I-V Curves, Electrical Performance of PV Devices

34553: Applied Photovoltaics

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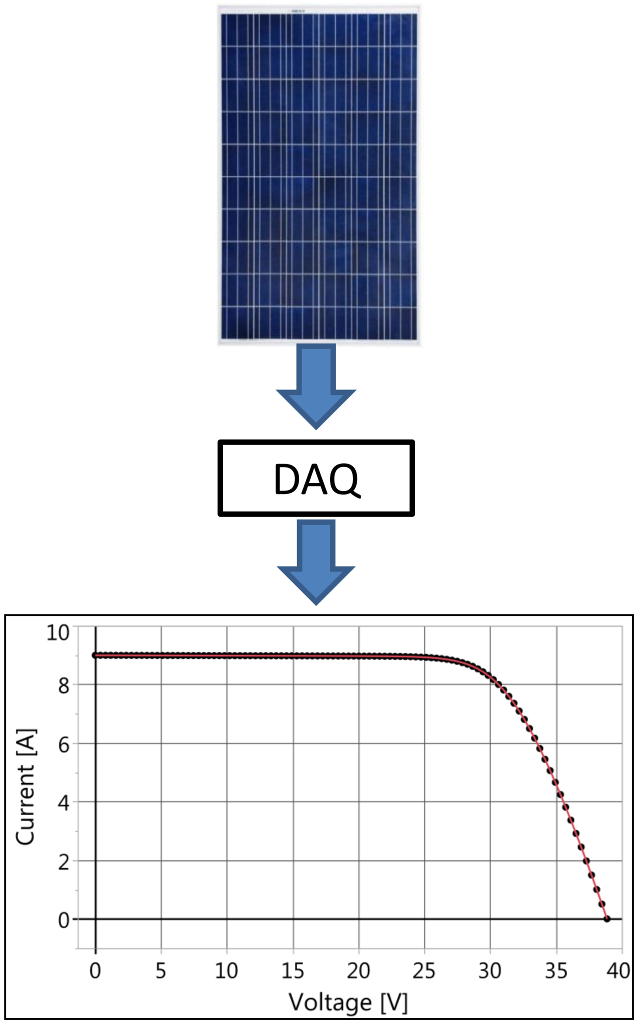
Outline

- Equivalent circuit models for the IV curve
  - 1 diode model
  - Use and application
- The I-V curve of PV devices
  - Parameters on the curve
  - Effects of irradiance and temperature
  - Solar simulators and methods for electrical characterization.
- Correction of I-V curves to standard conditions

Our Subject of Study: Electrical Characteristics of PV Devices

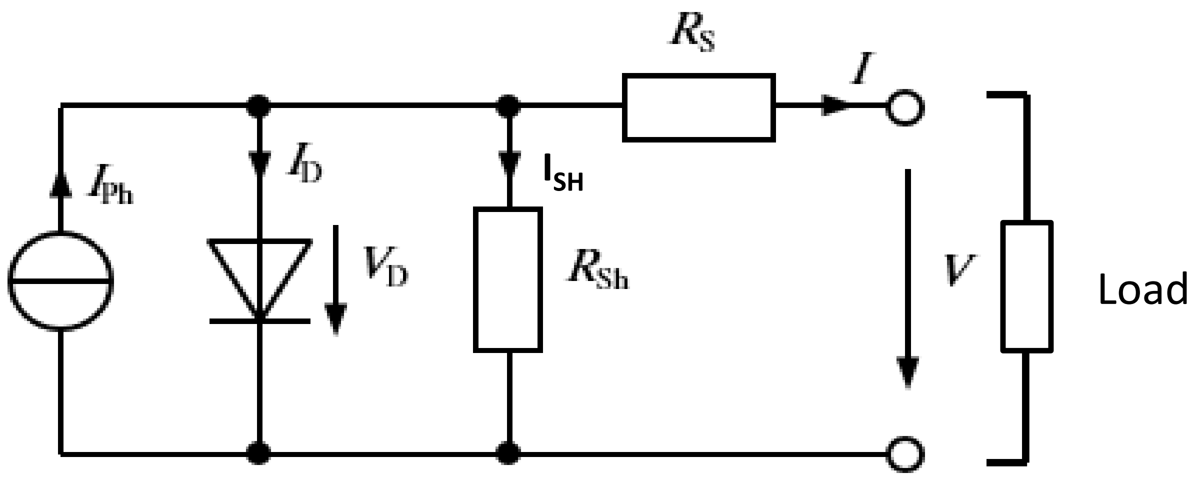


Units we'll be using:

- Basic electrical units:
  - Current [A]
  - Voltage [V]
  - Resistance [Ω]
  - Power [W]
  - Diode quality factor [unitless]

- Basic Meteo units
  - Irradiance [W/m^2]
  - Temperature [°C]

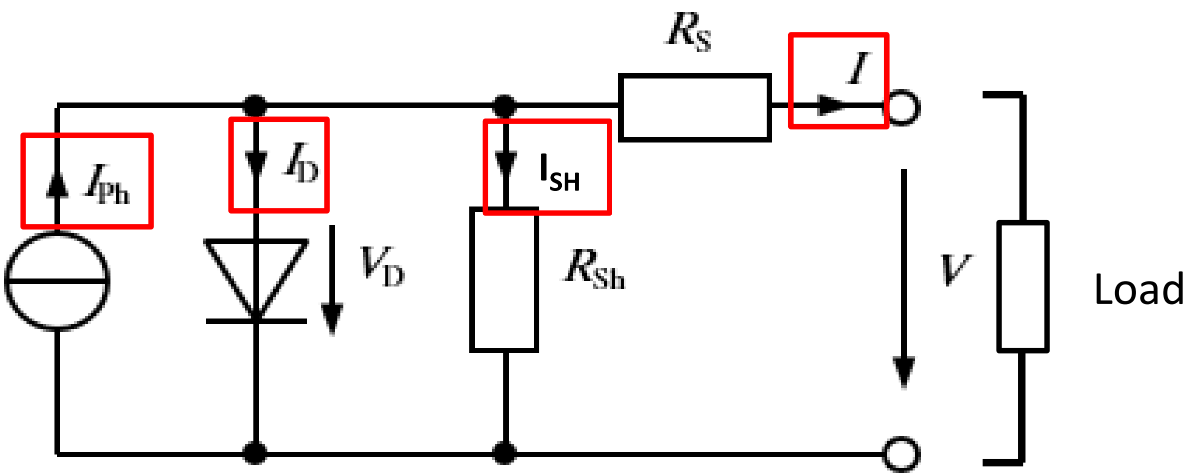
The One-Diode Model



- Can be used to model the I-V curve of PV device.
- This model is based on physical principles outlined in [1].

[1] Gray, J.L., *The Physics of the Solar Cell*, in *Handbook of Photovoltaic Science and Engineering*, A. Luque, Hegedus, S., Editor. 2011, John Wiley and Sons.

The One-Diode Model



- With Kirchhoff's current law (KCL) we see that:

$$I = I_{PH} - I_D - I_{SH}$$

Where:
I_{PH} = The photo generated current
I_D = The voltage dependent diode current
I_{SH} = The current lost through the shunt resistance
I = Output current to the load

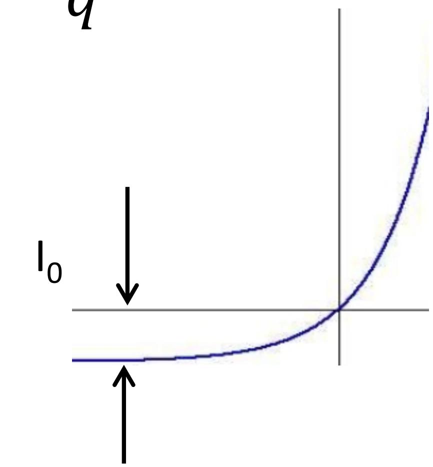
The One-Diode Model

- I_D is modeled using the Schockley diode equation
  - Note the voltage drop due to Rs

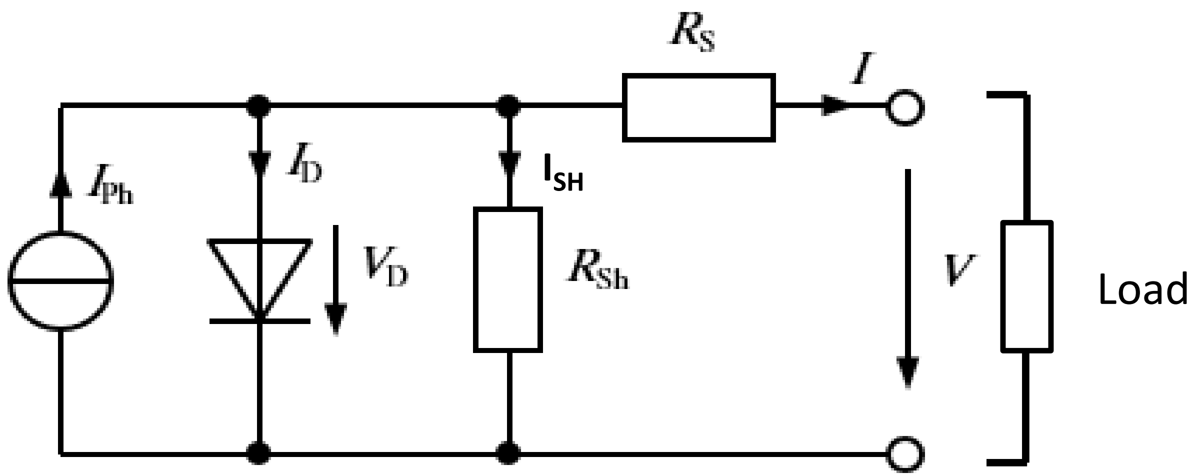
$$I_D = I_O \left[\exp\left(\frac{\boxed{V + I * R_S}}{n * \boxed{V_T}} \right) - 1 \right]$$

$$V_D = V + I * R_S \qquad V_T = \frac{k * T_C}{q}$$

Where:
I_0 = The reverse saturation current (A)
n = diode quality factor (dimensionless, between 1 and 2)
V_T = The thermal voltage
k = boltzmann's constant (1.381×10^{-23} J/K)
q = elementary charge (1.602×10^{-19} C)
T_C = p-n junction temperature (°C)



The One-Diode Model



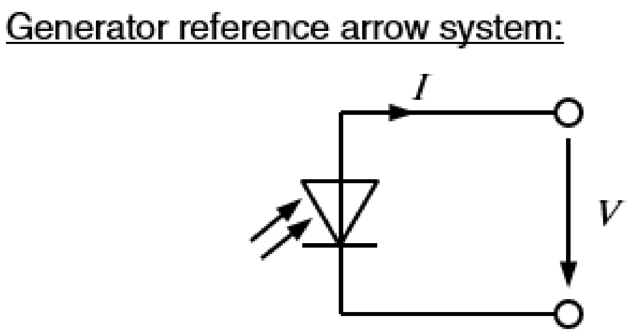
- Accounting for Rsh, we arrive at the final form of the equation:

$$I = I_{Ph} - I_0\left[\exp\left(\frac{V + I * R_S}{n * V_T}\right) - 1\right] - \boxed{\frac{V + I * R_S}{R_{SH}}}$$

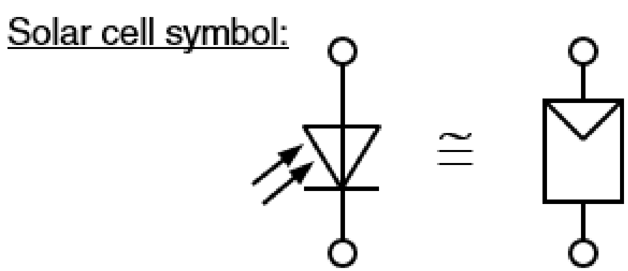
$$I_{SH} = \frac{V + I * R_S}{R_{SH}}$$

The Current-Voltage (I-V) Curve of a PV Device

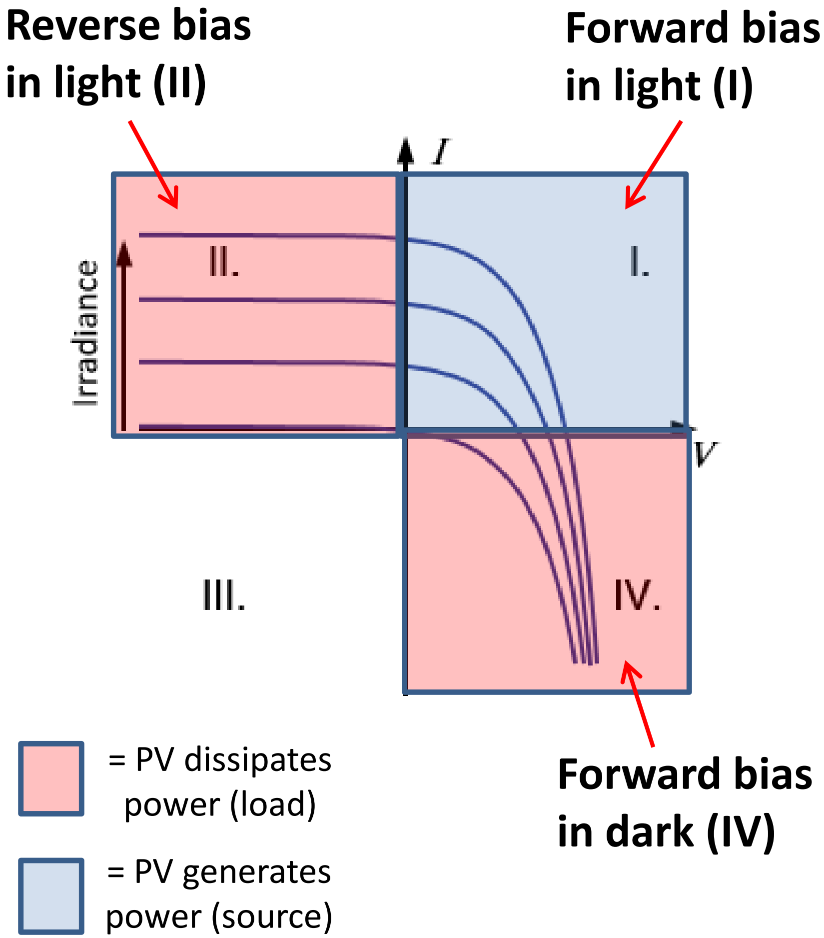
- PV devices are p-n junction diodes



Photodiode circuit in the absence of parasitic resistances.



Photodiode symbol (left) and PV symbol (right).



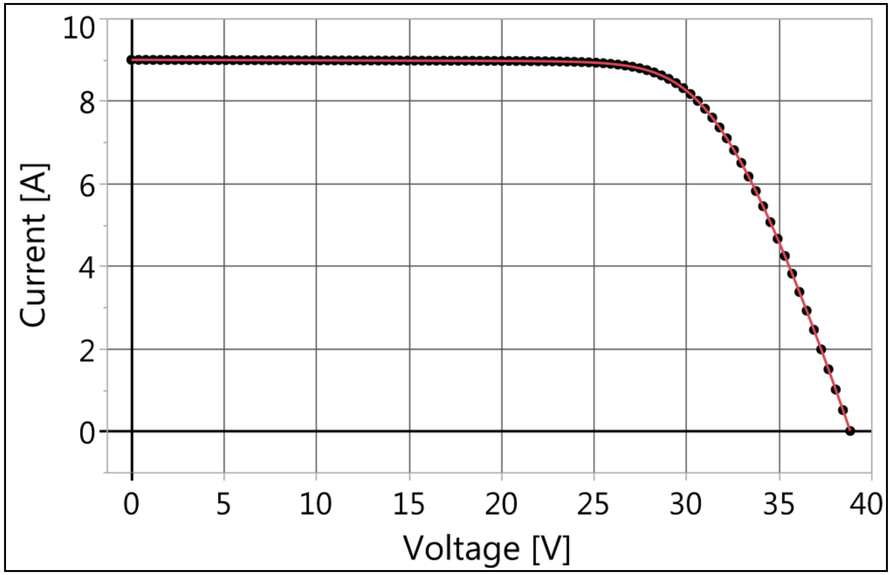
The Current-Voltage (I-V) Curve of a PV Device

- Shows all the possible operating points (I and V) a PV device will have at a specified set of conditions:
  - Spectrum
  - Irradiance
  - Cell temperature

- The most typical set of conditions (e.g. in datasheets) are called **S**tandard **T**est **C**onditions (**STC**):
  - AM 1.5G spectrum
  - 1000 W/m^2
  - 25 °C

- A wide range of conditions are possible in the field.

Quadrant I



Q: what determines precisely where on this curve the PV device will operate?

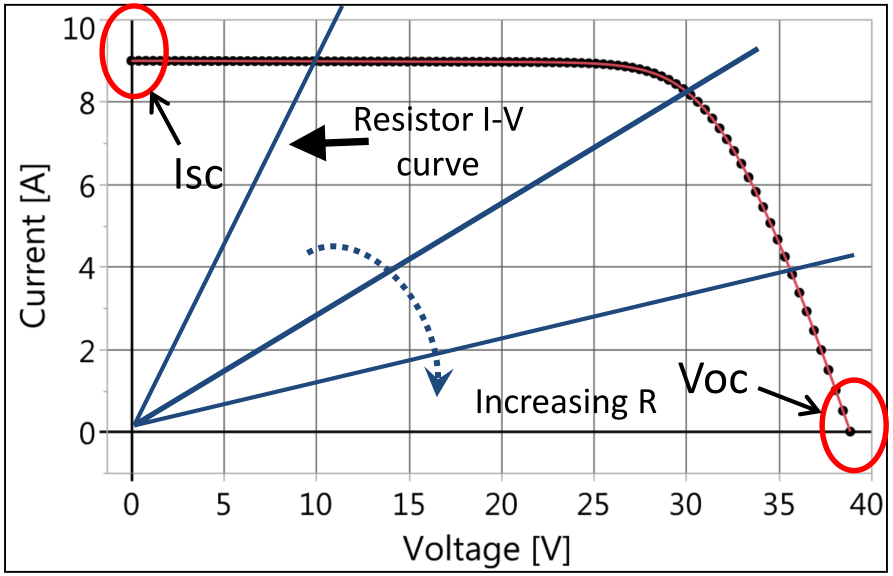
A: The load resistance!

The Current-Voltage (I-V) Curve of a PV Device

- There a three key measured points on the I-V curve of most interest they are:
  - The max power point (Pmp or Pmax)
  - **The short circuit current (Isc)**
  - **The open circuit (Voc)**

- **Voc**: operating point @ zero current i.e. when very *high* resistance is present.

- **Isc**: operating point when @ zero voltage i.e. when zero resistance is present.



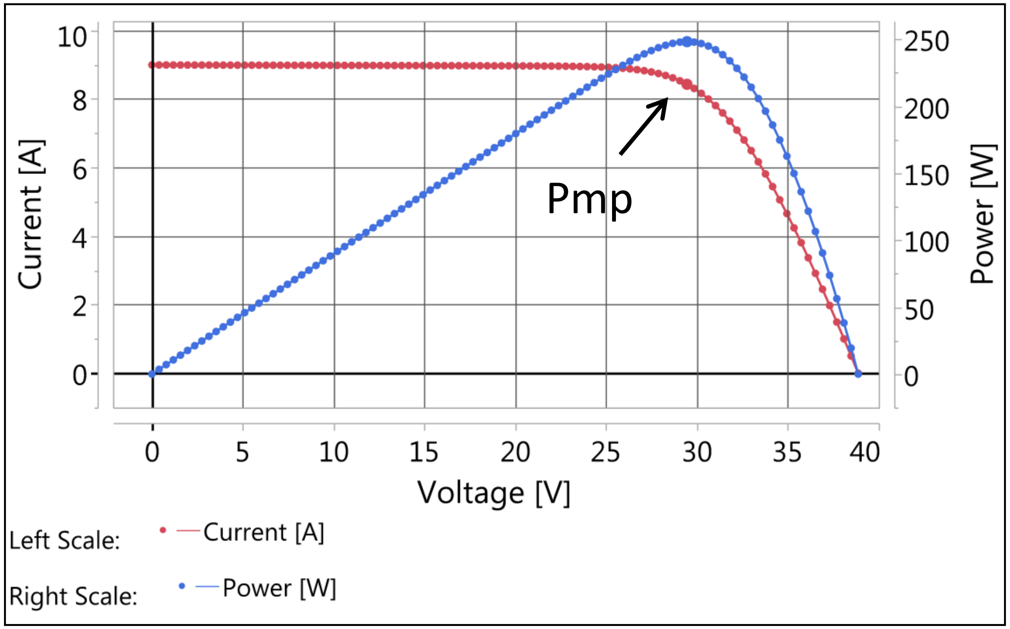
$$V = I \times R \qquad R = \frac{V}{I}$$

$$slope = \frac{Rise}{Run} = \frac{I}{V} = \frac{1}{R}$$

The Power-Voltage (P-V) Curve

- There a three key measured points on the I-V curve of most interest they are:
  - **The max power point (Pmp or Pmax)**
  - The short circuit current (Isc)
  - The open circuit (Voc)

- **Pmp**: operating point where the maximum power (I x V) can be extracted from the device.
  - The ideal resistance value (Rm) is only valid for a single set of conditions! (e.g. STC)

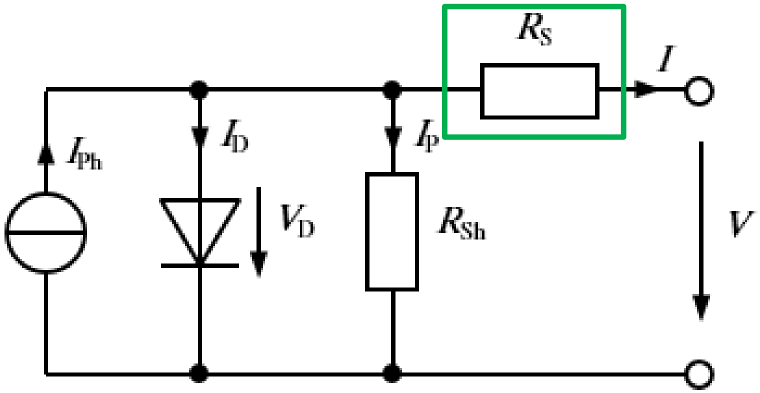


$$Pmp = Imp \times Vmp$$

$$Rm = \frac{Vmp}{Imp} =$$ Resistance when maximum power is transferred to the load

The Effect of Parasitic Resistances

- All solar cells have some level of **series** and **shunt** resistance.
  - This reduces efficiency and fill factor through dissipation of heat.



- **Series resistance**:
  - Prevents flow of I_{PH}.
  - Caused by metallization, bus bar contact to cell, and resistances in semiconductor itself.

Q: for the ideal solar cell **Series resistance** is high or low?

A: Rs should be low

The Effect of Parasitic Resistances

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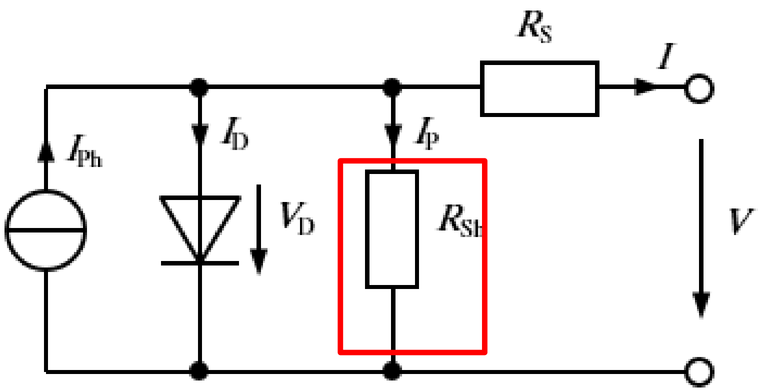


- **Shunt resistance**:
  - Provides an alternate current path for I_{PH} (short circuits).
  - Caused by Si manufacturing defects, impurities, but can become worse in field over time (PID, hotspots etc.)

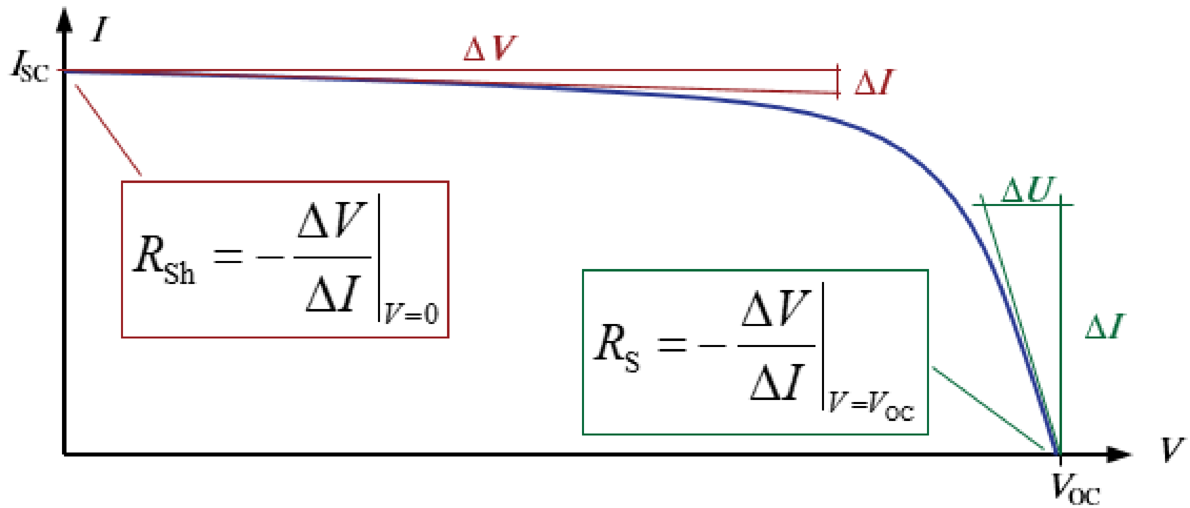
Q: for the ideal solar cell **Shunt resistance** is high or low?

A: Rsh should be high

Series and Shunt Resistance Estimation

$$V = I \times R \qquad R = \frac{V}{I}$$

$$slope = \frac{Rise}{Run} = \frac{I}{V} = \frac{1}{R}$$



$$R_{SH} = \left|\frac{\Delta V}{\Delta I}\right|_{V=0}$$

$$R_S = \left|\frac{\Delta V}{\Delta I}\right|_{V=V_{OC}}$$

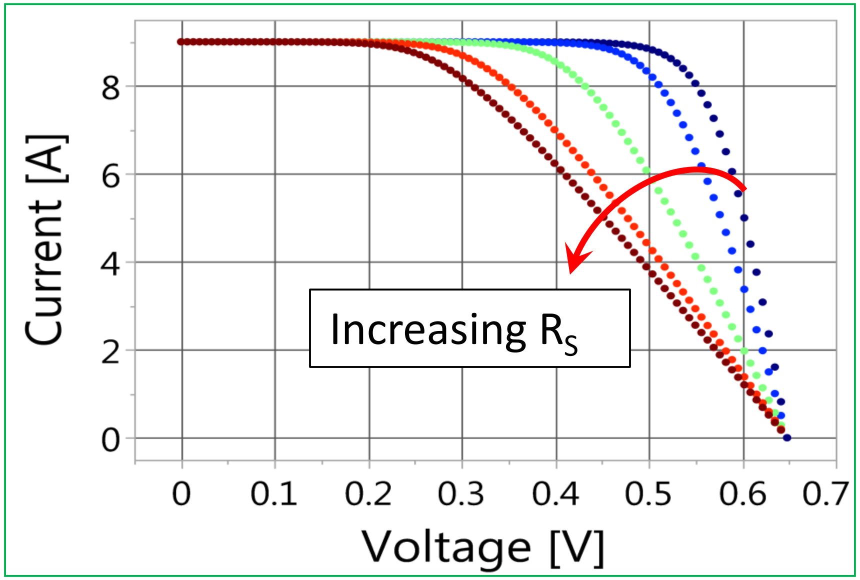
The range chosen for ΔV and ΔI will affect the R_{SH} and R_S values

- 0V to 0.1*Voc is a good start for R_{SH}
- 0A to 0.3*Isc is a good start for R_S

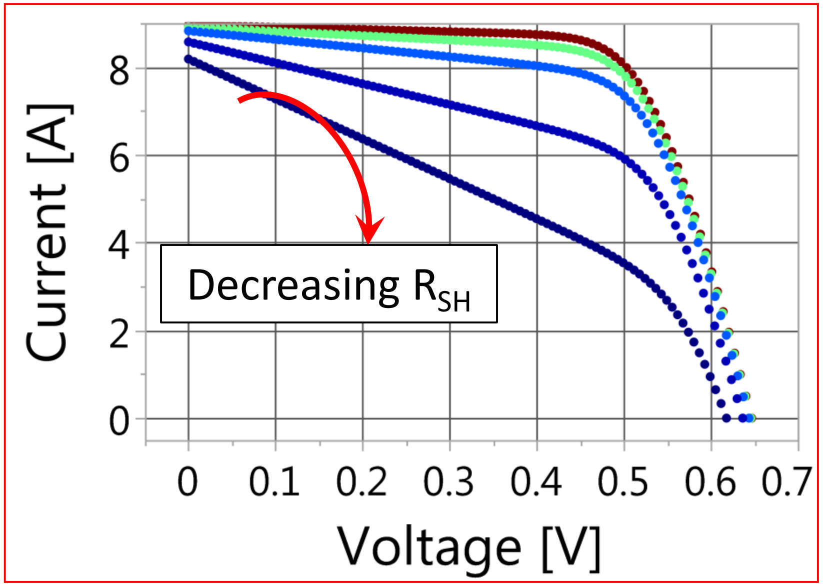
*Fitting the measured I-V curve to the one or two diode model can also be done to estimate R_{SH} and R_S

*Additional methods for estimating R_s are outlined in IEC 60891

Effects of Series and Shunt Resistance on the I-V Curve



Simulated for a single 6” cell with Rs from 5mΩ to 35mΩ



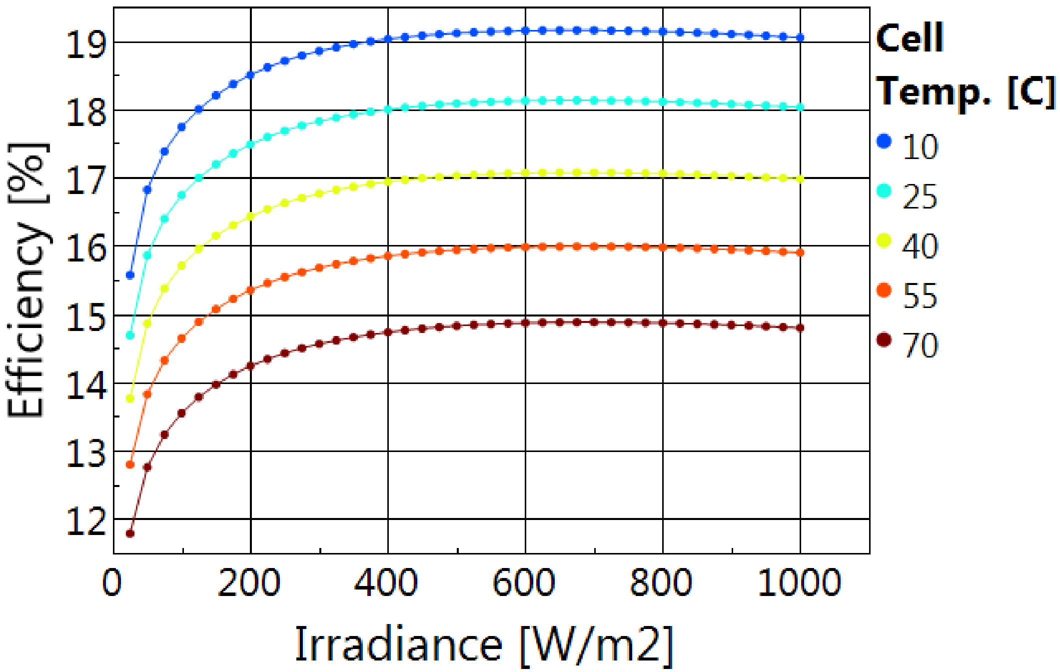
Simulated for a single 6” cell with Rsh from 2Ω to 0.1Ω

Calculating Efficiency

$$\eta = \frac{Power\ out}{Power\ in}$$

$$\eta = \frac{Pmp}{G * A} * 100$$

Where:
η = efficiency [%]
G = in plane irradiance [W/m^2]
A = module area [m^2]



Efficiency as a function of irradiance for a 295Wp module with 5 bus bars (simulated in PVSyst)

Calculating Efficiency

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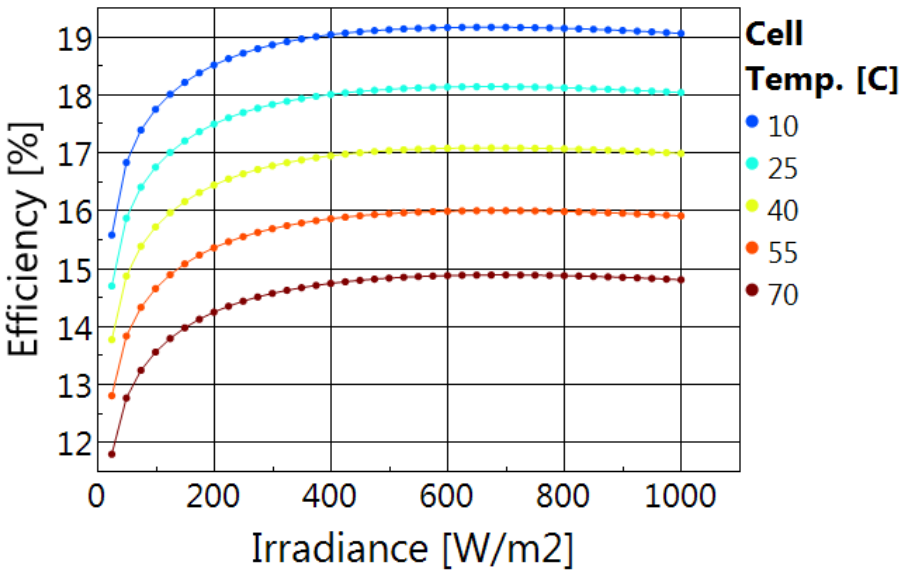
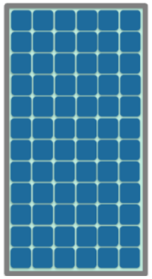
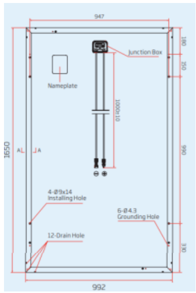


Efficiency as a function of irradiance for a 295Wp module with 5 bus bars (simulated in PVSyst)

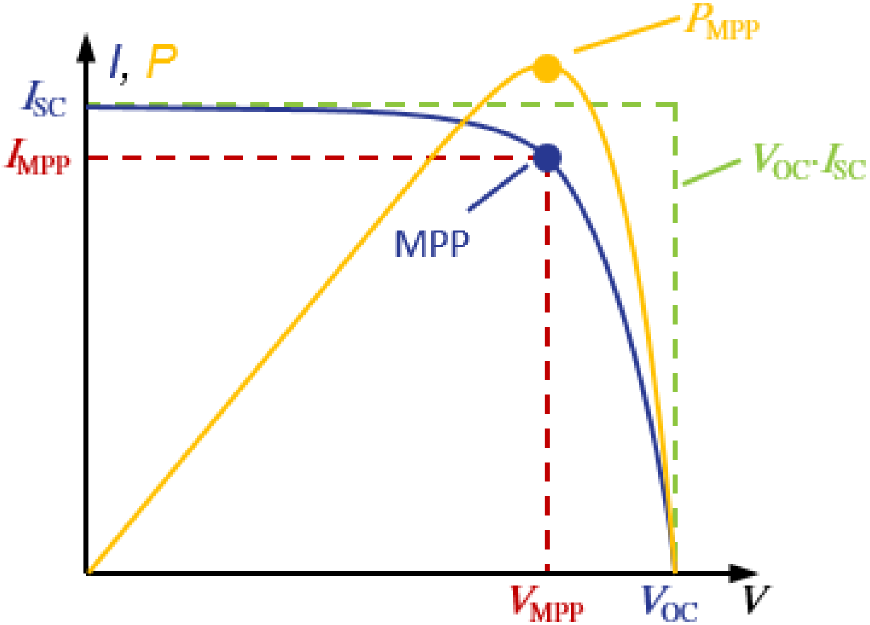
Which area!?

For modules it is standard to use the area that includes the frame (i.e. inactive area is included)





Calculating Fill Factor (FF)



$$FF = \frac{V_{MPP} \cdot I_{MPP}}{V_{OC} \cdot I_{SC}}$$

- FF is a measure of the I-V curve's "squareness".
- FF decreases with increase in R_S and decrease in R_{SH}

Fill Factor: Typical Values

Polycrystalline Si cell: 0.75-0.80

Monocrystalline Si cell: 0.80-0.85

Source: http://iea-pvps.org/fileadmin/dam/intranet/ExCo/IEA-PVPS_T13-01_2014_Review_of_Failures_of_Photovoltaic_Modules_Final.pdf

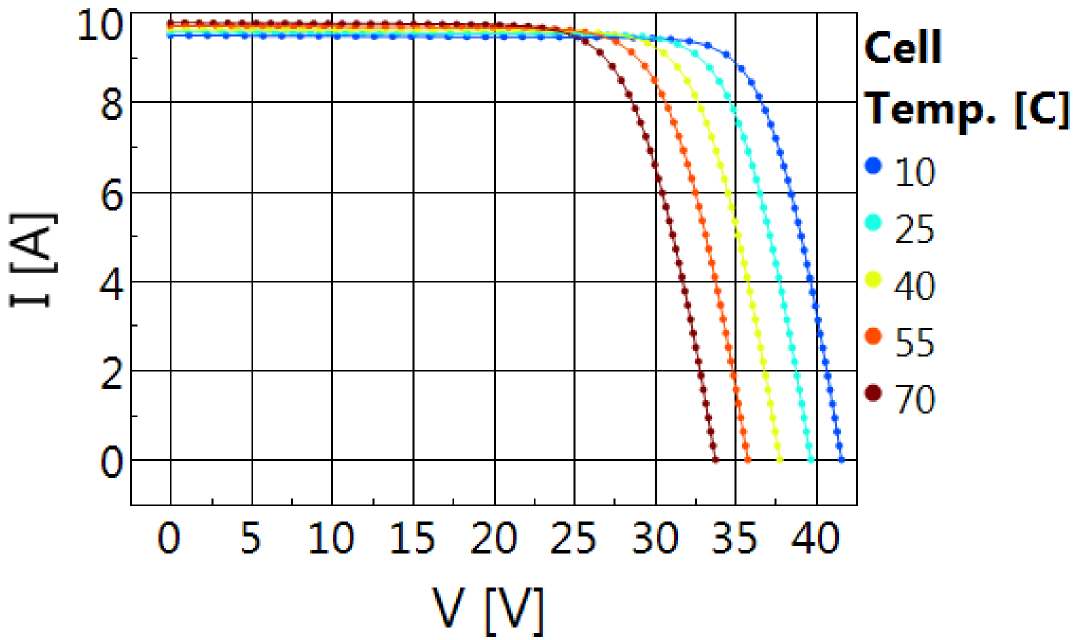
The Effects of Irradiance and Temperature on the I-V curve

Irradiance (W/m^2)	Module Temperature (°C)			
	15	25	50	75
1100	NA	x	x	x
1000	x	x	x	x
800	x	x	x	x
600	x	x	x	x
400	x	x	x	NA
200	x	x	x	NA
100	x	x	NA	NA

Irradiance and temperature measurement matrix specified in IEC 61853-1

- Modules are rated at STC conditions (x)
  - But STC is practically never seen in the field.
- Since PV behavior is primarily driven by irradiance and temperature:
  - It is useful to characterize performance at more conditions than STC.
- Let's look at how the I-V curve changes with irradiance and temperature.

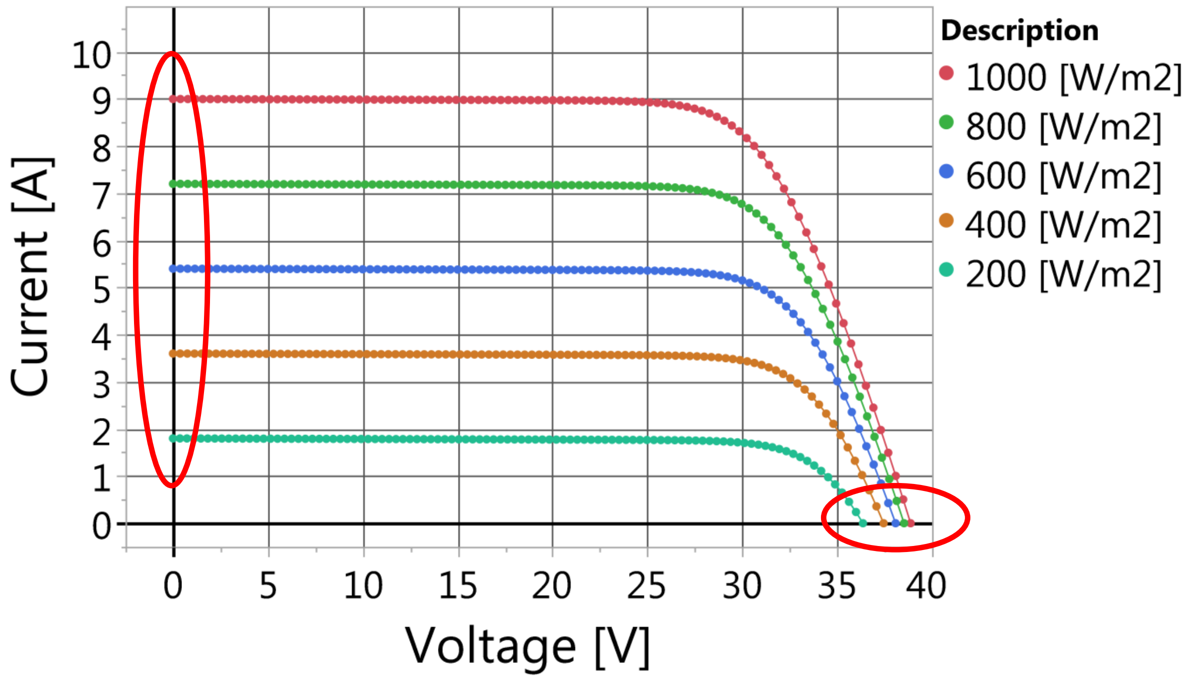
The Effect of Temperature on the I-V Curve



$$I_0 = qA\frac{D\boxed{n_i^2}}{LN_D}$$

- Voc, Vmp and Pmp *decrease* with increasing temperature.
  - High intrinsic carrier concentration (n_i)-> higher saturation current (I_o)-> lower Voc.
- Isc *increases* with increasing temperature
  - Due to decreased bandgap energy at higher temperature

The Effect of Irradiance on the I-V Curve

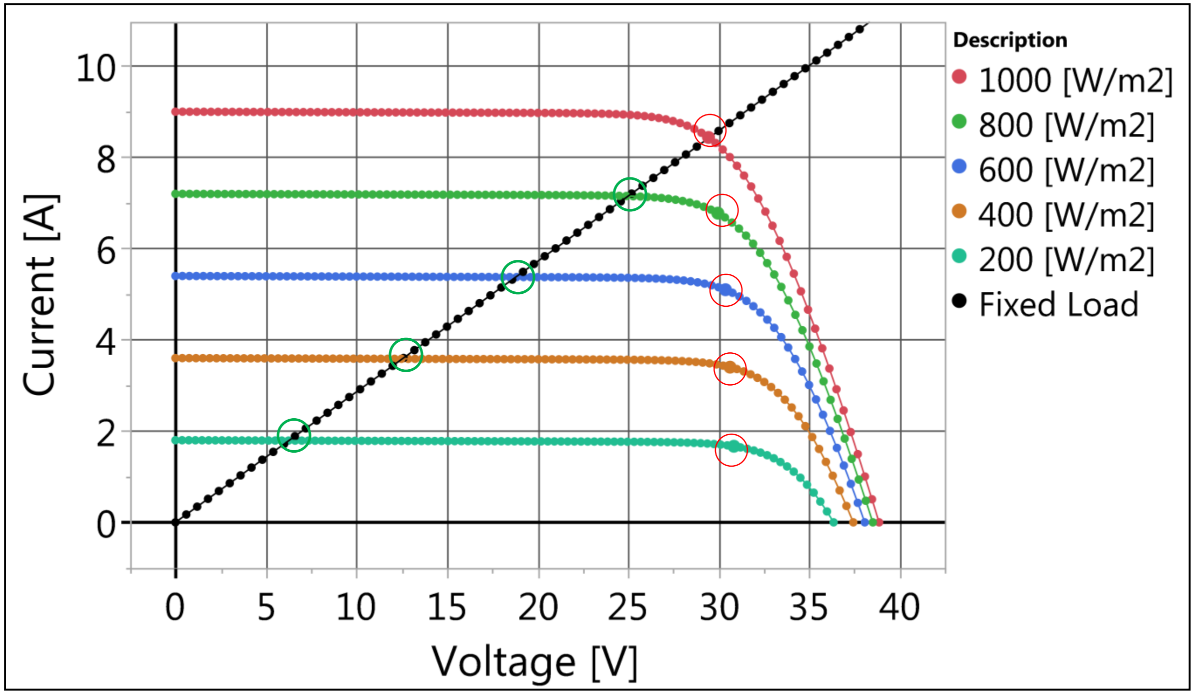


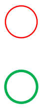
- Current (I_{sc} and I_{mp}) change *linearly* with irradiance.
  - This is a good assumption down to ≈ 100 W/m^2
  - You can check this assumption w/ simple regression of Isc by Irradiance (see IEC 60904-10).
- Voltage changes *logarithmically* with irradiance.
  - Thus, power is also subjected to this effect.

$$V_{OC} = \frac{nkT}{q} \ln\left(\frac{I_L}{I_0} + 1\right)$$

Pmp at Multi-Irradiance with Fixed Load

- Attaching a fixed load optimized for STC (Rm) wouldn't be a clever idea!
- Using a fixed load would result in significant efficiency loss at low irradiance.
- Thus, we can see the need for max power point tracking (MPPT)
  - *Week 6 lecture*





STC Measurements of Solar Devices

IV Curve Parameters to be measured:

- Irradiance Measurement
- Temperature Measurement
- Voltage Measurement
- Current Measurement

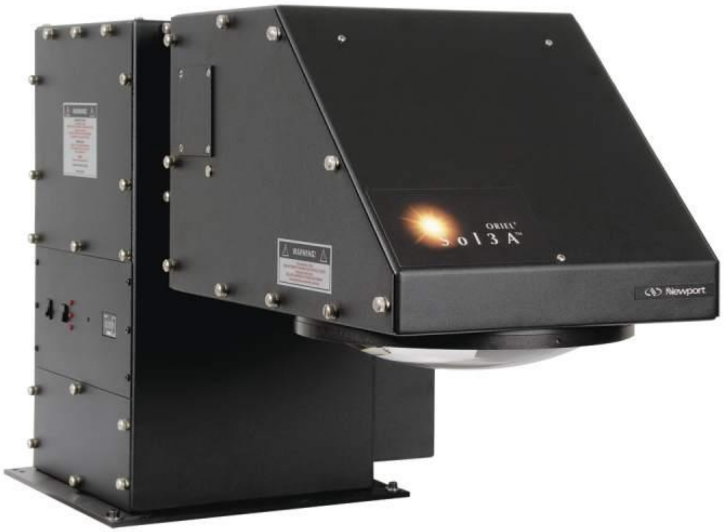
Equipment in a typical test setup:

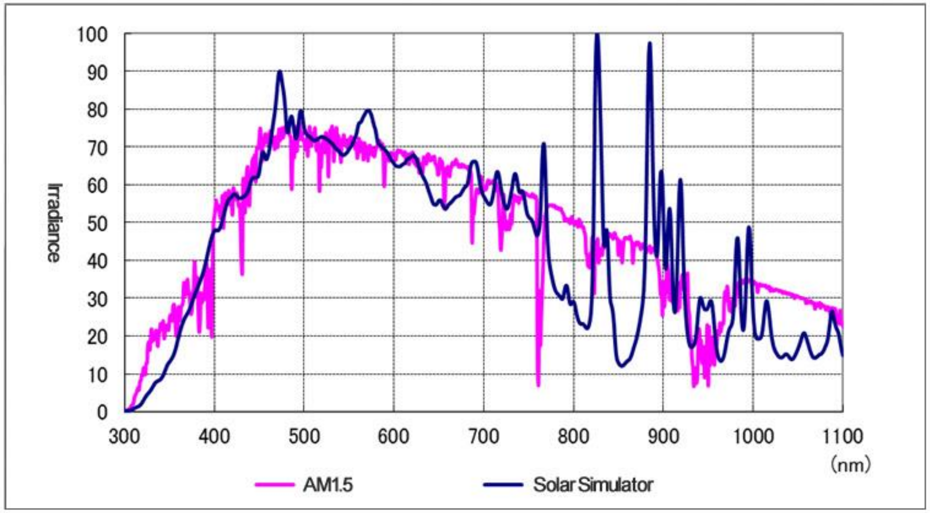
- Light Source (Solar Simulator)
- Irradiance Sensor
- Temperature Sensor
- Active Load
- Acquisition system
- Other elements: Working reference devices, irradiance filters, connectors, etc.

STC Measurements of Solar Devices

Light Source (Solar Simulator)

- Irradiance should be homogeneous within the cell active area
- Irradiance should remain stable in time within the IV curve acquisition
- Pulsed Light (pulse duration in ms, no temperature rise on device)
- Steady State (heats up the device but best for avoiding capacitive effects)





STC Measurements of Solar Devices

Light Source (Solar Simulator)

Standard IEC 60904-9: Solar simulator Performance Requirements

Classification	Spectral match to all intervals as specified in Table 1	Non-Uniformity of irradiance	Short Term Instability (STI)	Long Term Instability (LTI)
A	0.75 – 1.25	2%	0.5%	2%
B	0.6 – 1.4	5%	2%	5%
C	0.4 – 2.0	10%	10%	10%

- Classification as Class A, B or C regarding temporal stability (LTI and STI), spatial uniformity and spectral energy distribution of irradiance closely matching AM1.5 spectrum

STC Measurements of Solar Devices

Irradiance Sensor

- Calibrated Reference cell with known output at STC conditions.
- Should be temperature monitored as well if possible.
- The Spectral Response should closely match the one of the device to have low MM error on Isc measurement.

STC Measurements of Solar Devices

Temperature Sensor

- Surface mounted on the back of the DUT (PT100 sensors or thermocouples)
- The DUT can be mounted in a temperature controlled surface to keep it at 25 ˚C

- Non-contact IR temperature sensor **(+/-1°C).**
- Allows faster sample change between measurements.
- Emissivity of different materials (e.g. polymers and glass) are different and can introduce an error if not configured properly.
- Sensitive to surrounding heat sources and reflections from glass.

- Contact resistive temperature device (RTD) – Class A PT100 (**accuracy +- 0.15°C at 0C, +-0.21°C at 30C)**
- Needs to be manually attached and removed for each sample measured.
- A poor contact quality with the surface of the DUT can produce measurement errors.

STC Measurements of Solar Devices

Temperature Sensor

Nevertheless, temperature related uncertainties exceeding 2ºC may strongly (>1%) affect the power rating.

Ambient temperature may not be a good indication of the module temperature. The temperature non-uniformity and gradient must be considered.

Additional error sources related to sensor specific issues may also occur (e.g contact quality for contact sensors and radiative emission of surrounding heat sources for IR sensors).

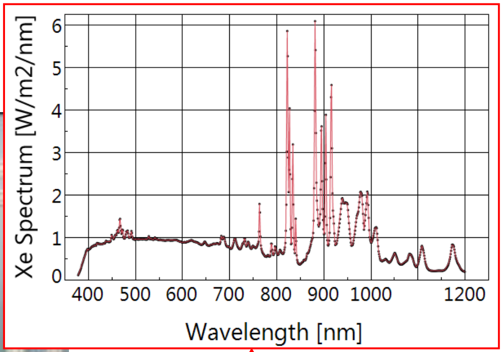
C. Monokroussos et al., “Impact of Calibration Methodology into the Power Rating of c-Si Modules under Industrial Conditions” 28th EUPVSEC, 2013

Typical Indoor Solar Simulator for PV Module Testing

Electronics (in back):
- Load (MOSFET)
- Flash regulator
- Data acquisition

Reference cell

PV module under test



Xe flash lamp
- 100-1100 W/m^2 variable intensity.
- 10-40ms flash time.

- Simulators with LED based light sources can also be used.
- Quality of indoor light sources defined according to:
  - Spectral match to AM 1.5G
  - Spatial non-uniformity
  - Stability

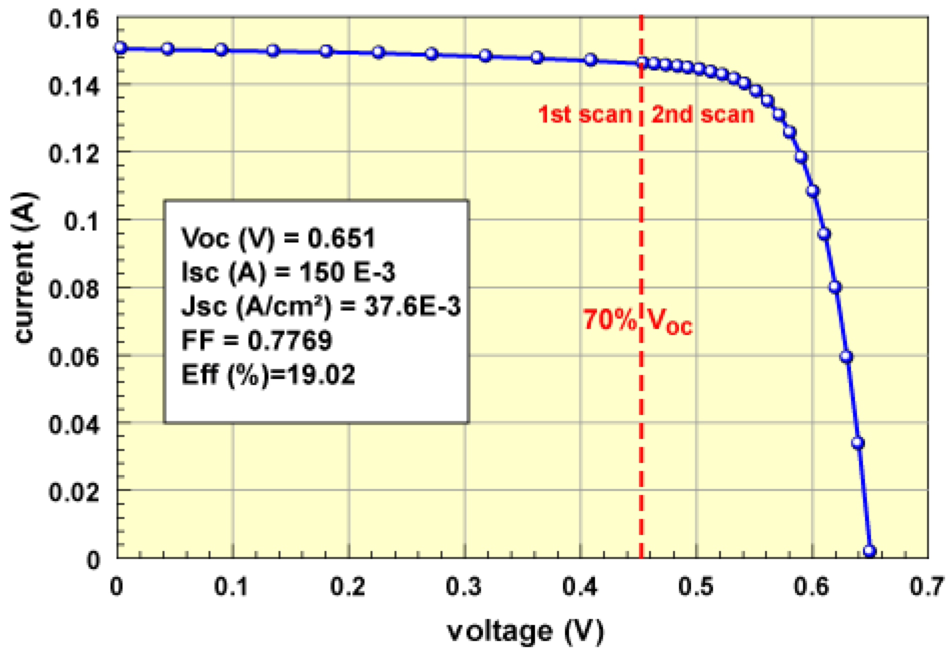
STC Measurements of Solar Devices

Active Load

- Should allow to reach currents higher than Isc and voltages above Voc.
- 4 quadrant loads allow measured zero crossings in I and V.
- Performs a voltage sweep from V=0 to Voc.
- Speed and direction of voltage sweep can be important if measuring cells with capacitive effects.

Acquisition system

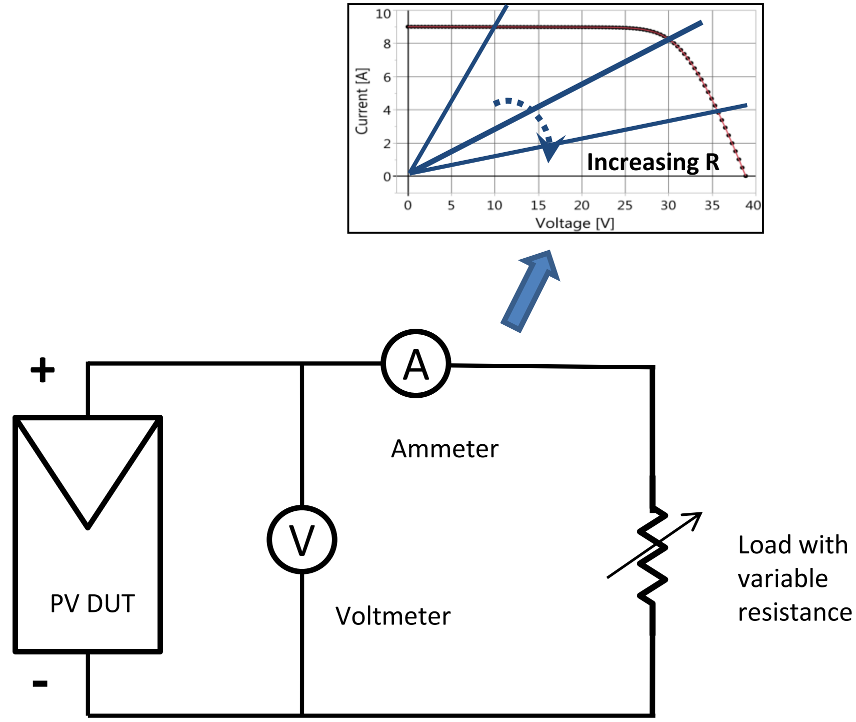
- Acquires Irradiance, Temperature, Voltage and Current within the duration of the voltage sweep and light pulse.
- Samples should be concentrated around the Pmax to obtain maximum resolution.



STC Measurements of Solar Devices

Active Load

- As we've seen the Operating Point change as a function of the load resistance, this offers a straight forward way of measuring an I-V curve.
  - **Via potentiometers or rheostats.**
  - **Via electronic loads (allow 4 quadrant measurements)**
  - **Other alternatives (e.g. capacitor loads)**



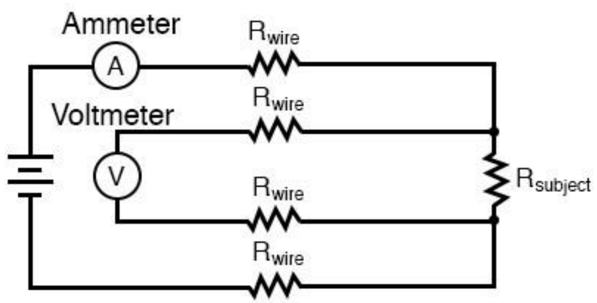
Excellent review paper on this topic

E. Duran et al., "Different methods to obtain the I-V curve of PV modules" proceedings of the 2008 IEEE PVSC conference

STC Measurements of Solar Devices

Other Considerations

- 4-wire connection between the measurement system and the device should be used always for cells with high current. The wires which measure the DUT voltage are separated from the wires where the high current flows, avoiding incorporating their voltage drop into the measurements.



$$R_{subject} = \frac{\text{Voltmeter indication}}{\text{Ammeter indication}}$$

- Cell should be placed on a flat surface and perpendicular to the light source. Inclination between device and incident light would produce angle of incidence errors.

- When irradiance is to be measured with a reference cell, the reference cell is at the same plane of irradiance as the device to be measured.

Reference Devices & Calibration Traceability

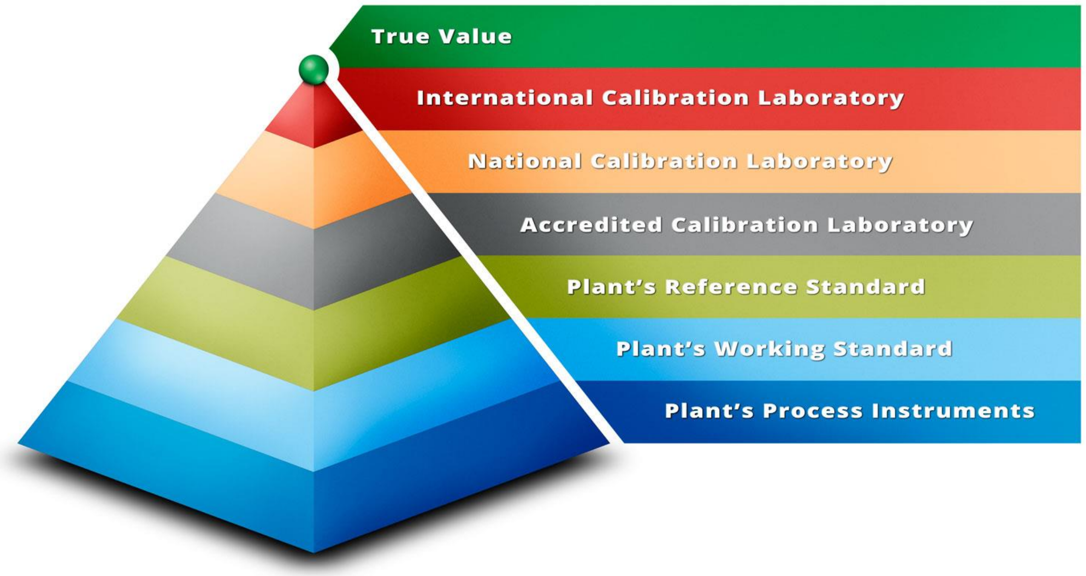
Irradiance measurement is the biggest uncertainty contributor in the determination of electrical performance of PV devices.

A reference device is a calibrated device used to measure irradiance of simulated or natural sunlight. It can also be used as the sensor in the feedback loop to set the irradiance level of the solar simulator to measure solar devices of similar characteristics.

The standard IEC 60904-2 : ”Requirements for reference solar devices” establishes requirements for the classification, selection, marking, packaging, calibration and care of reference solar devices.

Reference Devices & Calibration Traceability

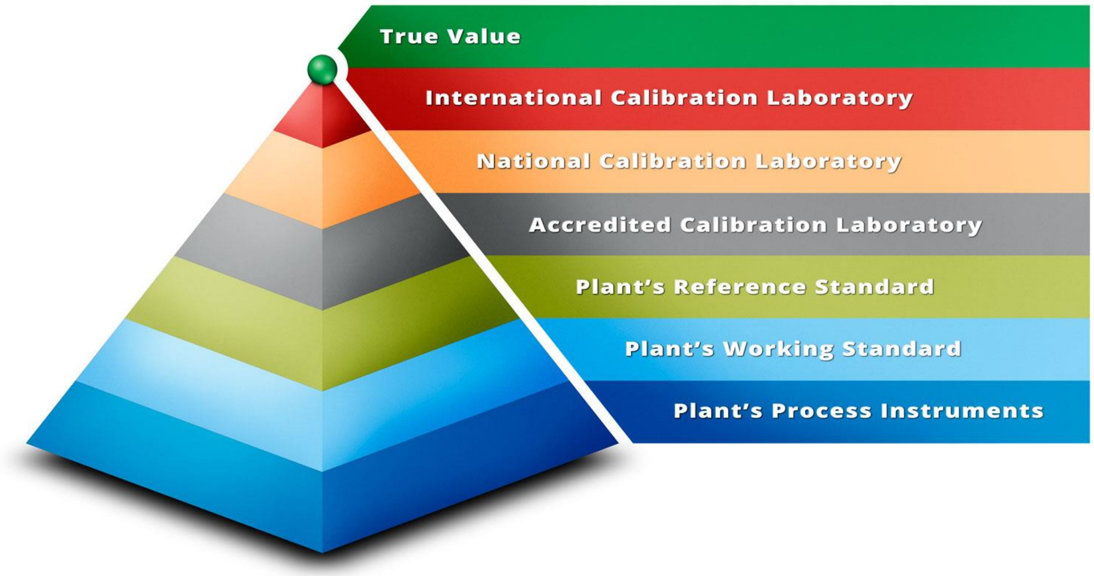
A requirement for a reliable measurements conveying legal validity is that there is an unbroken traceability chain to an international primary standard and a documented uncertainty calculation for each transfer step in the chain by ISO 17025 accredited laboratories.



The calibration is transferred down the traceability chain, and the uncertainty attached to the measured value in the calibration increases as it goes towards the base of the pyramid. .

Reference Devices &Calibration Traceability

For almost all laboratories the traceability chain of the reference device will be provided by an external organisation in the form of the calibration (including calibration certificate with stated uncertainty).



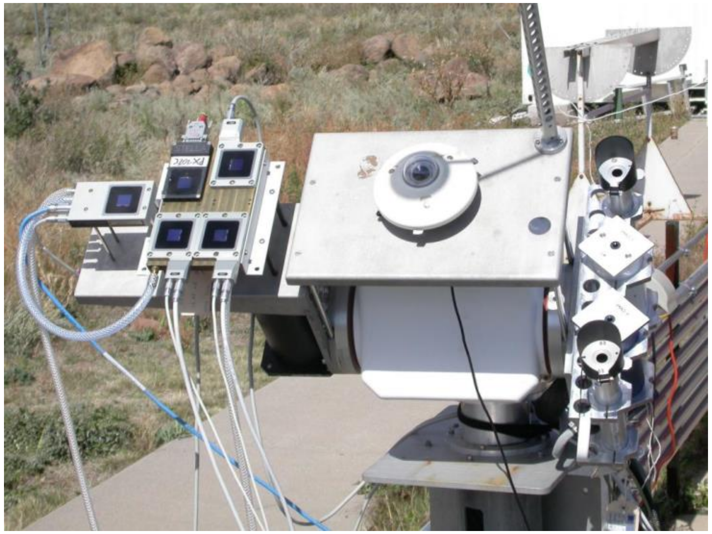
- Use of these references in daily work will minimise uncertainty, but brings the risk in case of damage during handling or degradation due to frequent use.
- It is common to transfer the calibration to working references for daily use and keep the higher level reference stored safely.
- This requires an in-house procedure for the calibration transfer.

Reference Devices & Calibration Traceability

The standard 60904-2 also stablishes procedures for the calibration transfer between devices lower in the traceability chain. They are defined as:

Primary Reference Device

A reference device whose calibration is based on a radiometer or standard detector or standard light source traceable to SI units.



Secondary Reference Device

A reference device calibrated under natural or simulated sunlight against a primary reference device.

Working Reference Device

A reference device calibrated under natural or simulated sunlight against a secondary reference device.

Reference Devices & Calibration Traceability

- The reference device can be a PV cell or module. For industry the choice of a reference device of same size and technology to the PV devices to be measured is preferable.

- The reference needs to be stable, handled and stored with care and regularly checked, also in the periods between the periodic recalibrations.

Irradiance Calibration at Isc or Pmax

I_{SC} of the reference module

Advantage: Almost independent from module temperature and connection technique.

Disadvantage: Sensitive to illumination non-uniformity of a module. Increase of non-uniformity will cause lower I_{SC}. Thus a higher irradiance setting is required to deliver calibrated I_{SC}. This means an overestimation of module power.

P_{MAX} of the reference module

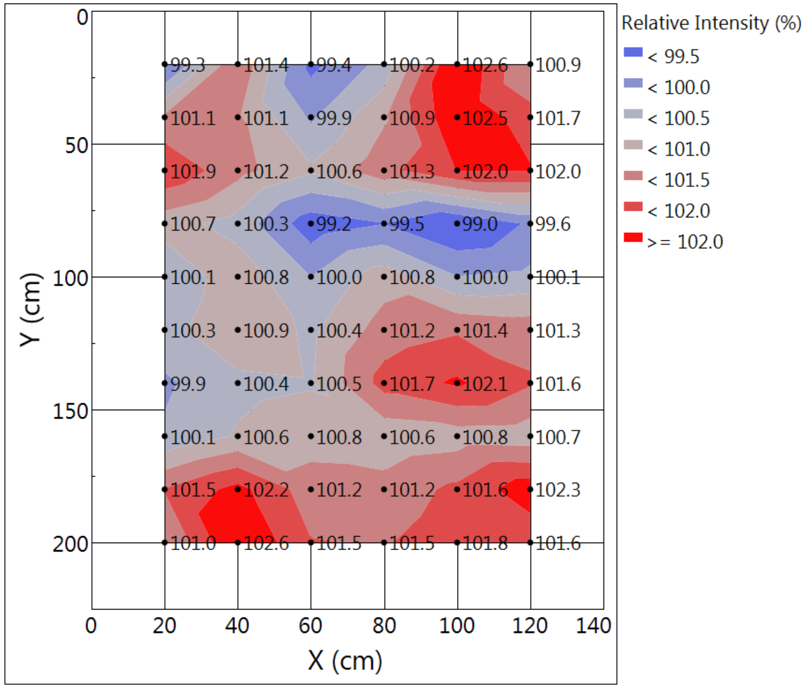
Advantage: Better compensation of illumination non-uniformity effects.

Disadvantage: Requires a careful module temperature measurement and connection technique. Bad contact will cause higher irradiance level to deliver calibrated P_{MAX}. This means overestimation of module power.

Irradiance Calibration at Isc or Pmax

It is preferable for example to employ calibration based on PMAX of the reference module for systems with Class B non-uniformity of irradiance.

In contrast Isc calibration is superior for systems with Class A non-uniformity, but poorer temperature control or electrical connections.



C. Monokroussos et al., “Impact of Calibration Methodology into the Power Rating of c-Si Modules under Industrial Conditions” 28th EUPVSEC, 2013

I-V Curve Correction Procedures

- When measuring I-V curves, we almost never measure at repeatable set of G and T conditions (especially in the field).
- Therefore, it is useful to know some basic equations to correct your I-V measurements to a common condition.
  - e.g. STC

I-V Curve Correction Procedures

- It is always best practice to measure the I-V curve as close to the target conditions as possible. This minimizes measurement error.
  - e.g measuring at ~28°C and normalizing to 25°C is less prone to error than measuring at ~48°C and normalizing to 25°C.
  - However, this is not always possible, even under controlled conditions.

- The next two slides will provide equations for basic corrections/normalization of current and voltage.
  - But for more detailed procedures see IEC 60891.

I-V Curve Correction Equations: Irradiance

$$I_{corr} = I_{meas} * \frac{1000\ W/m^2}{G_{meas}}$$

Where:
I_{corr} = The current corrected to 1000W/m^2 (A)
I_{meas} = The measured PV current (A)
G_{meas} = The measured solar radiation in plane of array (W/m^2)

***Note** that current can be corrected to any desired solar radiation intensity by substituting 1000 W/m^2 in the numerator for the desired intensity in W/m^2

I-V Curve Correction Equations: Temperature

$$V_{corr} = V_{meas} * \{1 + \beta * (25°\mathrm{C} - T_{meas})\}$$

Where:
V_{corr} = The voltage corrected to 25C (V)
V_{meas} = The measured PV voltage (V)
T_{meas} = The measured module temperature (°C)
β = The temperature coefficient for voltage (-0.4%/°C is a good assumption for Vmp of c-Si when data are not available).

***Notes**

- Voltage can be corrected to any desired temperature by substituting 25°C in parenthesis for the desired temperature in °C
- Corrections for power (W) can be made using the same equation, but the temperature coefficient must be updated accordingly.
- The logarithmic effect of irradiance on voltage is not shown here.

Detailed Multi-Parameter Correction Procedures: IEC 60891

IEC 60891 contains three semi empirical I-V correction procedures with different parameters.

Correction Procedure 1 (4 parameters):

$$V_2 = V_1 - \boxed{R_S}\,(I_2 - I_1) - \boxed{\kappa}\, I_2 \cdot (T_2 - T_1) + \boxed{\beta}\,(T_2 - T_1)$$

$$I_2 = I_1 + I_{SC} \cdot \left(\frac{G_2}{G_1} - 1\right) + \boxed{\alpha}\,(T_2 - T_1)$$

Index 1 = measured V, I, or G
Index 2 = corrected V, I, or G

α = Current temp. Coeff. [A/°C]
β = Voltage temp. Coeff. [V/°C]
K = "Curve correction factor" [Ω/°C]
Rs = series resistance [Ω]

Correction Procedure 2 (5 parameters):

$$V_2 = V_1 + V_{OC1} \cdot \left(\boxed{\beta_{rel}}\,(T_2 - T_1) + \boxed{a} \cdot \ln\left(\frac{G_2}{G_1}\right)\right) - \boxed{R_S'} \cdot (I_2 - I_1) - \boxed{\kappa'}\, I_2 \cdot (T_2 - T_1)$$

$$I_2 = I_1 \cdot (1 + \boxed{\alpha_{rel}}\,(T_2 - T_1)) \cdot \frac{G_2}{G_1}$$

αrel = Current temp. Coeff. [%/°C]
βrel = Voltage temp. Coef. [%/°C]
K' = "curve correction factor" [Ω/°C]
Rs' = series resistance [Ω]
a = irrad. correction factor for Voc (0.06 typical) [a.u.]

Detailed Multi-Parameter Correction Procedures: IEC 60891

- The correction procedures in 60891 all have advantages and disadvantages.
- Ex: Procedure 1 (P1) requires the fewest parameters, but large irradiance corrections may require extrapolation to obtain Voc.
- P2 can produce complete I-V curves at high irradiance, but also requires the most parameters.
- P3 (not shown) gives best results because interpolation (vs extrapolation) is used, but requires I-V curves at many G and T values.

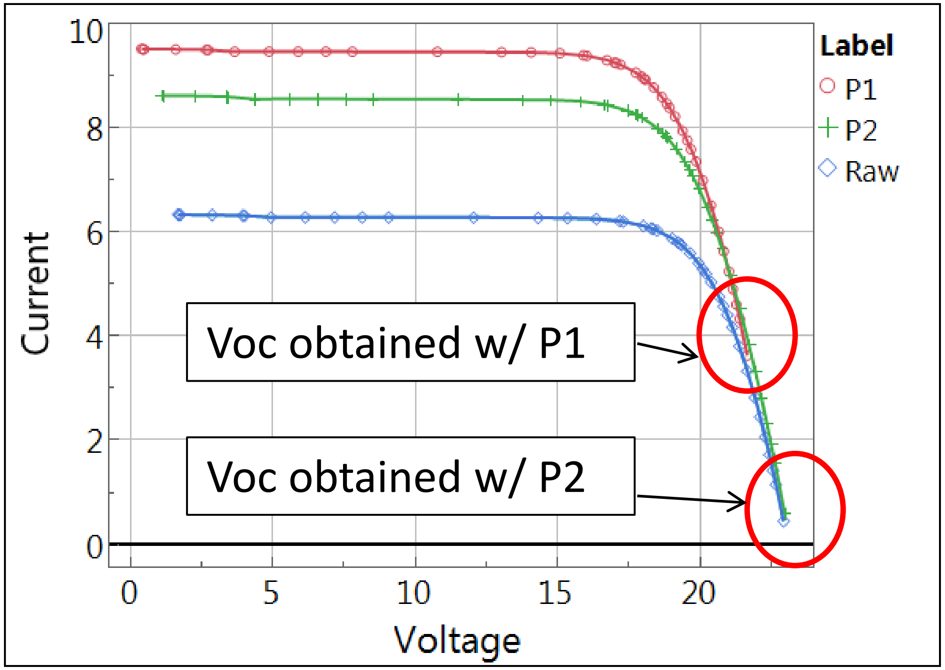


Figure: I-V curves corrected to STC using procedures 1 (P1) and 2 (P2). The raw data was measured at 735 W/m^2 and Tcell of 20°C

Thank you for your attention!