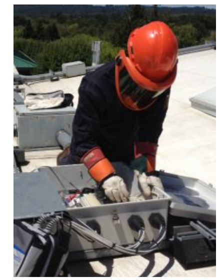
Benefits of I-V Curve Measurements

Compared with Voc/Clampmeter and ac-side measurements

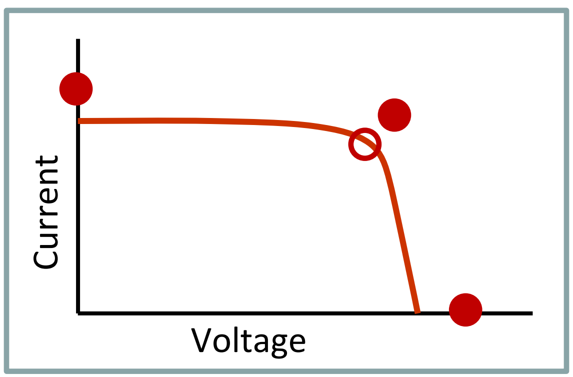
Reduces cost

- ✓ Only one test per string
- ✓ Test earlier in the project
- ✓ Selective Shading troubleshooting method



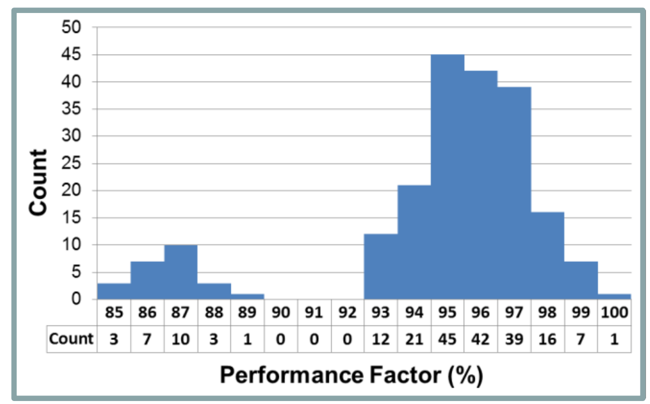
Reduces arc flash hazard

- ✓ System need not be operating
- ✓ Combiner dc disconnect is opened



Most complete performance test

- ✓ Full I-V curve
- ✓ Independent of rest of system
- ✓ Best baseline



More granular than AC tests

- ✓ Each PV source circuit is tested
- ✓ Statistics are valuable!

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Additional Benefits of Solmetric PVA

Compared with other I-V curve tracers

22.5% 24% 21% 19%

High Efficiency Modules

- ✓ High curve fidelity
- ✓ Handles surge currents

Best Acc'cy/Weight

- ✓ High I and V accuracy
- ✓ Compact, power-sipping circuits, lightweight battery

Advanced PV Model

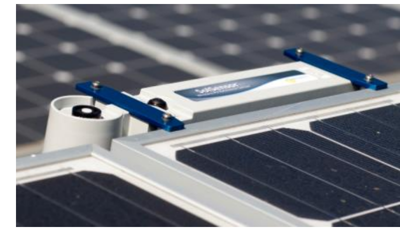
- ✓ Correction for module technology, AOI effects

Friendliest Interface

- ✓ Large display, clearly labeled
- ✓ Rich function set

High Throughput

- ✓ Doesn't overheat
- ✓ More strings per day in hot climates



SolSensor™

- ✓ Integrated irradiance, temperature, and tilt
- ✓ 300ft wireless range

Low Impact of Ramping

- ✓ Rapid trace avoids bumps and dips in I-V curve
- ✓ Simultaneous I-V and sensor measurements

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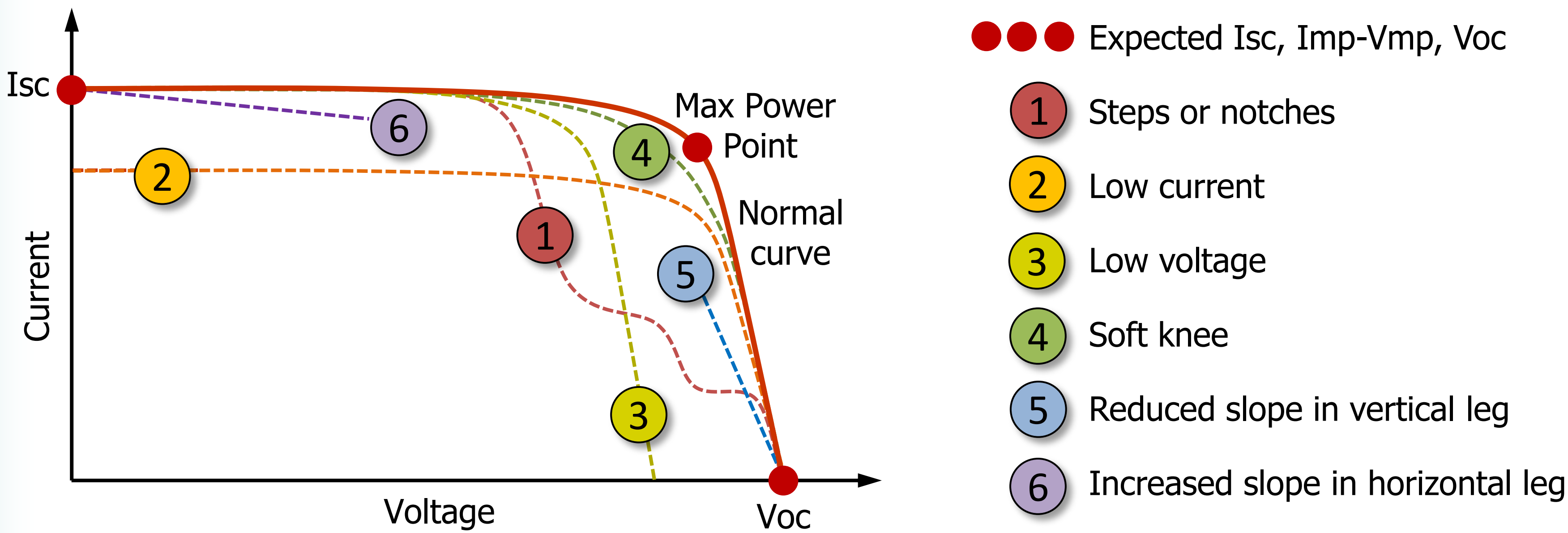
Types of I-V Curve Deviations

From normal, expected shape



- Classifying the deviations by shape narrows the range of possible causes and speeds troubleshooting (see the *Solmetric PV Array Troubleshooting Flowchart*)
- Earlier methods miss much of this information.
- Later we'll look at the possible causes of each deviation.

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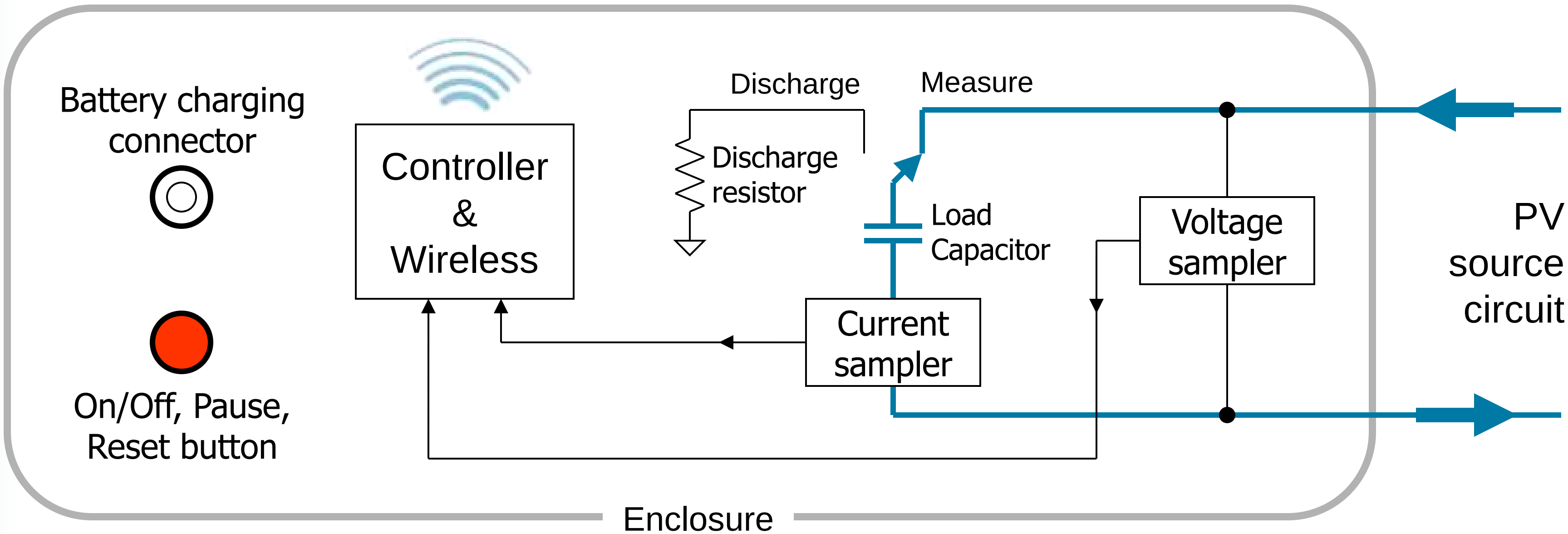
How It Works

I-V curve tracer block diagram (simplified)



- Curve tracers temporarily load the PV source circuit, moving it through 'I-V space'. The PV Analyzer uses a capacitive load for smooth and reliable operation.
- When the user clicks 'Measure Now', the discharged (0V) capacitor is switched across the PV source circuit. The operating point smoothly advances from Isc to Voc in typically less than 1 second as the capacitor charges, and 100 or 500 points (I,V pairs) are captured along the way.
- Approximately 5-6 seconds after hitting 'Measure Now', the data appears on your tablet PC screen, compared with the expected curve shape.

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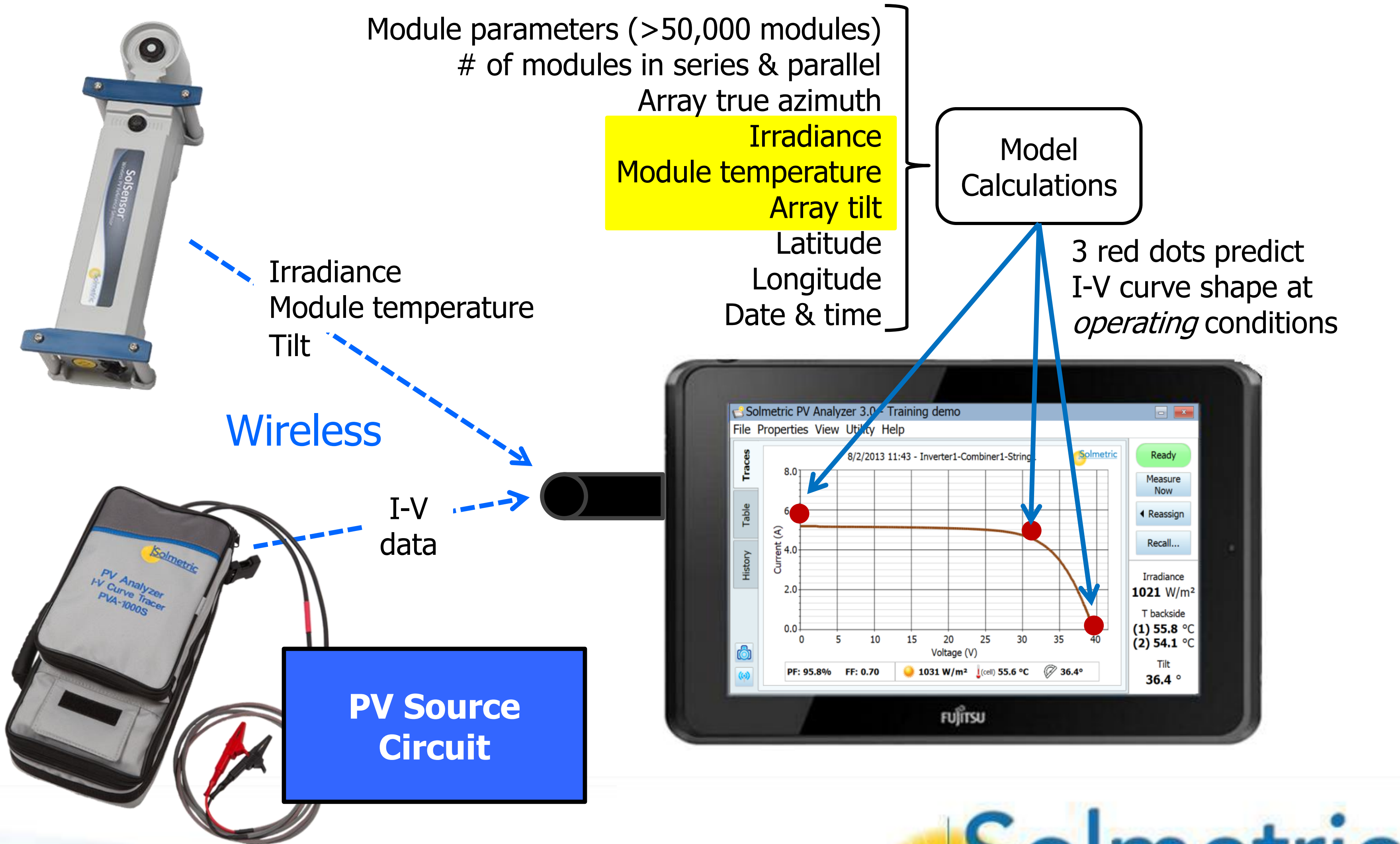
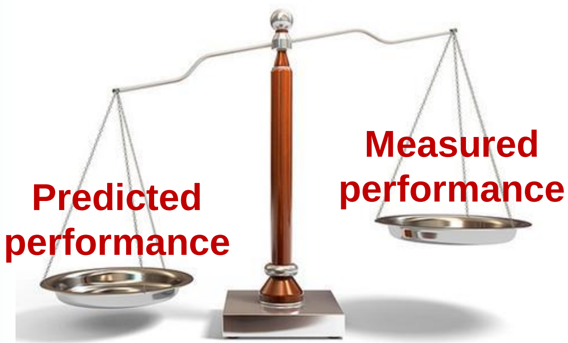
How It Works

Comparing measured and predicted I-V curve shapes

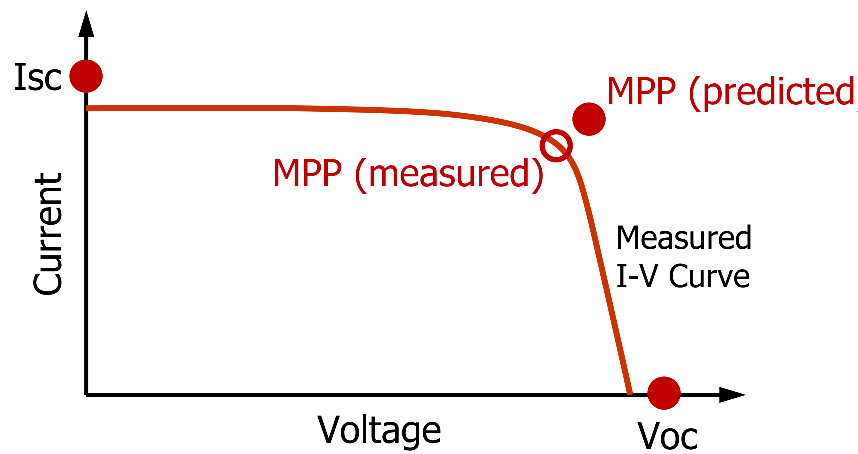


Performance Factor
The key performance metric



$$\text{Performance Factor} = \frac{\text{Pmax (measured)}}{\text{Pmax (predicted)}}$$

- If measured and predicted Pmax agree, Performance Factor is 100%.
- Even in a new array with healthy modules, not all readings will be 100%. PV modules are not all identical, irradiance and temperature are not exact measurements, cell temperature is not uniform across the modules, and the electrical measurements have slight errors. A newly constructed array should have Performance Factor values in the 90-100% range.



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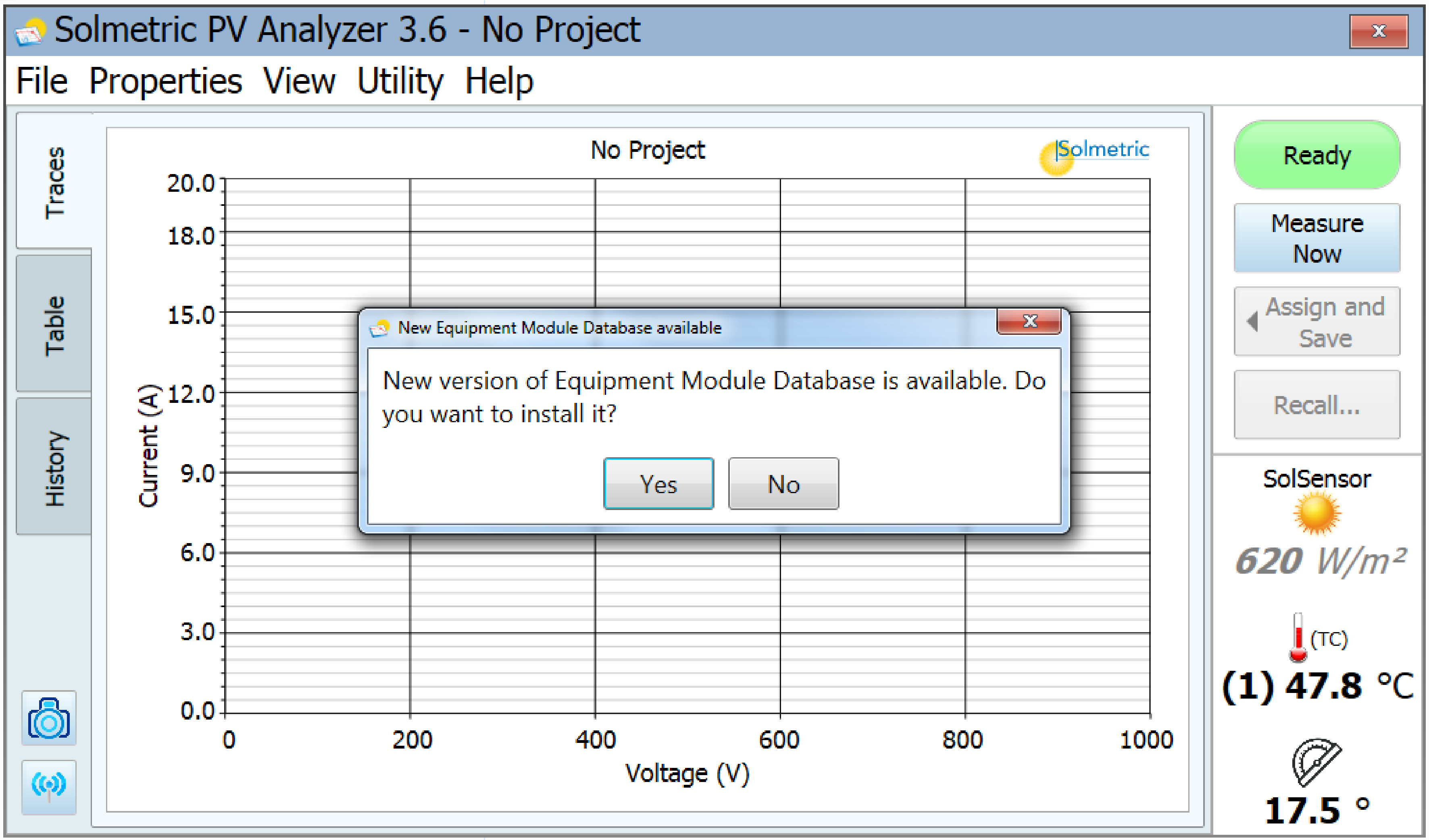
Equipment Database Updates

Checks at software launch, when web connected



Example Equipment Setup
I-V curve tracer set up at dc combiner box

Courtesy of Chevron Energy Solutions © 2011

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Example Equipment Setup
SolSensor mounted on frame of PV module

- SolSensor measures irradiance, temperature, and tilt
- Unit is clamped to the module frame (or torque tube in tracking systems) to orient the irradiance sensor in the plane of the array. A bar clamp is provided.
- For best irradiance accuracy early & late in the day, mount it on a horizontal leg of the frame.
- The irradiance sensor 'eye' (white dot at left) is a sensitive optical instrument. Attach the lens cover when the sensor is not in use.

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SOLARPRO
Optimal Design, Installation & Performance
solarprofessional.com

Solar I-V Curves
Interpreting Trace Deviations

Array Layout for Low-Slope Roofs
Designing Commercial Systems for Fire Code Compliance

String Inverter Specifications
140 Inverter Models for North American PV Installations

Projects
Fronius ITRAC
Seattle Aquarium
St. Louis Science Center

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Westcoast Solar Energy
Multi-Contact USA Headquarters
Windsor, CA

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Topics

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- Using the software
  - Overview
  - Live demonstration
- Making I-V curve measurements
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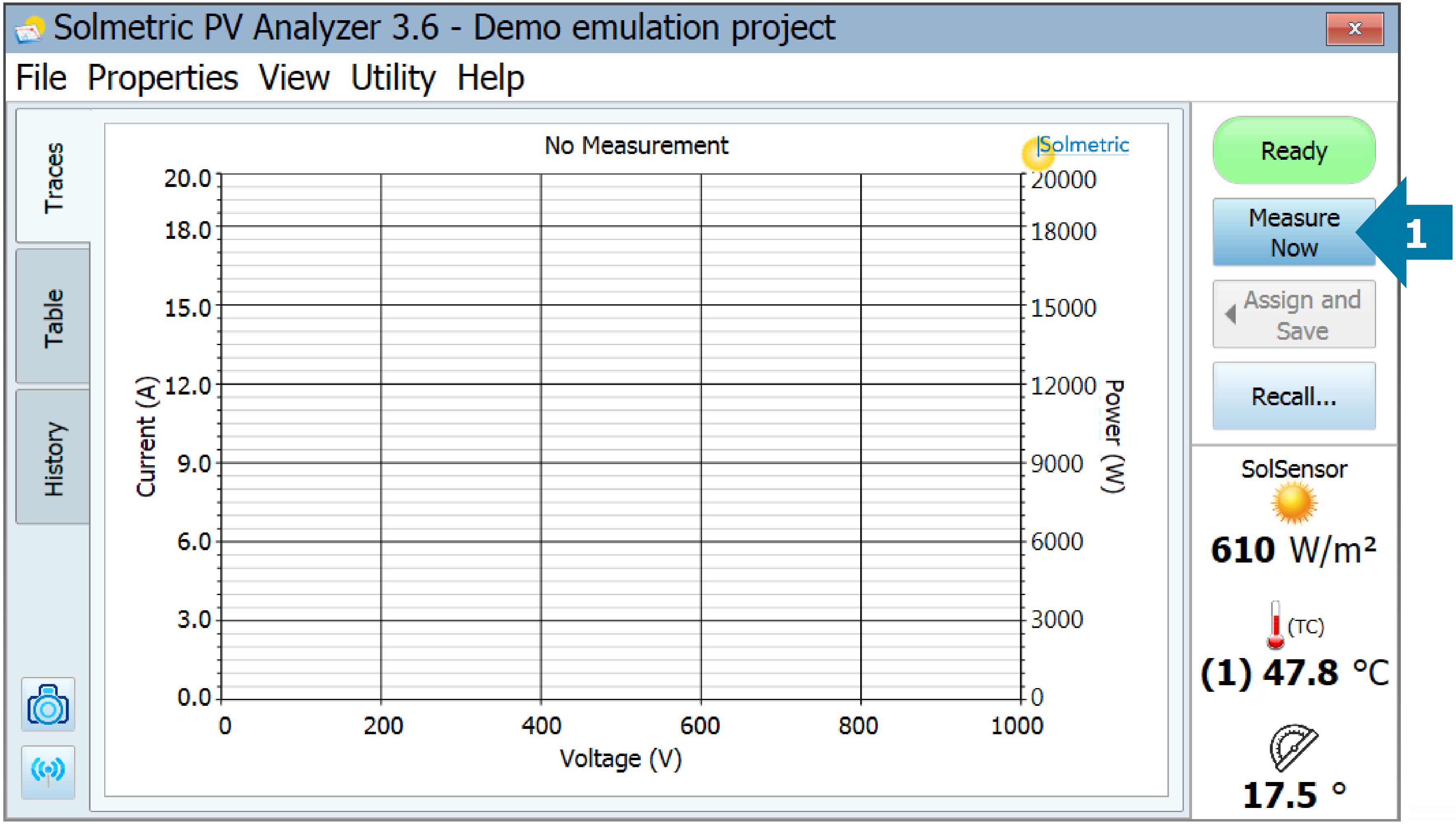
Making a Measurement

Step 1: Press *Measure Now*



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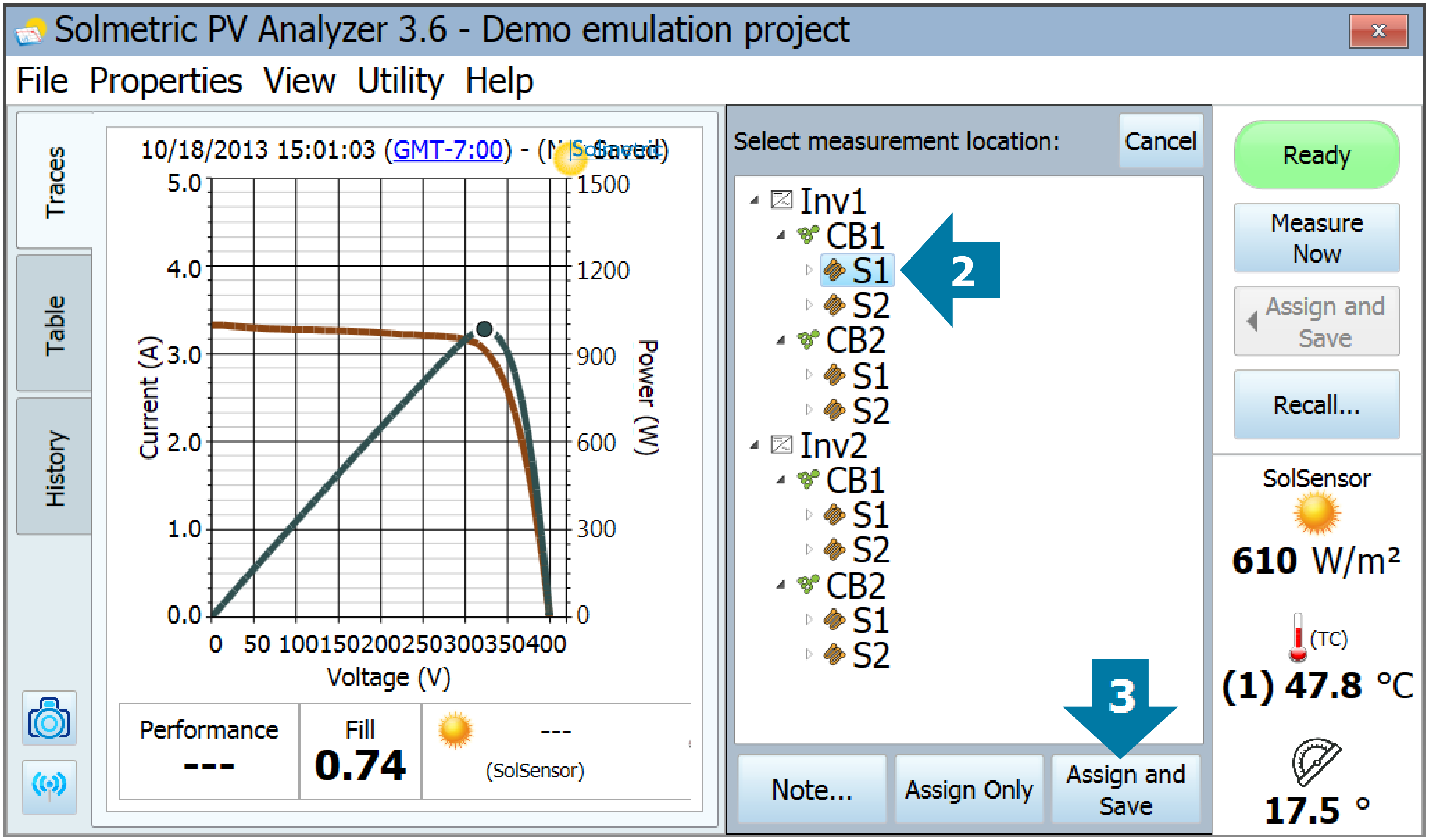
Making a Measurement

Steps 2 & 3: Click the array tree and save the data



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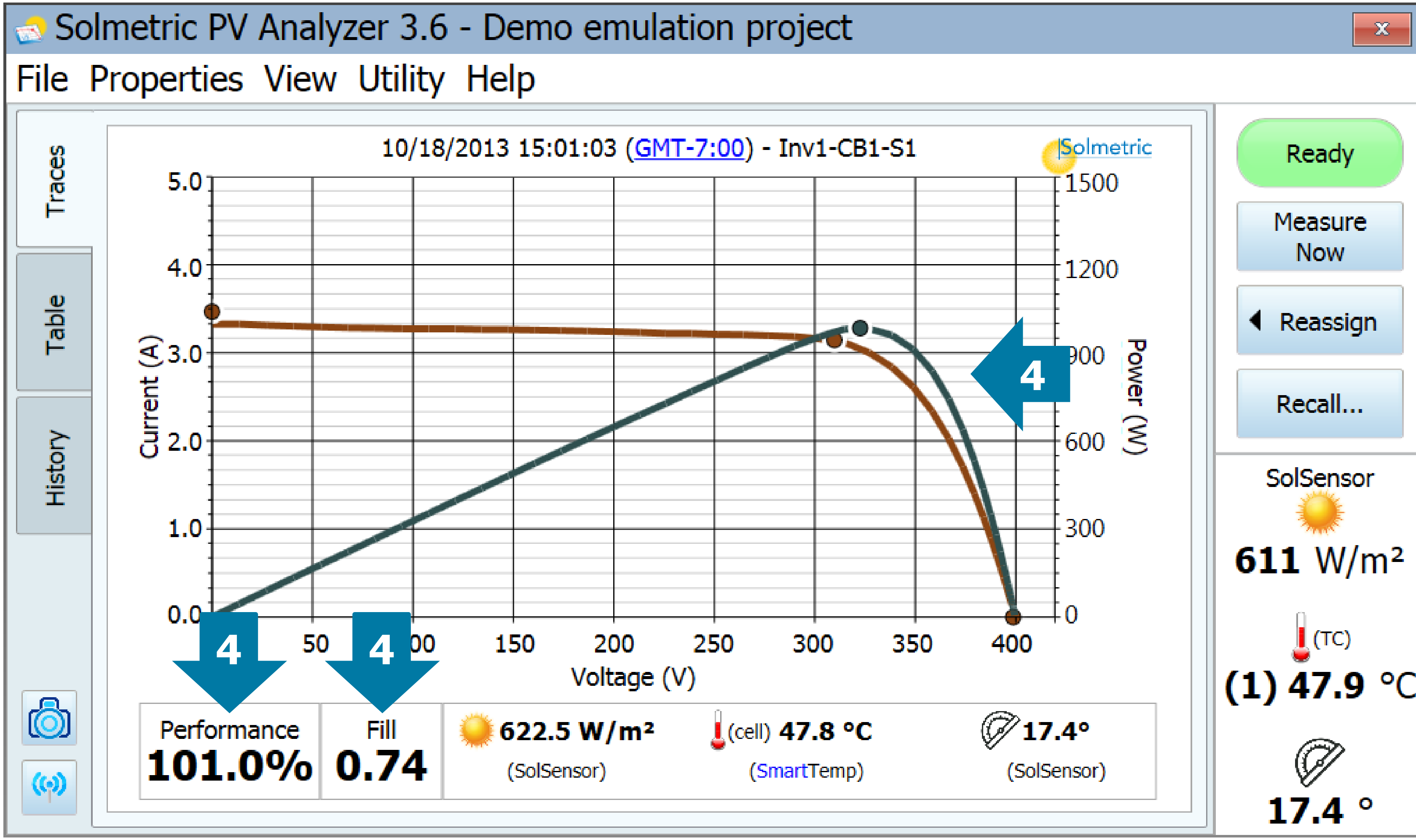
Making a Measurement

Step 4: Review the results



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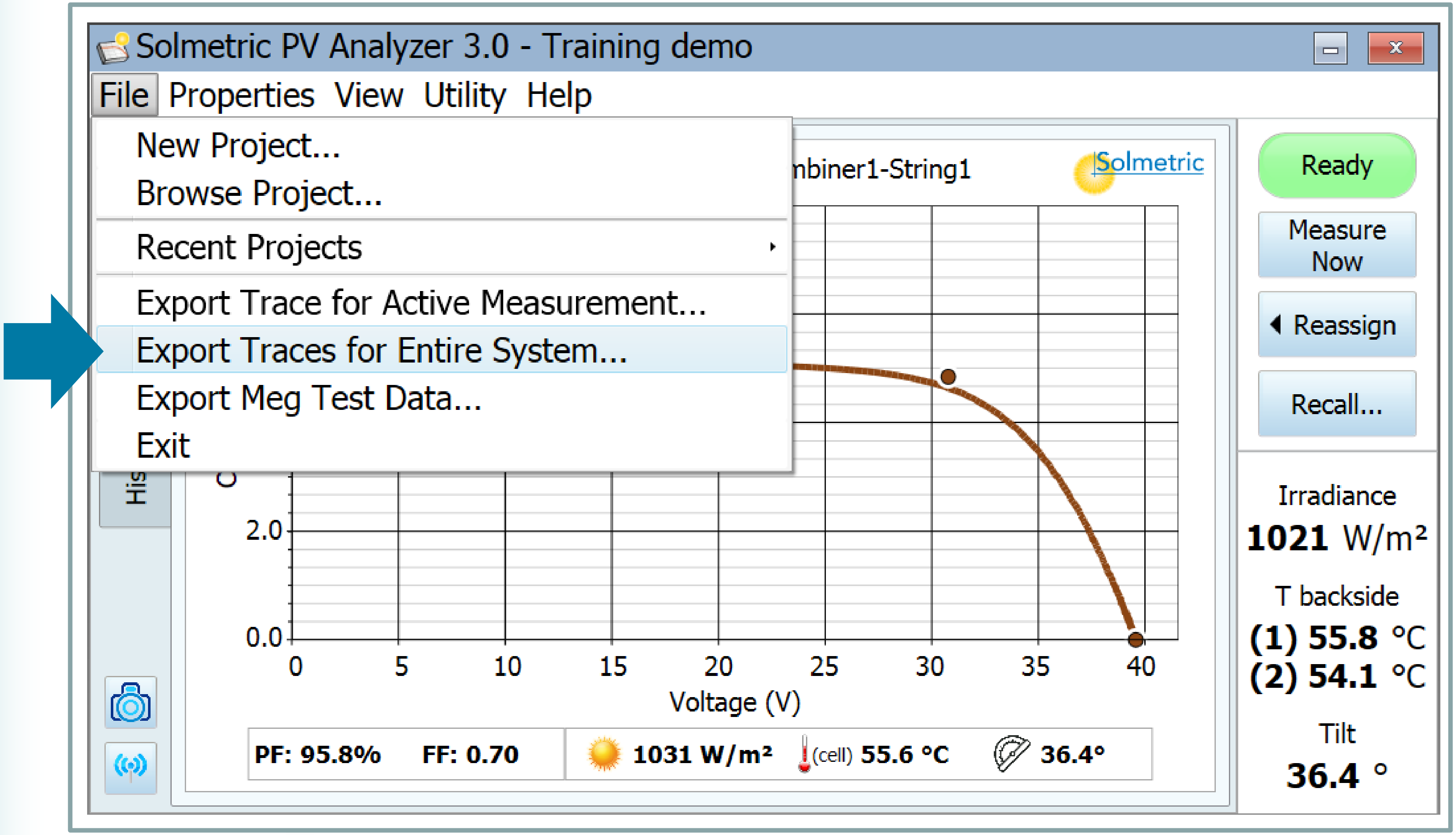
Exporting Your Data

For analysis and reporting



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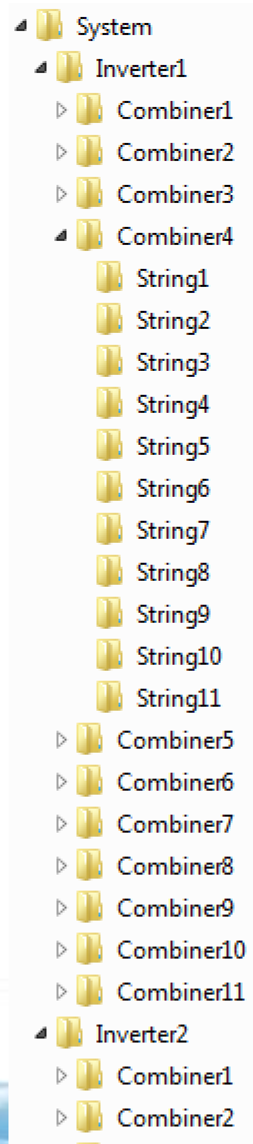
Exporting Your Data

Exported folder tree (created on your hard drive)



- The PVA software automatically creates this folder tree on your hard drive (you select the location).
- Each string folder contains a data file of a string measurement (csv format).
- If you also measured the individual modules that make up the string, there are module-level folders below the string folders.
- You access this data using the <u>I-V Data Analysis Tool</u> (DAT).
- You can select any level of the ‘tree’ to analyze with the DAT: the entire system, or a single inverter, or a single combiner.

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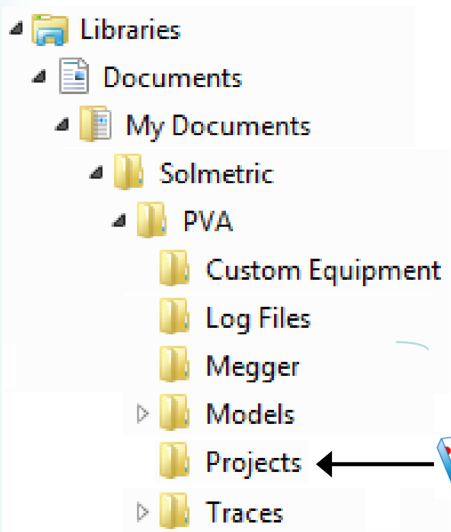
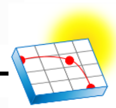
The Project File

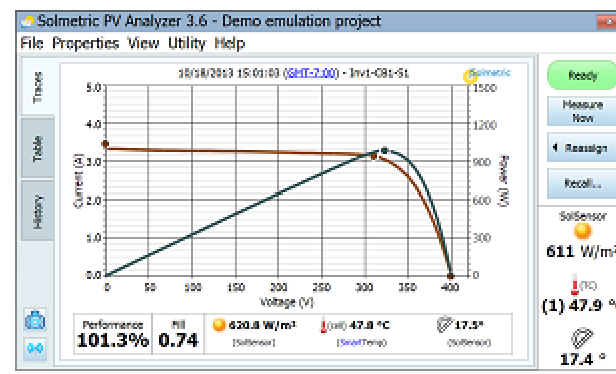
Contains your setup and data





Projectname.pvapx (v3.x)

- The ‘Project’ file is a container that holds all of your setup information, performance model, and I-V measurement data.
- To share your work, just attach the Project file to an email. The recipient double clicks the icon to launch their PVA software* and show the data.



*The PVA software is free at www.Solmetric.com, just select Downloads from the Support menu and navigate to the PVA software.

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Time and Date
Set to local coordinates before making measurements

- The date, time, latitude, longitude, tilt and azimuth are all used to calculate the Performance Factor. The predictive model needs this information.
- Before measuring, be sure your PC is set to the correct local date, time, time zone, and daylight savings status.

		Pacific time	Mountain time	Central time	Eastern time
UTC/GMT Offset (hours)	DST off	-8	-7	-6	-5
	DST on	-7	-6	-5	-4

www.timetemperature.com

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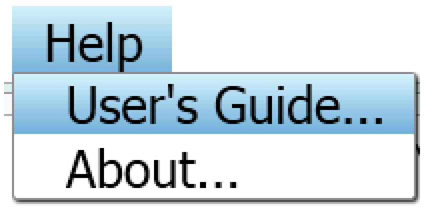
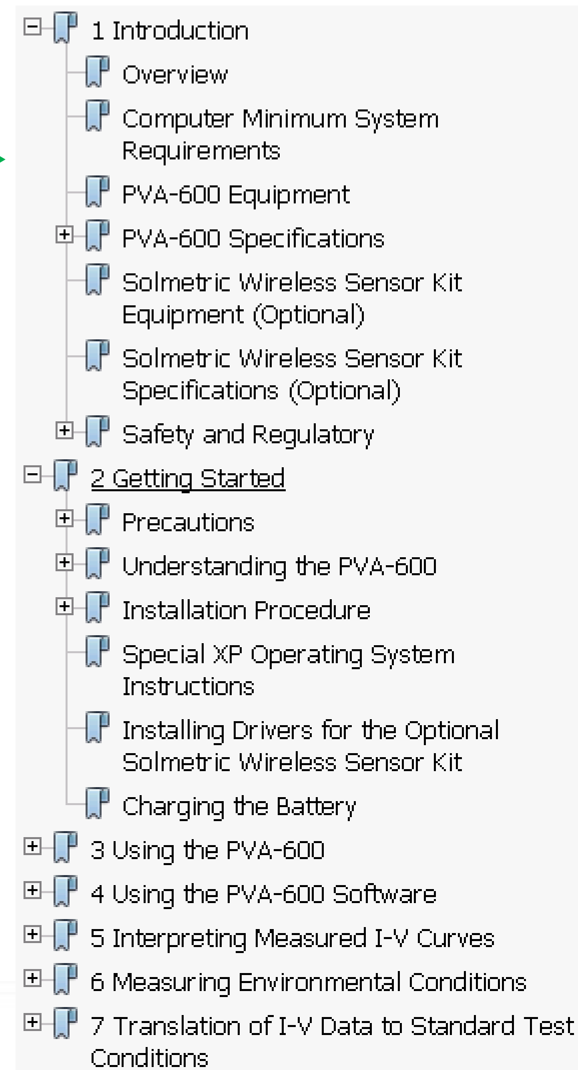
User Guide

Built-in & hyperlinked, for easy use in the filed





PV Module Parameters

Editing the PV module parameters

Nominal Power	175 Wp
Max Power Voltage (Vmp)	35.4 V
Max Power Current (Imp)	4.94 A
Open Circuit Voltage (Voc)	43.6 V
Short Circuit Current (Isc)	5.45 A
Temp. Coeff. of Voc	-0.365 %/K
Temp. Coeff. of Nominal Power	-0.468 %/K
Temp. Coeff. of Vmp	-0.527 %/K
Temp. Coeff. of Imp	0.068 %/K
Temp. Coeff. of Isc	0.097 %/K
Cell Technology	Monocrystalline Si
Noct	46.5 °C
Vmp at 200 W/m²	34.8 V
Imp at 200 W/m²	1.02 A
Ideality Factor (Aref)	1.98 V
Front Glass AR Coating	False
Front Glass Texture	Light

The built-in PV module database contains approximately 60,000 module types.

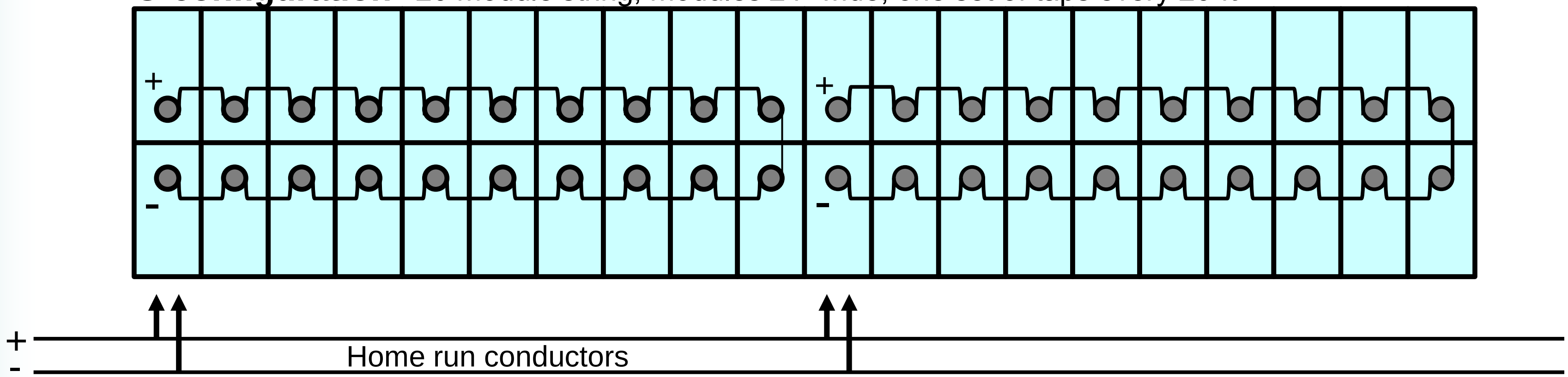
All 17 of the PV model parameters can be edited. Editing allows you to:

- Create modules that are not yet in the database
- Adjust values to match datasheet values, if necessary
- Multiply the values of nominal power and current by the number of strings you are testing in parallel. This is useful when measuring harnessed arrays from the combiner box. Check out the application note *Measuring I-V Curves in Harnessed PV Arrays* under the Support tab at the Solmetric website.

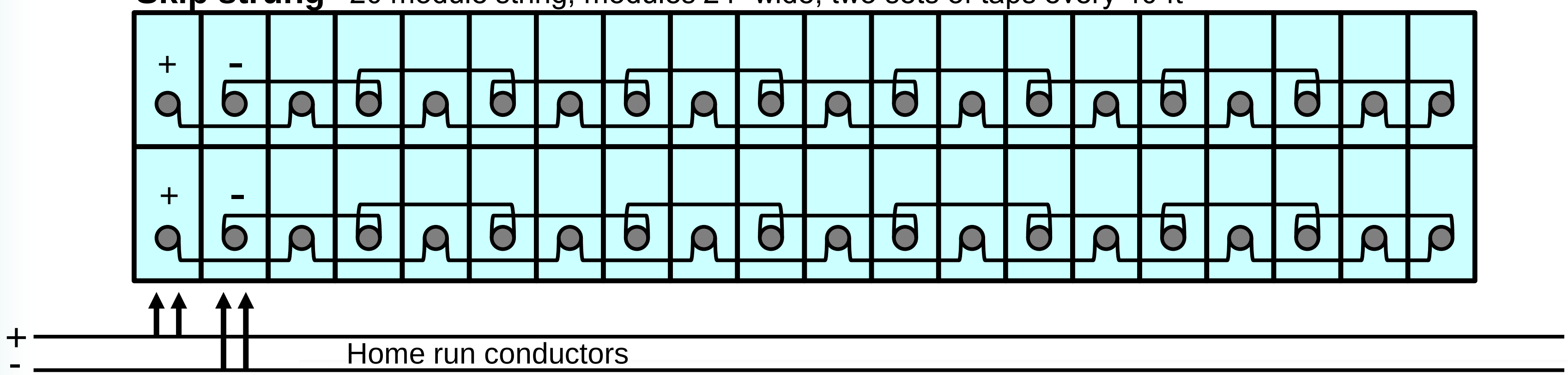
Harnessed strings

Examples of ‘U’ and ‘skip-strung’ configurations

U-configuration 20 module string, modules 24” wide, one set of taps every 20 ft



Skip strung 20 module string, modules 24” wide, two sets of taps every 40 ft



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Test Process

Example: Measuring strings at a combiner box

Hardware setup (do once at each combiner box)

1. Mount SolSensor to PV module and attach thermocouple*
2. Open the combiner DC disconnect
3. Lift the string fuses
4. Clip PVA test leads to the combiner buss bars

Electrical measurement (repeat for each string)

1. Insert a string fuse
2. Press "Measure"
3. View and save results
4. Lift the fuse

- This takes 10-15 seconds/string
- Typically, moving between combiner boxes takes more time than the actual testing.

*You may prefer to move SolSensor only needed to maintain wireless connection.

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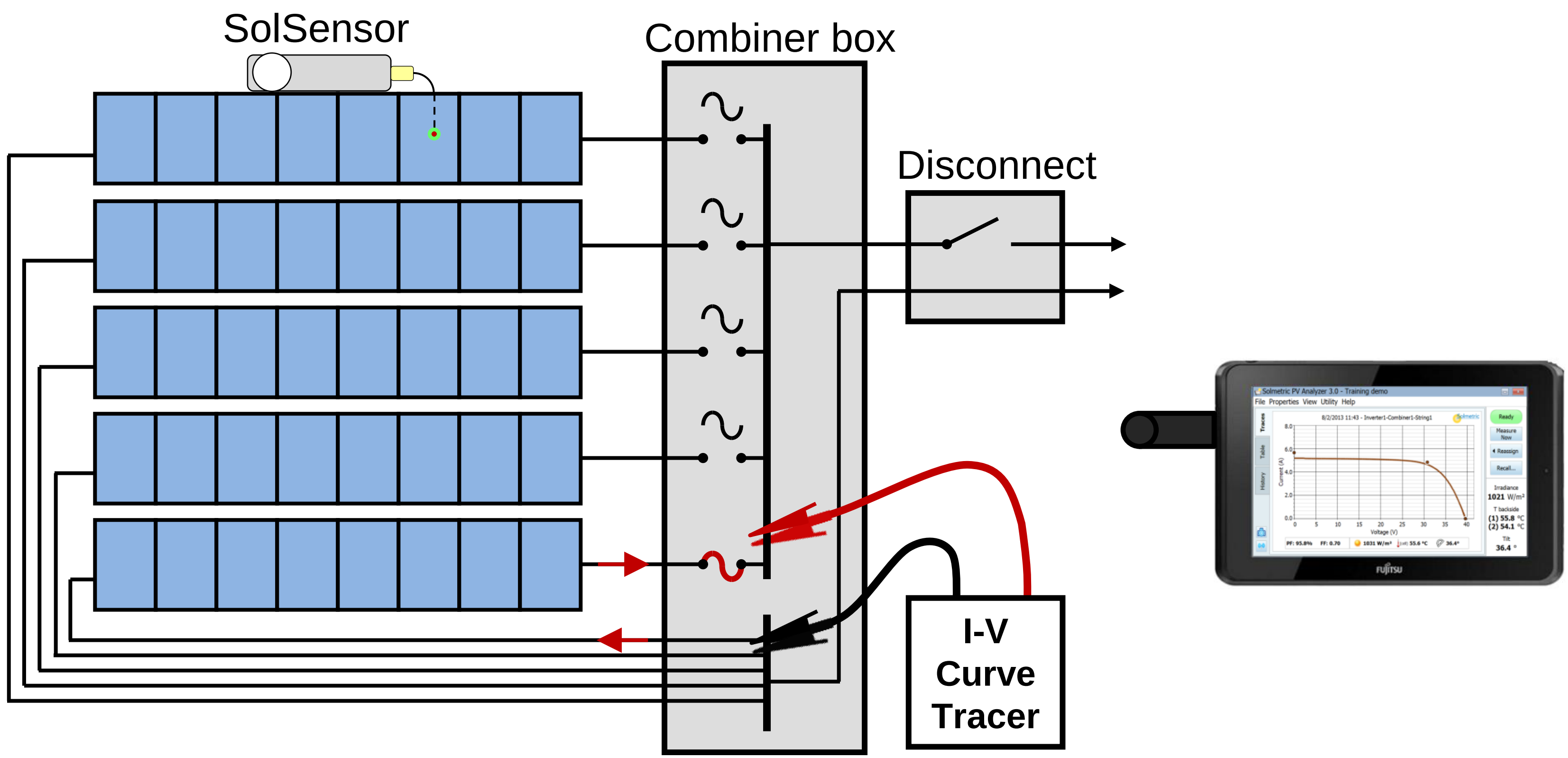
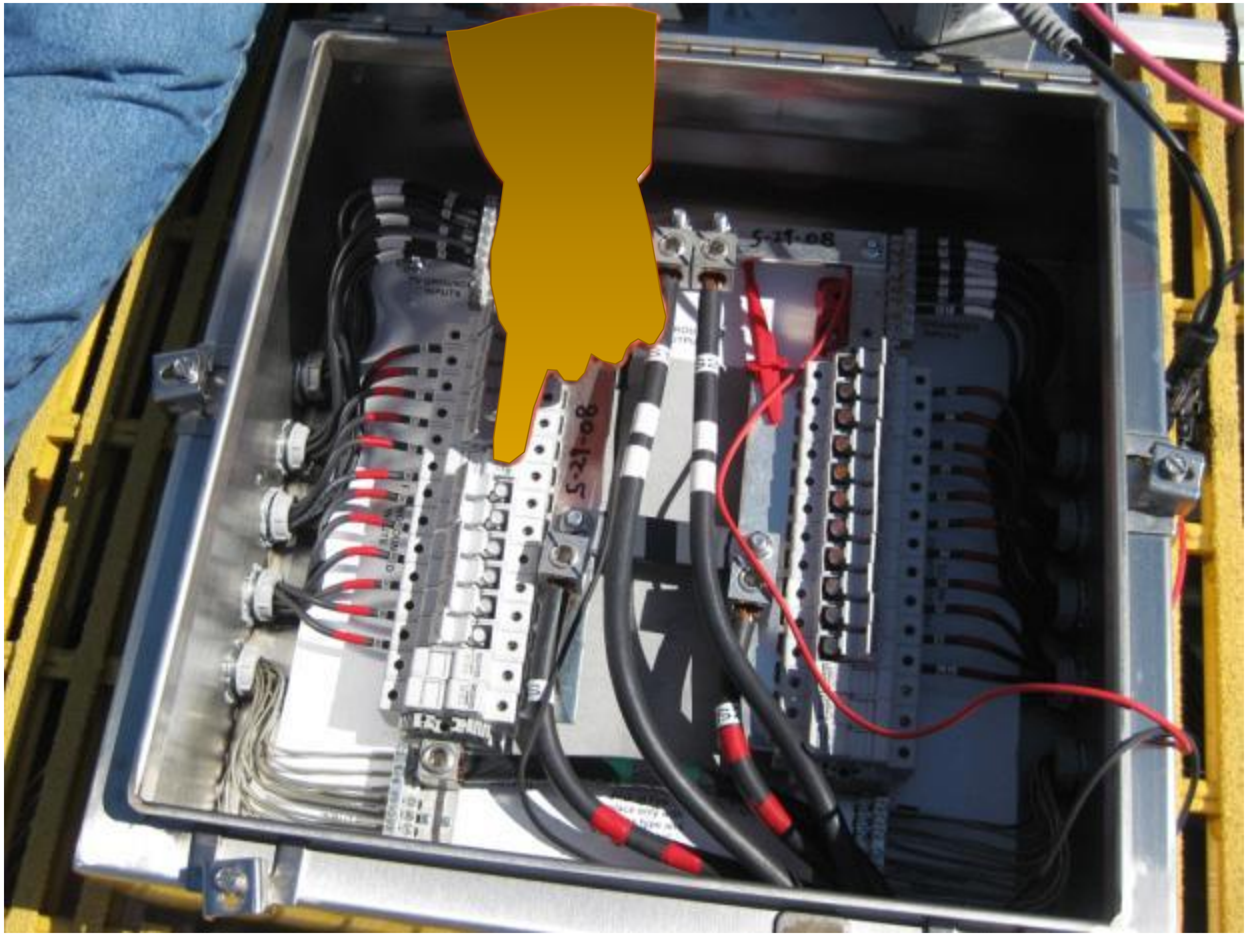
Test Setup

Measuring strings at a combiner box



Selecting a String to Test

Insert one fuse at a time



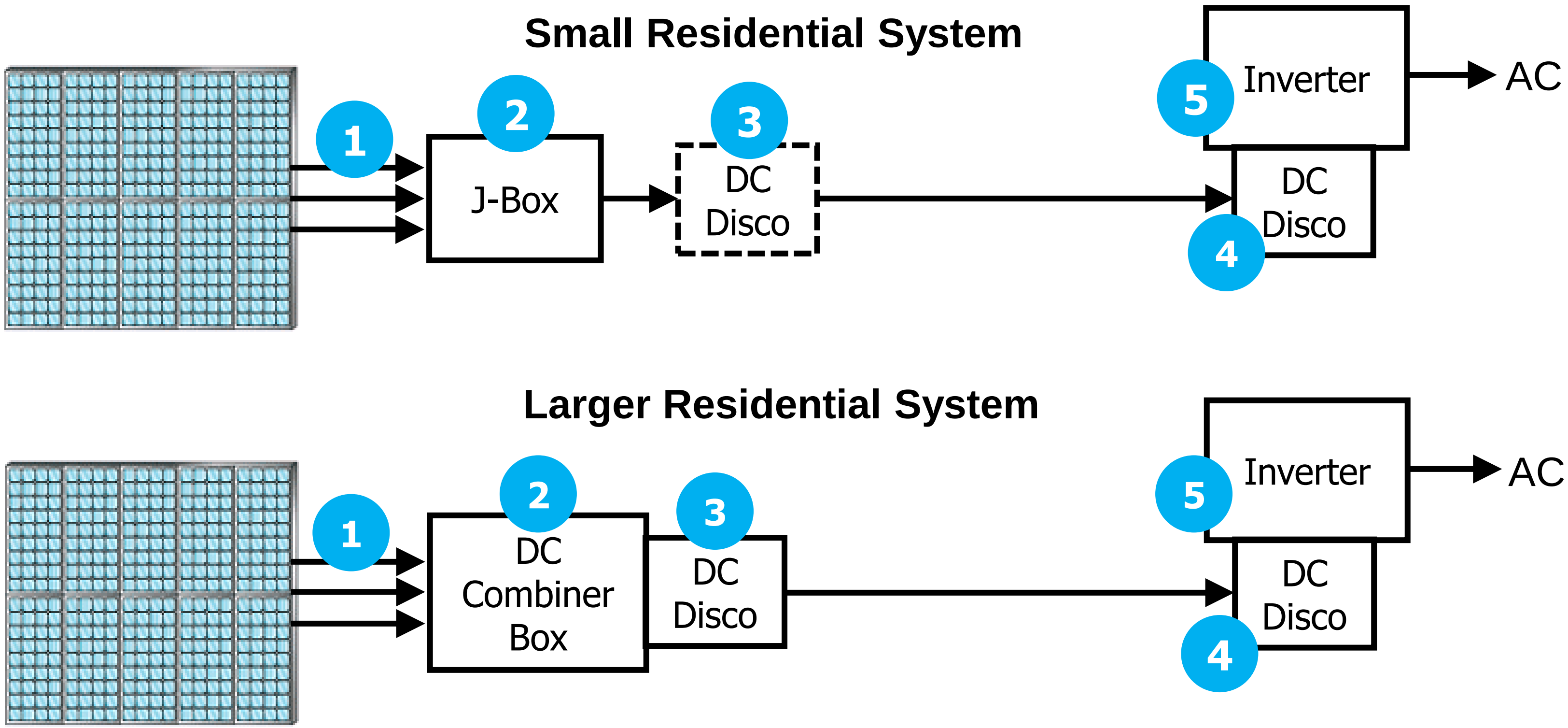
Application Examples
Measuring strings at a combiner box

Photos courtesy of
West Coast Solar Energy
and…

Multi-Contact US HQ
Windsor CA

Charles Shultz Museum
Santa Rosa, CA

Accessing PV Source Circuits
in residential systems



- Accessing a source circuit means both **isolating** it and **connecting** to it
- For a particular system layout, choose the safest and most convenient point of access
- Shut down inverter and open the dc disconnect before accessing PV source circuits.

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Access Challenges
Dead-front terminal blocks

- Dead-front terminal blocks make it more difficult to connect the I-V curve tracer.
- Fuse clips can be used as a test point for the ungrounded conductor.
- To create a test point for the grounded conductor, insert a short piece of home-run wire in a spare terminal slot.
- Another approach is to use test probes (for example Fluke FTP-1) in place of one or both alligator clips.

Fluke FTP-1

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Maximizing Wireless Range

- To optimize wireless range, mount SolSensor in a location that has a clear line of sight to your PC.
- In fixed tilt arrays, mount SolSensor on an upper edge or on an end where it can see your PC as you move between combiner boxes.
- Avoid placing the transmitter or the receiver on metal surfaces, as this will dramatically reduce the wireless range.
- Mounting SolSensor on a tripod is another option. SolSensor has tripod mounting threads on its backside. Be sure to orient SolSensor to the tilt and azimuth of the array.

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Preparing for Site Visits

- Review the construction drawings (one-line and array layout)
- Set up the PVA ‘project’ (typically at the office, for convenience)
- If strings are harnessed in parallel, scale up module power and currents accordingly
- Charge the PVA and SolSensor overnight (at least 6 hours)
- Make sure your PVA, SolSensor, and their accessories are all present.
- You may want to purchase a spare wireless USB adapter (easy to lose them!)
- Check the weather forecast & try to pick a good day
- Arrange for site and system access
- Bring along:
  - Hand tools, DMM & clamp meter, even if host says you don’t need them
  - Bring appropriate PPE, based on flash hazard calculations
  - Lock-out, tag-out gear
  - Cleaning equipment if clean/dirty tests are needed
  - Black rubber sheet if you’ll be troubleshooting using selective shading

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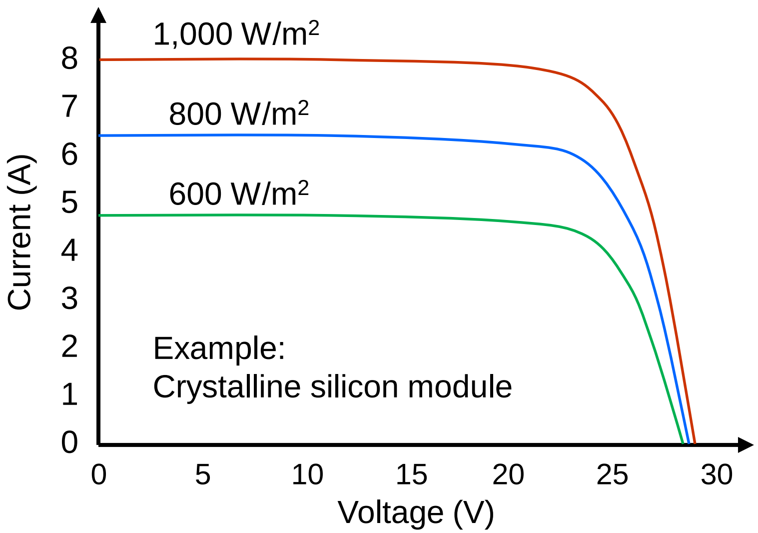
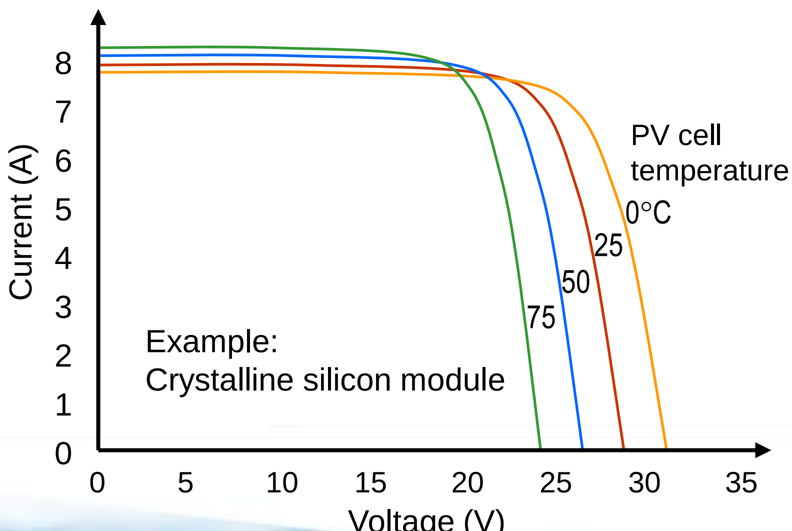
Why Measure Irradiance & Temperature?

Important factors determining PV output





- As shown by these graphs, irradiance and temperature have a big effect on PV output power.
- For crystalline silicon modules, the maximum power rises with increasing irradiance and drops with increasing temperature.
- We'll discuss this in more detail later, in the section on PV fundamentals for troubleshooting.
- For now, the important thing to realize is that to predict what our measured PV curve SHOULD look like, we need to know the irradiance and module temperature at the time of the I-V measurement.

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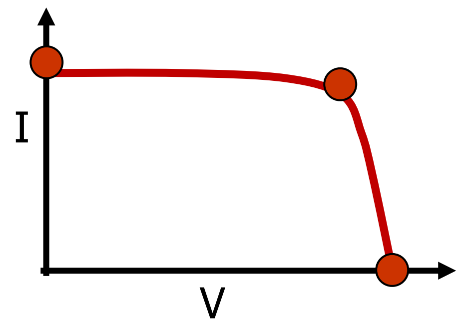
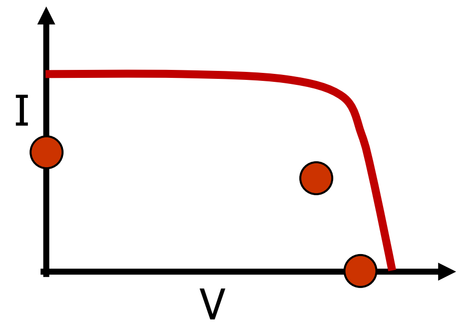
Why Measure Irradiance & Temperature?
Important factors determining PV output

When our expected I-V curve shape (3 red dots) is based on accurate irradiance and temperature data, comparing it to our measured curve is a fair and informative **apples-to-apples** comparison.



When our sensor measurements are not accurate, it's an **apples-to-oranges** comparison! It can lead us to believe a healthy string of modules is under-performing, or an underperforming string is healthy. It's just not a fair or useful comparison.



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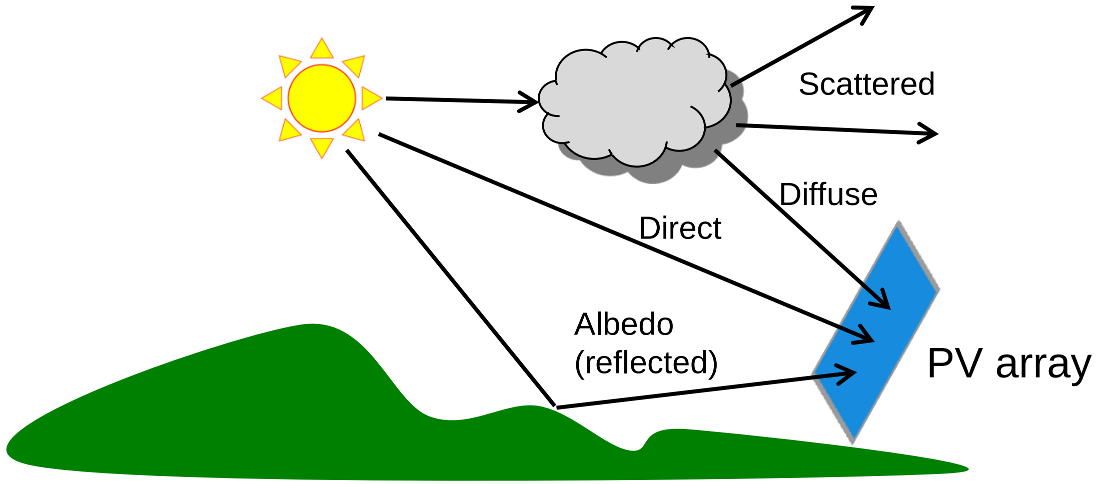
What is Irradiance?
Irradiance components



Irradiance is defined as the solar power incident on a flat surface divided by the area of the surface. The units of irradiance are watts per square meter (W/m^2). The irradiance incident on a PV array has three components:

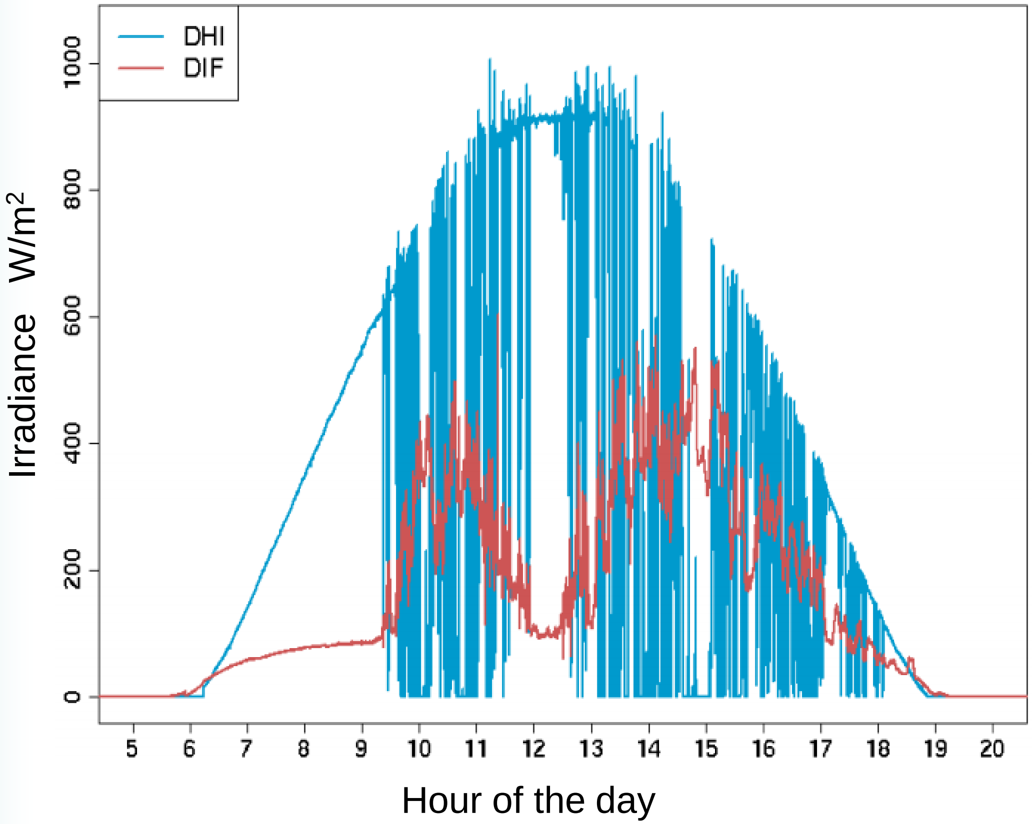
Direct light – light arriving in a straight line from the sun

Diffuse light – light scattered to array modules by clouds or particles in the atmosphere

Albedo – light reflected off objects or surfaces within view of the array

The mix of these components, and thus their relative contributions to PV production, changes with time and atmospheric conditions.

Dynamics of Direct & Diffuse Light



Philippe Beaucage et. al., AWS Truepower, 2012

This chart compares direct and diffuse irradiance across a day's time.

When the direct light curve (in blue) plunges, the diffuse light curve (in red) jumps up. This is the action of clouds moving across or near the sun.

Notice that there is still some diffuse light even in the early morning when the blue curve is smooth. This is expected. Even a clear sky has some water vapor that scatters a small fraction of the light.

View of the Sky

Under diffuse light conditions

- Under diffuse light conditions, light hits the PV modules *from all directions in the sky.*
- Trees and buildings can block some of this scattered light, even if they do not block the direct rays of the sun.
- In this situation *where you place your irradiance sensor* makes a difference. It could make PV system performance look better or worse, depending on where the irradiance sensor and the array itself are located relative to the tree or other shading object.
- Try to mount SolSensor in a location that has the same view of the whole sky as the array itself.

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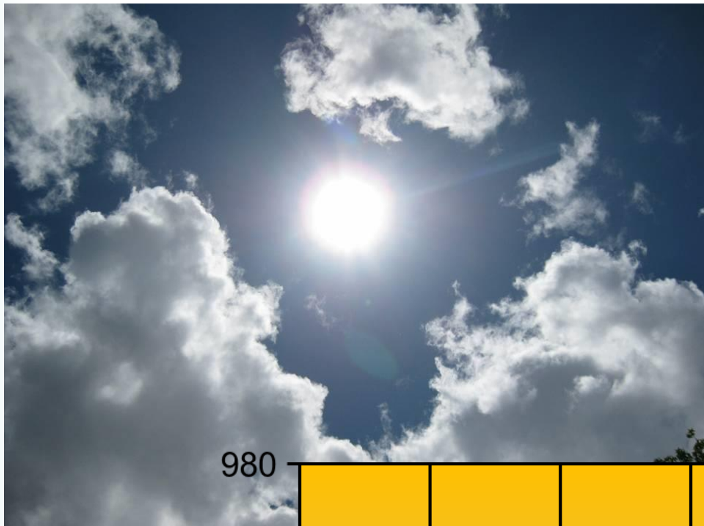
Recommended Weather Conditions

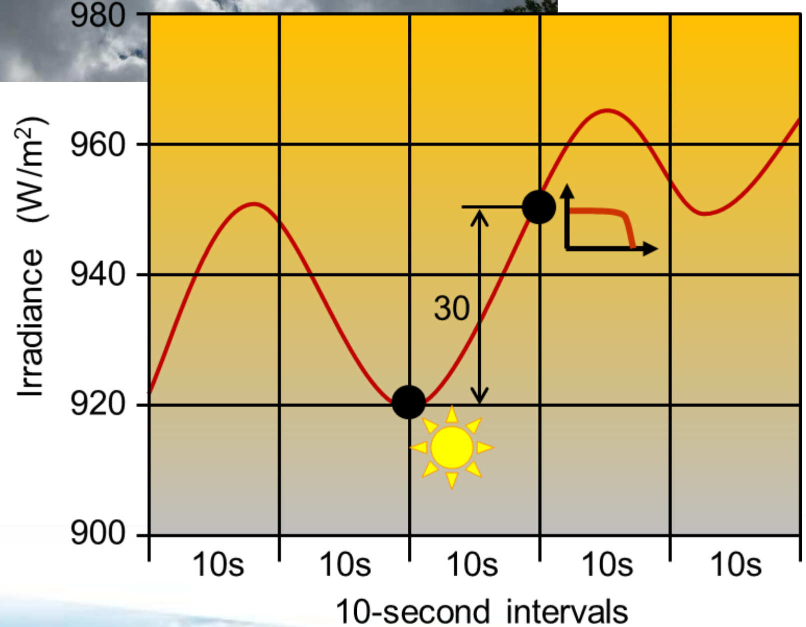
For *performance* measurement

- **High and stable irradiance**
  - Ideally >800 W/m^2, not lower than 400 W/m^2 .
  - The I-V curve of cSi changes shape at low light, especially below 400, making it a less useful predictor of performance at high irradiance.
  - Stable irradiance means less irradiance & temperature error due to time delay between I-V and irradiance measurements, and less distortion of the I-V curve due to irradiance variation during data acquisition.
- **4-5 hour window centered on solar noon**
  - For good irradiance level and reduced angle of incidence effects
  - http://www.esrl.noaa.gov/gmd/grad/solcalc/
- **Little or no wind**
  - To reduce temperature-related performance variation
  - Higher cell temperature → lower Voc

Why <u>Stable</u> Conditions?

Instability → measurement error





- If there is any time delay between the I-V and irradiance measurements, irradiance variations during that time interval cause *irradiance errors that are random in both magnitude and direction*.
- The greater the time delay, or the steeper the irradiance ramp, the greater the irradiance error.
- There is no way to correct or 'back out' these random errors during data analysis.
- The same type of error affects temperature measurement, but to lesser degree because temperature ramping is slower, and the dependence of performance on temperature is less profound.

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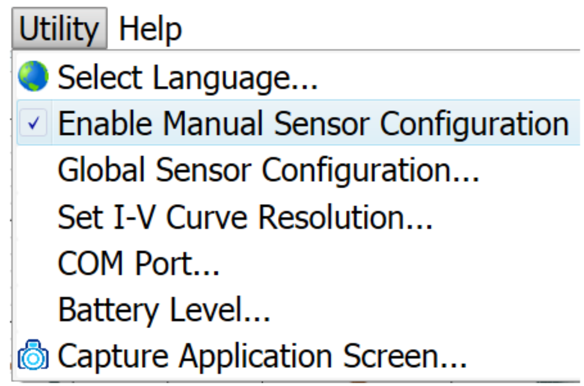
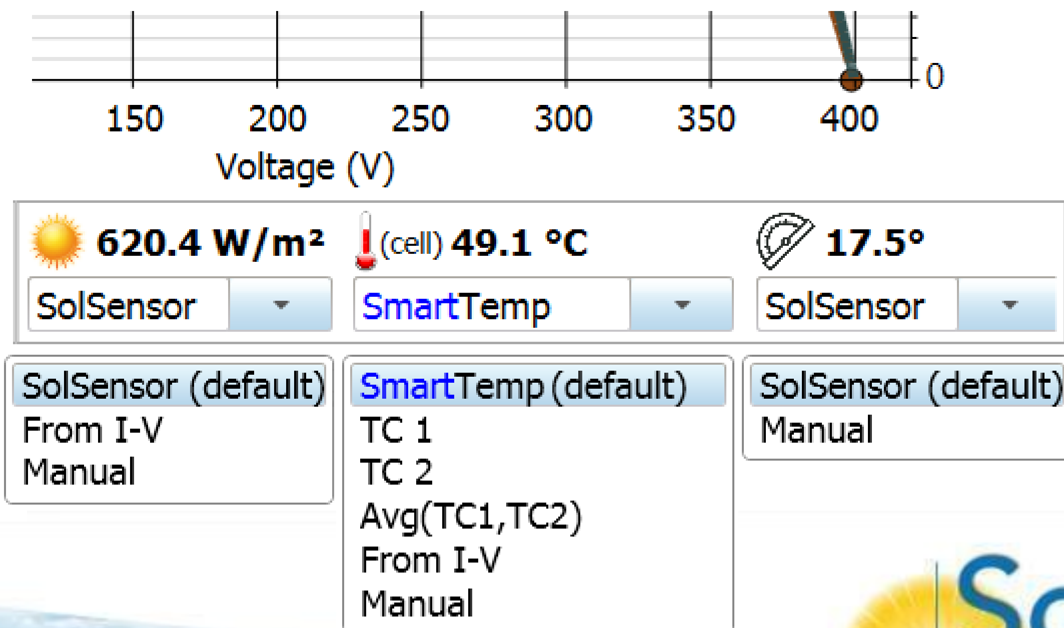
Selecting Sensor Methods

The PVA provides several methods for determining irradiance and several for module temperature.

Click this menu item and the options will appear in drop boxes below the I-V graph.





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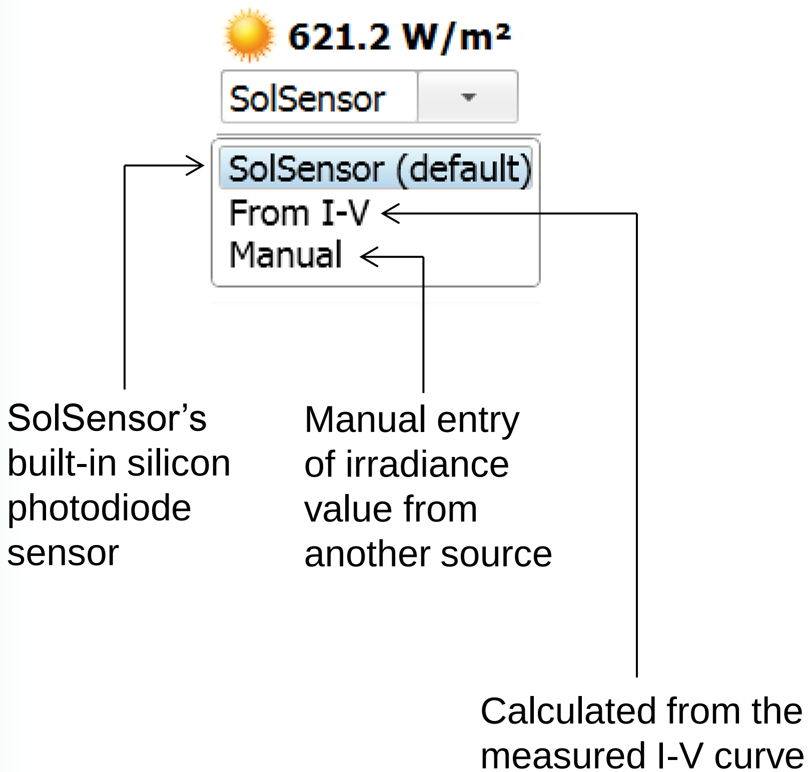
Irradiance Measurement Options

Overview



SolSensor is the default method. It uses SolSensor's built-in silicon photodiode sensor.

The **From I-V** method calculates the irradiance from the measured I-V curve, relying primarily on Isc but also involving Voc.

The **Manual** method enables the user to manually enter irradiance values that are obtained from another source when SolSensor is not available.

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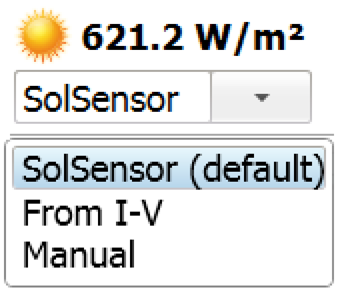
Irradiance Measurement Options

Strengths and limitations of the options



The SolSensor option uses SolSensor's built-in silicon photodiode sensor. It's spectral response is similar to crystalline silicon solar cells, and software-based spectral corrections adapt it to other common solar cell technologies. The sensor is also corrected for angular effects and is temperature compensated.

The **From I-V** method calculates the irradiance from the measured I-V curve, relying primarily on Isc but also involving Voc. This option eliminates the need for the hardware based measurement of irradiance, but is not accurate if the array is soiled or significantly degraded.

The **Manual** method enables the user to manually enter irradiance values that are obtained from another source when SolSensor is not available. It saves deploying the irradiance sensor, but takes much more time for manual data entry. Also, under unstable irradiance conditions, the time delay between I-V curve and irradiance measurements translates into irradiance error.

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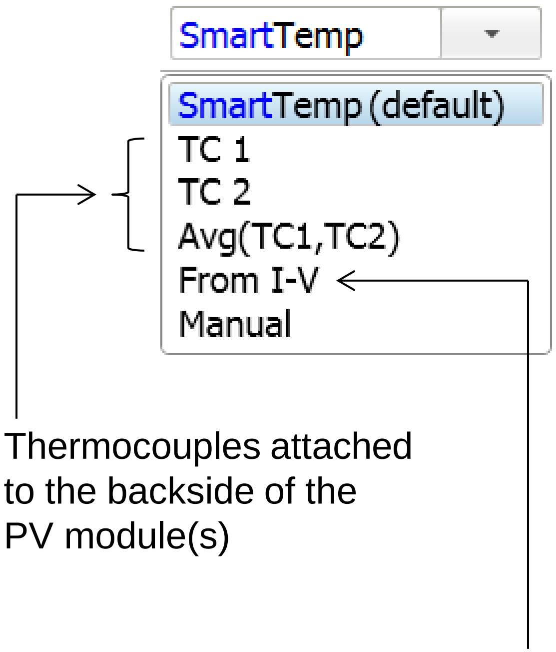
Temperature Measurement Options

Overview



Thermocouples attached to the backside of the PV module(s)

Calculated from the measured I-V curve, primarily from Voc.

SmartTemp is the default method. It is a blend of the thermocouple (TC) and From I-V methods. When irradiance is above 800W/m^2 SmartTemp uses only From I-V, and below 400W/m^2 it uses only the thermocouple data. Between those irradiance levels, From I-V and thermocouple values are blended in changing proportion.

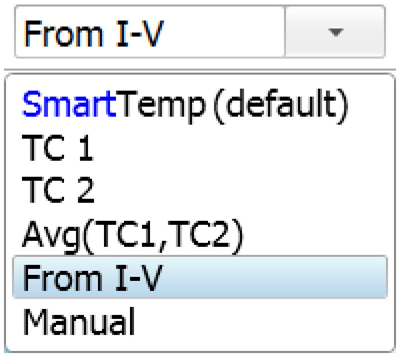
TC1, TC2, Avg(TC1, TC2) are thermocouple methods. SolSensor provides two thermocouple inputs, labeled TC1 and TC2. In most commissioning and O&M work, a single thermocouple is used.

The **From I-V** method calculates the average cell temperature from the measured I-V curve, relying primarily on Voc but also involving Isc.

The **Manual** method enables the user to manually enter temperature values that are obtained from another source when SolSensor is not available.

Temperature Measurement Options

From I-V method - strengths



The PV model needs to know the module temperature in order to predict the expected I-V curve shape and calculate the Performance Factor. The From I-V method provides an indirect measure of the *average cell temperature* of the PV module or string under test.**

The From I-V method has several advantages:

1. Average cell temperature is the best input to the PV model because it accounts for the unpredictable variation in temperature across any PV array.
2. The temperature determination is simultaneous with measurement of the I-V curve. This eliminates temperature errors related to time delays, which can be a problem under gusty wind conditions or rapidly ramping irradiance.
3. Since the From I-V method does not involve a thermocouple, there is no error related to where on the modules the thermocouple is mounted.
4. In Building Integrated PV applications, it is often not practical to mount a thermocouple on the backside of a PV module. The From I-V method eliminates that need.

**IEC 60904-5:2011 describes the preferred method for determining the equivalent cell temperature (ECT) of PV devices (cells, modules and arrays of one type of module), for the purposes of comparing their thermal characteristics, determining NOCT (nominal operating cell temperature) and translating measured I-V characteristics to other temperatures.

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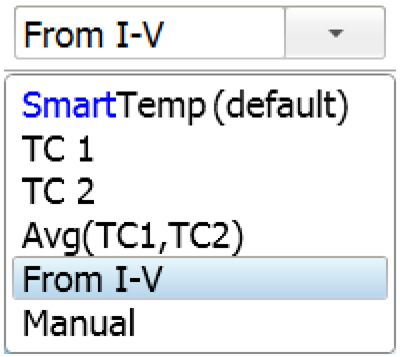
Temperature Measurement Options

From I-V method - limitations



The From I-V method has several limitations.

1. Calculation of cell temperature from Voc is reliable at high irradiance levels, but at lower irradiance levels Voc varies increasingly with irradiance, thus introducing a temperature error.

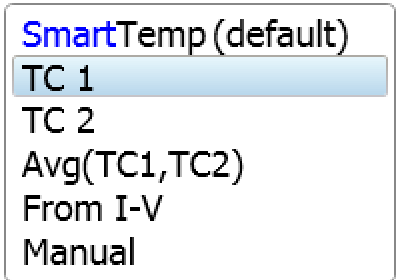
2. The From I-V method calculates temperature using the temperature coefficient of Voc as found on the PV module datasheet. If the PV modules are damaged or degraded in ways that reduce Voc, the calculated temperature will be too hot. Fortunately, in the crystalline silicon technology, Voc has the lowest aging rate of all the PV module parameters.

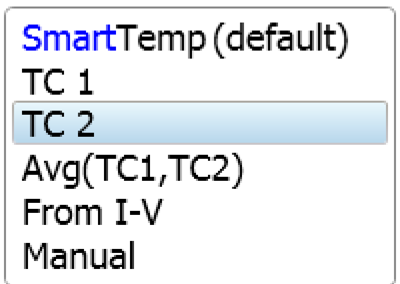
3. Shorted bypass diodes significantly reduce Voc, resulting in an overly high temperature value.

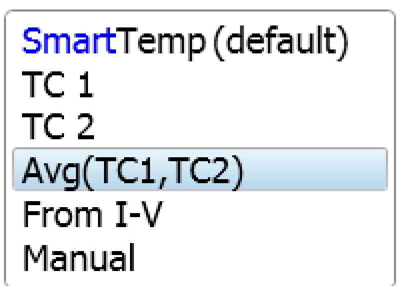
If you are using the From I-V measurement and you notice a particularly high temperature value, it is good practice to check the measured Voc. If Voc is significantly low compared to the rest of the population of strings, the Voc issue may require troubleshooting.

Temperature Measurement Options

Thermocouple (TC) choices







The thermocouple (TC) method determines module temperature from a thermocouple attached to the back of a module. SolSensor provides two thermocouple sockets and you can choose to use one or the other, or both. If Avg(TC1, TC2) is selected, the software uses the average of the two thermocouple values.

Backside surface temperature sensors have a long history in PV array performance measurements, but there are two significant limitations:

1. Temperature is not uniform across PV arrays, so the temperature reported by the thermocouple depends upon *where* it is attached.
2. The temperature of interest to the PV model is the temperature of the PV cells themselves, not the module backside temperature. Research has shown that cell temperature is typically 3C warmer than the back surface under high light conditions. For the purposes of the PV model, the PVA software adds 3C to the thermocouple temperature at 1000 W/m^2, and scales down the temperature offset at lower irradiance values.

If you plan on measuring a system again and again as the system ages and degrades, the thermocouple option has an advantage over From I-V and SmartTemp in that it is not influenced by aging of Voc.

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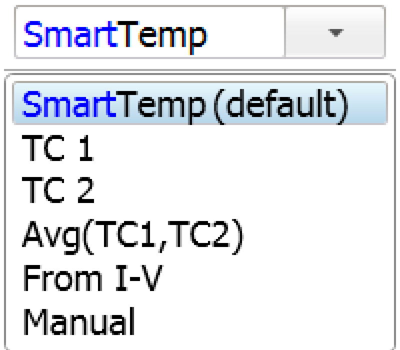
Temperature Measurement Options
SmartTemp method



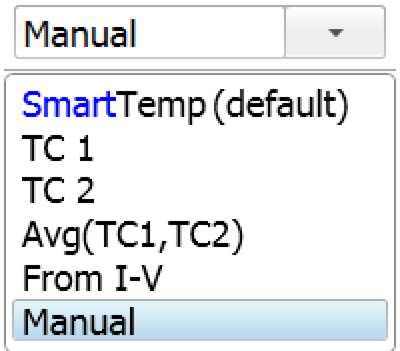
As mentioned earlier, **SmartTemp** is the default method. It is a blend of the thermocouple (TC) and From I-V methods. When irradiance is above 800W/m^2 SmartTemp uses only From I-V, and when irradiance is below 400W/m^2 it uses only the thermocouple data. Between those irradiance levels, the From I-V and thermocouple values are blended in changing proportion. SmartTemp uses the From I-V and TC methods where they are strongest, as shown below:

Irradiance	From I-V	Thermocouple
High	(+) Little affected by irradiance variations	(-) Greater temperature offset between backside and cells
Low	(-) Strongly affected by irradiance variations	(+) Smaller temperature offset between backside and cells

If you plan on measuring a system again and again as the system ages and degrades, the thermocouple option has the advantage over From I-V and SmartTemp that it is not influenced by aging of Voc.

Temperature Measurement Options

Manual entry method



The **Manual** method allows the user to enter temperature values obtained from other instruments, such as:

- Hand-held surface temperature meter
- Infrared thermometer or imager
- Monitoring system connected to the PV plant

The manual method has some limitations:

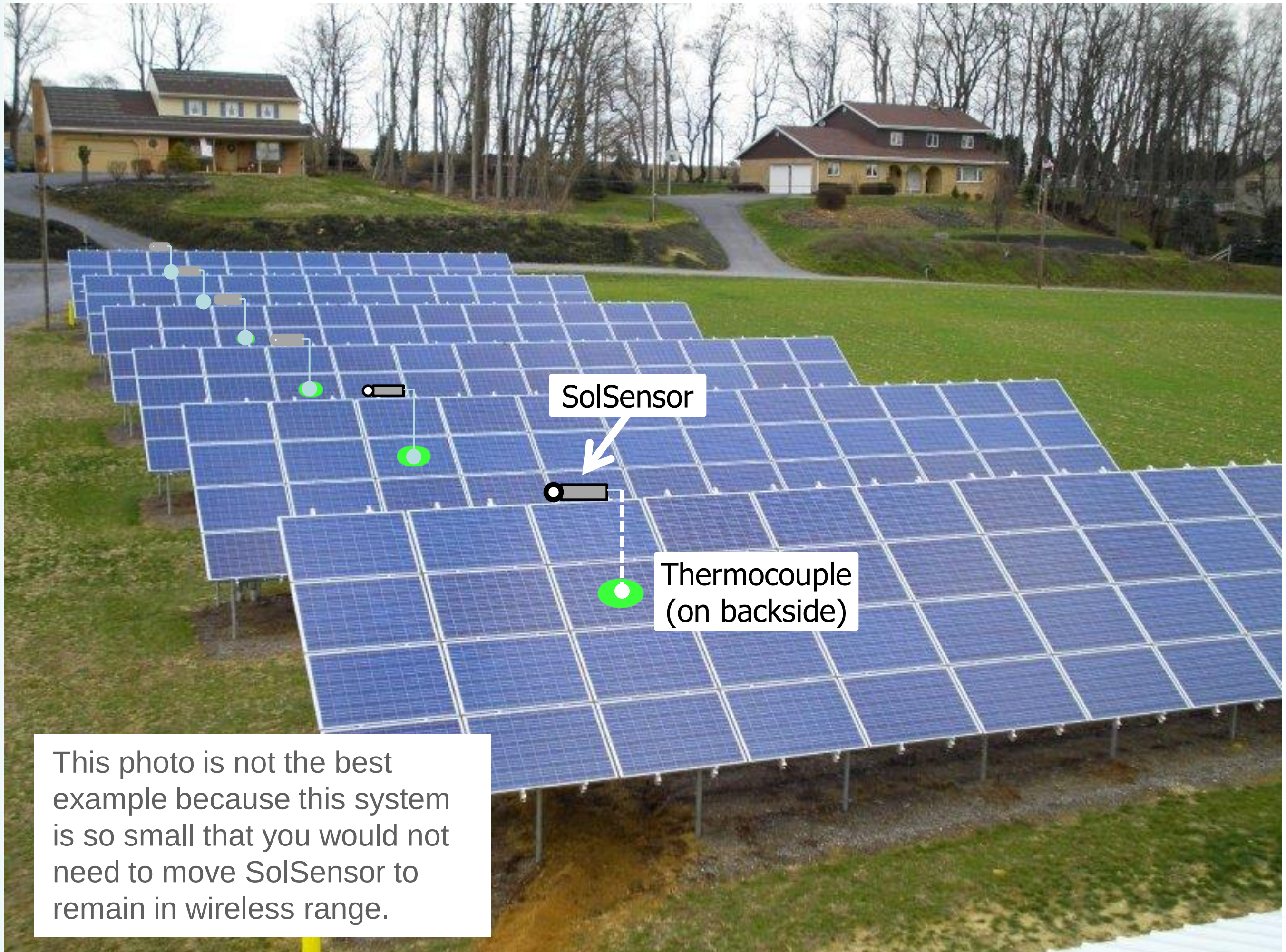
1. It takes time to read and enter the temperature values. Under conditions where irradiance is ramping or the wind is gusting, a time delay between temperature and I-V measurements translates into a temperature error which in turn affects the shape of the predicted I-V curve and the value of the Performance Factor.

2. Other temperature methods may be less accurate or precise than SolSensor's methods.

3. The time required to manually enter temperature values greatly reduces the number of strings that can be measured in a day's time. Over a few projects, increased labor costs can add up to more than the purchase cost of SolSensor.

Thermocouple Mounting

Choosing your TC mounting location



This photo is not the best example because this system is so small that you would not need to move SolSensor to remain in wireless range.

Photo courtesy of Sun Lion Energy Systems

Avoid mounting your TC at the cooler edges of the array.

In large arrays you may need to move SolSensor from time to stay in wireless range.

When you move SolSensor to a new subarray, mount it in the same relative location.

Why?

Temperature is not uniform across PV arrays, and using a consistent mounting location avoids introducing more variation than necessary into the TC data.

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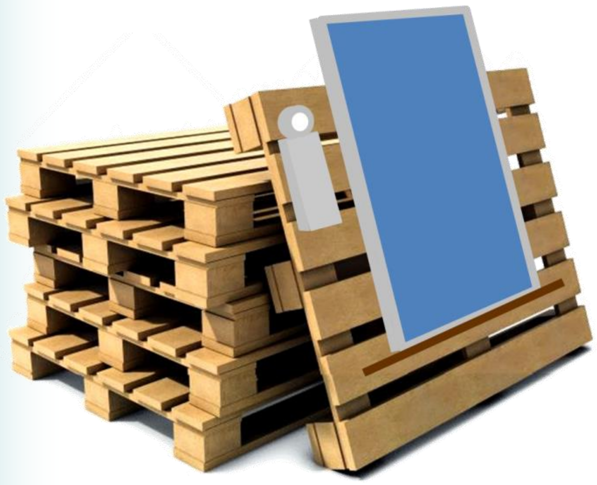
Thermocouple Mounting

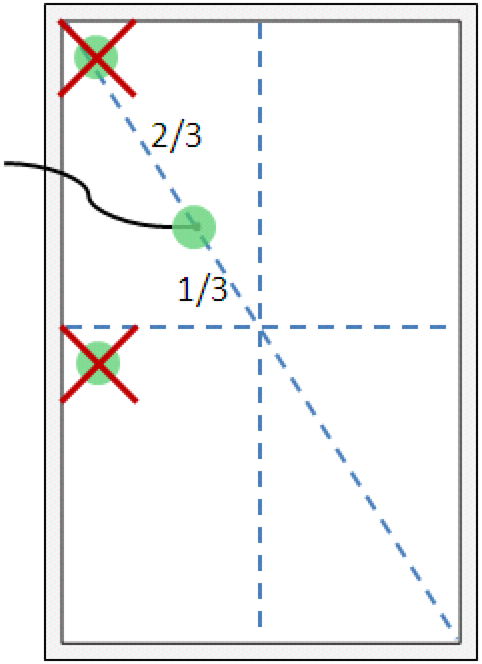
Choosing your TC mounting location



When testing single modules, mount the thermocouple ~2/3 of the way between the corner and center of the module.

Press tape and thermocouple into firm contact with module backside

For all thermocouple mounting applications, use high-temperature tape (eg 1-3/4 inch green Kapton dots**). Electrical tape and cheap big box store duct tape sag at high temperatures, allowing the tip of the thermocouple to break contact with the backside of the module. Even a tiny airgap can cause temperature measurement error.

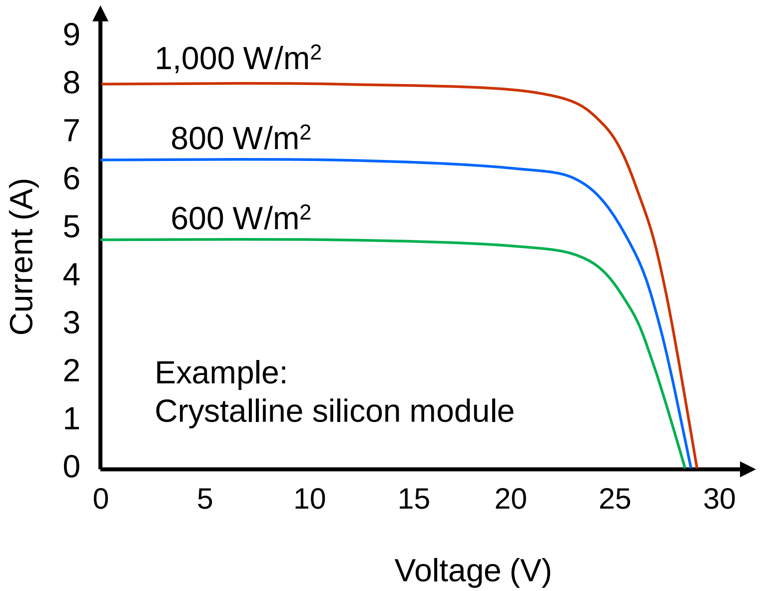


** MOCAP MCD-PE 1.75” green Kapton poly dots
$80 for a roll of 1000 dots
customerservice@mocap.com

Topics

- Introduction to the PVA-1000S PV Analyzer
- Using the software
- Making I-V curve measurements
- Measuring irradiance & temperature
- PV fundamentals for troubleshooting
- Troubleshooting PV arrays
- Using the I-V Data Analysis Tool (DAT)

Impact of Irradiance on the I-V Curve



- This graph shows the typical effect of irradiance on the I-V curve for crystalline silicon modules. The short circuit current Isc always increases in direct proportion to irradiance. If the irradiance doubles, the short circuit current doubles.
- The shape of the I-V curve itself changes slightly with changing irradiance, especially below 400W/m^2. This change can be hard to detect by eye, but easier to detect by comparing max power or fill factor values at different irradiance levels.
- Clouds have a major effect on irradiance, producing variations like those seen in this figure. Testing performance on clear days assures that I-V curves measured within a few minutes of one another will be close to the same height, making it easier to visually detect any other differences between the curves.

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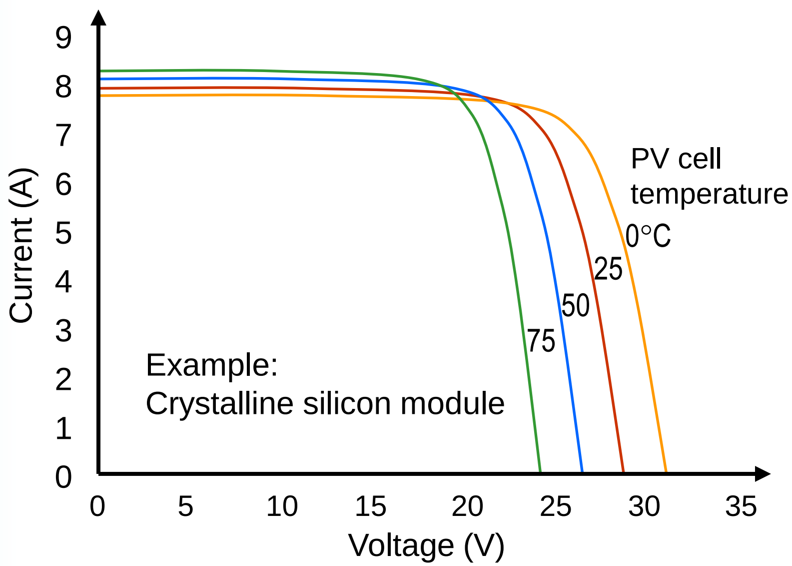
Impact of Temperature on the I-V Curve

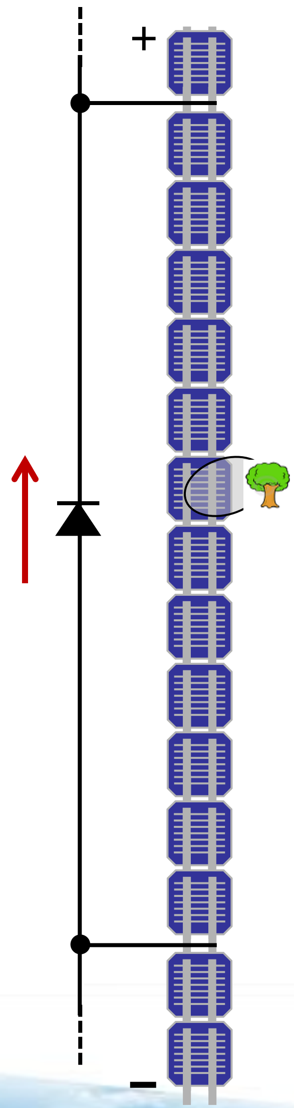


- This graph shows the typical effects of module temperature on the I-V curve for crystalline silicon PV modules,
- Temperature has its largest effect on the module voltages. The open circuit voltage changes approximately -0.45% for each 1°C increase in temperature. The effect on currents is much smaller, typically causing the short circuit current to rise approximately +0.10% for each 1°C increase in temperature. The maximum power value changes approximately -0.5% for each 1 °C increase in temperature.
- For most accurate performance prediction, the PV model wants to know the temperature of the solar cells within the PV module. Since we can't access them, we measure the temperature of the module backside.
- Solar cell temperature is not constant across a PV module, string, or array. This is mainly due to non-uniform ventilation and also the effect of wind.
- Module temperature is strongly dependent on irradiance and also on ambient temperature.
- The rate at which cell temperature can change is moderated by the mass of the solar panel. It takes several seconds for a significant temperature change to take place. Irradiance can change much more rapidly, on a percentage basis.

Bypass Diodes

- **If you will be maintaining PV arrays or analyzing I-V curve data, it's important to understand the behavior of bypass diodes. The next few slides explore this topic.**
- Crystalline silicon PV modules designed for grid-tie systems use semiconductor bypass diodes to protect shaded, locally soiled, or cracked cells from electrical and thermal damage.
- These conditions cause *current mismatch* because the affected cells cannot generate as much current as the uncompromised cells.
- The more a cell is obstructed, the more it acts as an electrical load, dissipating power in the cell itself. If it was not protected by bypass diodes, it could rapidly overheat and could destroy the module and even cause a fire.
- A beneficial side effect of bypass diodes is that they preserve the performance of the unobstructed cell groups and modules.
- In most module designs, the bypass diodes are mounted in the junction box on the module backside.
- Each bypass diode protects a different group of cells within the module. For example, in a conventional 72-cell crystalline silicon module there may be three bypass diodes, each protecting a group of 24 cells, usually laid out as two adjacent columns as viewed in portrait mode.

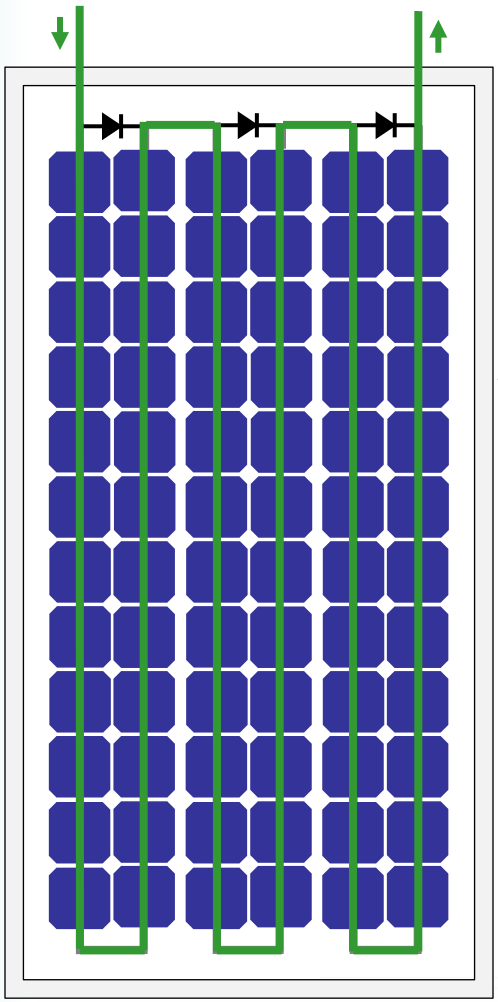
Bypass Diodes
Basic operation



- In conventional grid-tie PV modules, all of the PV cells are connected in series. This means an obstructed cell becomes a bottleneck to the flow of current.
- Without bypass diodes, the obstructed cell is forced into reverse voltage breakdown in order to pass the same high current of the rest of the module and string. This combination of high current and high reverse voltage (typically 15V or more) dissipates high power in the obstructed cell.
- As shown in this graphic, the bypass diode spans a group of cells (a 'cell group'). The bypass diode prevents the cell from seeing a large enough reverse voltage to drive it into reverse breakdown operation and overheat it.

Bypass Diodes

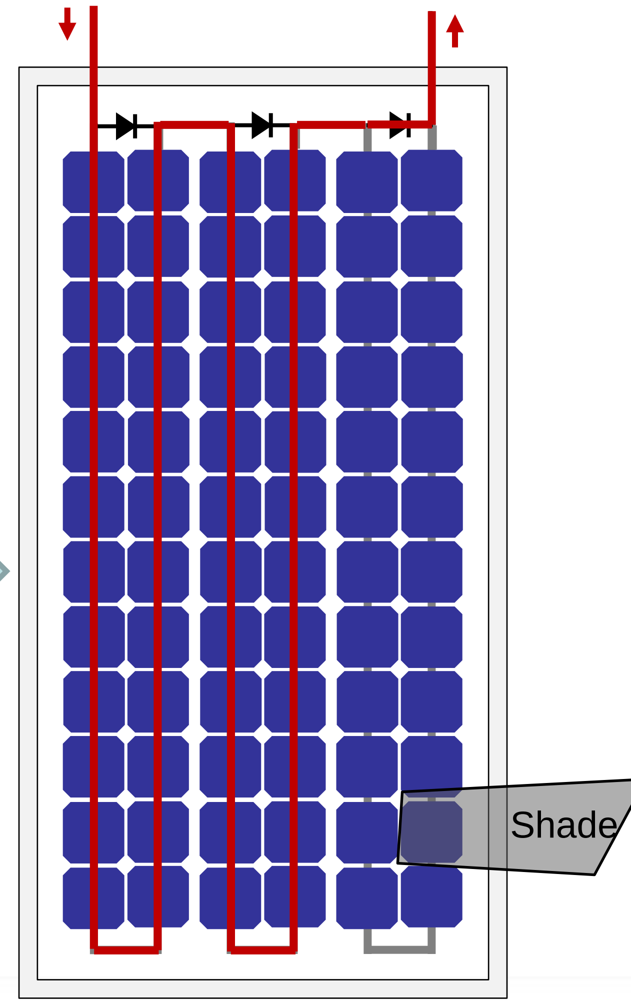
Basic operation in response to shade



Here we have a typical 72-cell PV module with 3 bypass diodes. The cells are series connected in a vertical serpentine pattern.

If none of the cells is shaded, the current flows as shown by the green path. The bypass diodes do not conduct current.

If a cell is shaded, the bypass diode protecting its cell group turns on, allowing string current to bypass that cell group. This prevents damage to the shaded cell and allows the other cell groups to produce more energy.



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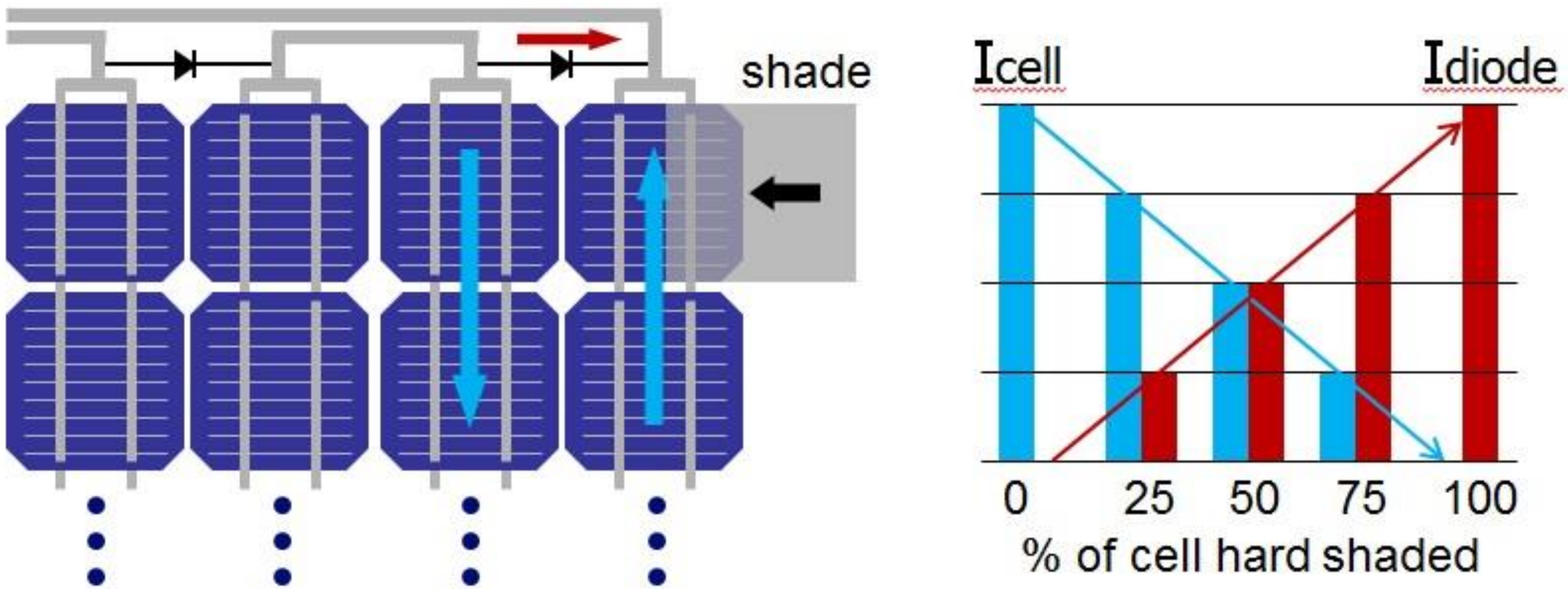
Bypass Diodes
Basic operation



- The amount of current that flows through the bypass diode depends on the percentage of its light is blocked, relative to other cells.
- Gradually covering one cell with a piece of cardboard causes current to divert from the cell group to the bypass diode. The shift in current is proportional to the percentage of the cell that is obstructed.

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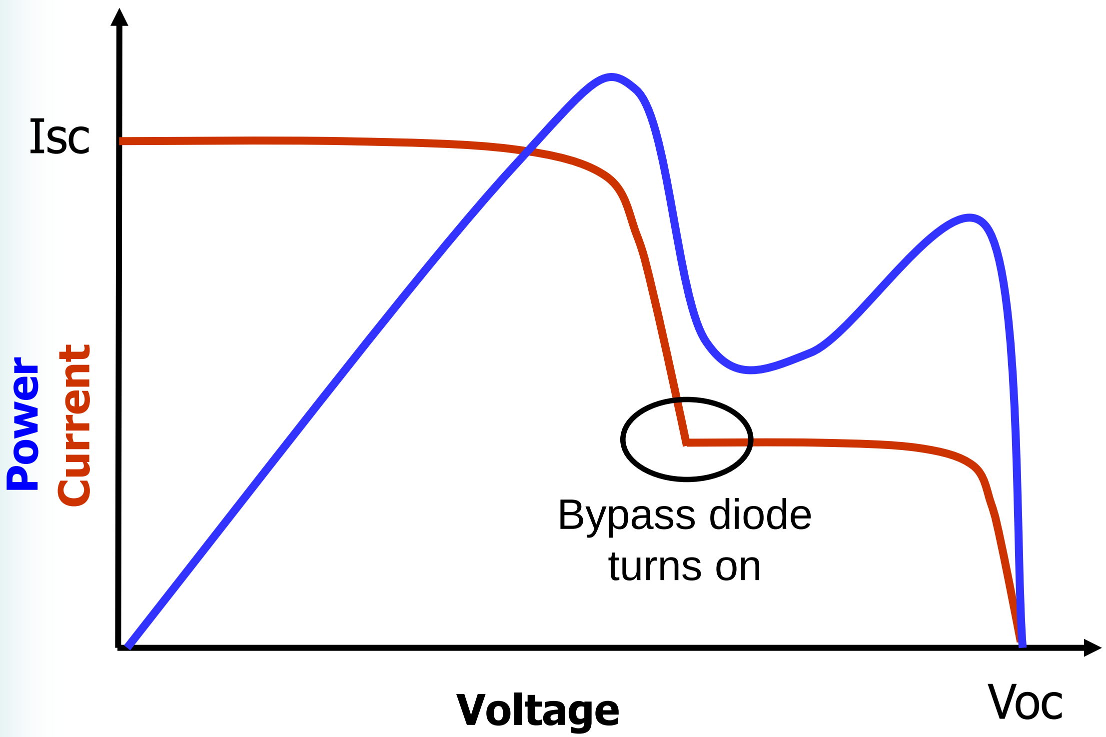
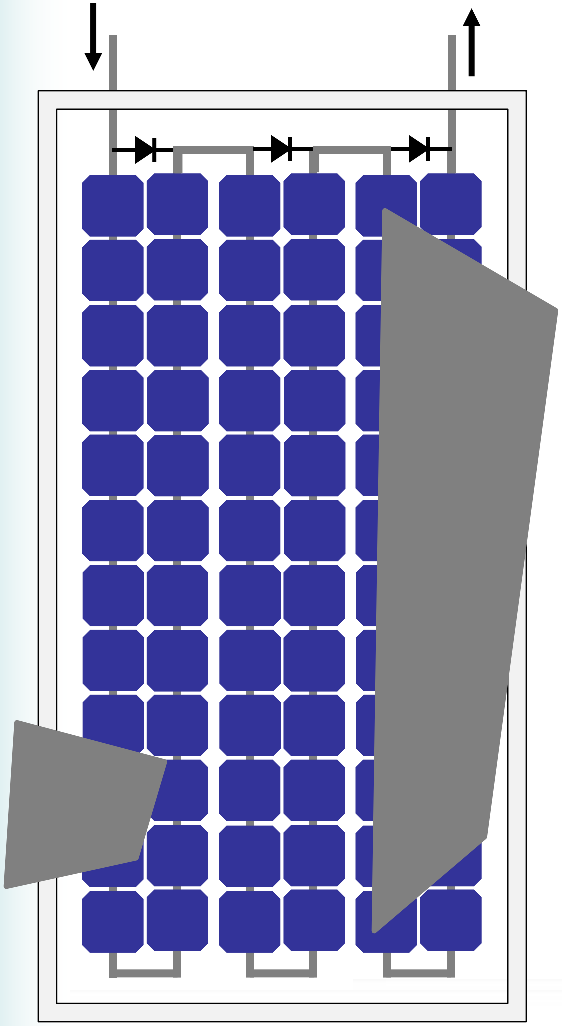
Bypass Diodes
Basic operation



- Current mismatch from shade or other causes creates steps in the I-V curve. The more the cell is blocked, the lower the current at the step.
- The 'corner' of the step is the point at which the bypass diode turns on, protecting that obstructed cell and allowing the current to rise to the level of the unobstructed cells.
- In real life, often multiple cell groups in the same PV string are current mismatched (shade, non-uniform soiling or debris). This results in multiple steps in the I-V curve, and sometimes it is not so obvious that there are distinct steps.

Bypass Diodes

Basic operation

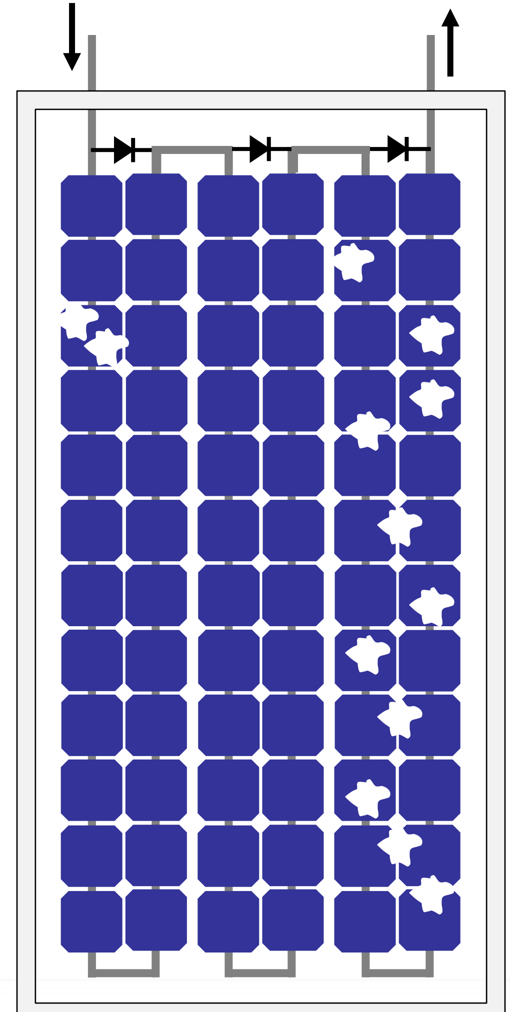


The current level at which a bypass diode turns on is determined by *the most obstructed cell* in it's cell group*.

In the left-hand example, which shading pattern causes the greatest loss of performance? Answer: They both cover at least one cell, so they force their bypass diodes ON and performance suffers by about the same amount for each.

In the right-hand example the outcome is not so obvious. The right-hand cell group has a lot more total obstruction, but in fact the left hand cell group is more current limited because the cell is more completely obstructed.

* Since cells are not perfect, some current will still flow even if a cell is hard shaded. But hard shading two or more cells typically forces all the current to flow through the bypass diode. This is useful to know when you are troubleshooting using the selective shading method, discussed later.



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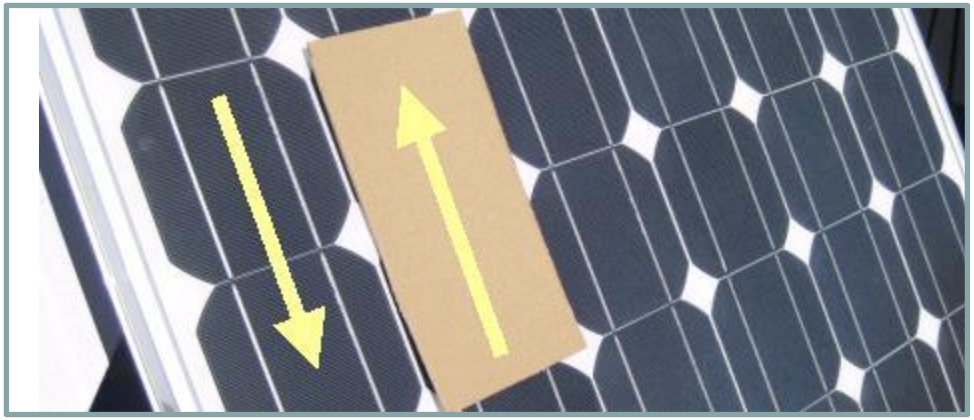
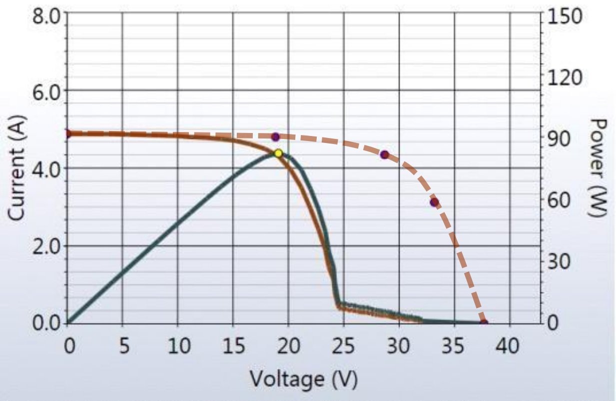
Bypass Diodes

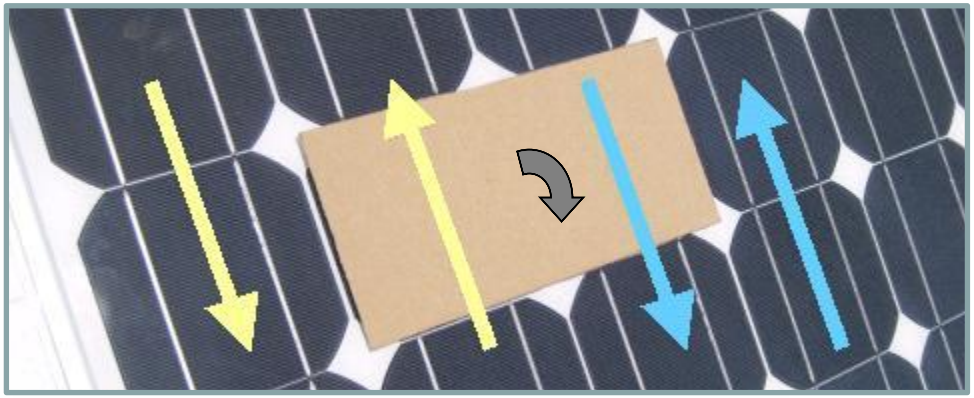
Basic operation

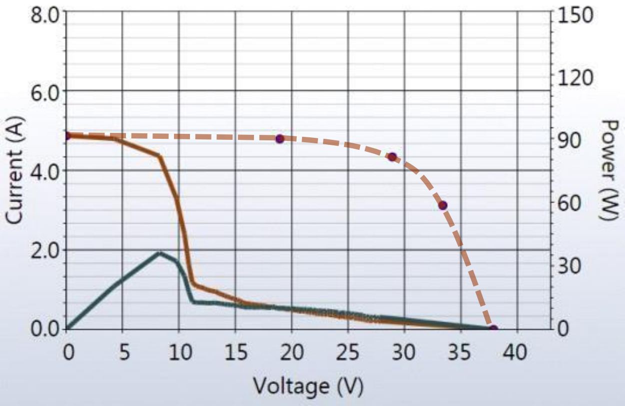
The impact of shade can depend more on where the shade lands, than on the area of the shade





One cell string bypassed *





Two cell strings bypassed *

* 72 cell module, 3 bypass diodes

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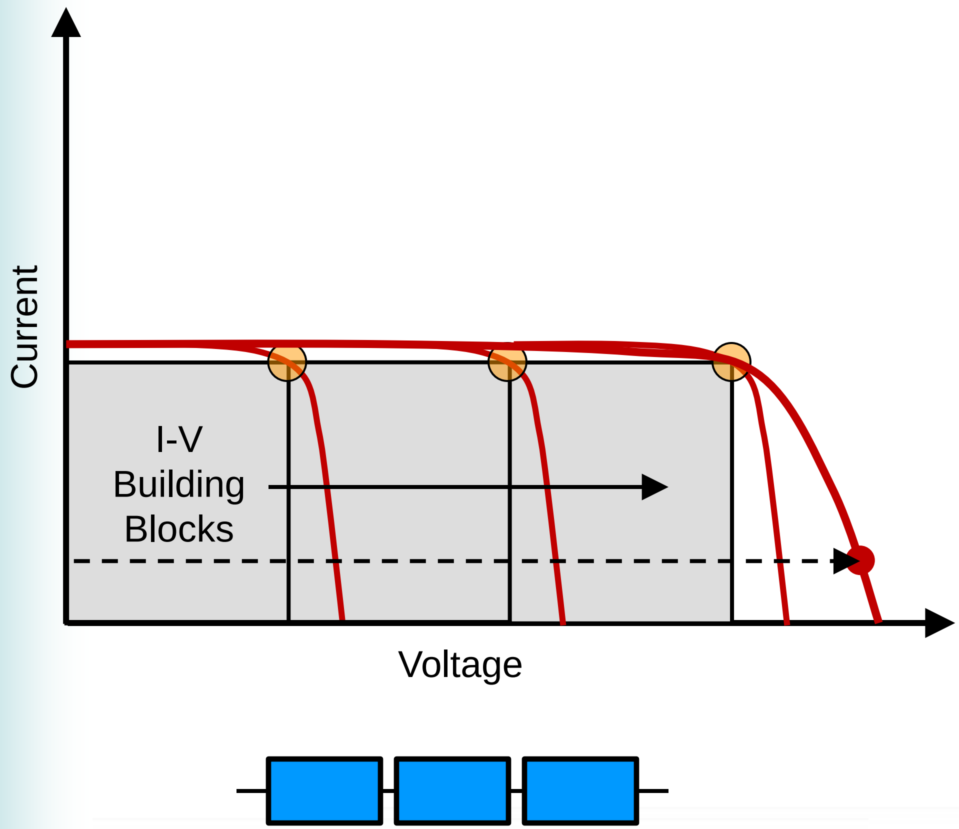
Connecting Modules in Series

Add voltages at each level of current



- Modules are connected in ‘strings’ to provide the higher DC voltage required by string inverters.
- The string I-V curve can be drawn by adding the module voltages at each level of current (example: dashed line).
- The string has the same short circuit current as the modules, assuming identical modules.
- The location of an individual I-V curve ‘building block’ does not correspond to the location of a particular module within the string. For example, if we short circuit any of the modules, the right-hand building block disappears.

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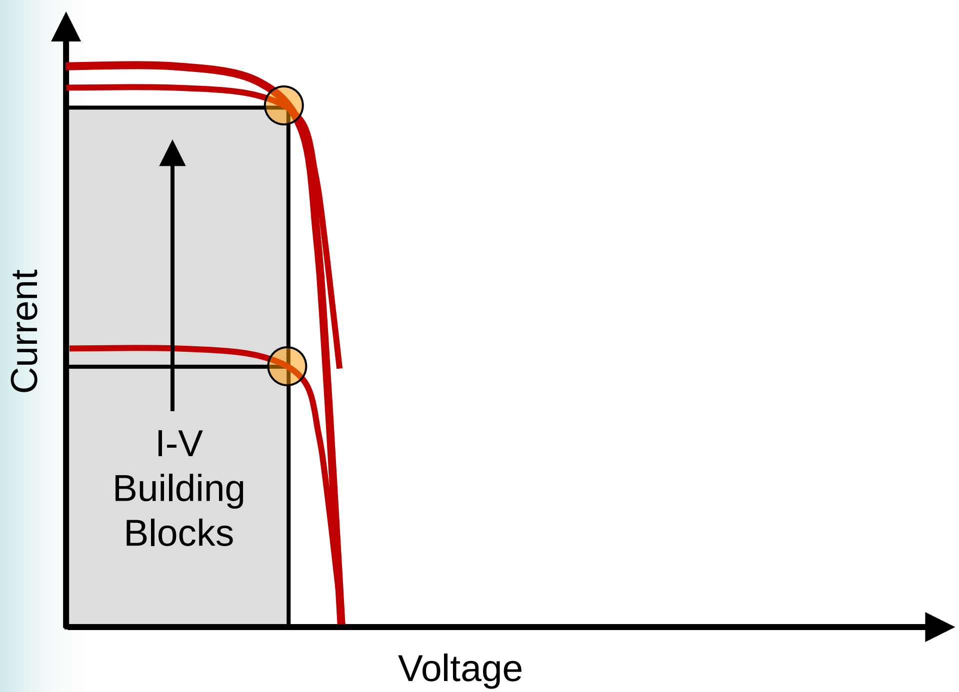
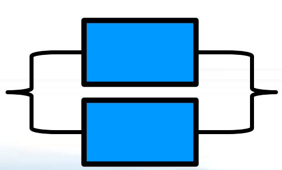
Connecting Modules in Parallel

Add currents at each level of voltage

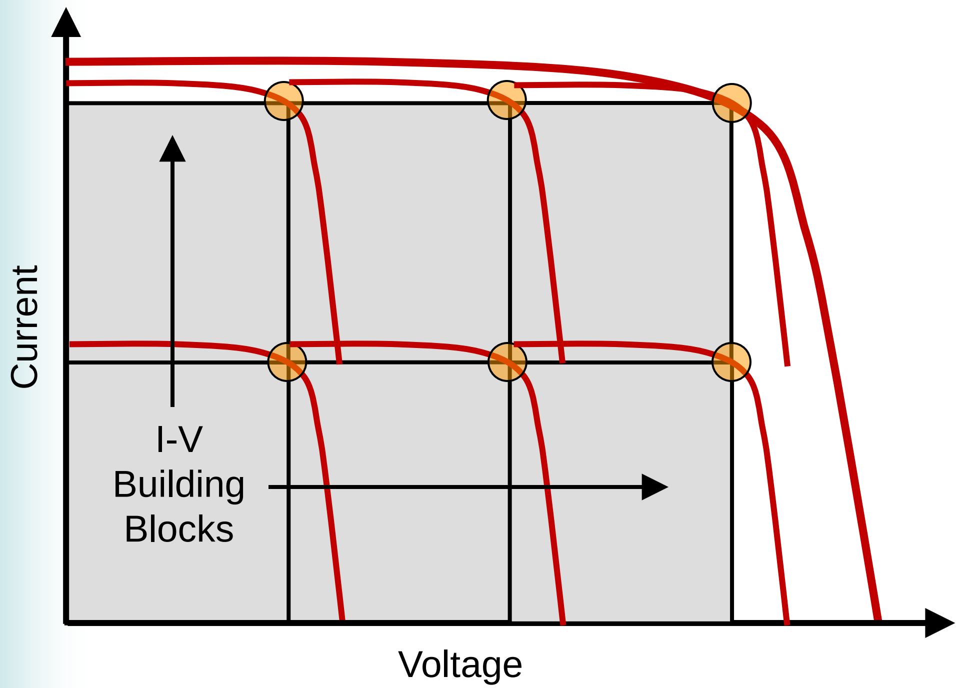


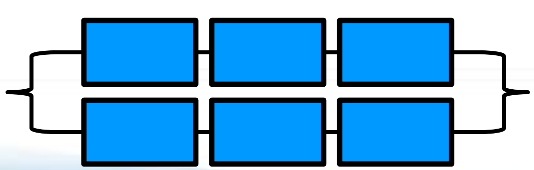


- Modules are connected in parallel to provide more DC current.
- The total I-V curve can be drawn by adding the currents of the PV modules, at each value of voltage.
- The parallel combination has the same open circuit voltage string has the modules, assuming identical modules.
- The location of an individual I-V curve 'building block' does not correspond to the location of a particular module within the parallel combination. For example, if we remove either module from the combination, the top building block disappears.

Building Sub-arrays

Series and parallel connections

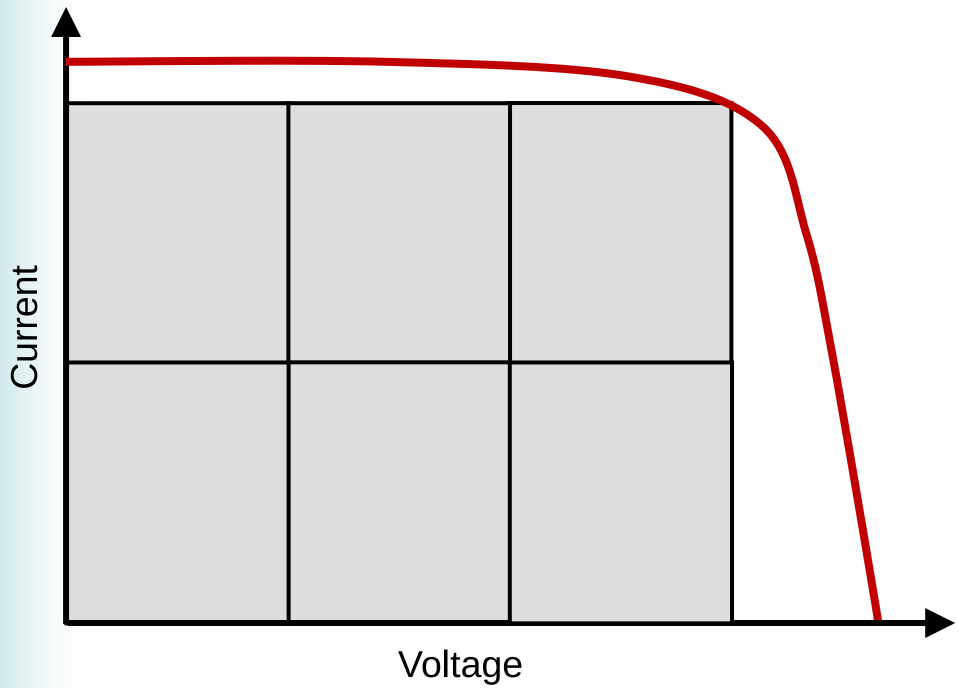


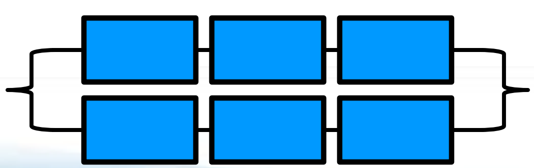


- Modules are commonly connected in series and parallel, to achieve greater economy of electrical interconnection and to take best advantage of the current, voltage, and power capabilities of the inverter.
- As with the earlier examples, the location of the I-V curve building blocks in this graph does not correspond to the location of actual modules in the array. For example, if we short circuit one of the modules anywhere in the array, we lose the upper right building block and the total I-V curve will have a step in its place. Later we will see that a step in the I-V curve is an important clue to the possible causes of PV array underperformance.

Array With Shorted Module

Step 1: Starting point, no short

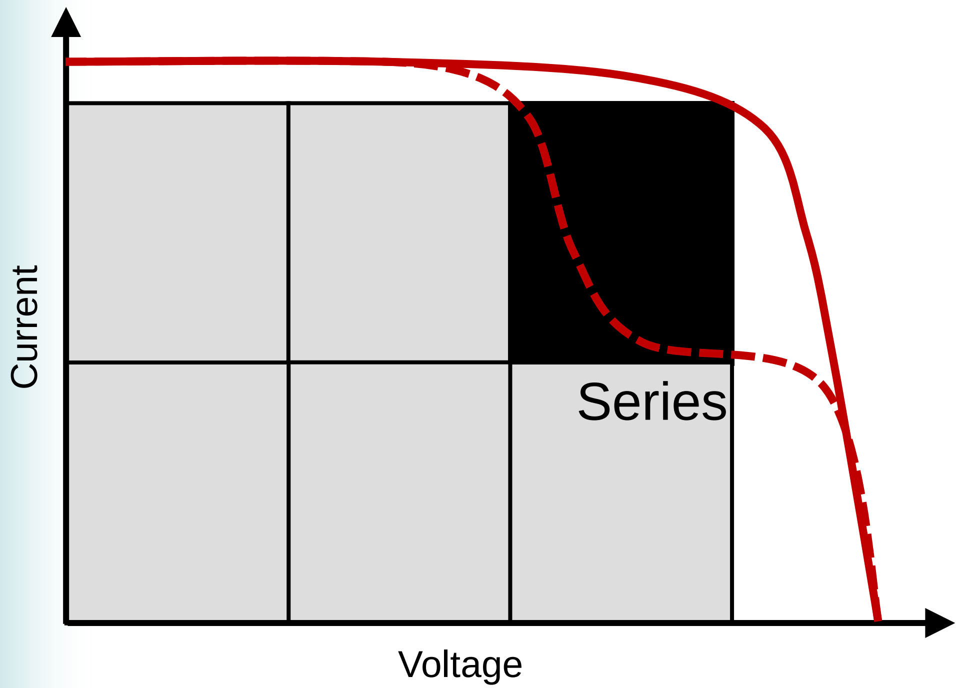


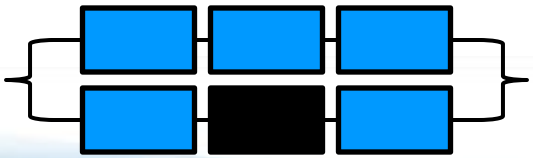


- As with the earlier examples, the location of the I-V curve building blocks in this graph does not correspond to the location of actual modules in the array.
- For example, let's electrically short out the bottom center PV module, which is equivalent to replacing it with a wire. Which building block will that remove in the I-V curve diagram, and what is the shape of the resulting total I-V curve?

Array With Shorted Module

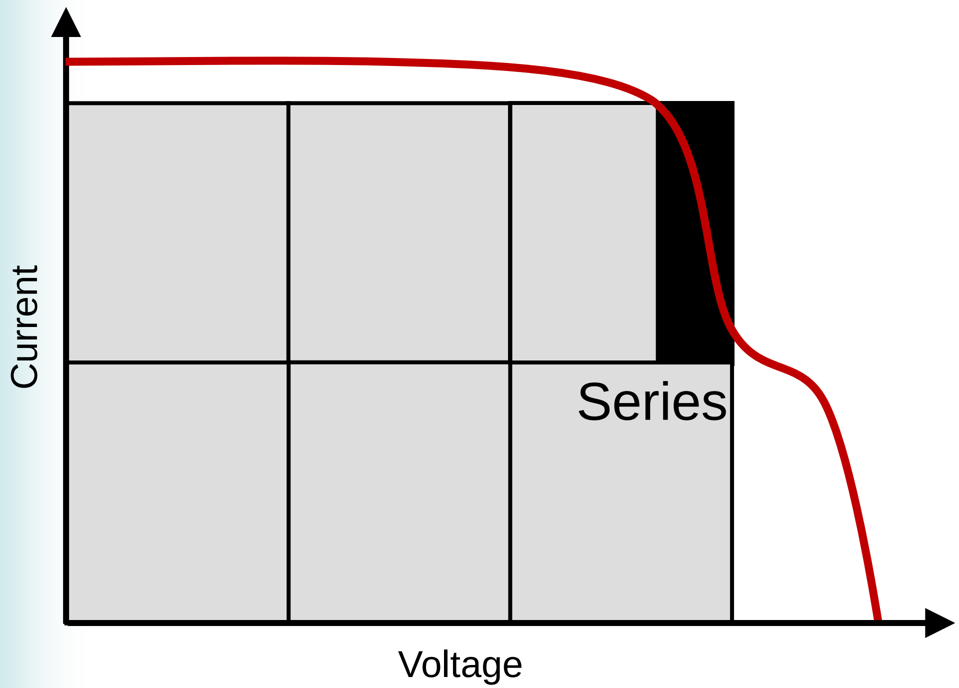
Step 2: Drop out a module

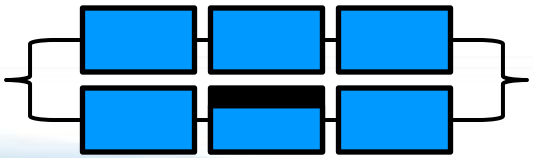




- Sometimes one of the strings in a subarray is missing a module, or one or more cell groups is bypassed by a fully conducting bypass diode.
- In this example, let's assume that a module is missing.
- The result is a step in the I-V curve of the array.
- The step always occurs at the upper right area of the I-V curve. This does not mean that the upper right module in the array is missing! The location of the step in the curve is a consequence of the fact that in an array, series-connecting modules increases voltage and parallel-connecting modules increases current.

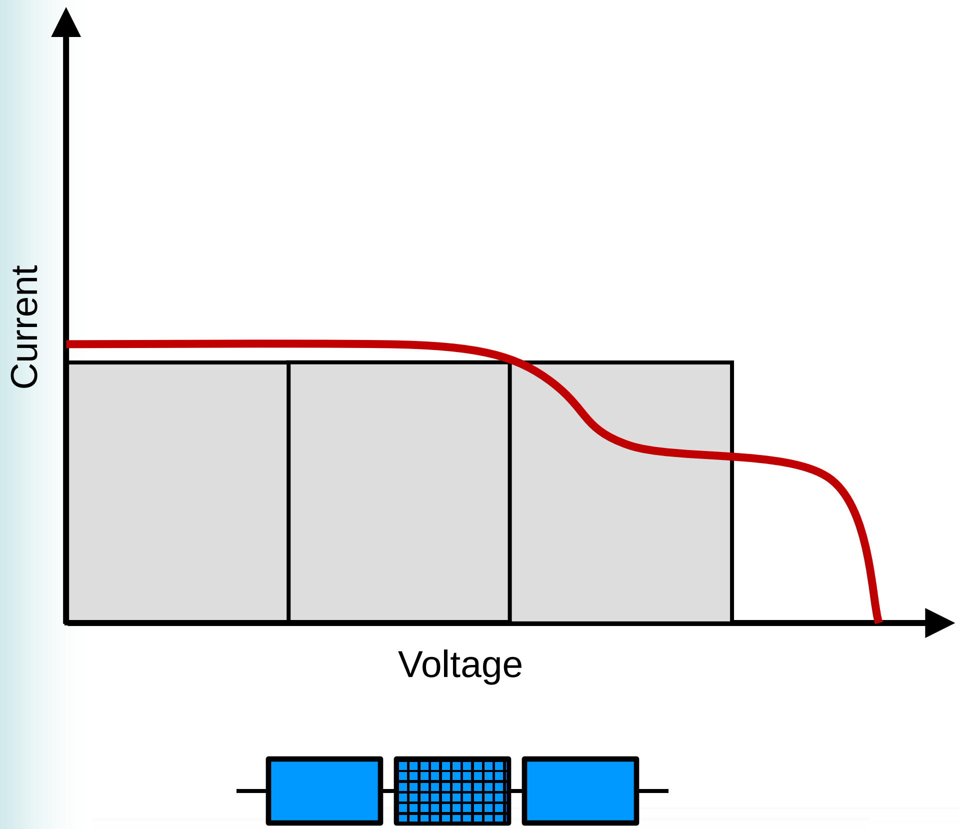
Array With Shorted Cell String





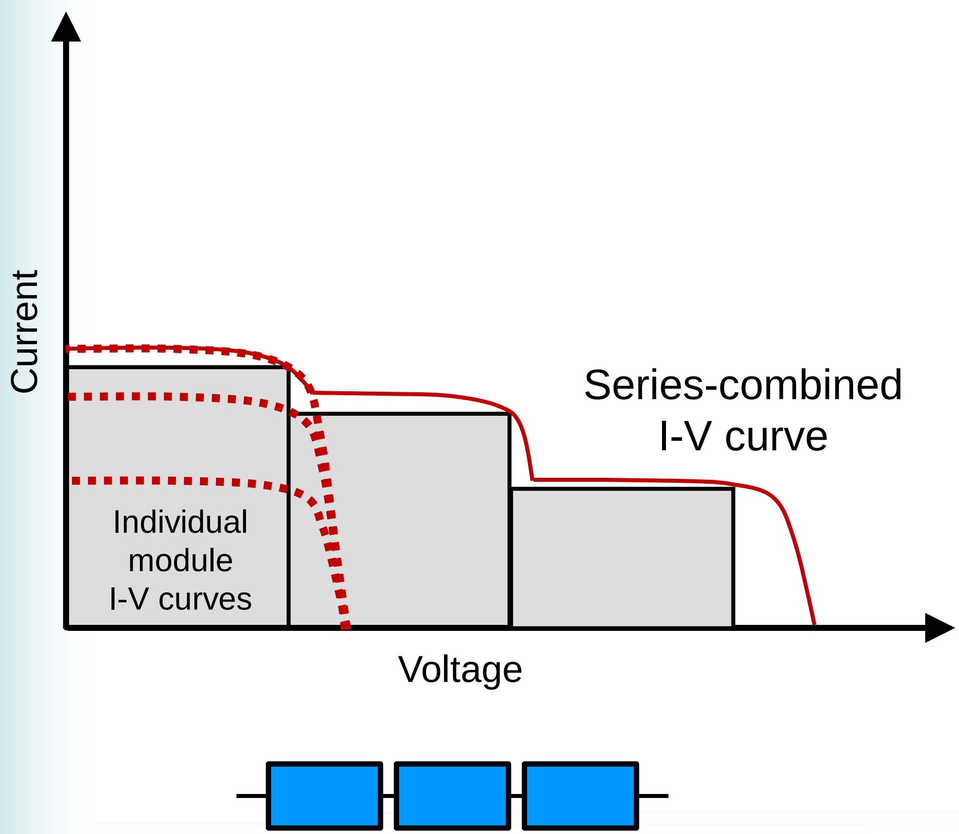
- We also see steps when we bypass or short out a cell string.
- As with the missing module, we can't tell from the I-V curve which cell string in which module is bypassed. (However, this can be determined using the selective shading troubleshooting method, which we'll discuss later).

Shaded Module



- In a single string, shorting a module results in a normal I-V curve with an open circuit voltage that is lower by one module. But what happens if we shade a module?
- Bypass diodes turn on after the string current rises to the limit of what the shaded cells can generate.
- In this example, we shade one entire module with 33% shade cloth, reducing the irradiance to 2/3 of the level seen by the rest of the array.
- The I-V curve for this shading configuration shows a step in the neighborhood of the knee of the curve regardless of the location of the shaded module. The height of the step is 2/3 the short circuit current of the non-shaded modules.

Mismatched Modules



- In this example, each of three modules in a string has a slightly different value of short circuit current Isc. What does the string I-V curve look like?
- The resulting curve can be estimated graphically by plotting the individual module I-V curves (dotted red, at left), and then adding their voltages. In other words, at each level of current, add the associated voltages of each of the three curves.
- Note that each step in Isc from one module to the next produces a notch in the I-V curve, where the bypass diodes turn on.
- The steps also each produce a local knee if the I-V curve, which in turn will cause a local peak in the P-V curve.

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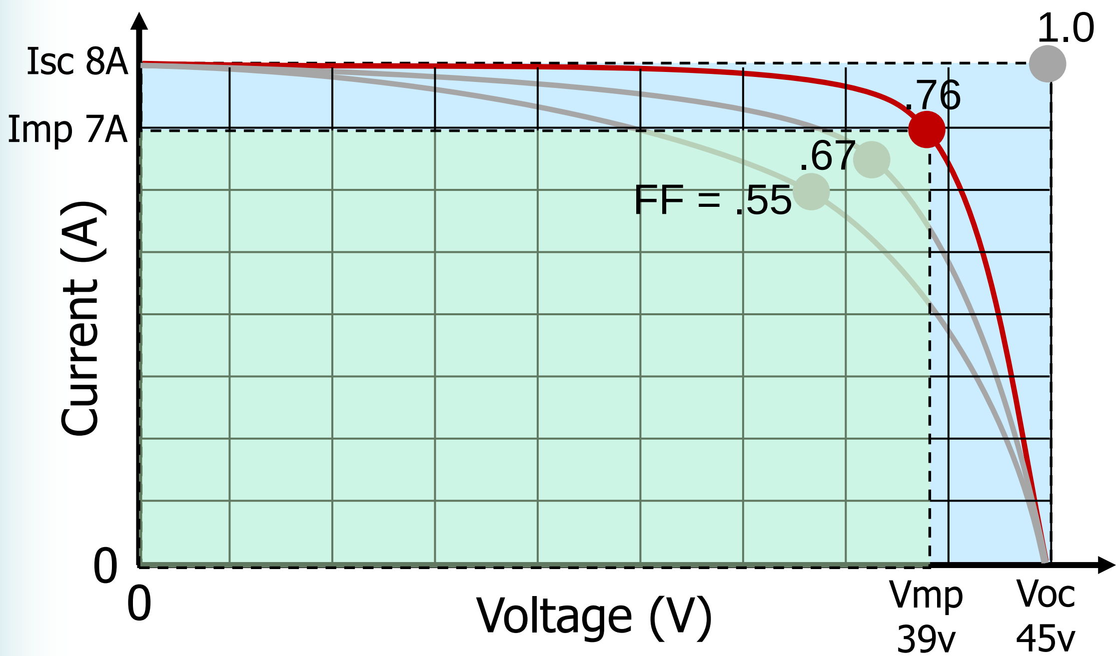
Fill Factor

Key metric for comparing I-V curve shapes



$$\text{Fill Factor} = \frac{\text{Imp x Vmp (watts)}}{\text{Isc x Voc (watts)}}$$

For the red curve: $FF = \frac{7A \times 39V}{8A \times 45V} = 0.76$

- Fill factor is a measure of the square-ness of the I-V curve. A squarer curve (less rounded) means higher output power (and higher module efficiency).
- At high irradiance, the value of the fill factor is not strongly influenced by irradiance, making it a great metric for comparing string shapes.
- Fill factor is determined entirely by the measured values of Imp, Vmp, Isc, and Voc (see equations). No PV model is required.
- Fill factor is easy to understand graphically. Just divide the area of the green rectangle (defined by the max power point) by the area of the blue rectangle (defined by Isc and Voc).

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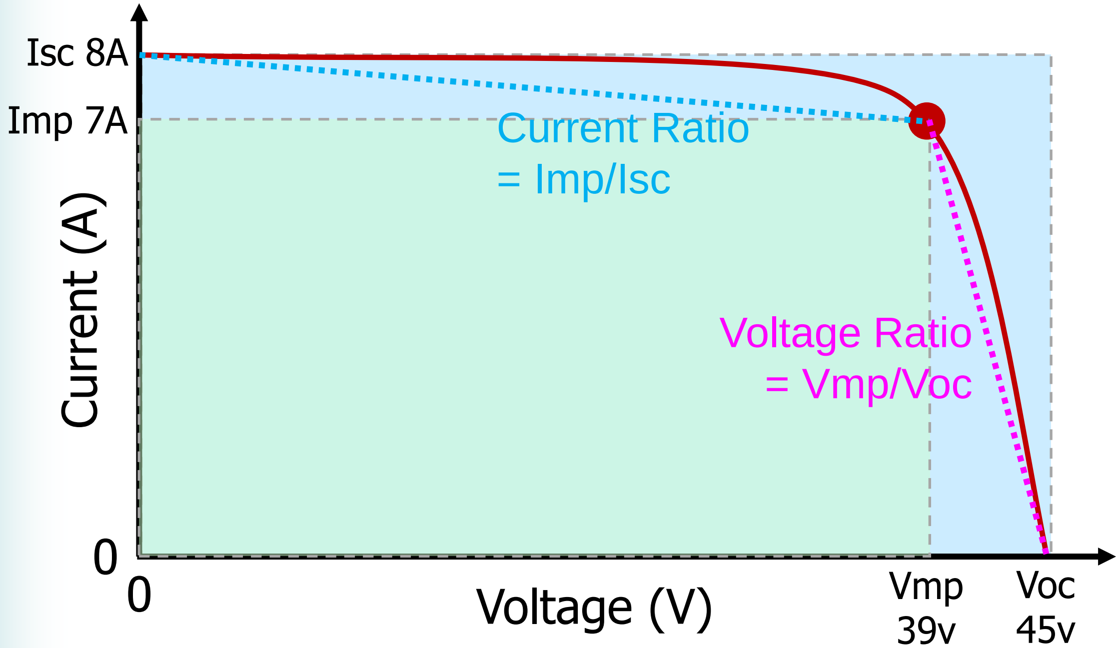
Voltage Ratio and Current Ratio

Indicators of slope differences



$$\text{Fill Factor} = \frac{\text{Imp} \times \text{Vmp}}{\text{Isc} \times \text{Voc}}$$

For the red curve:
Current Ratio = 7A/8A = .875
Voltage Ratio = 39V/45V = .867

- If a string or module has a low fill factor compared with the population, and there are no steps in the curve, the current and voltage ratios are clues that can help you troubleshoot the problem.
- The ratios are actually embedded in the equation for fill factor. They are a very rough approximation of the slopes of the horizontal and vertical legs of the curve.
- Although they are only approximate, they are good indicators of slope differences between strings.
- Example: If there are no steps in the curve, low voltage ratio may indicate excess electrical resistance somewhere in the circuit.

Topics

- Introduction to the PVA-1000S PV Analyzer
- Using the software
- Making I-V curve measurements
- Measuring irradiance & temperature
- PV fundamentals for troubleshooting
- Troubleshooting PV arrays
- Using the I-V Data Analysis Tool (DAT)

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Determining Actual Performance

Unclouding the picture

Shading
- Vegetation
- Buildings
- Rooftop equipment
- Other PV modules

Weather
- Low irradiance
- Unstable irradiance
- Wind

Actual Array Performance (goal)

Hmm…

Soiling & Debris
- Uniform soiling
- Dirt dams
- Leaves & branches
- Frisbees

Measurement Issues
- Irradiance sensor not in POA
- Thermocouple not attached
- Thermocouple location
- Resistive losses

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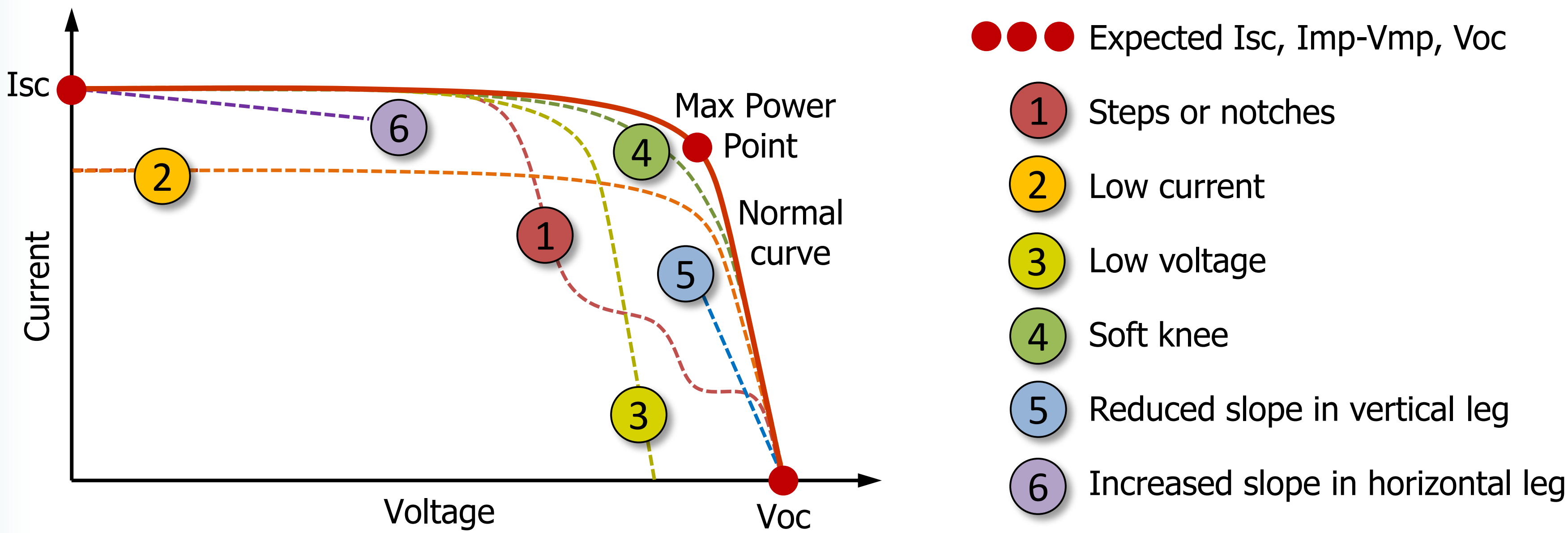
Types of I-V Curve Deviations

From normal, expected shape



- Each of the six deviations has multiple causes.
- Classifying the deviations by shape narrows the causes and speeds troubleshooting (see the *Solmetric PV Array Troubleshooting Flowchart*)
- Earlier measurement methods miss much of this information.

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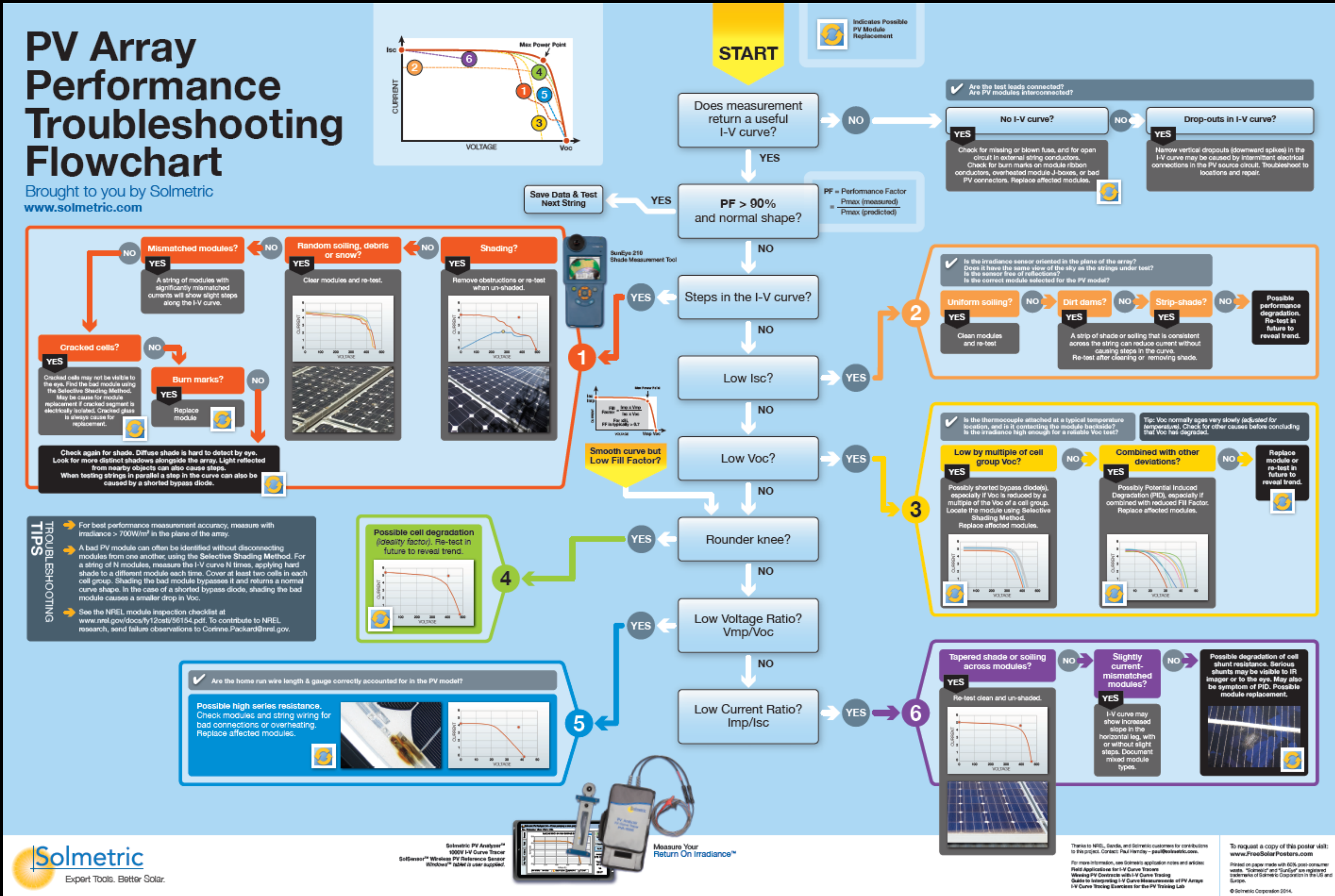

PV Array Performance Troubleshooting Flowchart
Brought to you by Solmetric
www.solmetric.com
Isc
Max Power Point
CURRENT
VOLTAGE
Voc
START
Indicates Possible PV Module Replacement
Does measurement return a useful I-V curve?
NO
YES
Are the test leads connected? Are PV modules interconnected?
No I-V curve?
YES
Check for missing or blown fuse, and for open circuit in external string conductors. Check for burn marks on module ribbon conductors, overheated module J-boxes, or bad PV connectors. Replace affected modules.
NO
Drop-outs in I-V curve?
YES
Narrow vertical dropouts (downward spikes) in the I-V curve may be caused by intermittent electrical connections in the PV source circuit. Troubleshoot to locations and repair.
Save Data & Test Next String
YES
PF > 90% and normal shape?
PF = Performance Factor = Pmax (measured) / Pmax (predicted)
NO
Steps in the I-V curve?
YES
SunEye 210 Shade Measurement Tool
1
Shading?
YES
Remove obstructions or re-test when un-shaded.
NO
Random soiling, debris or snow?
YES
Clear modules and re-test.
NO
Mismatched modules?
YES
A string of modules with significantly mismatched currents will show slight steps along the I-V curve.
NO
Cracked cells?
YES
Cracked cells may not be visible to the eye. Find the bad module using the Selective Shading Method. May be cause for module replacement if cracked segment is electrically isolated. Cracked glass is always cause for replacement.
NO
Burn marks?
YES
Replace module
NO
Check again for shade. Diffuse shade is hard to detect by eye. Look for more distinct shadows alongside the array. Light reflected from nearby objects can also cause steps. When testing strings in parallel a step in the curve can also be caused by a shorted bypass diode.
NO
Low Isc?
YES
2
Is the irradiance sensor oriented in the plane of the array? Does it have the same view of the sky as the strings under test? Is the sensor free of reflections? Is the correct module selected for the PV model?
Uniform soiling?
YES
Clean modules and re-test
NO
Dirt dams?
YES
NO
Strip-shade?
YES
A strip of shade or soiling that is consistent across the string can reduce current without causing steps in the curve. Re-test after cleaning or removing shade.
NO
Possible performance degradation. Re-test in future to reveal trend.
NO
Low Voc?
YES
3
Is the thermocouple attached at a typical temperature location, and is it contacting the module backside? Is the irradiance high enough for a reliable Voc test?
Tip: Voc normally ages very slowly (adjusted for temperature). Check for other causes before concluding that Voc has degraded.
Low by multiple of cell group Voc?
YES
Possibly shorted bypass diode(s), especially if Voc is reduced by a multiple of the Voc of a cell group. Locate the module using Selective Shading Method. Replace affected modules.
NO
Combined with other deviations?
YES
Possibly Potential Induced Degradation (PID), especially if combined with reduced Fill Factor. Replace affected modules.
NO
Replace module or re-test in future to reveal trend.
Smooth curve but Low Fill Factor?
Fill Factor = Imp x Vmp / Isc x Voc
NO
Rounder knee?
YES
4
Possible cell degradation (ideality factor). Re-test in future to reveal trend.
NO
Low Voltage Ratio? Vmp/Voc
YES
5
Are the home run wire length & gauge correctly accounted for in the PV model?
Possible high series resistance. Check modules and string wiring for bad connections or overheating. Replace affected modules.
NO
Low Current Ratio? Imp/Isc
YES
6
Tapered shade or soiling across modules?
YES
Re-test clean and un-shaded.
NO
Slightly current-mismatched modules?
YES
I-V curve may show increased slope in the horizontal leg, with or without slight steps. Document mixed module types.
NO
Possible degradation of cell shunt resistance. Serious shunts may be visible to IR imager or to the eye. May also be symptom of PID. Possible module replacement.
TROUBLESHOOTING TIPS
For best performance measurement accuracy, measure with irradiance > 700W/m² in the plane of the array.
A bad PV module can often be identified without disconnecting modules from one another, using the Selective Shading Method. For a string of N modules, measure the I-V curve N times, applying hard shade to a different module each time. Cover at least two cells in each cell group. Shading the bad module bypasses it and returns a normal curve shape. In the case of a shorted bypass diode, shading the bad module causes a smaller drop in Voc.
See the NREL module inspection checklist at www.nrel.gov/docs/fy12osti/56154.pdf. To contribute to NREL research, send failure observations to Corinne.Packard@nrel.gov.
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Expert Tools. Better Solar.
Solmetric PV Analyzer™
1000V I-V Curve Tracer
SolSensor™ Wireless PV Reference Sensor
Windows™ tablet is user supplied.
Measure Your
Return On Irradiance™
Thanks to NREL, Sandia, and Solmetric customers for contributions to this project. Contact: Paul Hernday – paul@solmetric.com.
For more information, see Solmetric application notes and articles:
Field Applications for I-V Curve Tracers
Winning PV Contracts with I-V Curve Tracing
Guide to Interpreting I-V Curve Measurements of PV Arrays
I-V Curve Tracing Exercises for the PV Training Lab
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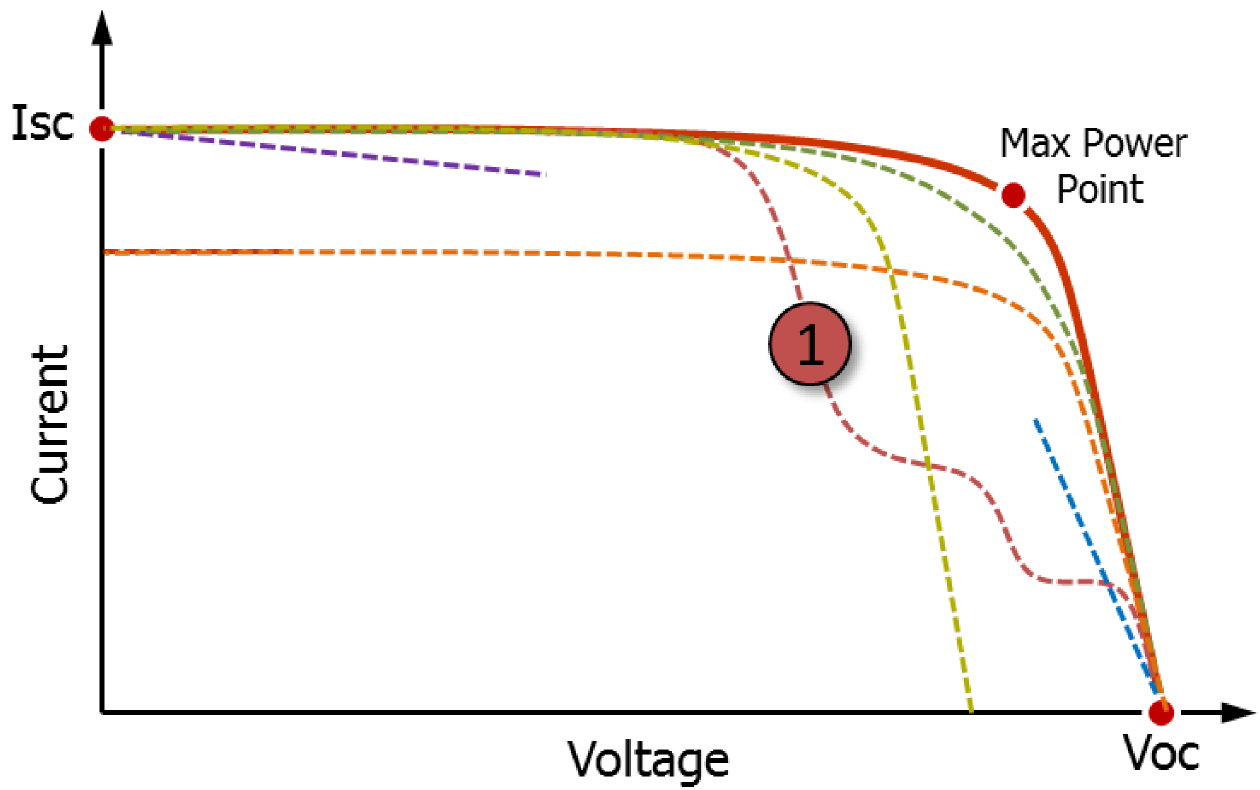
1 Steps in the I-V Curve



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① Steps in the I-V Curve
Possible causes

External performance factors

1. Shade
2. Non-uniform soiling
3. Reflected light illuminating only part of the string under test

Measurement technique

- None

Module performance

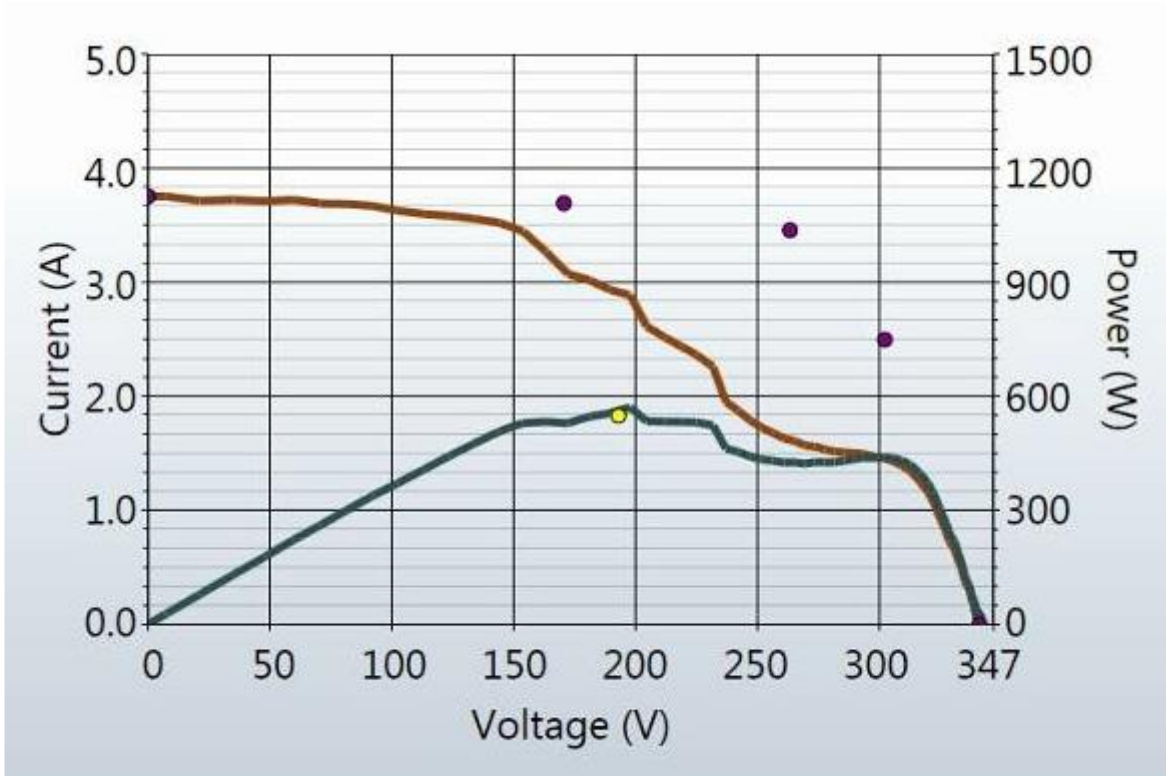
1. Shorted bypass diode (when measuring multiple strings in parallel)
2. Mix of different module current specs within the same string

1 Steps in the I-V curve

Example: scattered tree shade

1 Steps in the I-V curve

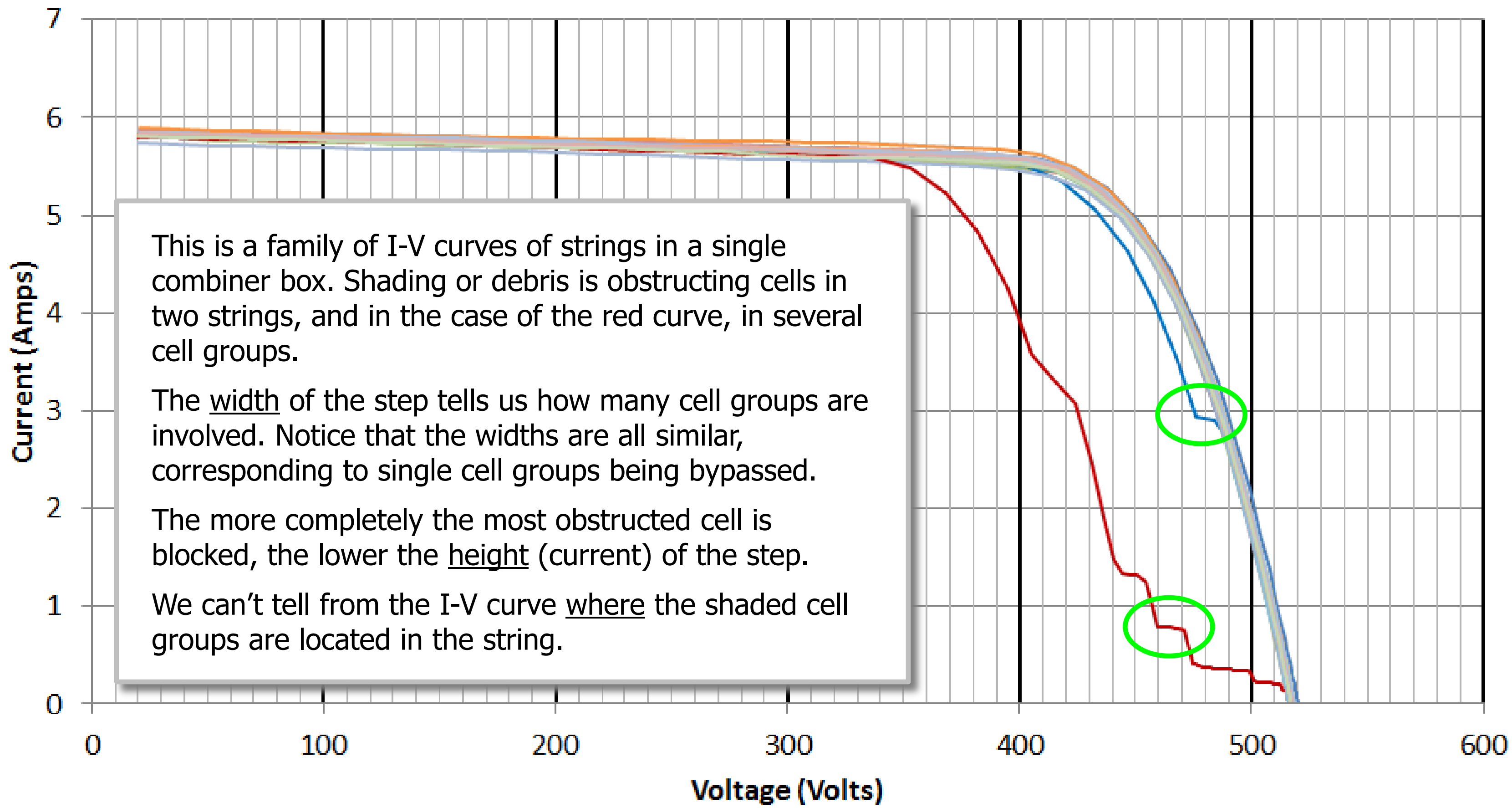
Example: scattered tree shade



Approximately 40% reduction in string's output power

1 Steps in the I-V Curve

Random narrow steps



This is a family of I-V curves of strings in a single combiner box. Shading or debris is obstructing cells in two strings, and in the case of the red curve, in several cell groups.

The width of the step tells us how many cell groups are involved. Notice that the widths are all similar, corresponding to single cell groups being bypassed.

The more completely the most obstructed cell is blocked, the lower the height (current) of the step.

We can't tell from the I-V curve where the shaded cell groups are located in the string.

Record the string ID (for example i3c4s7) for the punch list and/or report.

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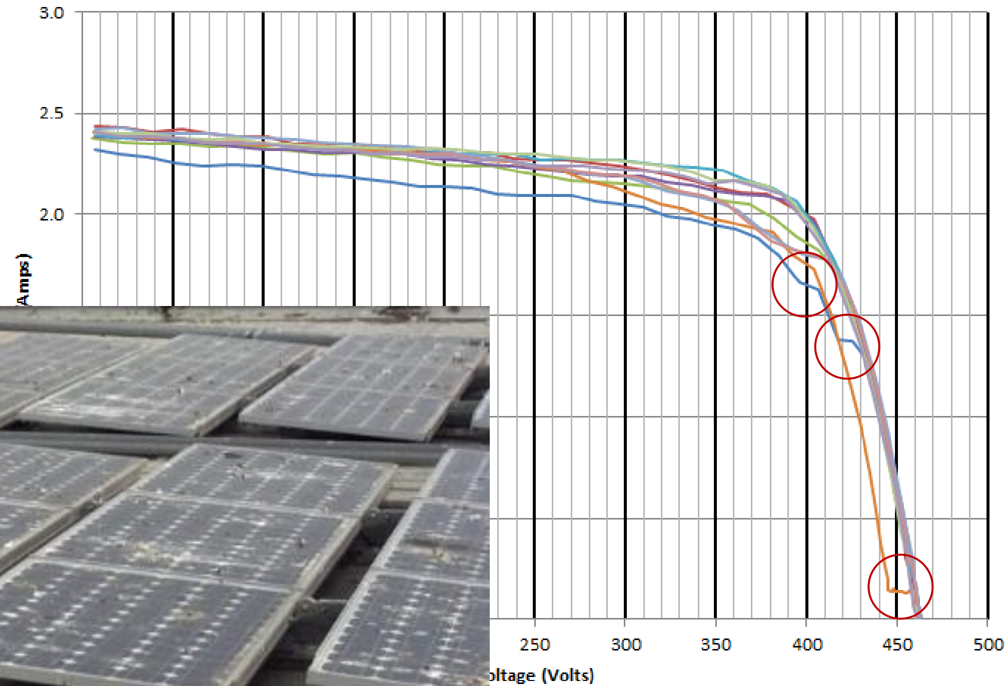
1 Steps in the I-V Curve

Example: seagull soiling

- Seagulls have bombed this array.
- The more completely the most obstructed cell is blocked, the lower the height (current) of the step.



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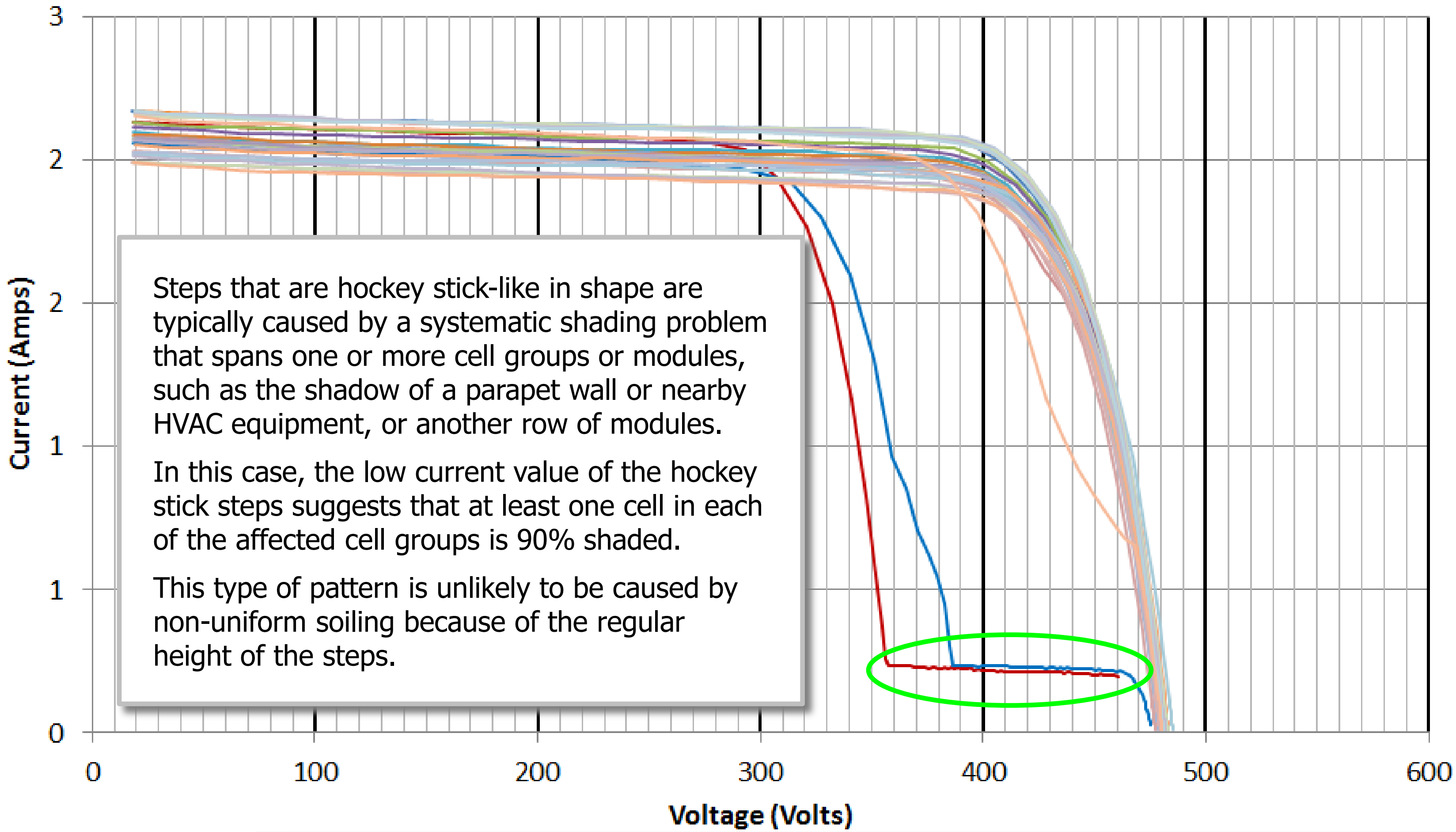
1 Steps in the I-V Curve

'Hocky stick' shade signature



Steps that are hockey stick-like in shape are typically caused by a systematic shading problem that spans one or more cell groups or modules, such as the shadow of a parapet wall or nearby HVAC equipment, or another row of modules.

In this case, the low current value of the hockey stick steps suggests that at least one cell in each of the affected cell groups is 90% shaded.

This type of pattern is unlikely to be caused by non-uniform soiling because of the regular height of the steps.

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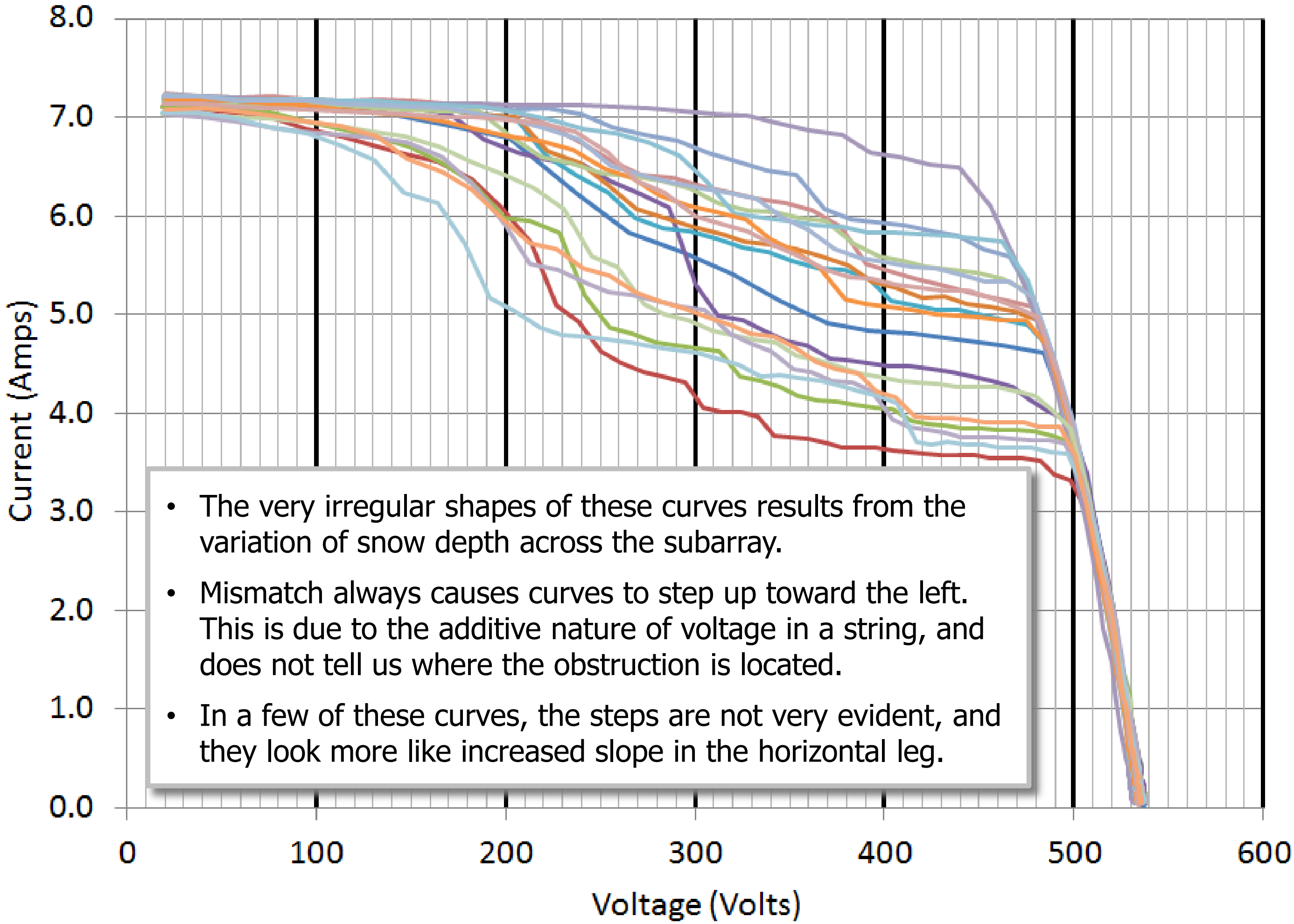
❶ Steps in the I-V Curve

Example: Light, variable snow cover



- The very irregular shapes of these curves results from the variation of snow depth across the subarray.
- Mismatch always causes curves to step up toward the left. This is due to the additive nature of voltage in a string, and does not tell us where the obstruction is located.
- In a few of these curves, the steps are not very evident, and they look more like increased slope in the horizontal leg.

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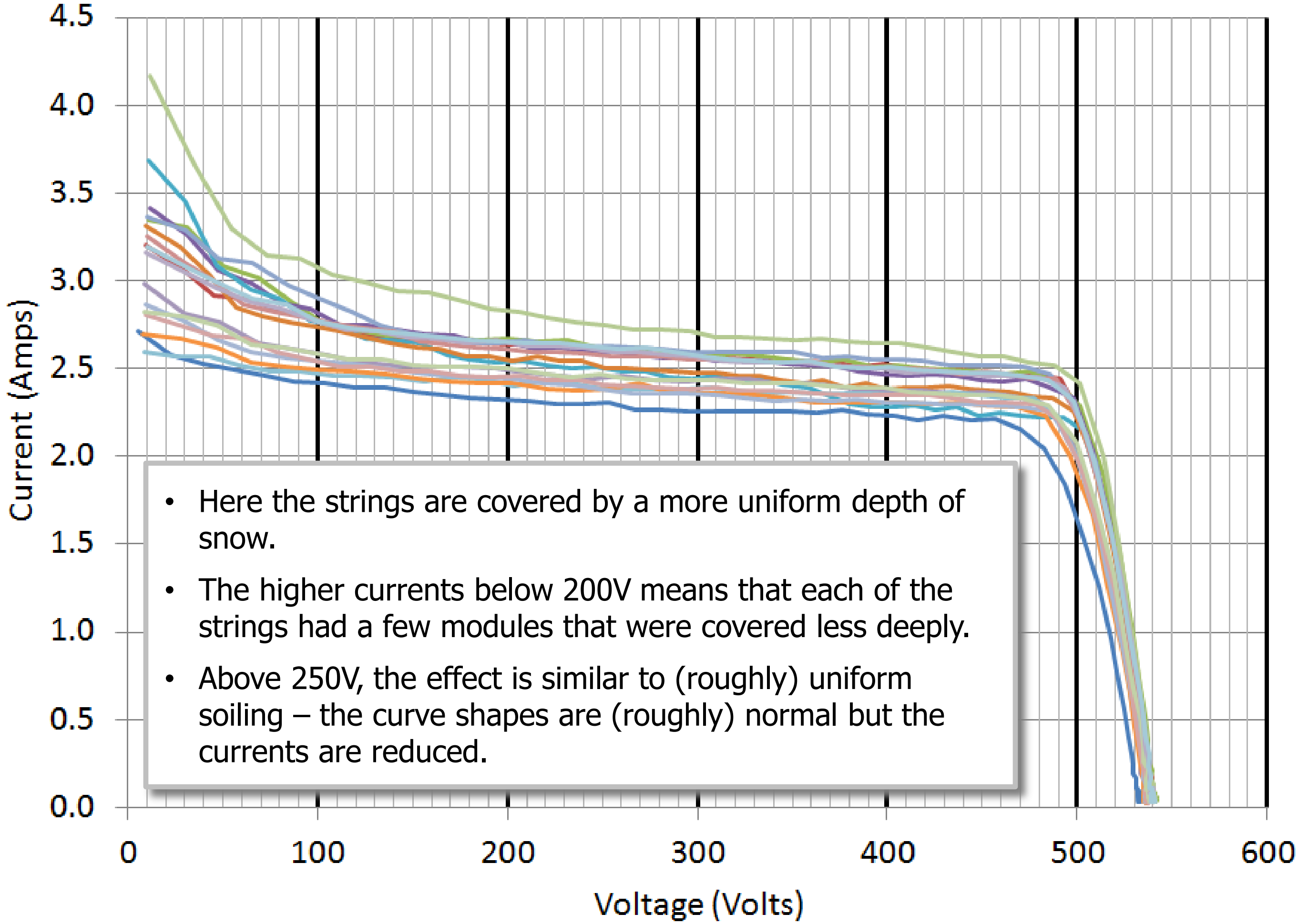
1 Steps in the I-V Curve

Example: Heavier, more consistent snow cover



- Here the strings are covered by a more uniform depth of snow.
- The higher currents below 200V means that each of the strings had a few modules that were covered less deeply.
- Above 250V, the effect is similar to (roughly) uniform soiling – the curve shapes are (roughly) normal but the currents are reduced.

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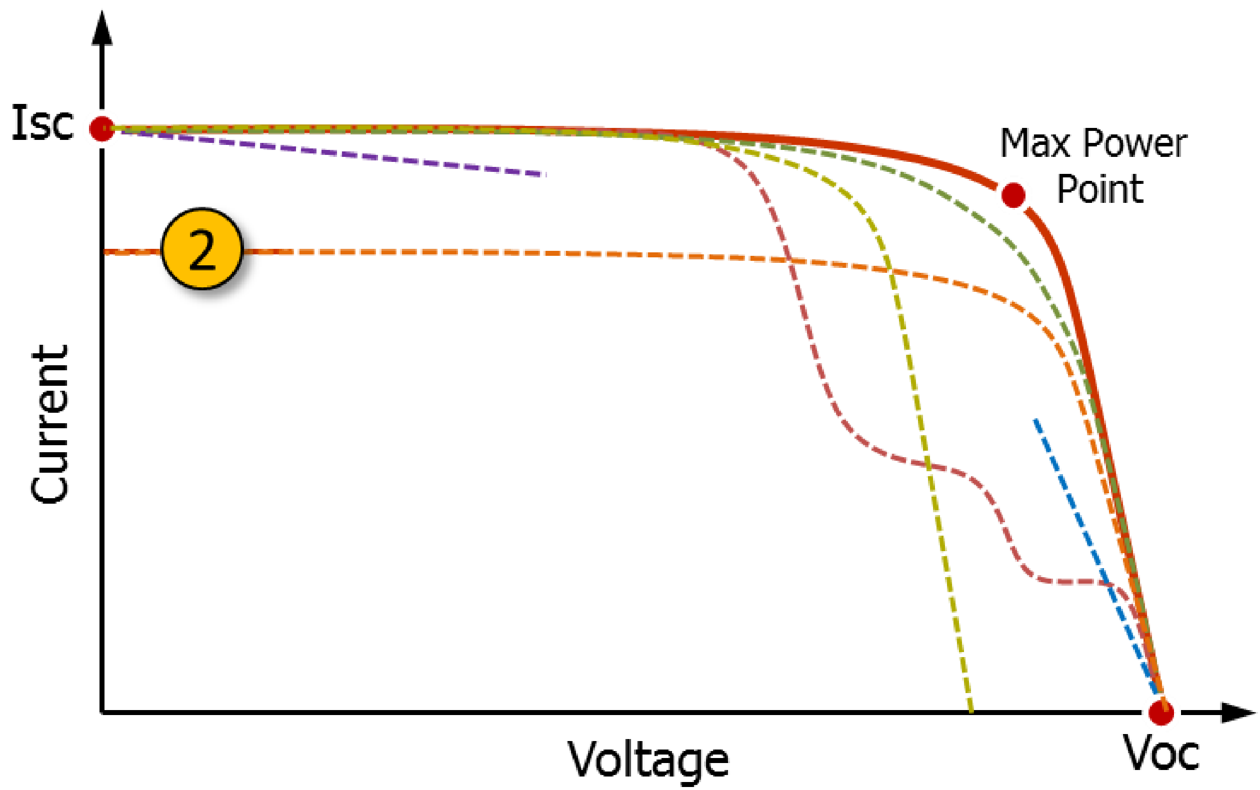
② Low Isc



② Low Isc
Possible causes

External performance factors

1. Uniform soiling
2. Strip soiling (lower edge of module, portrait orientation)
3. Strip shade (lower edge of module, portrait orientation)

Measurement technique

1. Irradiance sensor not in plane of array, pointing more toward sun.
2. Poor spectral match between irradiance sensor and module technology
3. Irradiance sensor sees more reflected light (albedo) than modules
4. Irradiance sensor sees more diffuse light than modules
5. Incorrect parameter values in the PV module model

Module performance

1. Reduced conversion efficiency

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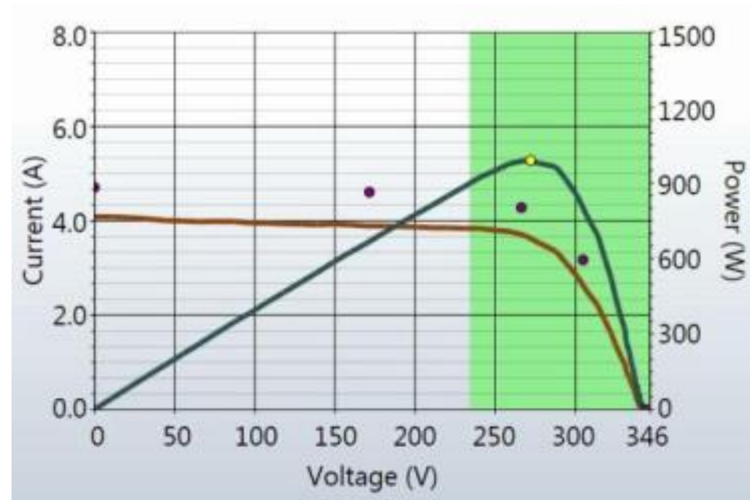
② Low Isc

Examples: Uniform soiling and strip soiling

Dirt dam

Uniform soiling



Uniform soiling and dirt dams can both reduce Isc without causing steps in the I-V curve. This string had both.

The I-V graph shows the performance before cleaning, which was done in 2 steps.

Clearing the uniform soiling recovered half the loss. Clearing the dirt dam recovered the other half.

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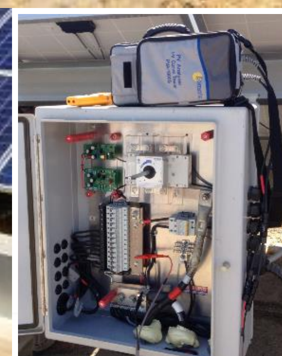
② Low Isc

Example: Rapid buildup of uniform soiling

In 27 days, the performance of this central valley California site dropped 22% due to uniform soiling.



Washher photo courtesy of Ken Mariscotti SMM Industries Clean Energy Solutions SMMIndustries.com

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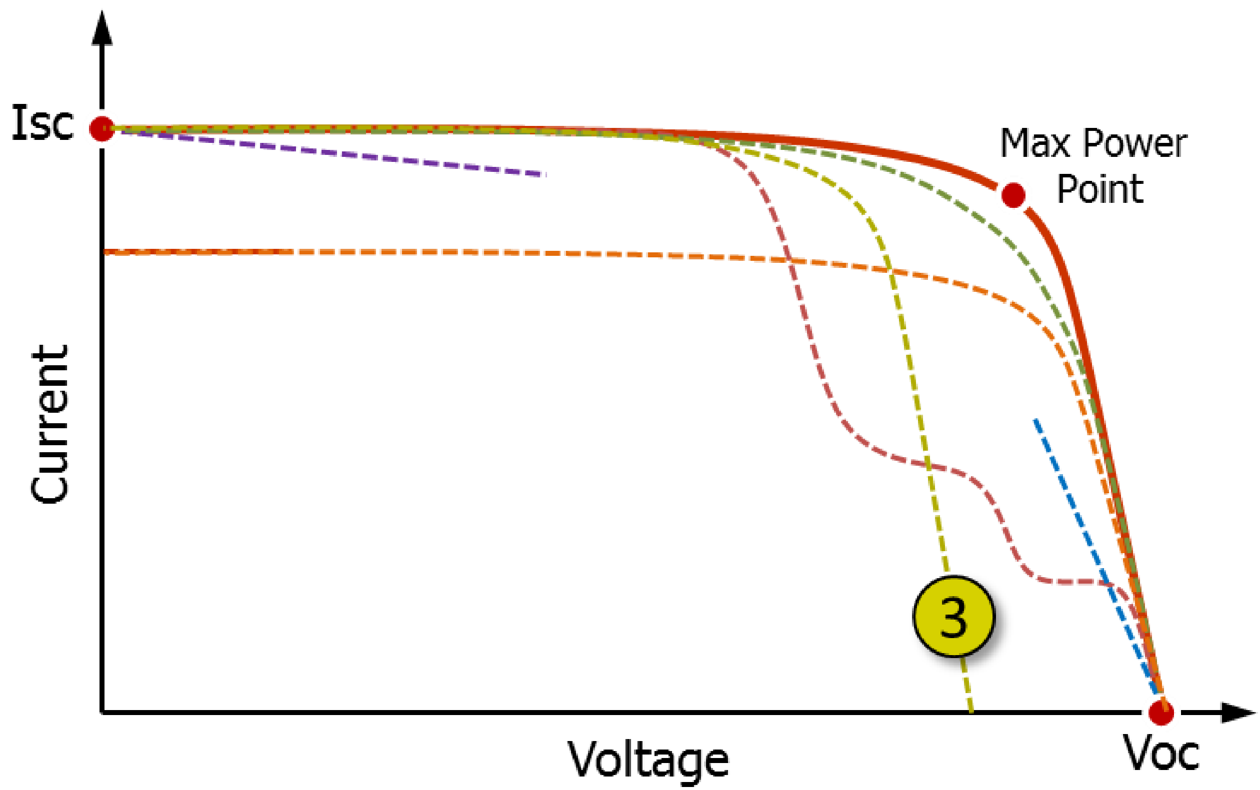
③ Low Voc



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③ Low Voc
Possible causes

External performance factors

1. Temperature instability due to wind or irradiance ramping

Measurement technique

1. Thermocouple not attached at average temperature location
2. Inconsistent location of sensor when moving between subarrays
3. Sensor not in intimate contact with module backside
4. Interpreting the last point in an incomplete I-V curve as Voc

Module performance

1. Shorted bypass diode
2. Degraded Voc (not a strong effect, Voc ages more slowly than other module parameters)
3. Potential Induced Degradation – PID (affects other module parameters too)

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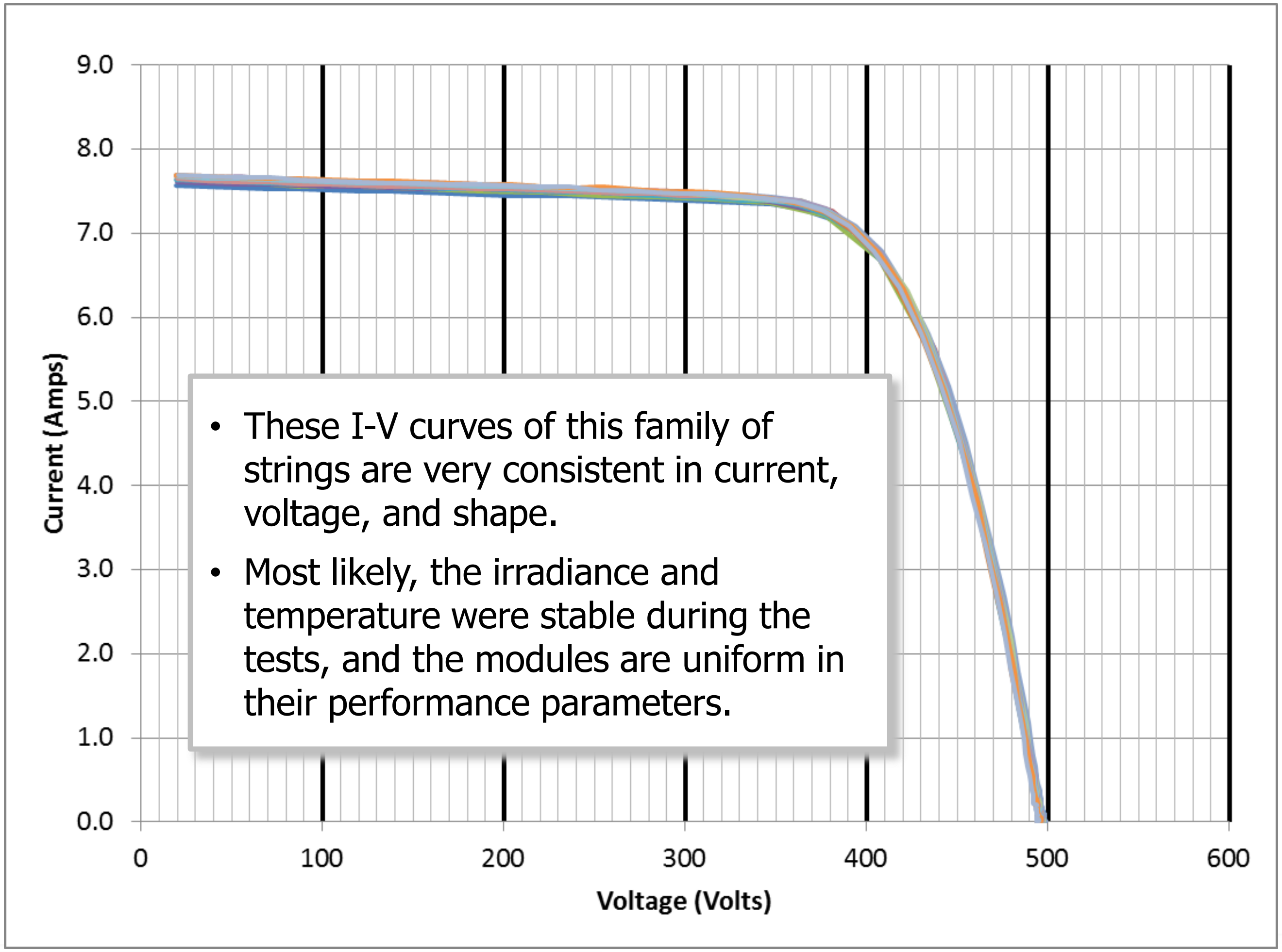
③ Low Voc

Normal variation of Voc



- These I-V curves of this family of strings are very consistent in current, voltage, and shape.
- Most likely, the irradiance and temperature were stable during the tests, and the modules are uniform in their performance parameters.

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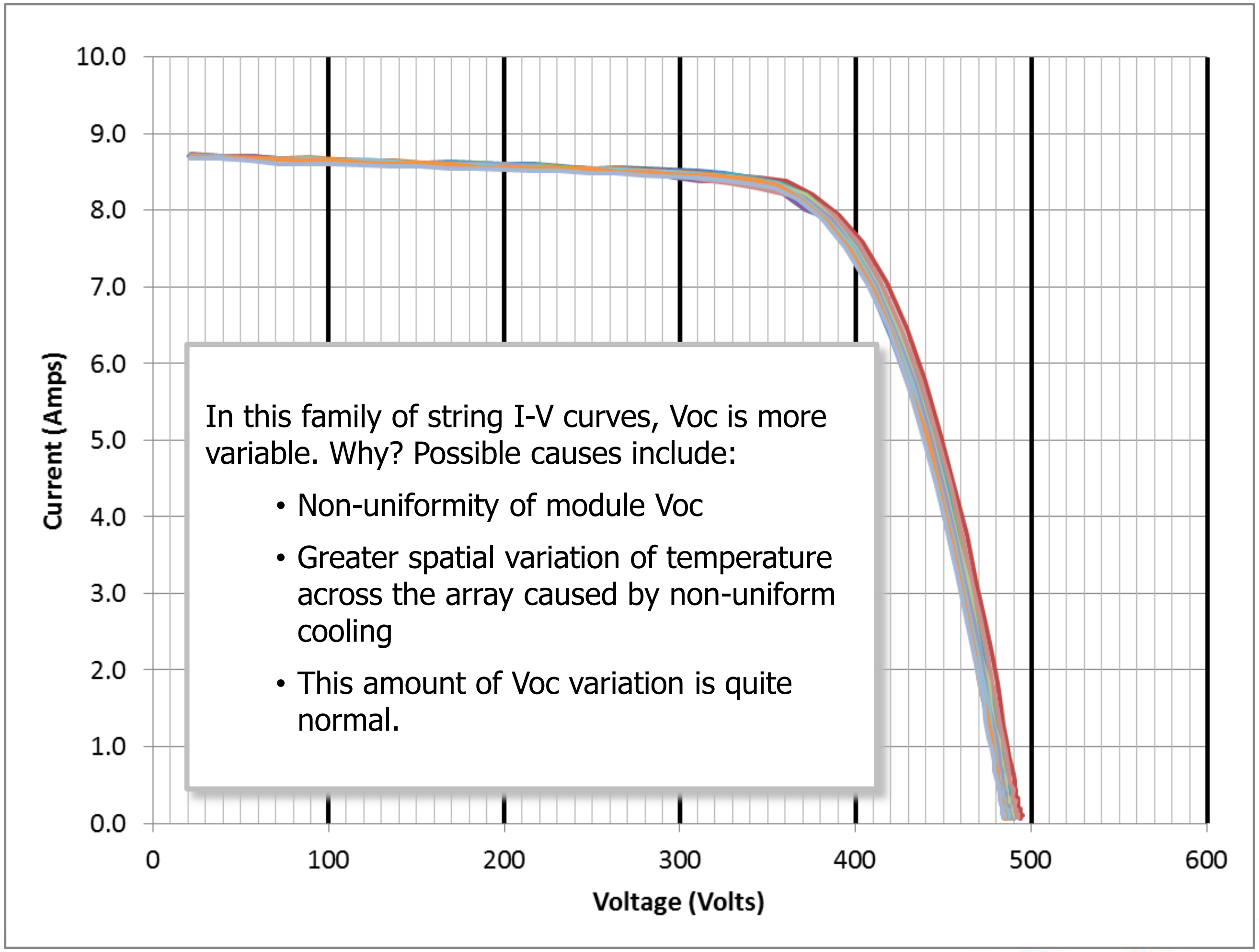
③ Low Voc

Normal variation of Voc



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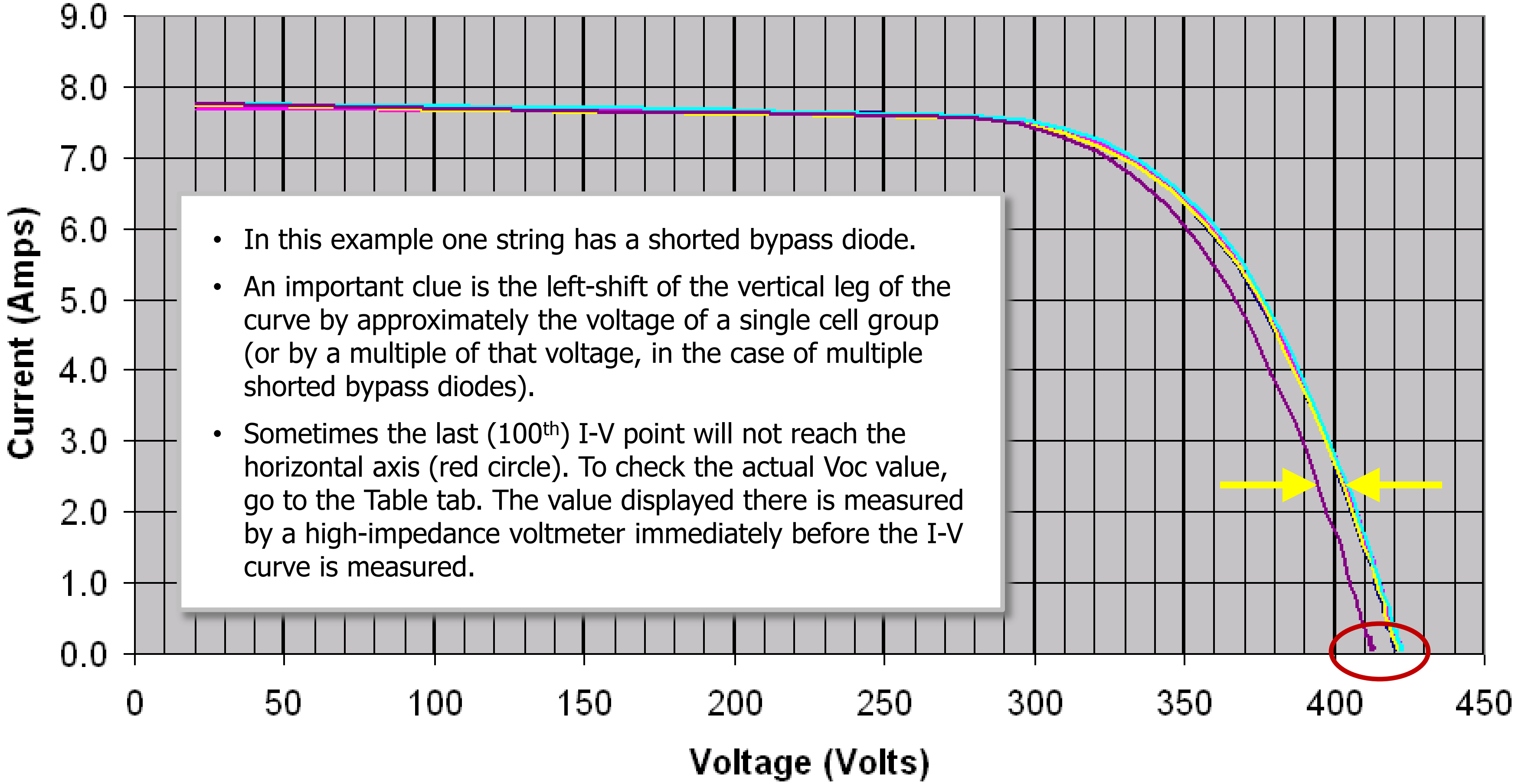
③ Low Voc

Example: Shorted bypass diode



- In this example one string has a shorted bypass diode.
- An important clue is the left-shift of the vertical leg of the curve by approximately the voltage of a single cell group (or by a multiple of that voltage, in the case of multiple shorted bypass diodes).
- Sometimes the last (100^{th}) I-V point will not reach the horizontal axis (red circle). To check the actual Voc value, go to the Table tab. The value displayed there is measured by a high-impedance voltmeter immediately before the I-V curve is measured.

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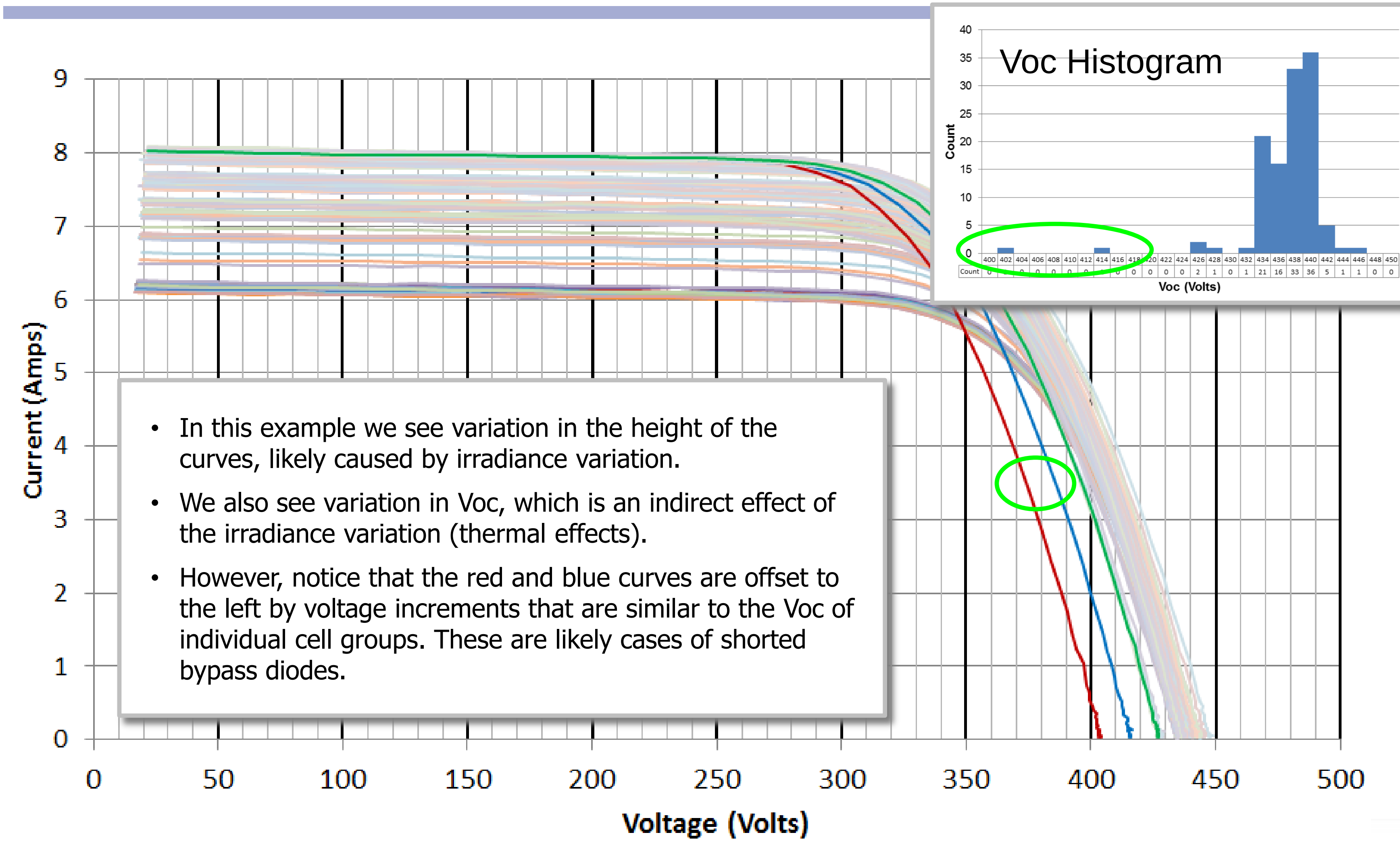
③ Low Voc

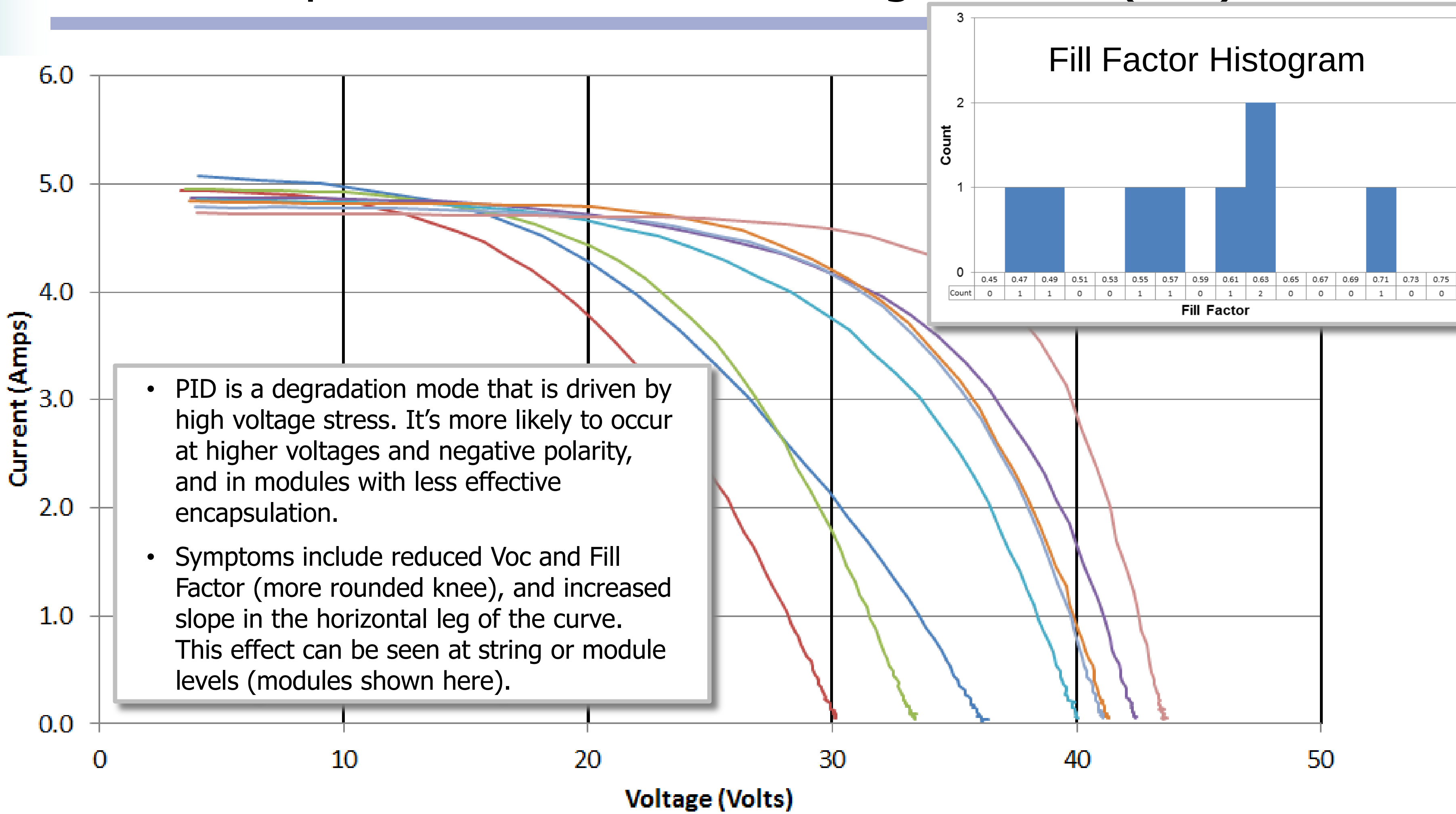
Example: Shorted bypass diodes



- In this example we see variation in the height of the curves, likely caused by irradiance variation.
- We also see variation in Voc, which is an indirect effect of the irradiance variation (thermal effects).
- However, notice that the red and blue curves are offset to the left by voltage increments that are similar to the Voc of individual cell groups. These are likely cases of shorted bypass diodes.

③ Low Voc

Example: Potential Induced Degradation (PID)



- PID is a degradation mode that is driven by high voltage stress. It's more likely to occur at higher voltages and negative polarity, and in modules with less effective encapsulation.
- Symptoms include reduced Voc and Fill Factor (more rounded knee), and increased slope in the horizontal leg of the curve. This effect can be seen at string or module levels (modules shown here).

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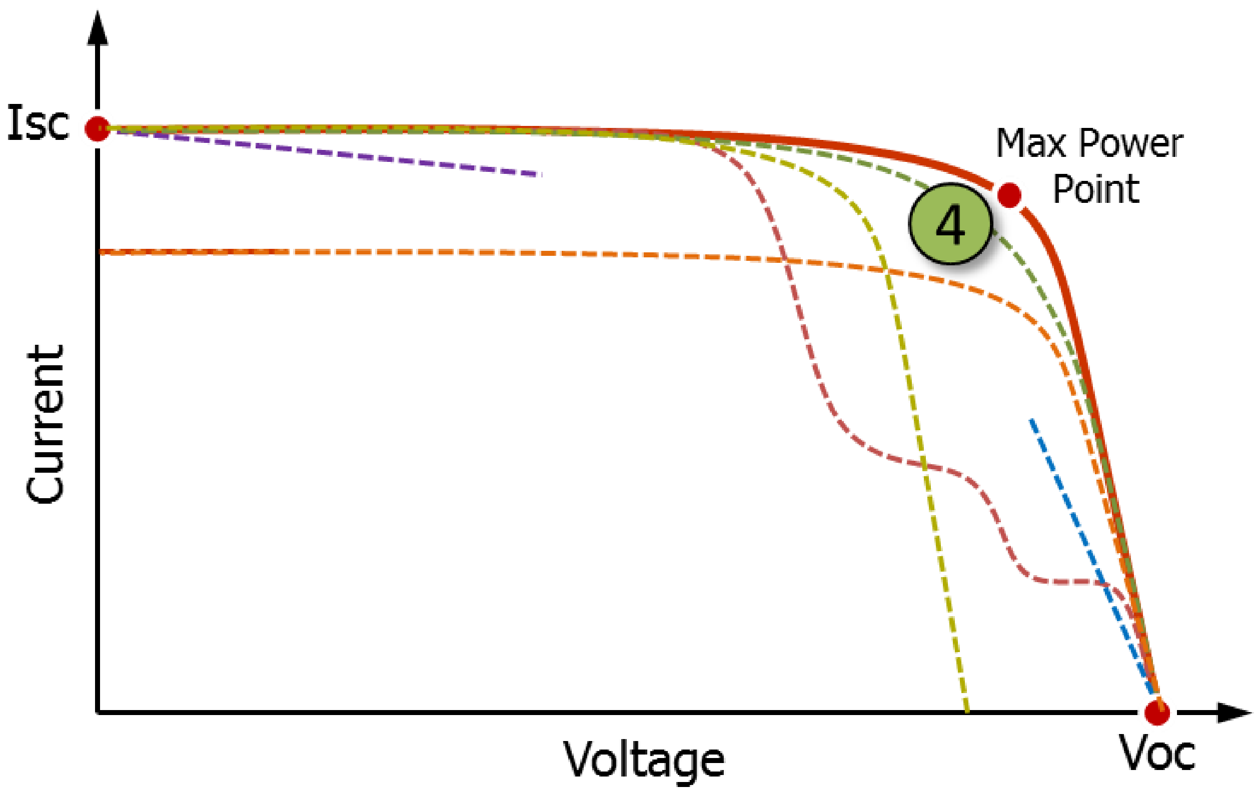
④ Rounder Knee



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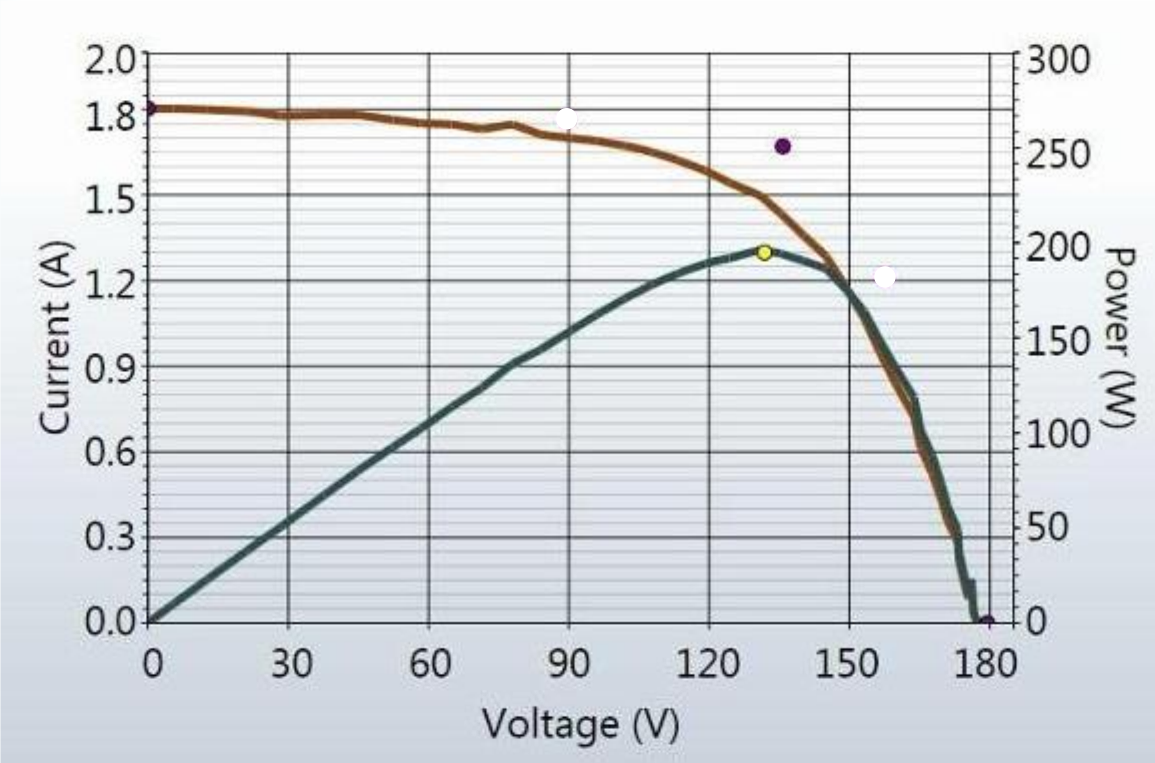
④ Rounder Knee



String of early thin film modules measured at PV-USA after approximately 8 years in the field.

- A rounder knee is difficult to differentiate from changes of slope in the horizontal and vertical legs of the curve (deviations 5 and 6).
- It is included as a class of I-V curve deviation on physical principles. The primary cause is degradation in the ideality factor of the cells, which represents how closely their performance agrees with the behavior of ideal diodes.

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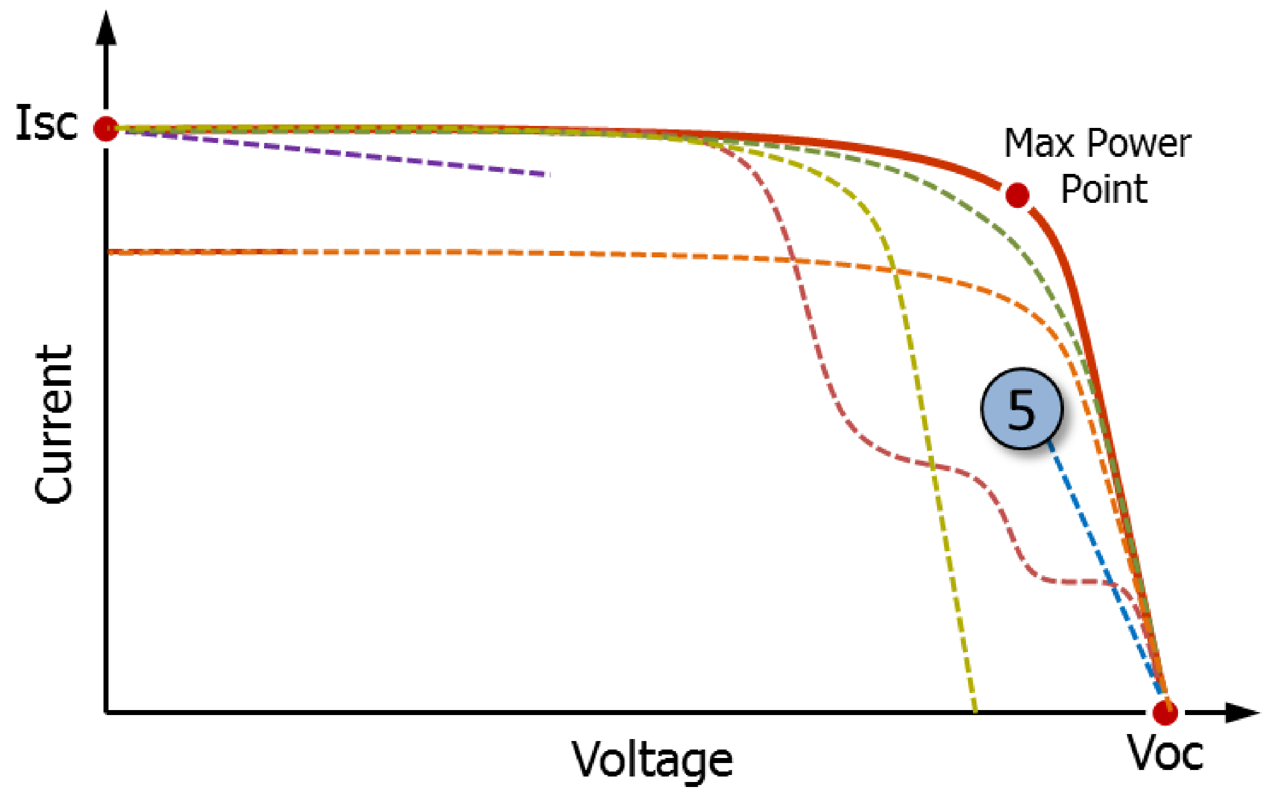
⑤ Reduced Slope in Vertical Leg



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⑤ Reduced Slope in Vertical Leg
Possible causes

External performance factors
1. Poor electrical connections in the external wiring
2. Incorrect wire gauge (too small) used in home runs

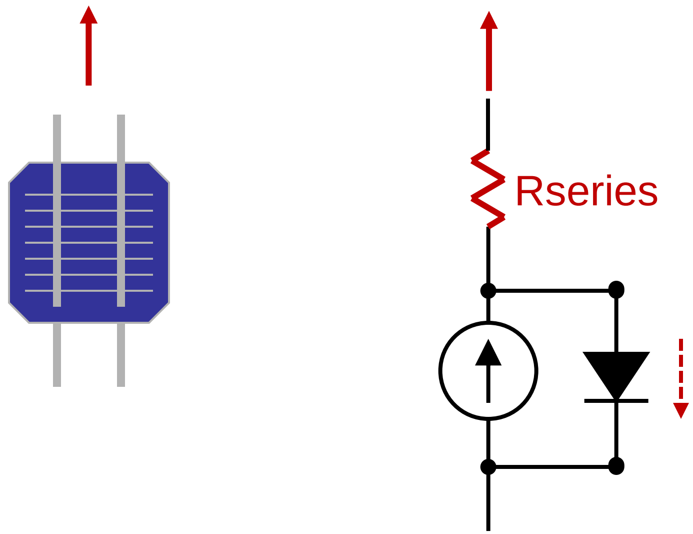
Measurement technique
1. Especially-long home run conductors were not accounted for in the PV model

Module performance
1. Broken or degraded solder bonds
2. Degraded connections in J-box

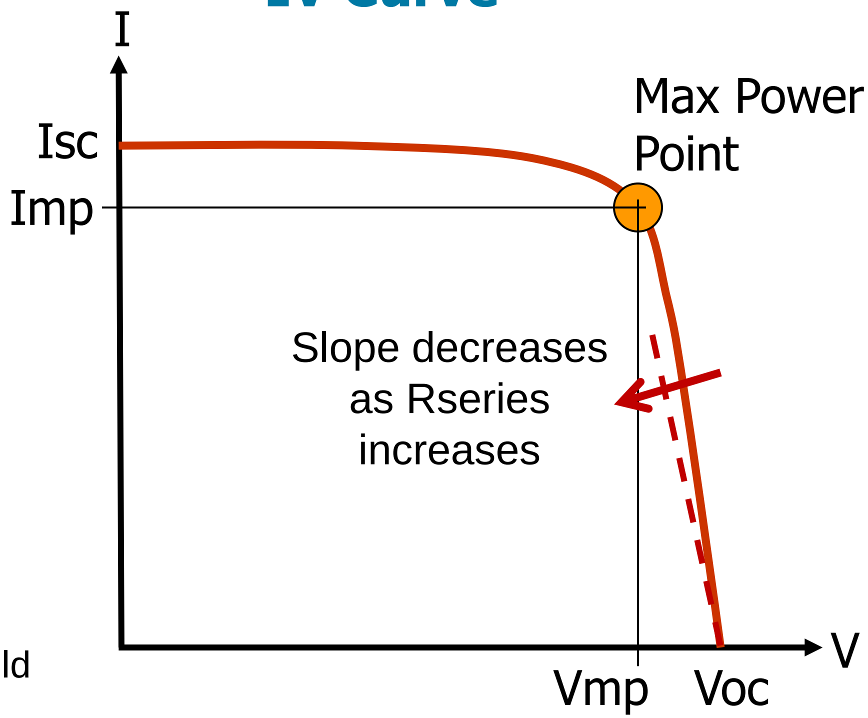
⑤ Reduced Slope in Vertical Leg

Background: Series resistance of PV cells

Solar cell **Equivalent circuit**



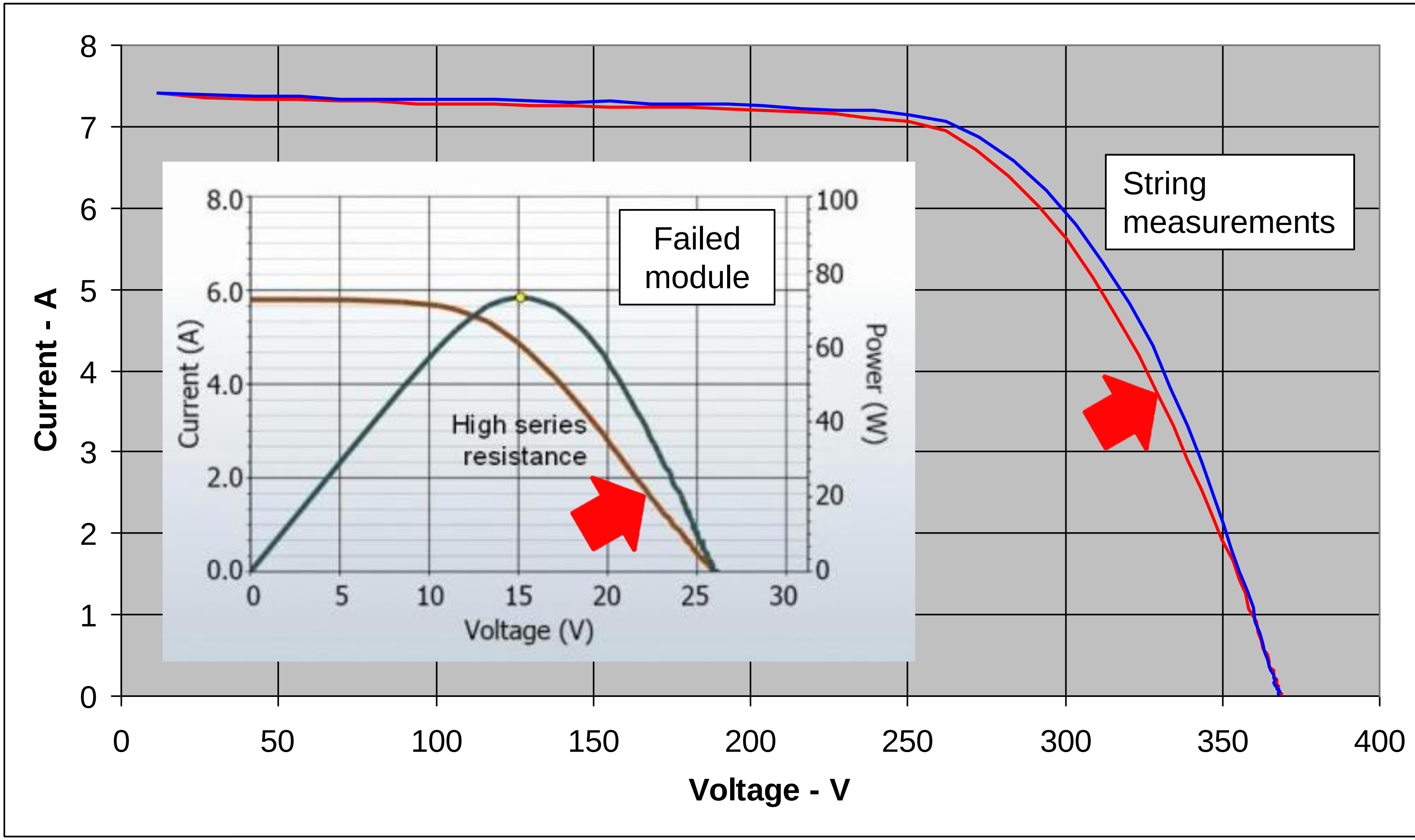
IV Curve



- Series resistance reduces the voltage that would otherwise be available to the load.
- The voltage drop across the series resistor is directly proportional to the current passing through it; doubling the current doubles the voltage drop.

⑤ Reduced Slope in Vertical Leg

Example: High series resistance in PV cells



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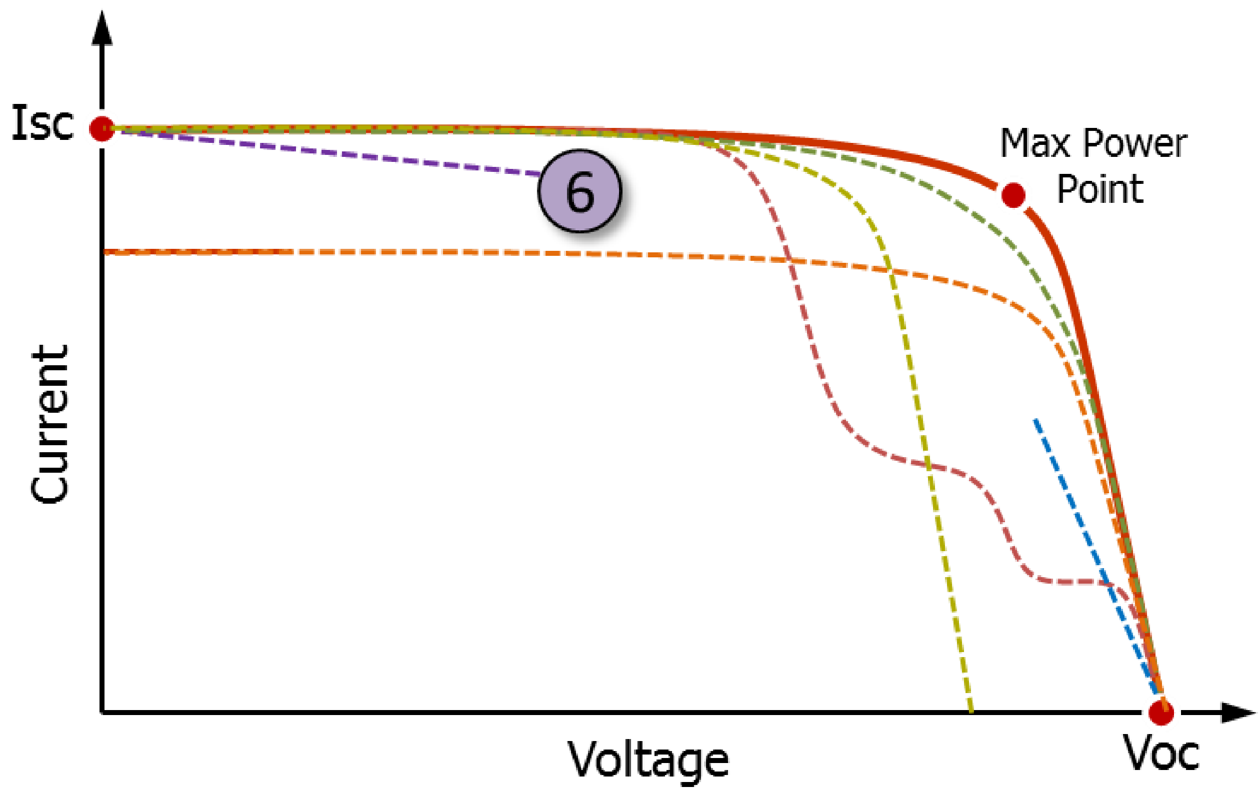
⑤ Reduced Slope in Vertical Leg

Example: Failed solder bond in module J-box

Probably failure mode:

Heat cycling → bond degradation → resistive heating

⑥ Increased Slope in Horizontal Leg



⑥ Increased Slope in Horizontal Leg

Possible causes

External performance factors

1. Tapered sliver of shade or soiling along bottom of modules that are mounted in portrait orientation
2. Special distributions of scattered shade, non-uniform soiling, or litter that limit cell groups to slightly different levels of current, such that the steps usually caused by mismatch are not observed (switching temporarily to 500 point resolution may reveal more detail).

Measurement technique

1. Incorrect module used in predictive model

Module performance

1. Degraded shunt resistance (increased shunt conductance)

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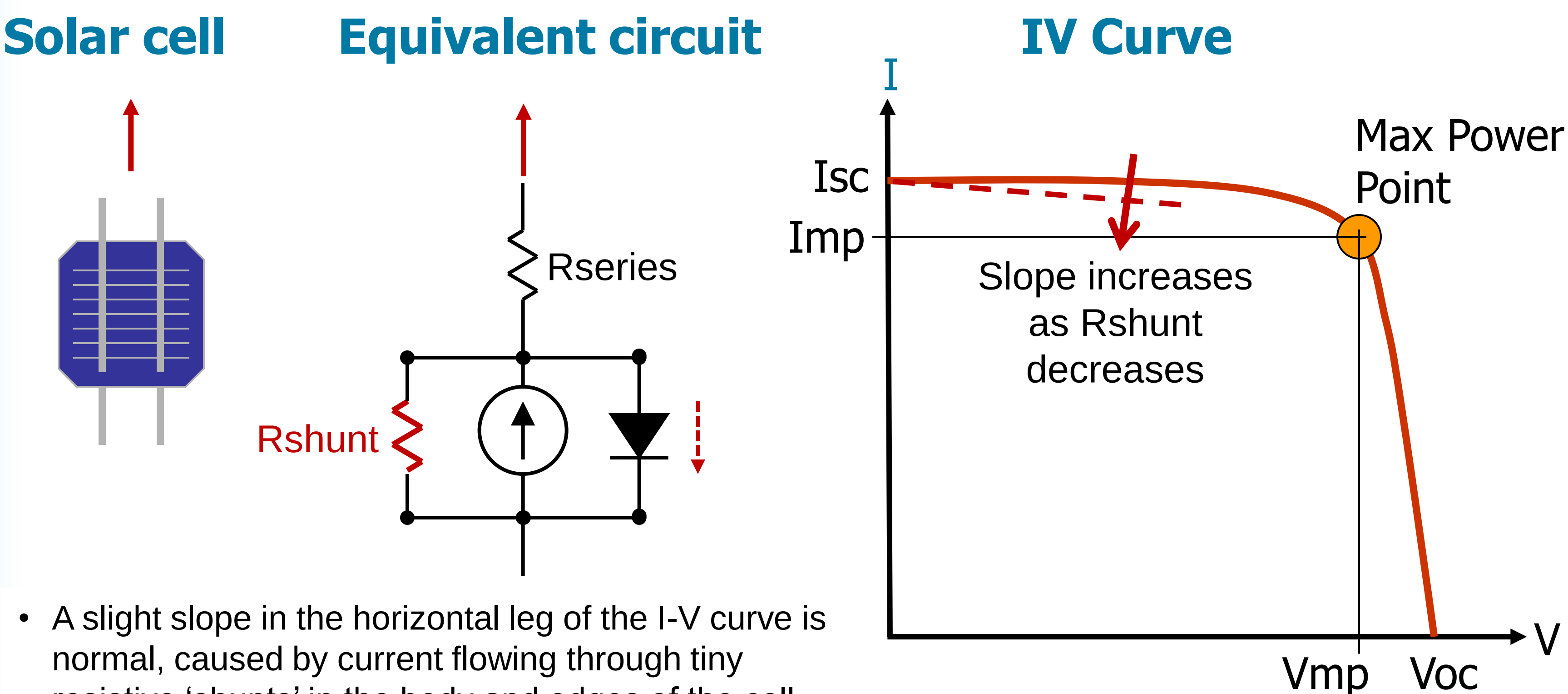
⑥ Reduced Slope in Horizontal Leg

Background: Shunt resistance of PV cells



- A slight slope in the horizontal leg of the I-V curve is normal, caused by current flowing through tiny resistive 'shunts' in the body and edges of the cell.
- The shunt current is proportional to cell voltage; doubling the voltage doubles the shunt current.
- Shunt resistance can shrink as cells age, increasing the slope of the 'horizontal' leg of the I-V curve and reducing Pmax.

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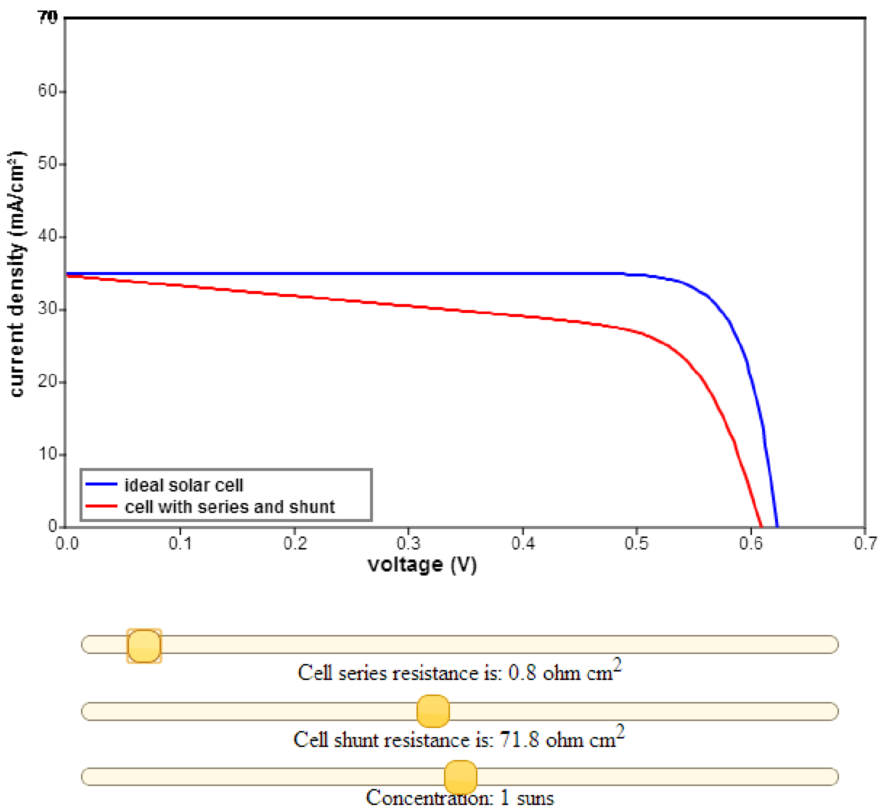
6 Increased Slope in Horizontal Leg

Effect of reduced shunt resistance

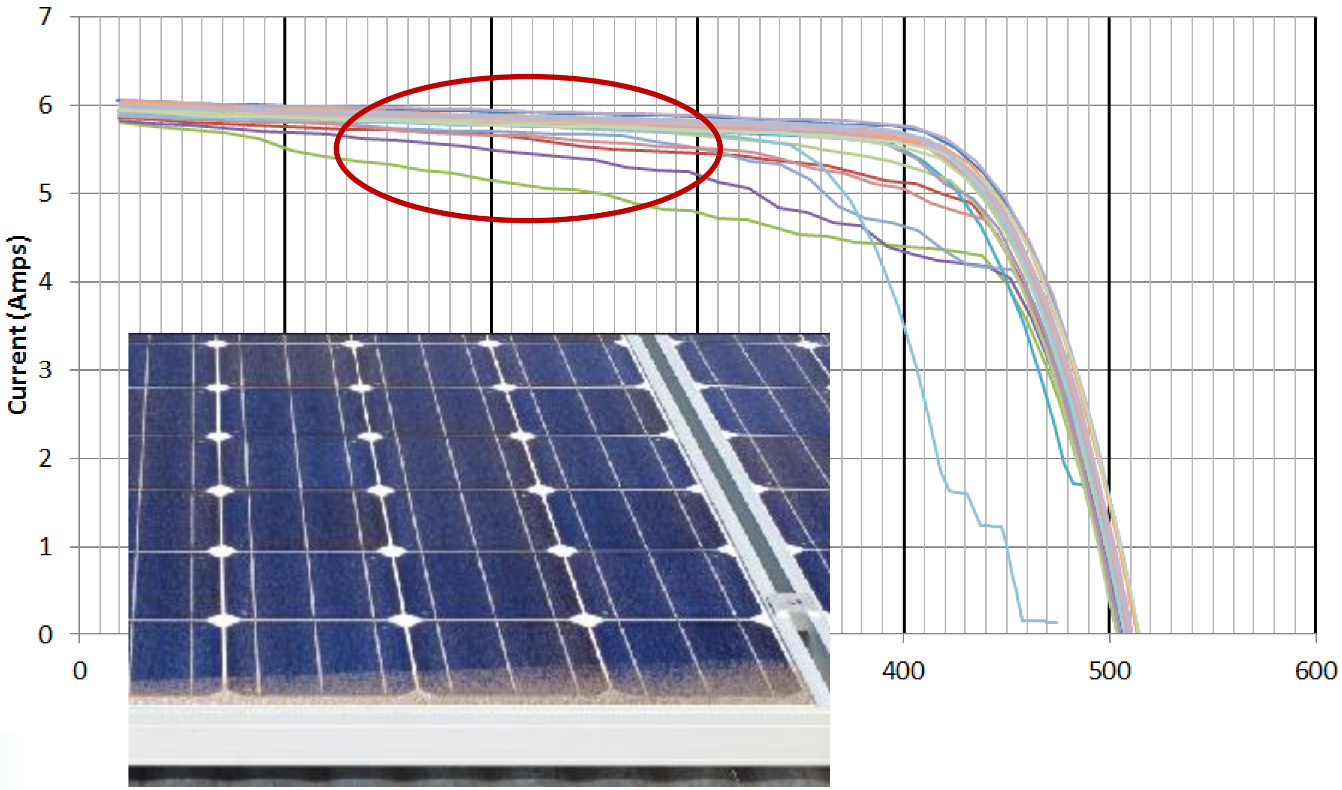


- The PVCDROM website provides an interactive demo of the effect of shunt and series resistance.

Image courtesy of: http://www.pveducation.org/pvcdrom/solar-cell-operation/effect-of-light-intensity

⑥ Increased Slope in Horizontal Leg

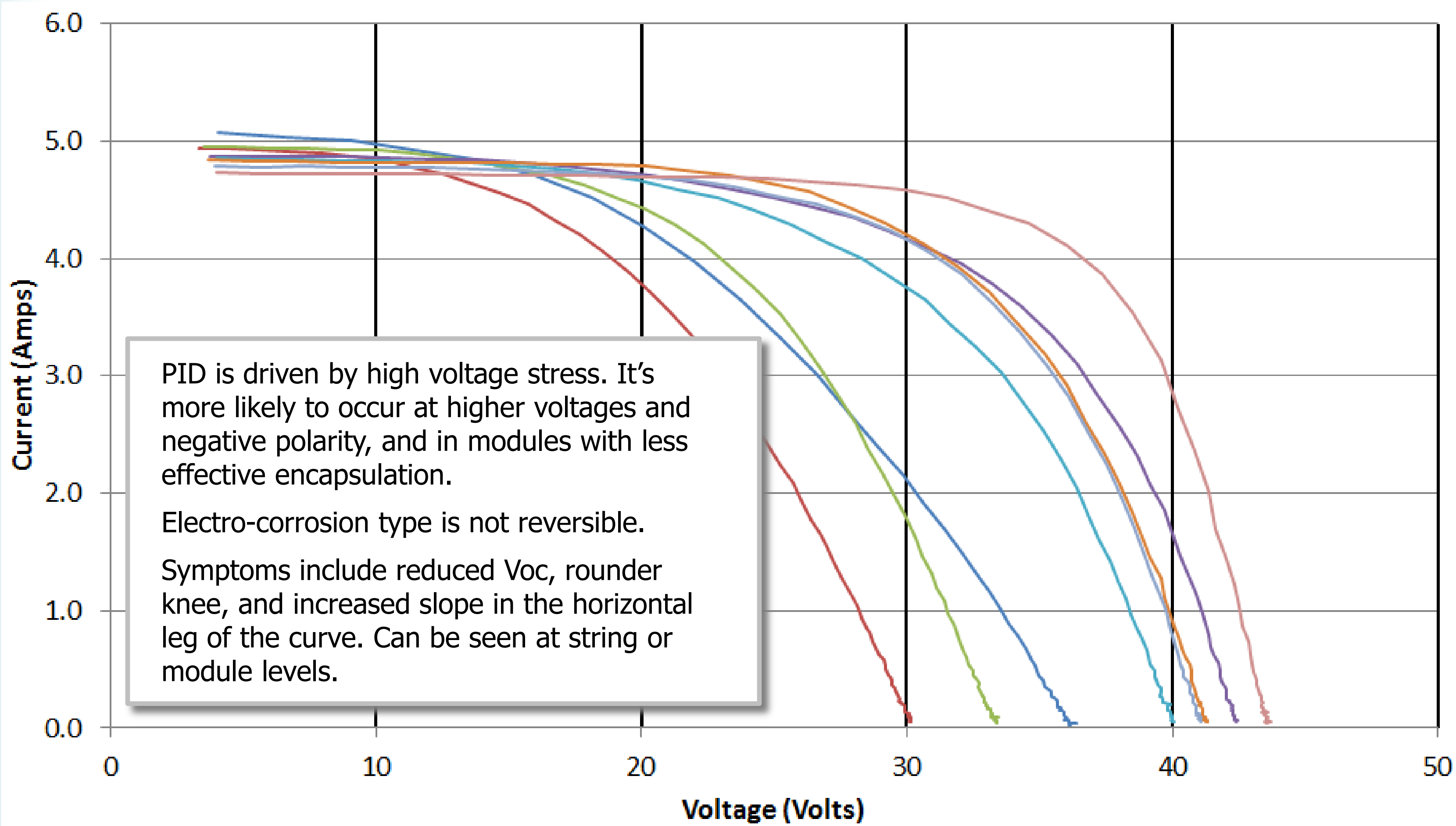
Example: Tapered shading or soiling (portrait mode)



- This is a common cause of increased slope in the horizontal leg.
- A thin, tapered or wedge-like ribbon of soiling or shading causes each cell group to have a slightly different short circuit current.
- It is a form of current mismatch in which the mismatch is so slight that the bypass diode action is 'soft' and not evident as steps.

⑥ Increased Slope in Horizontal Leg

Example: Potential Induced Degradation (PID)



PID is driven by high voltage stress. It's more likely to occur at higher voltages and negative polarity, and in modules with less effective encapsulation.

Electro-corrosion type is not reversible.

Symptoms include reduced Voc, rounder knee, and increased slope in the horizontal leg of the curve. Can be seen at string or module levels.

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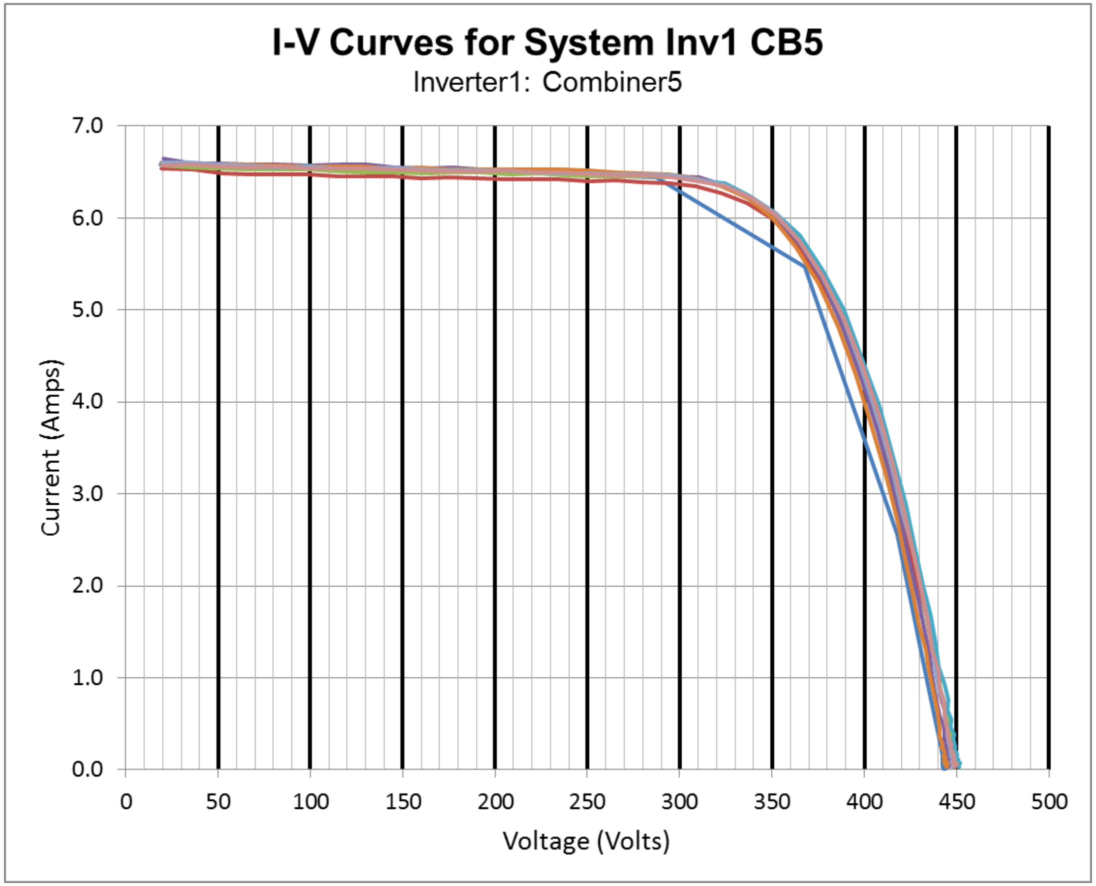
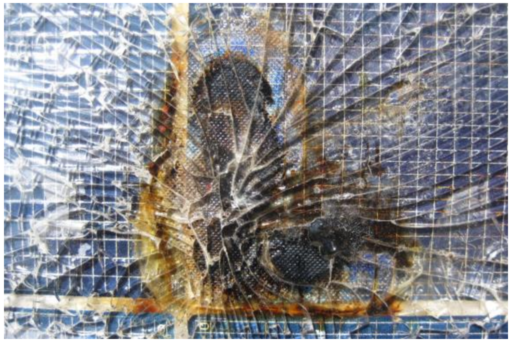
First Measurement Effect

Side effect of ‘learn mode’

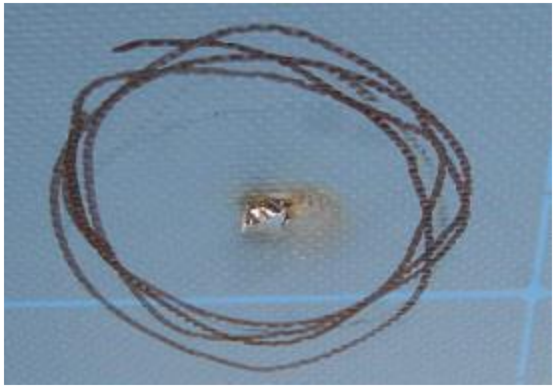


- The PV Analyzer’s I-V curve tracer circuitry is designed to automatically optimize its internal settings for best accuracy at the actual current and voltage levels of the PV source that you are testing. It does this by ‘learning’ from the first measurement you make, and applying the optimizations to the second measurement and beyond.
- You may occasionally see a first trace that seems to be made up of long, straight lines, like the blue curve in this graph. This means the PVA is learning about the PV source and will be optimizing its internal circuits based on this first measurement. Just ignore that measurement, click Measure Now again, and save the second test.

Hot Spot Failures

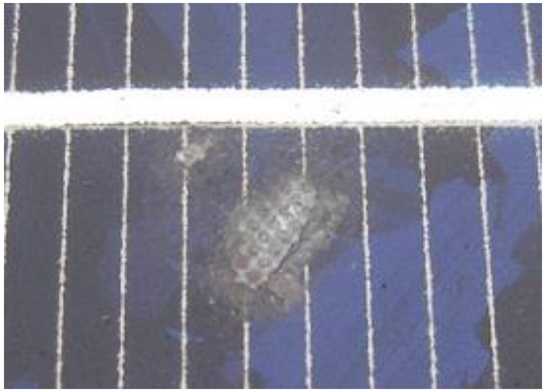


- Hot spots can be caused by cell series or shunt resistance issues.
- Hot spots sometimes progress to catastrophic failure.
- I-V curve tracing can detect some of these issues before they get that bad.



Backside

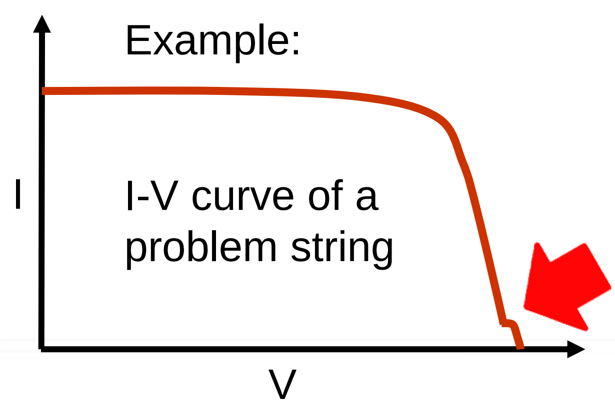
Backside zoomed



Frontside

Selective Shading
Troubleshooting method

Courtesy Harmony Farm Supply and Dave Bell (shown)



- Troubleshooting a bad string starts with a visual inspection. Infrared inspection (under high power operation) is another best practice.
- If nothing was found, the next step has traditionally been to break down the string and measure the modules, either individually or using the half-splitting method.
- With the I-V curve tracer, the Selective Shading method allows finding the bad module without disconnecting the modules from one another.
- The method requires physical access to the string to shade individual modules. Access is usually easy in tiltup, ground mount, and single axis horizontal tracker systems.

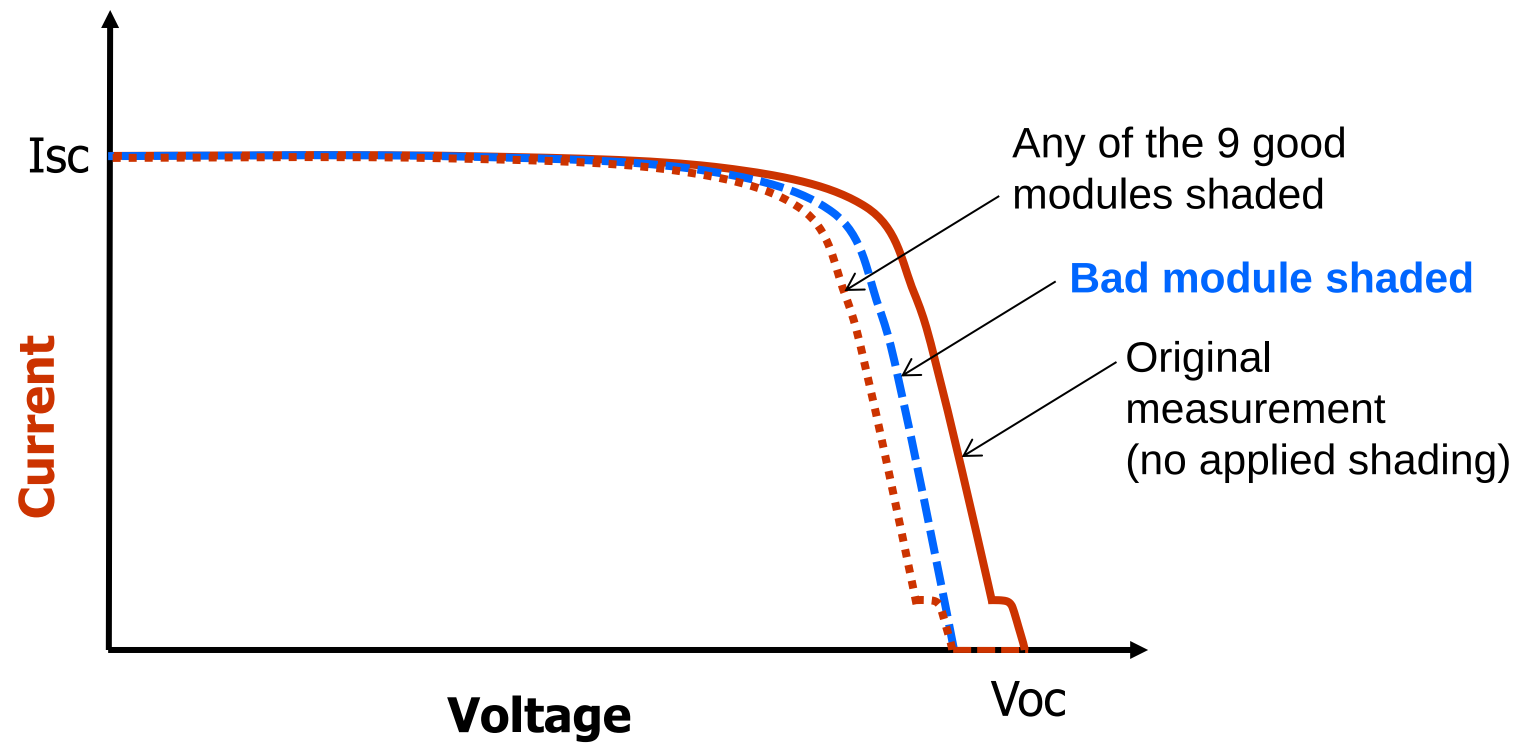
Selective Shading
Example: Finding which module causes the step

Courtesy
Harmony Farm
Supply and
Dave Bell (shown)

- In this example we find the module that is causing the step in the vertical leg of the I-V curve.
- Leaving the string wiring intact, measure the string multiple times.
- Each time, cover several complete rows of cells (portrait mode) with cardboard or a sheet of black rubber. This forces the module's bypass diodes to turn on and electrically remove that module from the string.
- If the problem is in the shaded module, that measurement will look clean.

Selective Shading

Example: Finding which module causes the step



The method can also be used to identify a bad cell string in a single module

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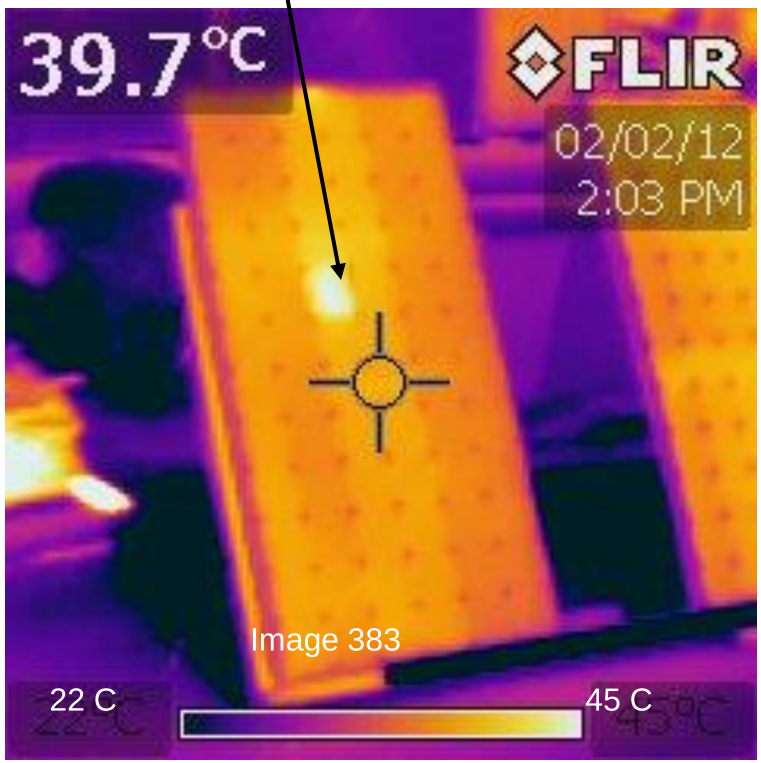
Infrared Imaging

Companion tool to I-V curve tracing

Measured using the FLIR i7 infrared camera

Demo example: Middle cell group is hotter because it is not exporting electrical power. Bypass diodes were forced ‘on’ by covering a cell with cardboard.



Thermal processes are an important piece of the PV system performance. Infrared imaging helps us find:

- Poor electrical connections that cause power loss and eventually arcs and fires
- Open-circuited PV strings and bypassed cell groups performance issue that disrupts thermal balance can be located with infrared imaging.
- PV cell hot spots

IR imagers are a great companion tool with I-V curve tracing:

	I-V	IR
Detect issue	✓	✓
Measure performance impact	✓	
Find bad module	✓	✓

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Infrared Imaging

Aerial imaging of large arrays

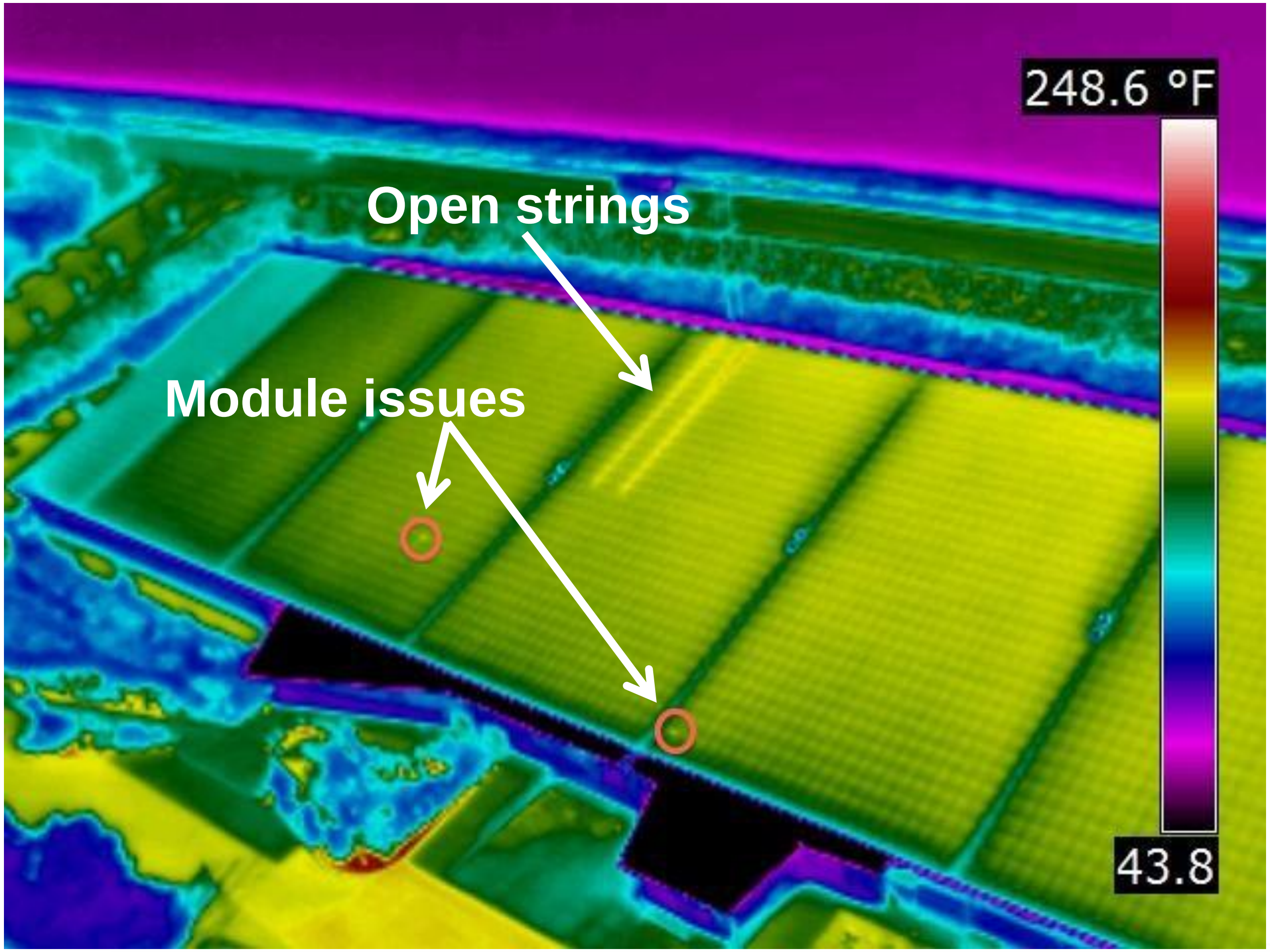

Image courtesy of Portland Habilitation Center, Oregon Infrared, and Dynalectric

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ALSOK (Japan)

Micro-Epsilon (UK)

Topics

- Introduction to the PVA-1000S PV Analyzer
- Using the software
- Making I-V curve measurements
- Measuring irradiance & temperature
- PV fundamentals for troubleshooting
- Troubleshooting PV arrays
- Using the I-V Data Analysis Tool (DAT)
  - Creating the data statistics displays
  - Generating your report

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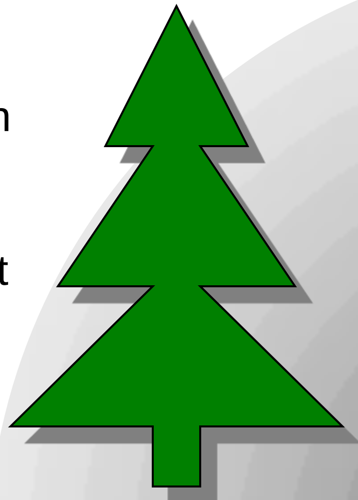
Determining Actual Performance

Correcting or accounting for external effects

Shading
- Vegetation
- Buildings
- Rooftop equipment
- Other PV modules



Weather
- Low irradiance
- Unstable irradiance
- Wind

Actual Array Performance

Measurement Issues
- Irradiance sensor not in POA
- Thermocouple not attached
- Thermocouple location
- Resistive losses

Soiling & Debris
- Uniform soiling
- Dirt dams
- Leaves & branches
- Frisbees

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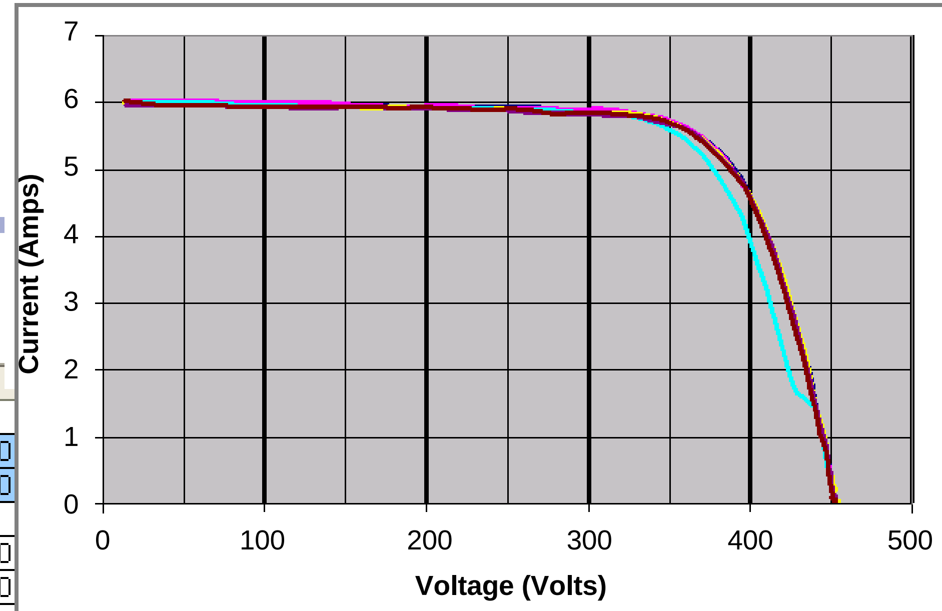
Overview of Data Analysis Process
Data display, interpretation, and reporting

1. Export data from PVA software
2. Use the Data Analysis Tool (Excel with macros) to display the data in tables, I-V graphs, and histograms
3. Review and interpret data
4. Generate a punch list if needed
5. After repairs and re-testing are finished, re-run the DAT
6. Generate the DAT report for your client
7. Prepare a brief, high-level summary of the findings of the DAT report. Often clients find this helpful.

DAT Displays

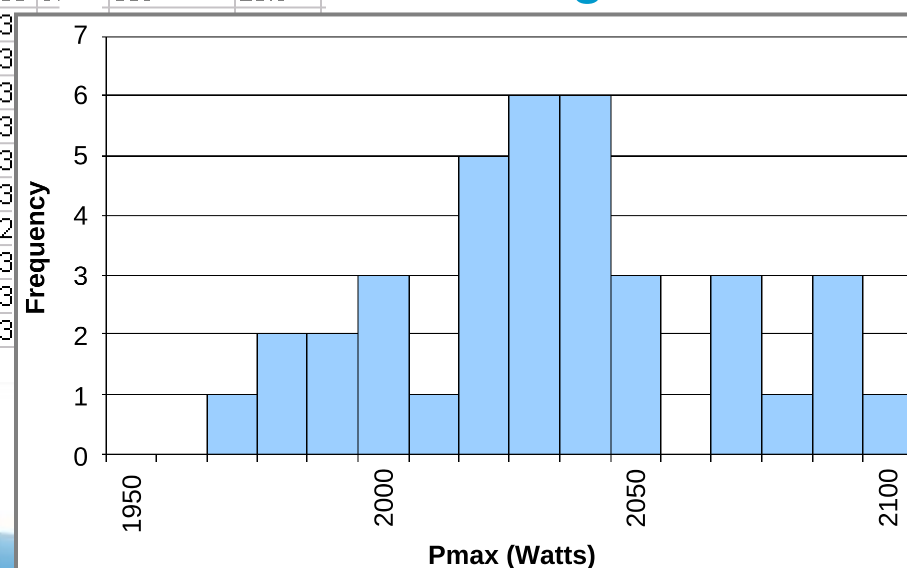
Table

	A	B	C	D	E	F	G	H	I	J	K	L
1	Home	Help										
2	Set Upper Limit	403.6	8.01	3,200	502.9	8.73	0.922	0.805	0			
3	Set Lower Limit	379.0	6.50	2,610	483.8	7.08	0.899	0.781	0			
4												
5	Max Value	403.6	8.01	3,102	502.9	8.73	0.922	0.805	0			
6	Mean Value	390.5	7.40	2,887	493.7	8.08	0.916	0.791	0			
7	Min Value	379.0	6.50	2,601	483.8	7.09	0.899	0.781	0.709	89.6	869	20.6
8	Std. Dev. (σ)	5.44	0.484	158.1	3.92	0.527	0.004	0.005	0.005	2.38	69	5.3
9	2 Std. Dev. (2σ)	10.87	0.968	316.1	7.84	1.055	0.007	0.011	0.011	4.76	138	10.5
10												
11		V_{mp}	I_{mp}	P_{max}	V_{oc}	I_{sc}	I_{mp} / I_{sc}	V_{mp} / V_{oc}	FF	PF	Irradiance	Temp.
12		Volts	Amps	Watts	Volts	Amps				%	(W/m^2)	deg C
13	Sample I-V Data Set\	400.4	6.50	2,602	499.6	7.09	0.917	0.801	0.735	[illegible]	869	28.9
14	Sample I-V Data Set\	399.6	6.52	2,606	499.1	7.09	0.920	0.801	0.73			
15	Sample I-V Data Set\	402.6	6.50	2,618	500.3	7.14	0.910	0.805	0.73			
16	Sample I-V Data Set\	399.2	6.52	2,603	498.7	7.12	0.916	0.800	0.73			
17	Sample I-V Data Set\	397.9	6.57	2,615	498.4	7.14	0.920	0.798	0.73			
18	Sample I-V Data Set\	397.7	6.58	2,615	498.2	7.14	0.921	0.798	0.73			
19	Sample I-V Data Set\	396.5	6.58	2,608	496.9	7.17	0.917	0.798	0.73			
20	Sample I-V Data Set\	398.2	6.53	2,601	497.5	7.18	0.909	0.801	0.72			
21	Sample I-V Data Set\	403.6	6.54	2,638	501.5	7.20	0.908	0.805	0.73			
22	Sample I-V Data Set\	399.7	6.59	2,634	499.5	7.19	0.916	0.800	0.73			
23	Sample I-V Data Set\	399.4	6.60	2,635	499.4	7.20	0.916	0.800	0.73			



I-V Curves

Histograms



Data Interpretation

The starting point for your analysis is a matter of personal preference, but if you like your information in graphical form, this is a good flow.

I-V Curve Graphs

- Scan for abnormal shapes. Hover with cursor to ID problem strings

Histograms

- Scan the parameter distributions for tails and outliers
- Correlate shapes with variability of irradiance and temperature

Table

- Check the parameter statistics (rows 5-9)
- Enter limit values (rows 2 & 3) to identify outliers, which are shaded yellow

	A	B	C	D	
1	Home	Help			
2	Set Upper Limit	403.6	8.01	3,200	5
3	Set Lower Limit	379.0	6.50	2,610	4
4					
5	Max Value	403.6	8.01	3,102	5
6	Mean Value	390.5	7.40	2,887	4
7	Min Value	379.0	6.50	2,601	4
8	Std. Dev. (σ)	5.44	0.484	158.1	3
9	2 Std. Dev. (2σ)	10.87	0.968	316.1	7
10					
11		V_{mp}	I_{mp}	P_{max}	V
12		Volts	Amps	Watts	V
13	Sample I-V Data Set\	400.4	6.50	2,602	4
14	Sample I-V Data Set\	399.6	6.52	2,606	4

In the following slides we explain the use of the Data Analysis Tool

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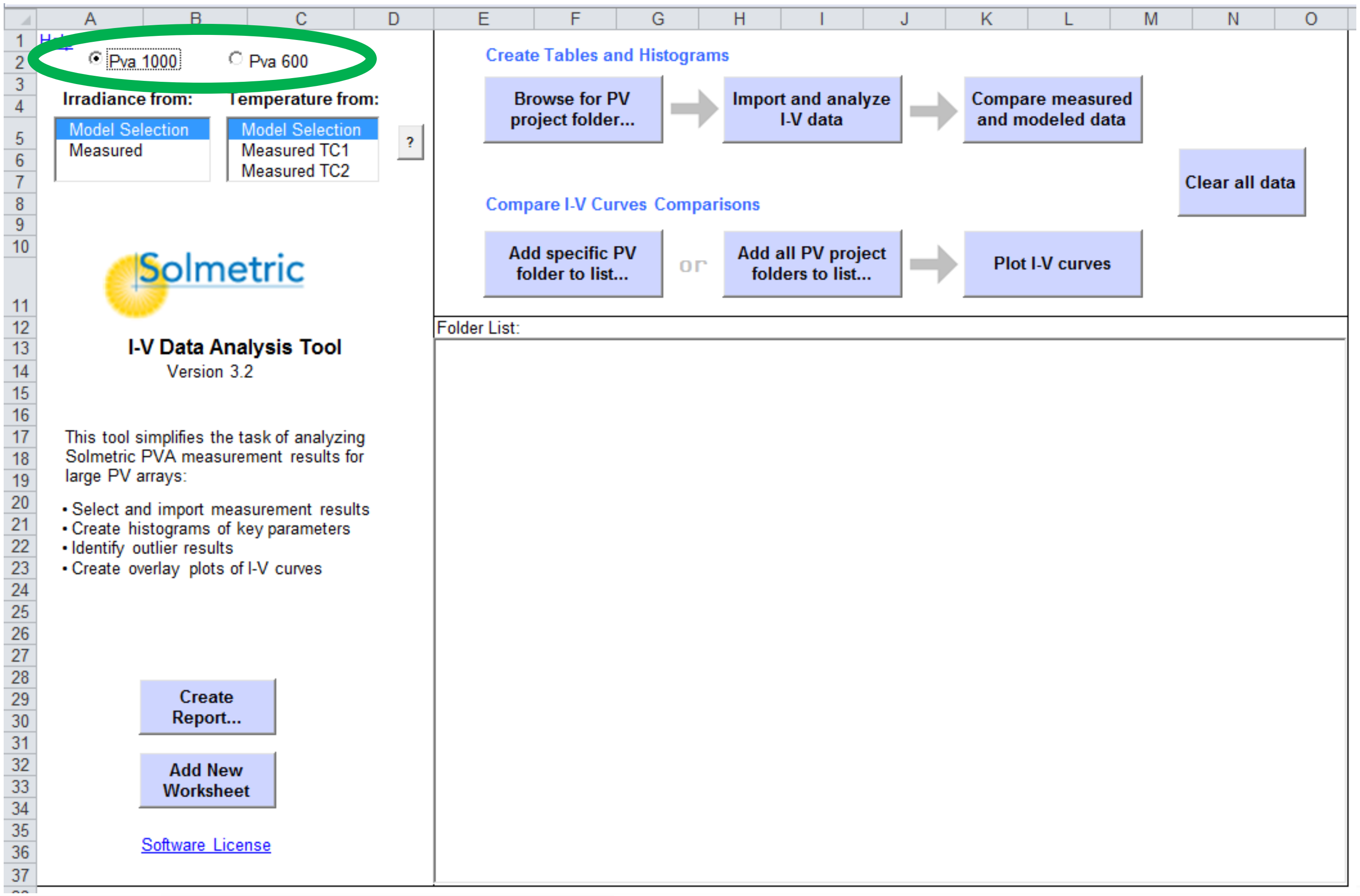
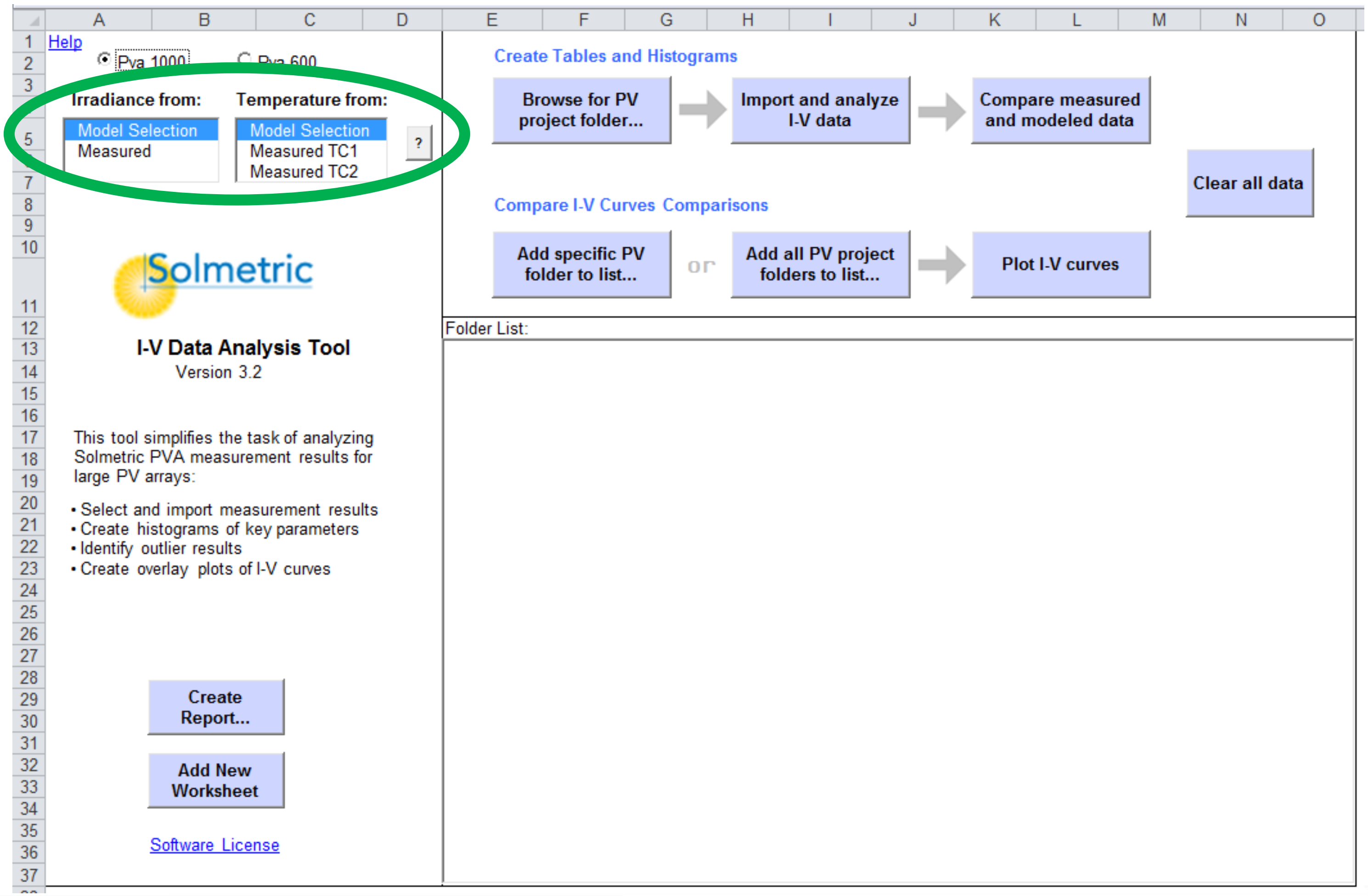
Using the Data Analysis Tool

1. Identify your PVA model number



Using the Data Analysis Tool

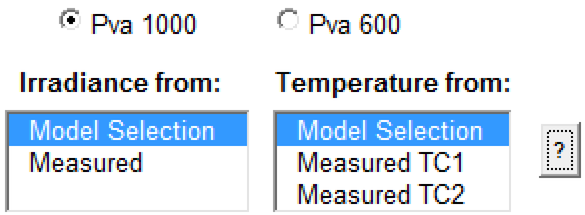
2. Select which irradiance and temperature values to import



Using the Data Analysis Tool

2. Select which irradiance and temperature values to import

PVA 1000

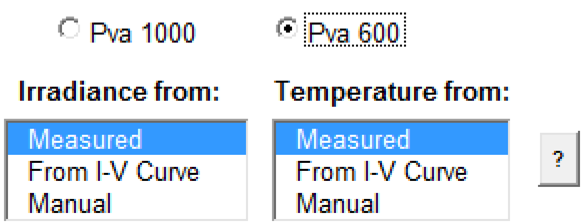


These controls select which set of irradiance and temperature data to import along with the I-V curve data. The choices are explained below.
The Performance Factor values are imported regardless of which irradiance and temperature methods you select. However, the Performance Factor correlates more closely with the irradiance and temperature methods that were in use at the time the I-V curves were measured. To import these irradiance and temperature values, chose Model Selection.

Irradiance
Model Selection - Data used in the PVA software for the performance model.
Measured - Data from the SolSensor irradiance sensor.

Temperature
Model Selection - Data used in the PVA software for the performance model.
Measured TC1 - Data from TC1 thermocouple.
Measured TC2 - Data from TC2 thermocouple.

PVA 600



These controls select which set of irradiance and temperature data to import along with the I-V curve data. The choices are explained below.
Performance Factor values are imported regardless of which irradiance and temperature methods you select. However, the Performance Factor correlates more closely with the irradiance and temperature methods that were in use at the time the I-V curves were measured.

Irradiance
Measured – Data from the irradiance sensor in the Wireless Sensor Kit.
From I-V Curve – Data calculated from the measured I-V curve.
Manual – Data entered by the user in the PVA software.

Temperature
Measured – Data from the temperature sensor in the Wireless Sensor Kit.
From I-V Curve – Data calculated from the measured I-V curve.
Manual – Data entered by the user in the PVA software.

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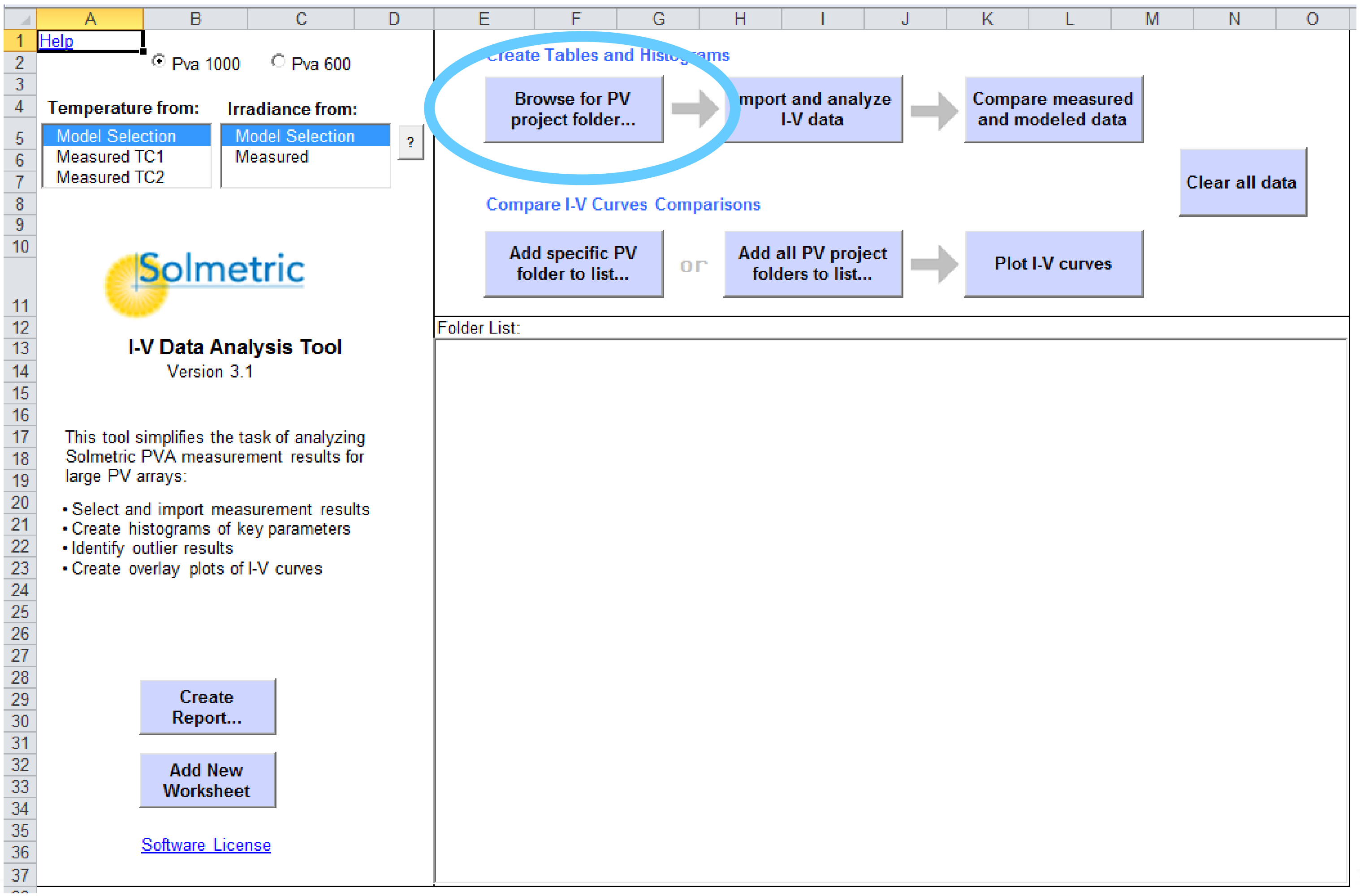
Using the Data Analysis Tool

3. Browse for your project data



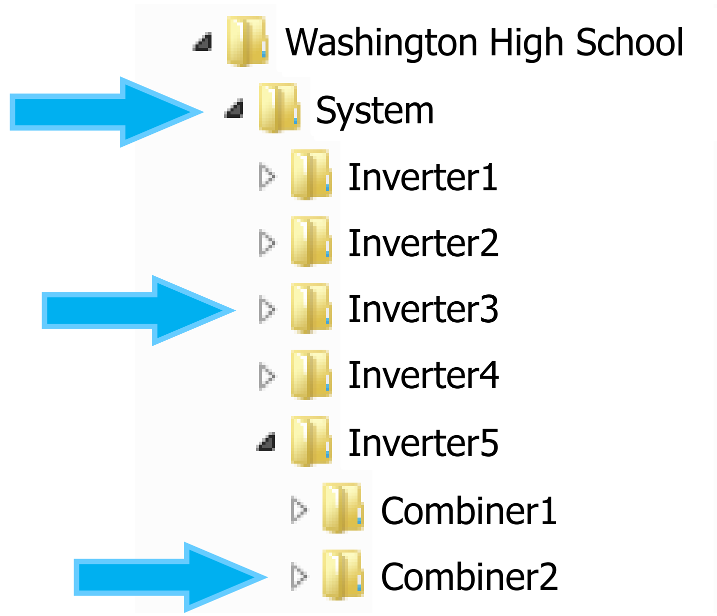
Using the Data Analysis Tool

3. Browse for your project data

Browse to the folder tree that was exported from the PVA.

Select the desired level.

All data below the selected level will be imported to the Data Analysis Tool.



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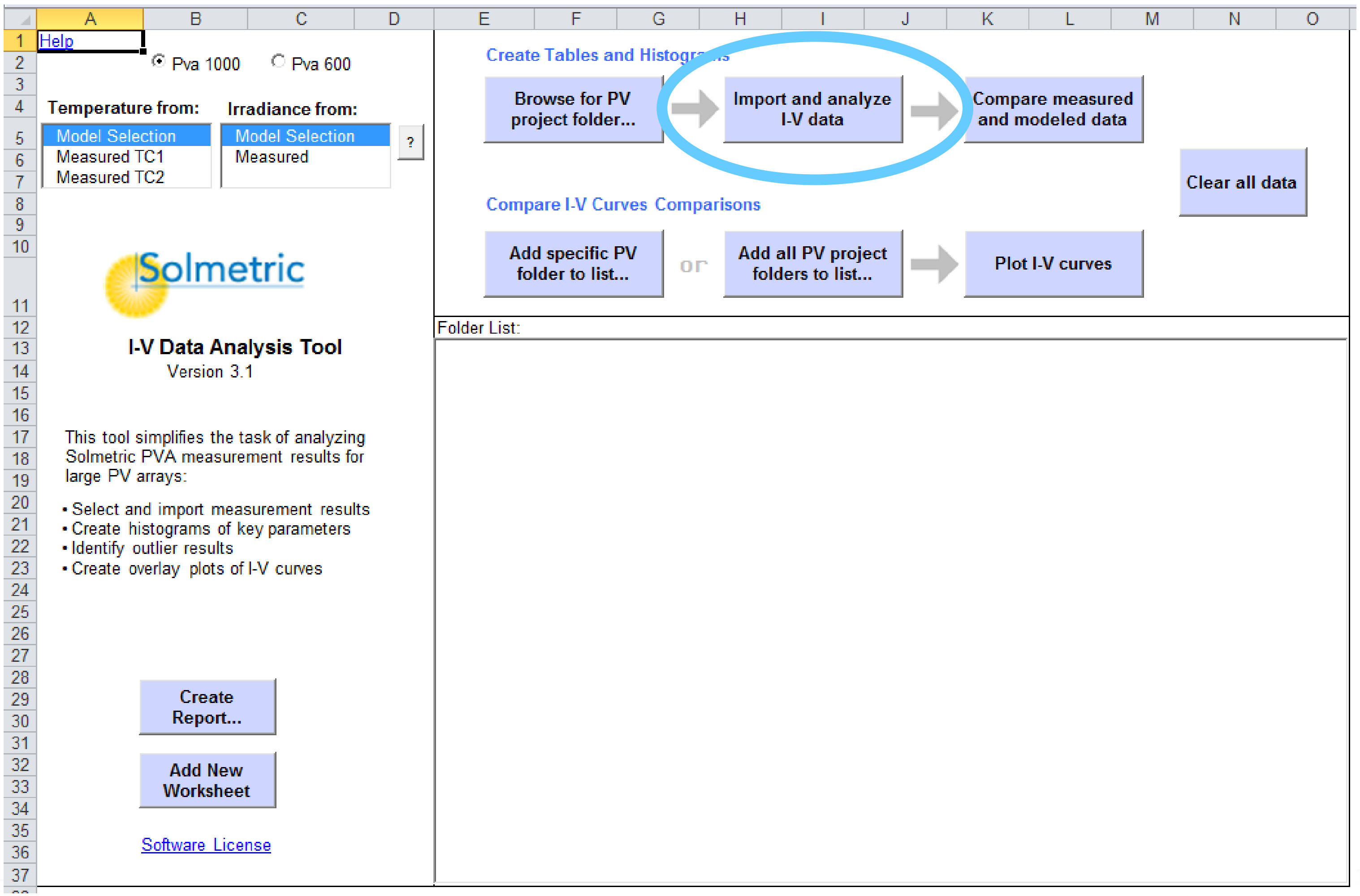
Using the Data Analysis Tool

4. Import the I-V data

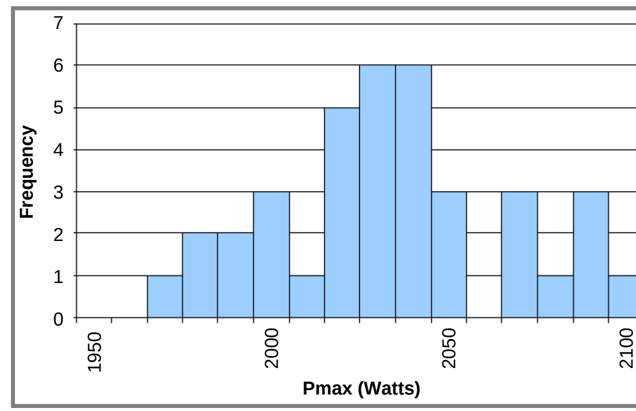


Using the Data Analysis Tool

4. Import the I-V data

	A	B	C	D	E	F	G	H	I	J	K	L
1	Home	Help										
2	Set Upper Limit	403.6	8.01	3,200	502.9	8.73	0.922	0.805	0.736	98.3	1,084	37.8
3	Set Lower Limit	379.0	6.50	2,610	483.8	7.08	0.899	0.781	0.709	89.6	869	20.6
4												
5	Max Value	403.6	8.01	3,102	502.9	8.73	0.922	0.805	0.736	98.3	1,084	37.8
6	Mean Value	390.5	7.40	2,887	493.7	8.08	0.916	0.791	0.724	94.0	998	28.9
7	Min Value	379.0	6.50	2,601	483.8	7.09	0.899	0.781	0.709	89.6	869	20.6
8	Std. Dev. (σ)	5.44	0.484	158.1	3.92	0.527	0.004	0.005	0.005	2.38	69	5.3
9	2 Std. Dev. (2σ)	10.87	0.968	316.1	7.84	1.055	0.007	0.011	0.011	4.76	138	10.5
10												
11		V_{mp}	I_{mp}	P_{max}	V_{oc}	I_{sc}	I_{mp} / I_{sc}	V_{mp} / V_{oc}	FF	PF	Irradiance	Temp.
12		Volts	Amps	Watts	Volts	Amps				%	(W/m^2)	deg C
13	Sample I-V Data Set\	400.4	6.50	2,602	499.6	7.09	0.917	0.801	0.735	96.7	869	28.9
14	Sample I-V Data Set\	399.6	6.52	2,606	499.1	7.09	0.920	0.801	0.736	96.6	872	28.9
15	Sample I-V Data Set\	402.6	6.50	2,618	500.3	7.14	0.910	0.805	0.733	97.0	873	28.9
16	Sample I-V Data Set\	399.2	6.52	2,603	498.7	7.12	0.916	0.800	0.733	96.3	875	28.9
17	Sample I-V Data Set\	397.9	6.57	2,615	498.4	7.14	0.920	0.798	0.735	96.6	874	28.9
18	Sample I-V Data Set\	397.7	6.58	2,615	498.2	7.14	0.921	0.798	0.735	96.4	874	28.3
19	Sample I-V Data Set\	396.5	6.58	2,608	496.9	7.17	0.917	0.798	0.732	96.3	876	28.9
20	Sample I-V Data Set\	398.2	6.53	2,601	497.5	7.18	0.909	0.801	0.728	96.1	876	28.9
21	Sample I-V Data Set\	403.6	6.54	2,638	501.5	7.20	0.908	0.805	0.731	97.3	877	28.9
22	Sample I-V Data Set\	399.7	6.59	2,634	499.5	7.19	0.916	0.800	0.733	96.8	878	28.9
23	Sample I-V Data Set\	399.4	6.60	2,635	499.4	7.20	0.916	0.800	0.733	96.9	879	28.9

This step also creates the string data table and the parameter histograms, one for each parameter.



Using the Data Analysis Tool

5. Translate key parameters to SEC (optional)

These controls translate measured values of Vmp, Imp, Pmax, Voc and Isc to a user-defined irradiance and temperature.

Translations are useful for comparing data taken at different times of day or on different dates, and for module warranty claims.

Module:	Example PV module	
Module Temperature Coefficients		
Alpha Isc	0.004	%/ºC
Beta Voc	-0.3	%/ºC
Gamma Pmax	-0.4	%/ºC

Translate To:

Temperature		Irradiance	
25	ºC	1000	W/m^2

STC **Average**

Translate **Clear**

Directions:
1. Enter the module manufacturer and model number
2. Enter the three temperature coefficients
3. Enter the desired translation temperature and irradiance, or:
   - Press "STC" to enter Standard Test Conditions of 1000W/m^2 and 25°C
   - Press "Average" to enter the average test conditions of the currently loaded dataset.
4. Press "Translate"

- Some contracts call for translating one or more performance parameters to STC conditions. The Table tab in the DAT provides a means for doing this.
- Enter the temperature coefficients in %/°C
- Click 'STC'. You can also translate to other conditions.
- Click 'Translate'. Five new columns of translated data appear.

Translation equations for reference:

$$V_{octrans} = V_{ocm} / \{1+ (\beta_{Voc} /100)*(T_m - T_{trans})\}$$

$$I_{sctrans} = I_{scm} * [E_{trans} / E_m] / \{1+(\alpha_{Isc}/100)*(T_m - T_{trans})\}$$

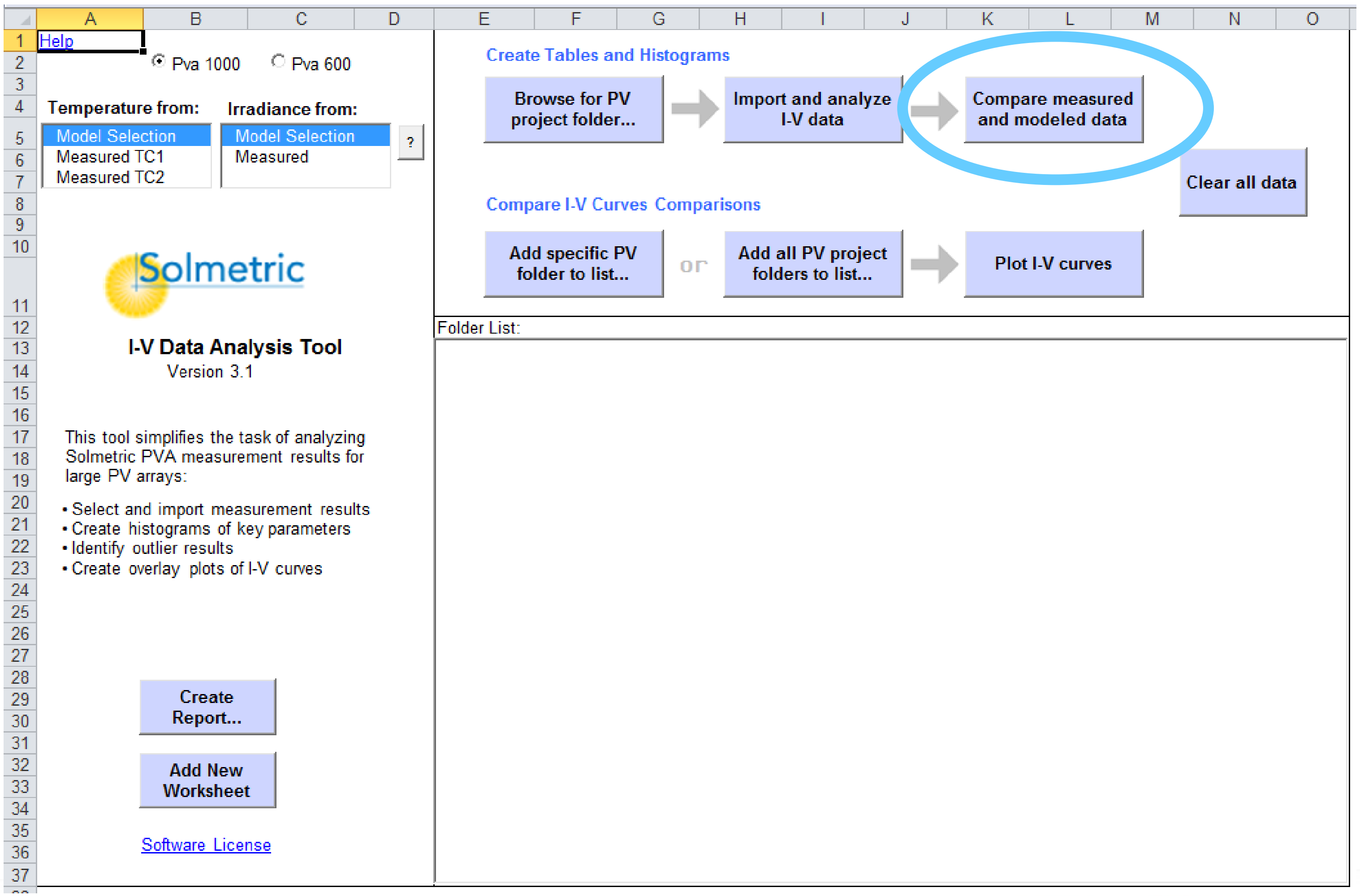
$$I_{mptrans} = I_{mp} * E_{trans} / E_m$$

$$V_{mptrans} = V_{mpm} / \{1+ (\gamma_{mpp} /100)*(T_m - T_{trans})\}$$

$$P_{mptrans} = I_{mptrans} * V_{mptrans}$$

Using the Data Analysis Tool

6. Compare measured and predicted values (optional)



Using the Data Analysis Tool

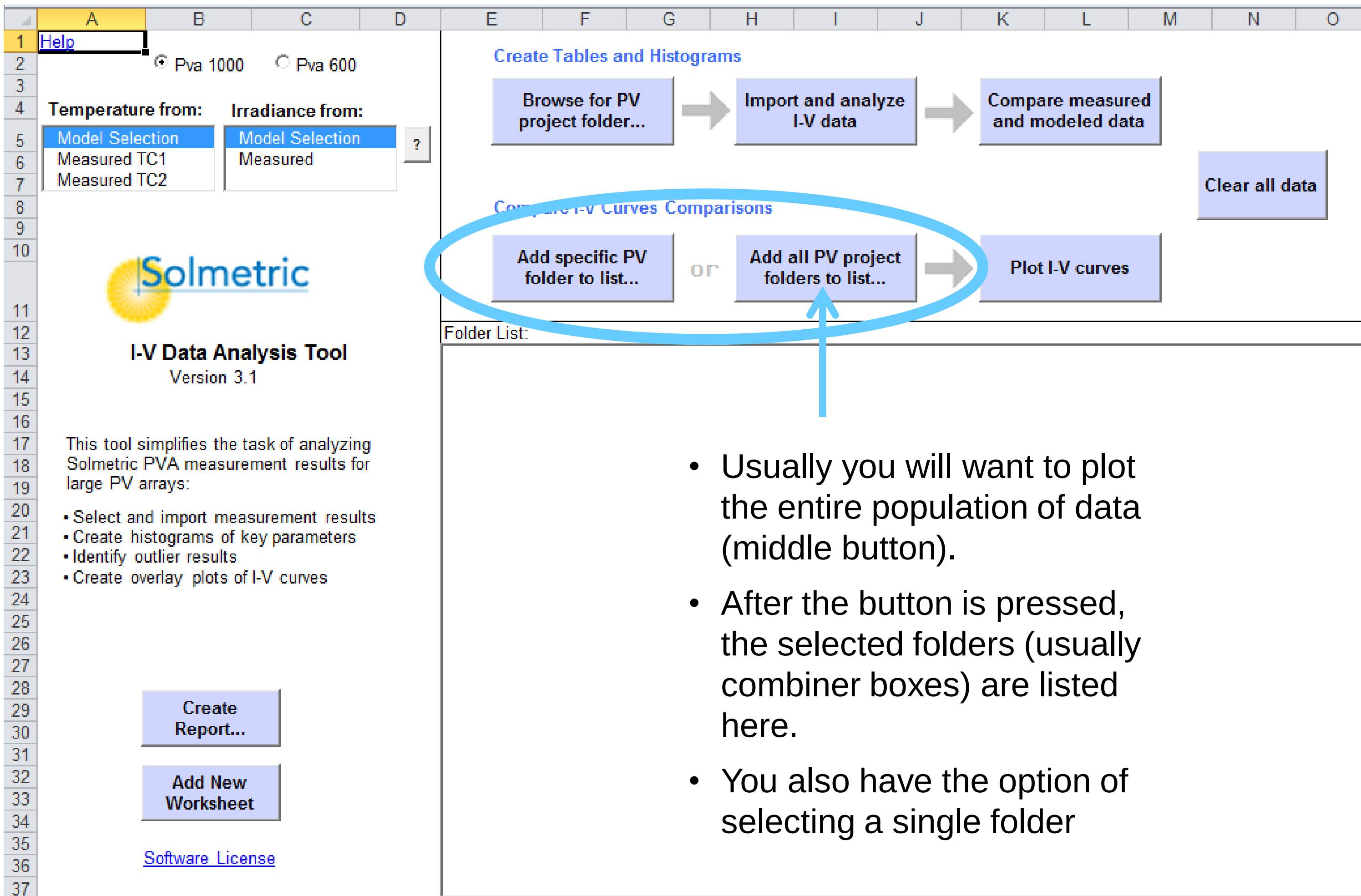
6. Compare measured and predicted values (optional)

Sample of the **Model** worksheet of the DAT

Home								
File Path	I_{sc} (Amps)		I_{mp} (Amps)		V_{mp} (Volts)		V_{oc} (Volts)	
	Measured	Model	Measured	Model	Measured	Model	Measured	Model
Combiner1\String1\String1 10-9-2013 02-01 PM.csv	6.09	6.17	5.63	5.74	354.8	369.6	449.0	458.8
Combiner1\String10\String10 10-9-2013 02-04 PM.csv	7.78	7.73	7.07	7.18	346.6	366.2	446.2	462.5
Combiner1\String11\String11 10-9-2013 02-05 PM.csv	6.96	6.85	6.37	6.37	348.5	369.9	445.1	462.2
Combiner1\String12\String12 10-9-2013 02-05 PM.csv	6.56	6.64	6.00	6.18	350.3	370.4	445.8	461.7
Combiner1\String13\String13 10-9-2013 02-05 PM.csv	5.97	6.25	5.43	5.82	353.9	371.3	445.1	460.8
Combiner1\String14\String14 10-9-2013 02-06 PM.csv	6.75	6.85	6.08	6.37	356.1	370.0	450.9	462.3
Combiner1\String15\String15 10-9-2013 02-06 PM.csv	6.92	7.07	6.35	6.57	357.6	370.4	453.5	463.6
Combiner1\String16\String16 10-9-2013 02-06 PM.csv	6.69	6.87	6.15	6.39	354.8	371.7	451.6	464.0
Combiner1\String17\String17 10-9-2013 02-07 PM.csv	7.22	7.50	6.61	6.97	354.3	370.4	453.2	465.5
Combiner1\String18\String18 10-9-2013 02-08 PM.csv	7.18	7.56	6.52	7.03	354.8	371.1	452.4	466.6
Combiner1\String19\String19 10-9-2013 02-08 PM.csv	7.20	7.25	6.61	6.74	353.2	371.7	452.1	465.7
Combiner1\String2\String2 10-9-2013 02-02 PM.csv	6.67	6.74	6.13	6.27	352.6	368.5	449.7	460.3
Combiner1\String20\String20 10-9-2013 02-08 PM.csv	7.16	7.38	6.58	6.86	354.0	370.6	453.0	465.3
Combiner1\String21\String21 10-9-2013 02-09 PM.csv	7.47	7.52	6.89	6.99	355.8	370.2	455.4	465.5

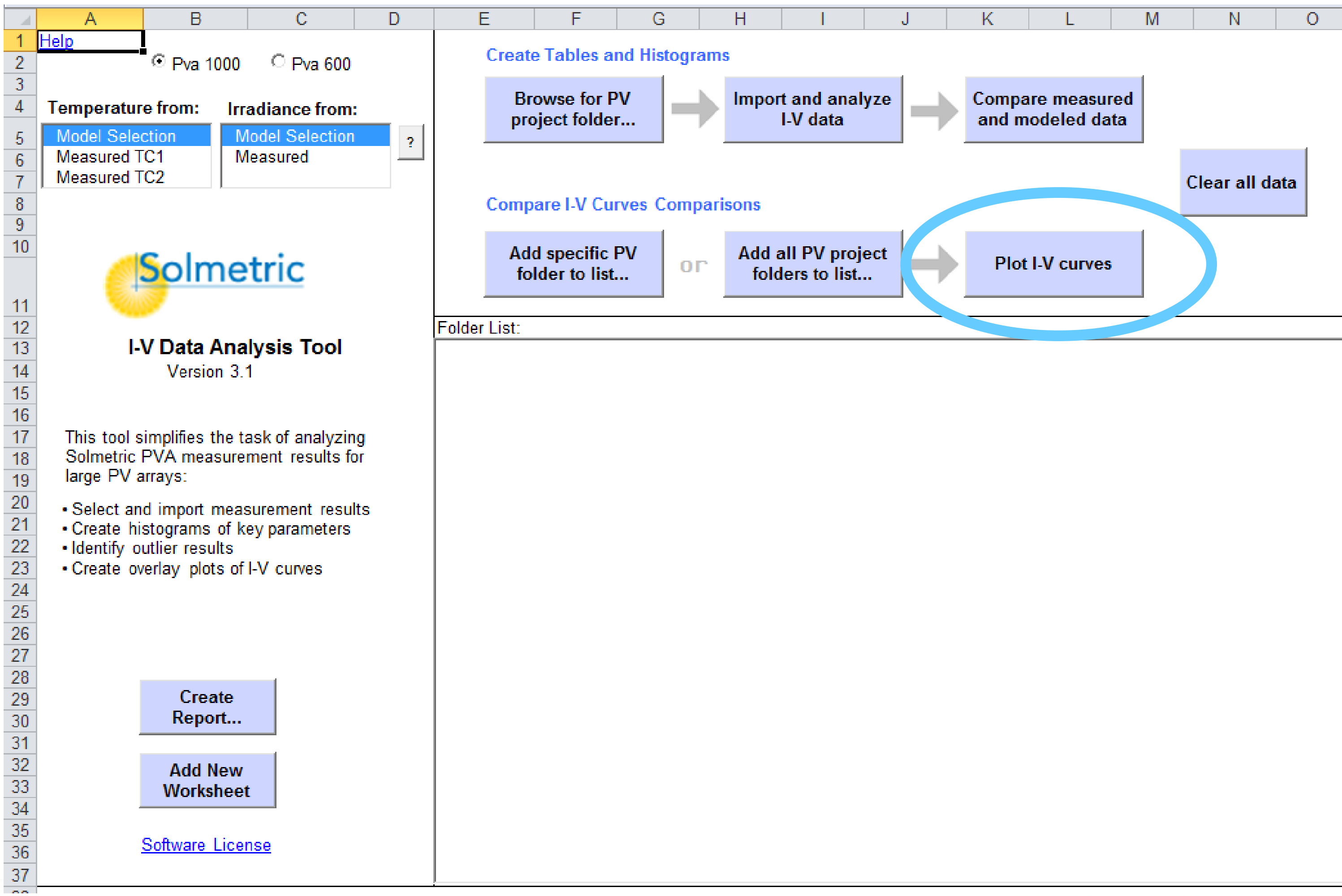
Using the Data Analysis Tool

7. Select which data to show in I-V graphs



- Usually you will want to plot the entire population of data (middle button).
- After the button is pressed, the selected folders (usually combiner boxes) are listed here.
- You also have the option of selecting a single folder

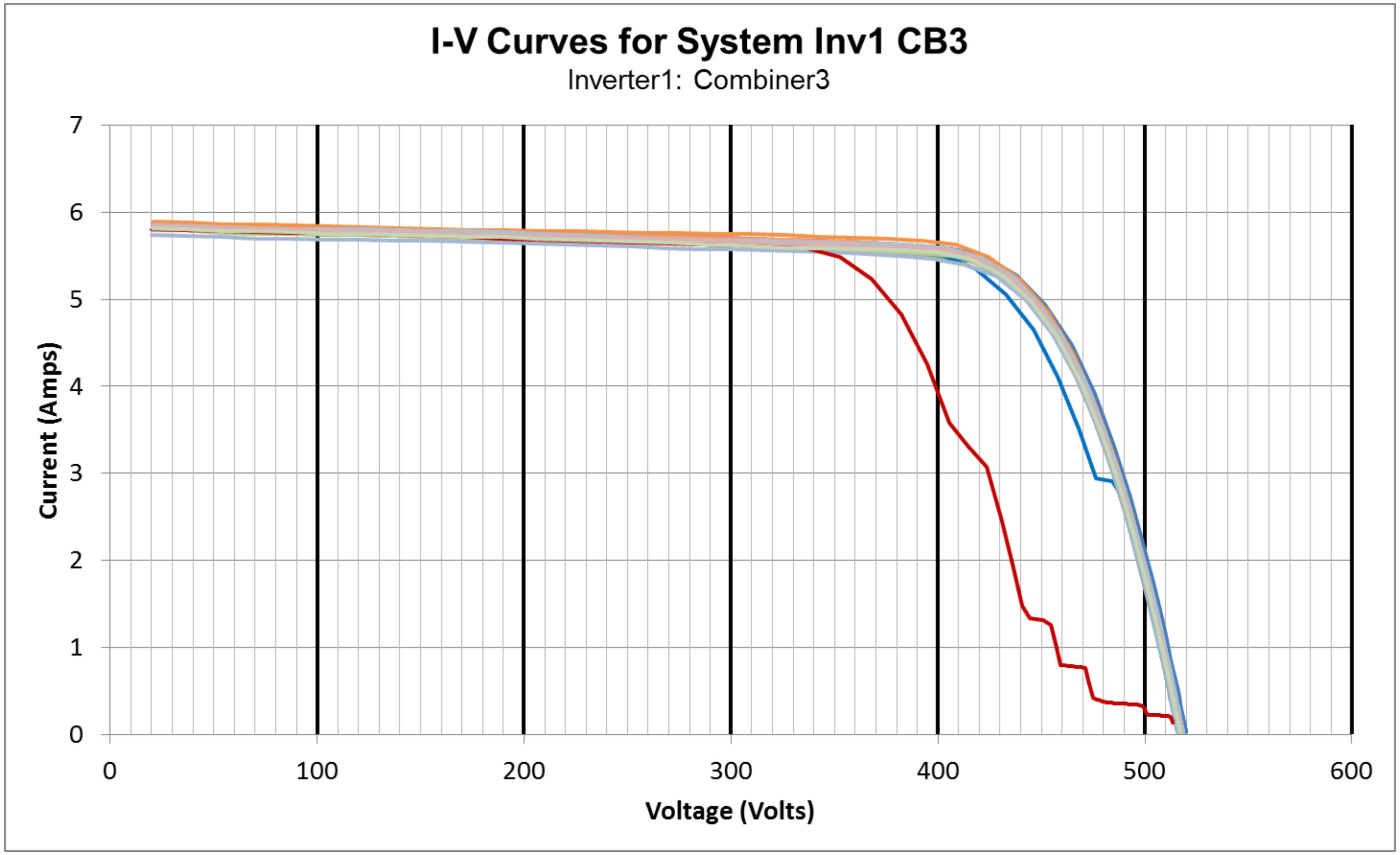
Using the Data Analysis Tool
8. Plot the I-V curves



Using the Data Analysis Tool

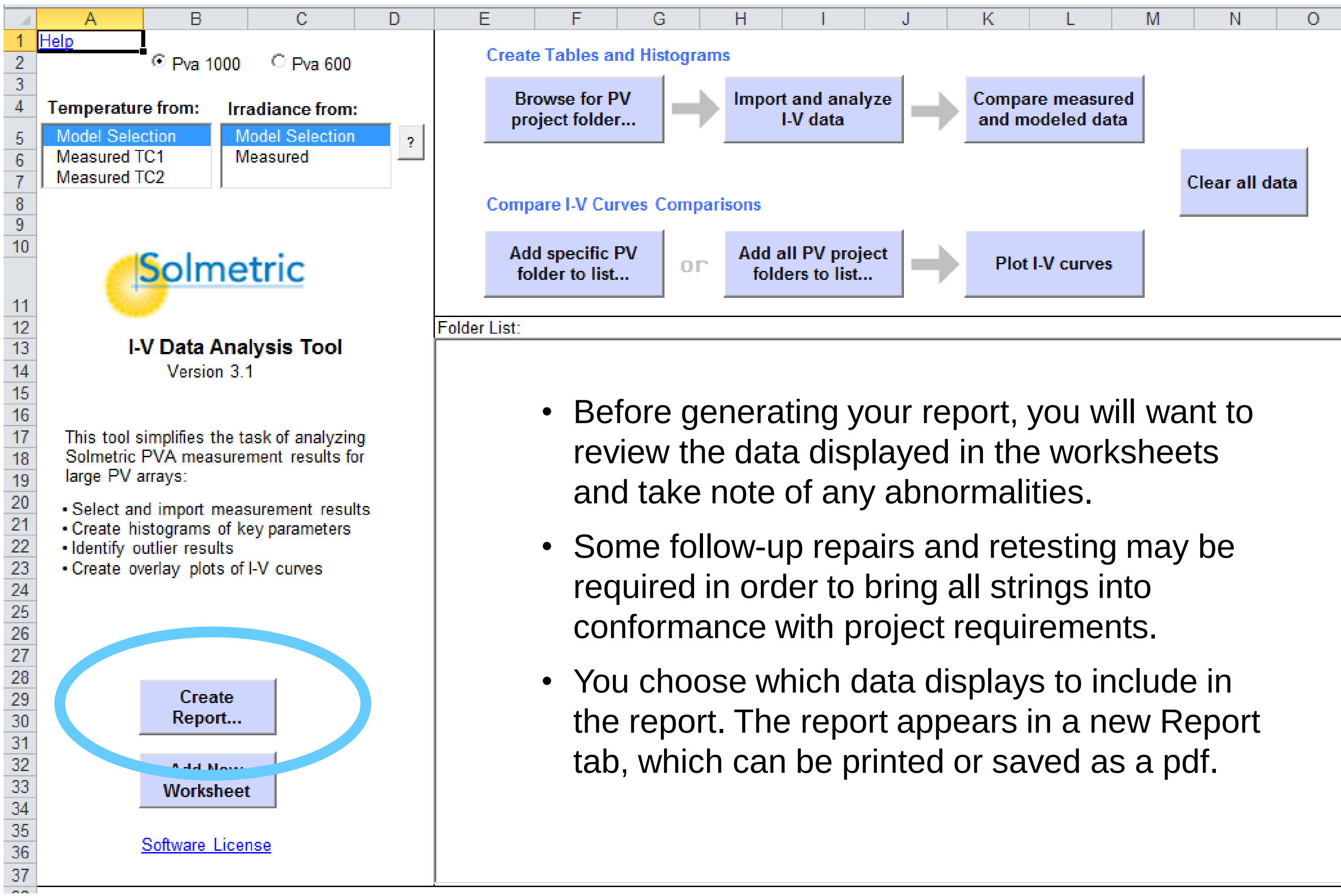
8. Plot the I-V curves

Sample of an **I-V Curves** worksheet of the DAT.



Using the Data Analysis Tool

9. Generate your report



- Before generating your report, you will want to review the data displayed in the worksheets and take note of any abnormalities.
- Some follow-up repairs and retesting may be required in order to bring all strings into conformance with project requirements.
- You choose which data displays to include in the report. The report appears in a new Report tab, which can be printed or saved as a pdf.

Solmetric PVA1000
Startup Training

March 22, 2015

Instructor:
Paul Hernday
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