10-Photovoltaics Part 2

ECEGR 452
Renewable Energy Systems

Overview

- Solar Radiation Absorption
- Illumination Current
- PV Circuit Equivalent
- PV Cell Arrangements
- Maximum Power Point
- PV Module Spec. Sheets
- Fill Factor
- Temperature Effects

Introduction

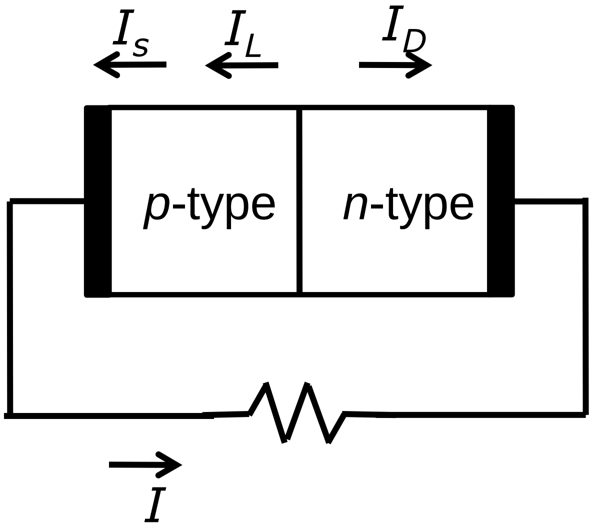
- Last lecture we described the behavior of a PV cell
    - In the dark, behaved like a diode
    - Under light, illumination current flows
- In this lecture we develop a circuit model for the PV cell and examine its power output characteristics

Illumination Current

- Current out of an illuminated pn-junction is:

$$I = I_L - I_{Sat}\left(e^{V/V_T} - 1\right)$$

- How is I_L determined?



Solar Radiation Absorption

- Solar radiation is composed of photons
- Energy carried by a photon: $e = \frac{\hbar c}{\lambda}$

- where:
  - e :energy of the photon (eV) [1 eV = 1.6e-19 J]
  - C: speed of light (m/s) (300,000,000 m/s)
  - λ: wavelength (m)
  - $\hbar$: Planck's constant 4.135 x 10^{-15} eV-s
- Recall the frequency/wavelength relationship

$$f = \frac{c}{\lambda}$$

Solar Radiation Absorption

- Spectrum of solar radiation

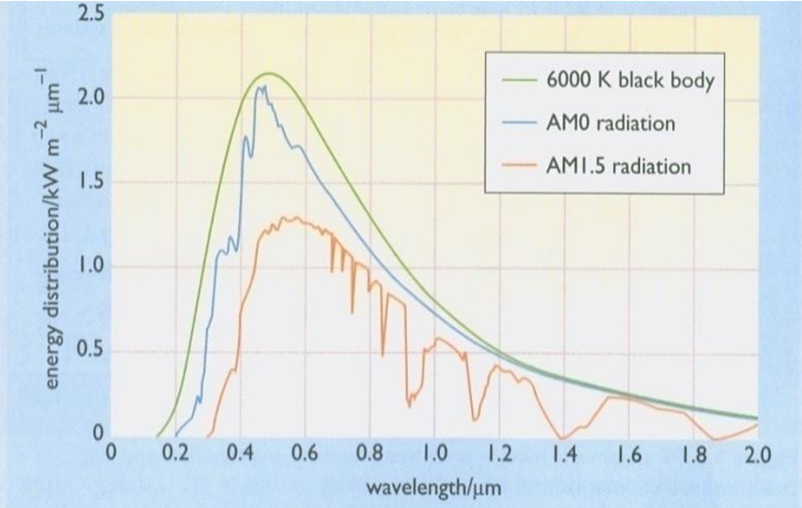


Figure 3.8 The spectral power distributions of solar radiation corresponding to Air Mass 0 and Air Mass 1.5. Also shown is the theoretical spectral power distribution that would be expected, in space, if the sun were a perfect radiator (a 'black body') at 6000 °C

Source: *Renewable Energy: Power for a Sustainable Future*, G. Boyle

Solar Radiation Absorption

- How many photons, N_{total}, are radiated on a square meter of earth per second?
- Assume:
  - $G = 1000\ W/m^2$
  - Assume average wavelength is $0.8\ \mu m$

Solar Radiation Absorption

- For 1 second over 1 m²: 1000 J
- Converting to eV: 6.25e21 eV

$$6.25\text{x}10^{21} = N_{total}e = N_{total}\frac{\hbar c}{\lambda}$$

$$\Rightarrow N_{total} = 6.25\text{x}10^{21}\frac{\lambda}{\hbar c} = 6.25\text{x}10^{21}\frac{(0.8\text{x}10^{-6})}{4.135\text{x}10^{-15}\text{x}\left(300\text{x}10^{6}\right)} = 4.03\text{x}10^{21}$$

- Note: this is rough approximation only!

Solar Radiation Absorption

- If each photon excited one electron into the conduction band then for each square meter:
  - I_L = (4.03e21) x (1.6e-19) = 644 Amperes!

Solar Radiation Absorption

- Generically the illumination current can be found from:
  - $I_L = q \times N \times A$
- Where
  - q: charge (C)
  - A: area of the junction (m^2)
  - N: number of photons that excite electrons per square meter

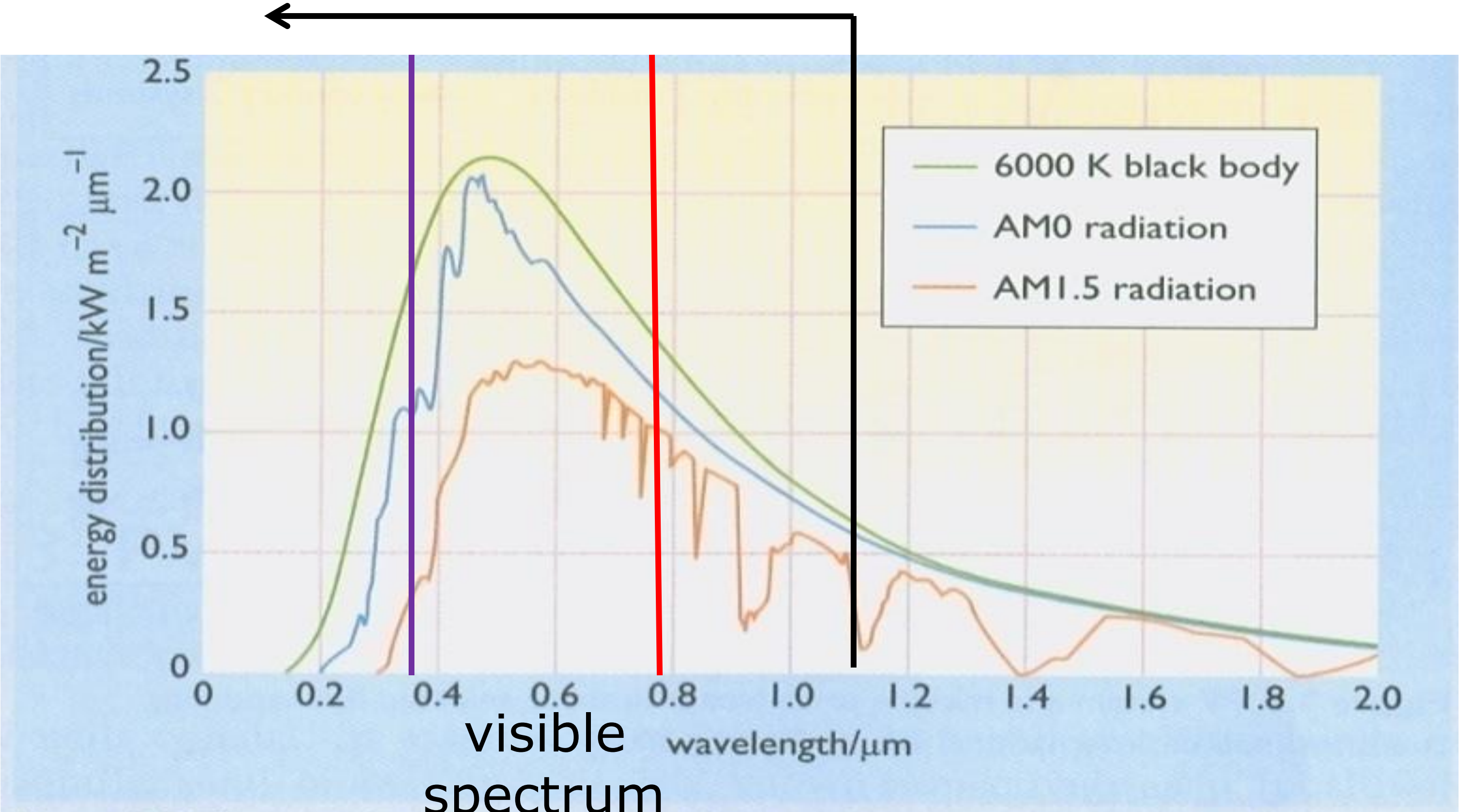
Solar Radiation Absorption

- Not all of the incident radiation is suitable for PV energy conversion
- If the photon has:
  - Too little energy, the electron does not jump to the conduction band
  - Too much energy, only the portion of the energy that is sufficient to promote the electron to the conduction band can be used

Solar Radiation Absorption

- Energy of the photon must be > 1.1 eV (wavelengths less than 1.1×10^{-6} m)
    - ~23% of the solar radiation (AM 1.5) does not meet this requirement
    - ~33% of solar radiation (AM 1.5) is wasted by having too much energy
- At most, <50% of energy radiated on a solar panel can be used
    - Actual efficiency is closer to 16%

Solar Radiation Absorption



Suitable for PV

visible spectrum

Figure 3.8 The spectral power distributions of solar radiation corresponding to Air Mass 0 and Air Mass 1.5. Also shown is the theoretical spectral power distribution that would be expected, in space, if the sun were a perfect radiator (a 'black body') at 6000 °C

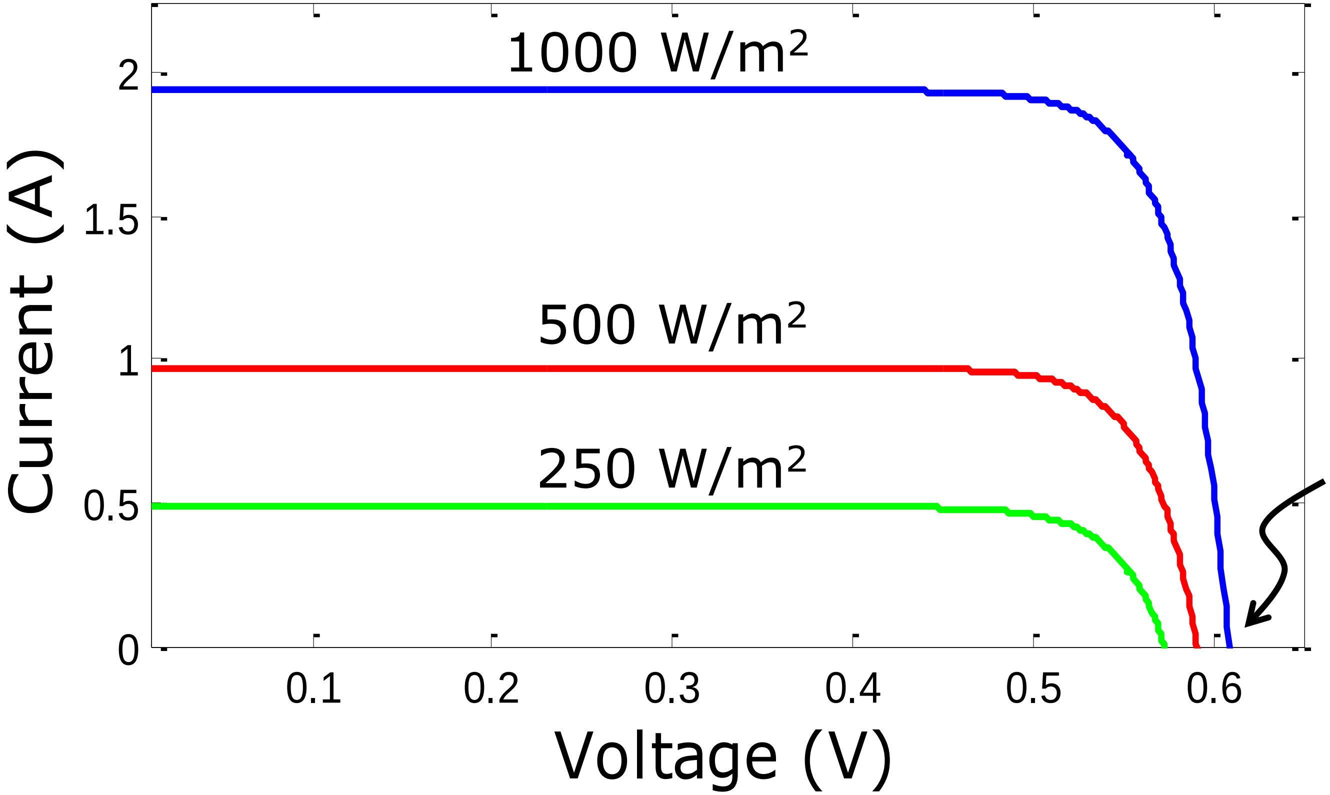
Illumination Current

- Irradiance and I_L are <u>proportionally</u> related under short circuit conditions ($I_{sc} = I_L$)
  - Double irradiance and I_L will double
- Mathematically:

$$I_L(G) = \left(\frac{G}{G_{STC}}\right) I_L(G_{STC}) \quad \text{(under short circuit)}$$

- Where
  - G: irradiance on the PV panel (W/m^2)
  - G_{STC}: rated irradiance of the PV panel under Standard Test Conditions (W/m^2)
  - $I_L(G_{STC})$: short circuit current of the PV panel under Standard Test Conditions (A)

Illumination Current



V_{oc} is insensitive to G

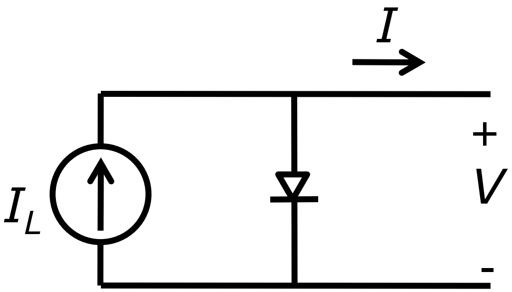
PV Circuit Equivalent

- Equivalent circuit of an ideal PV cell

$$I = I_L - I_{Sat}\left(e^{V/V_T} - 1\right)$$

$$V_{OC} \approx V_T \ln\left(\frac{I_L}{I_{Sat}}\right)$$

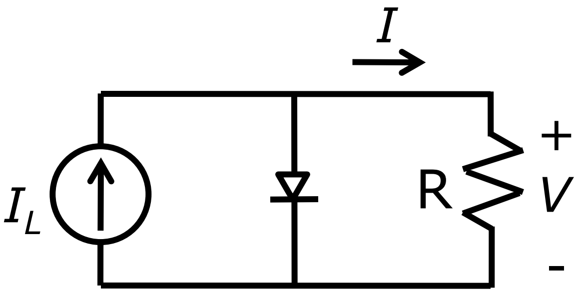
$$I_{SC} = I_L$$



Note: this reduces to a simple Diode in the dark (I_L =0)

PV Circuit Equivalent

- Let
  - $R = 0.25\ \Omega$
  - $I_{sat} = 10^{-10}$ A
  - $V_t = 25$mV
  - $I_L = 1.5$ A
- Find V



PV Circuit Equivalent

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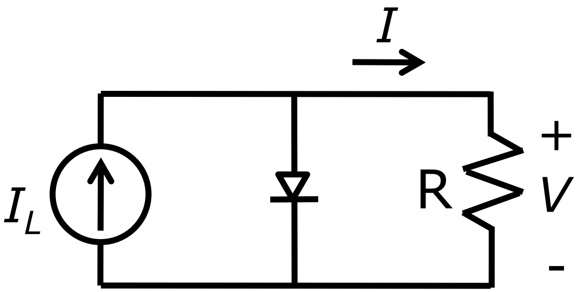


$$V = IR$$

$$I = I_L - I_{Sat}\left(e^{V/V_T} - 1\right)$$

$$\frac{V}{R} = 1.5 - 10^{-10}\left(e^{V/0.025} - 1\right)$$

Transcendental function, numerically solve

PV Circuit Equivalent

- We can take a brute force approach
  - Try a range of values of V until f (the error) is less than some tolerance (say, 0.025)

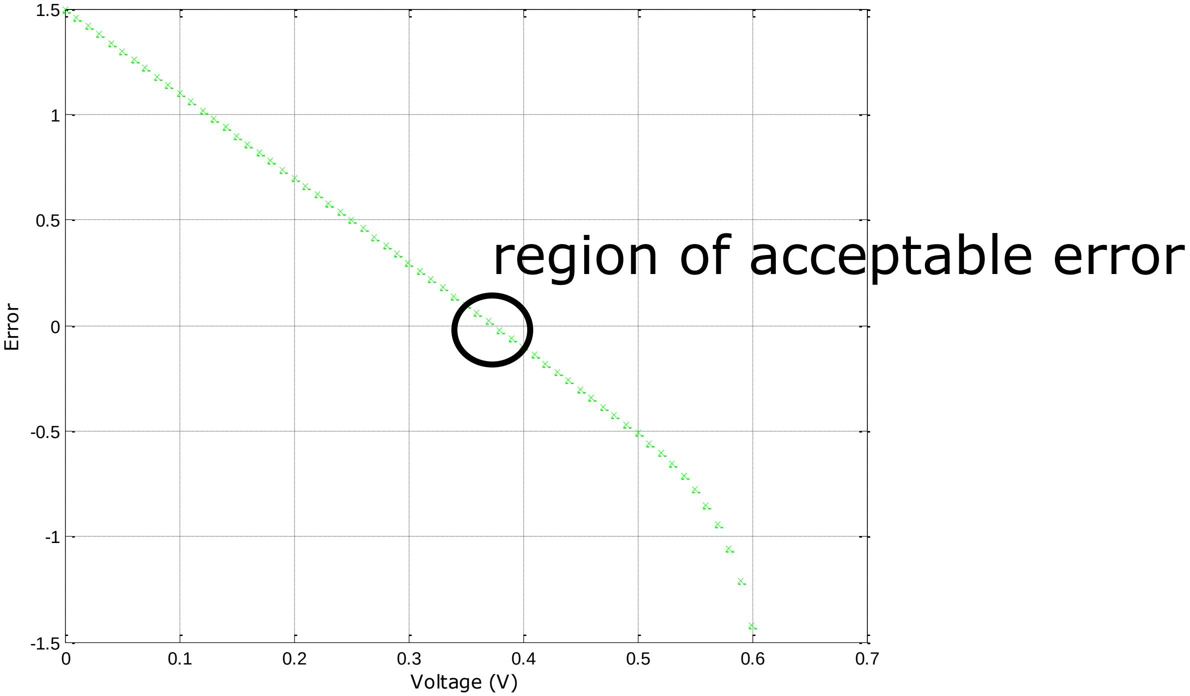
$$I = I_L - I_{Sat}\left(e^{V/V_T} - 1\right)$$

$$0 = \frac{V}{R} - I_L - I_{Sat}\left(e^{V/V_T} - 1\right)$$

$$f = \frac{V}{R} - I_L - I_{Sat}\left(e^{V/V_T} - 1\right)$$

PV Circuit Equivalent

- We are dealing with one PV cell, the range of voltage we should try should be between 0 and about 0.6 V.

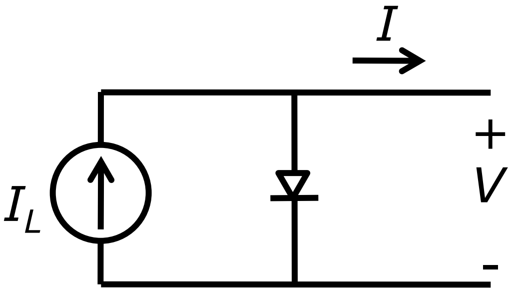


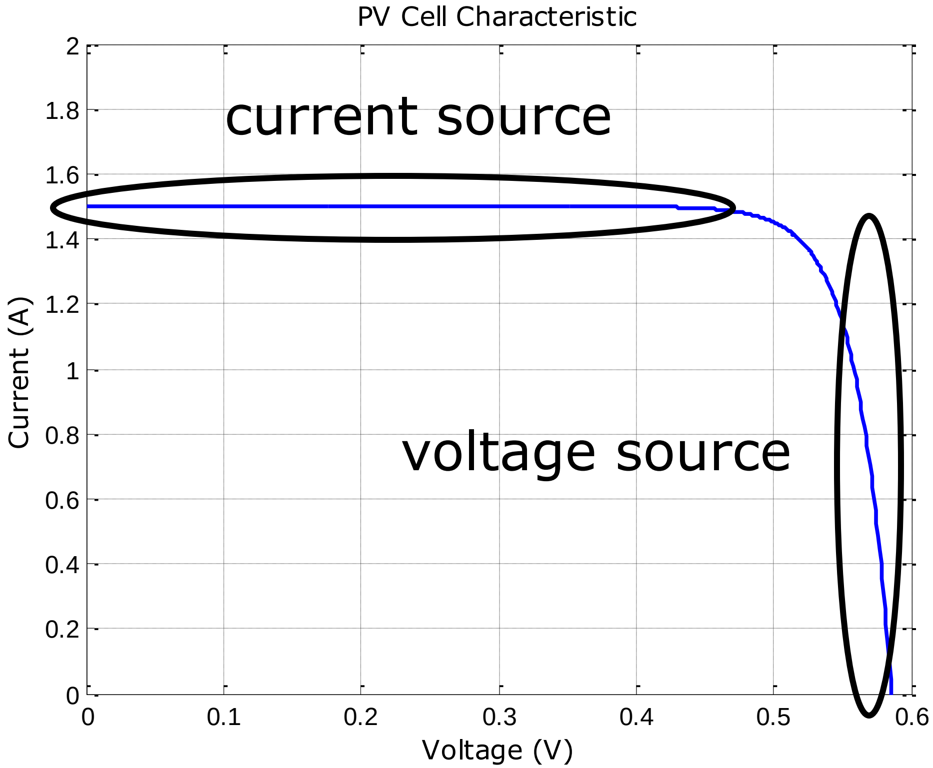
PV Circuit Equivalent

- We will rely on numerical solutions for solving PV circuits when a load is attached
  - Previous example: $V \approx 0.38$
- We can now directly solve the circuit for any other quantity

$$I = I_L - I_{Sat}\left(e^{V/V_T} - 1\right)$$

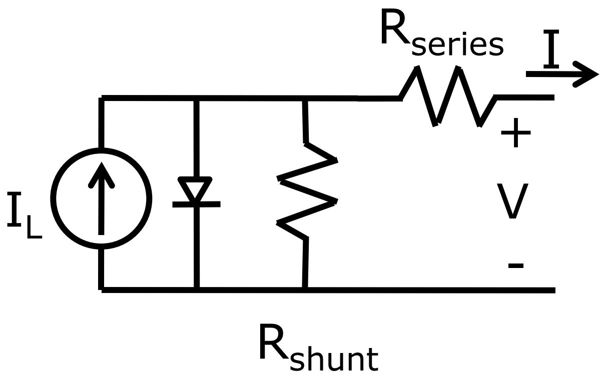
PV Circuit Equivalent





PV Circuit Equivalent

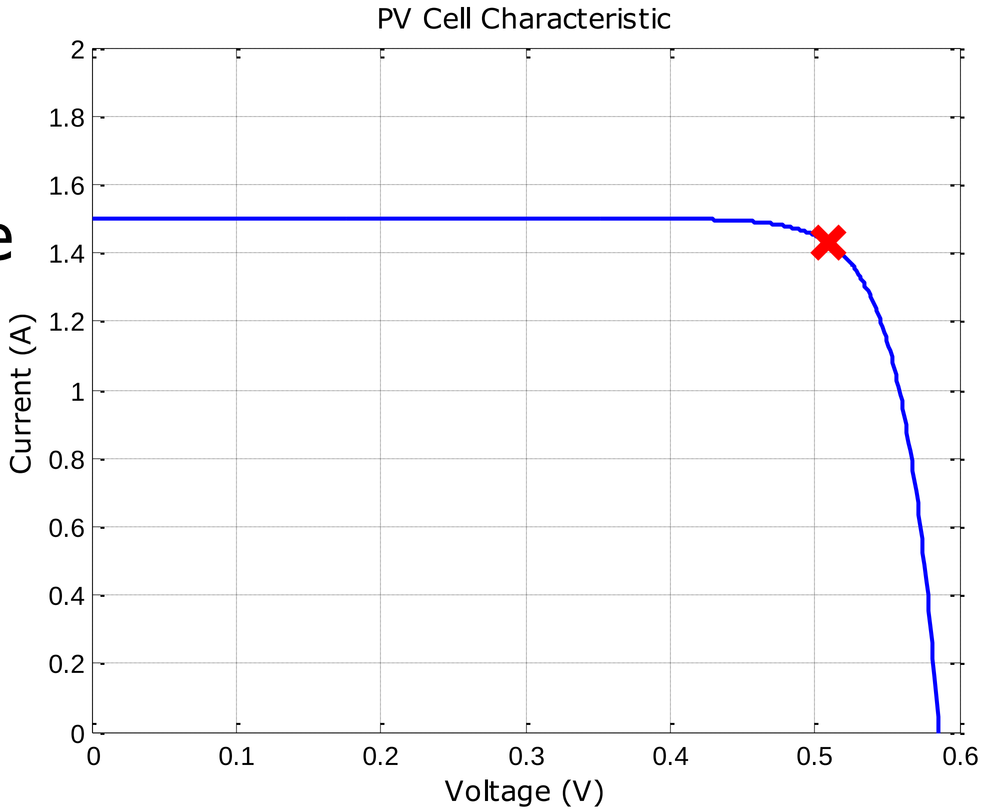
- Losses can be modeled by including shunt and series resistances



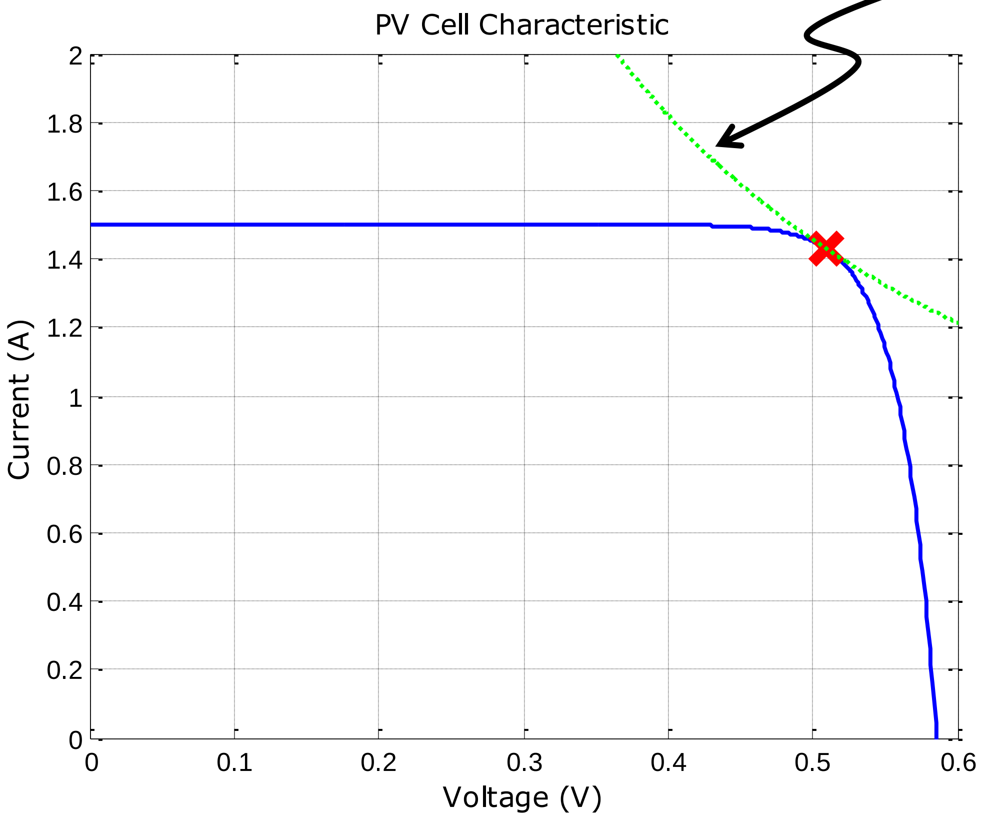
- We will assume the PV cell is ideal unless otherwise noted

Maximum Power

- Power out of the cell:
  - $P = IV$
- There is a unique point that maximizes P
- Goal often is to operate at this point



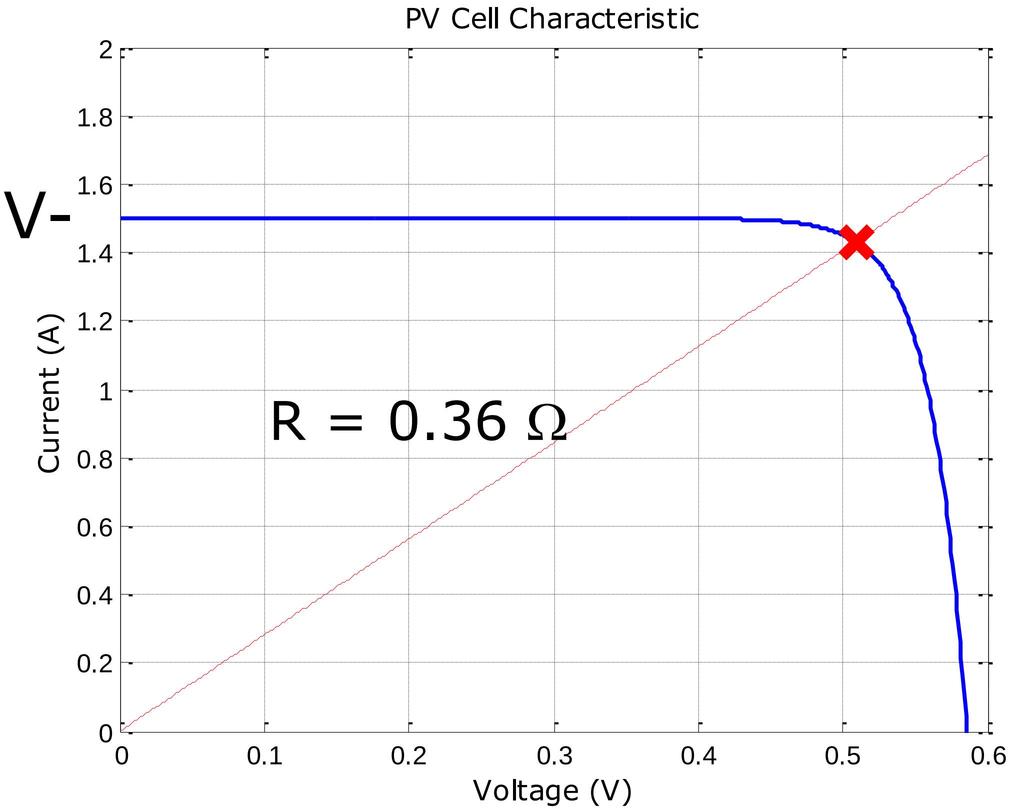
Maximum Power



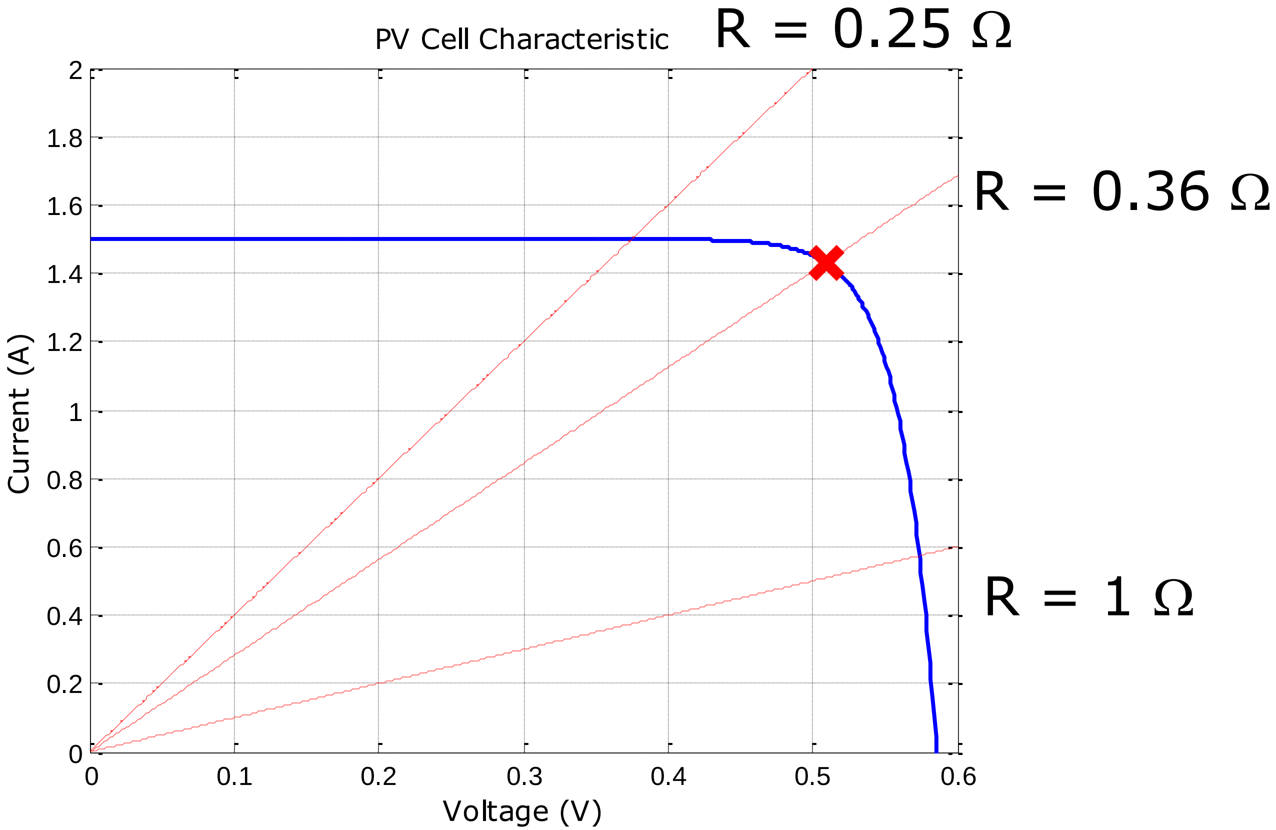
constant power

Maximum Power

- Want to find the value of R that maximizes power output
- Resistors have linear V-I characteristics
- Slope is 1/R



Maximum Power

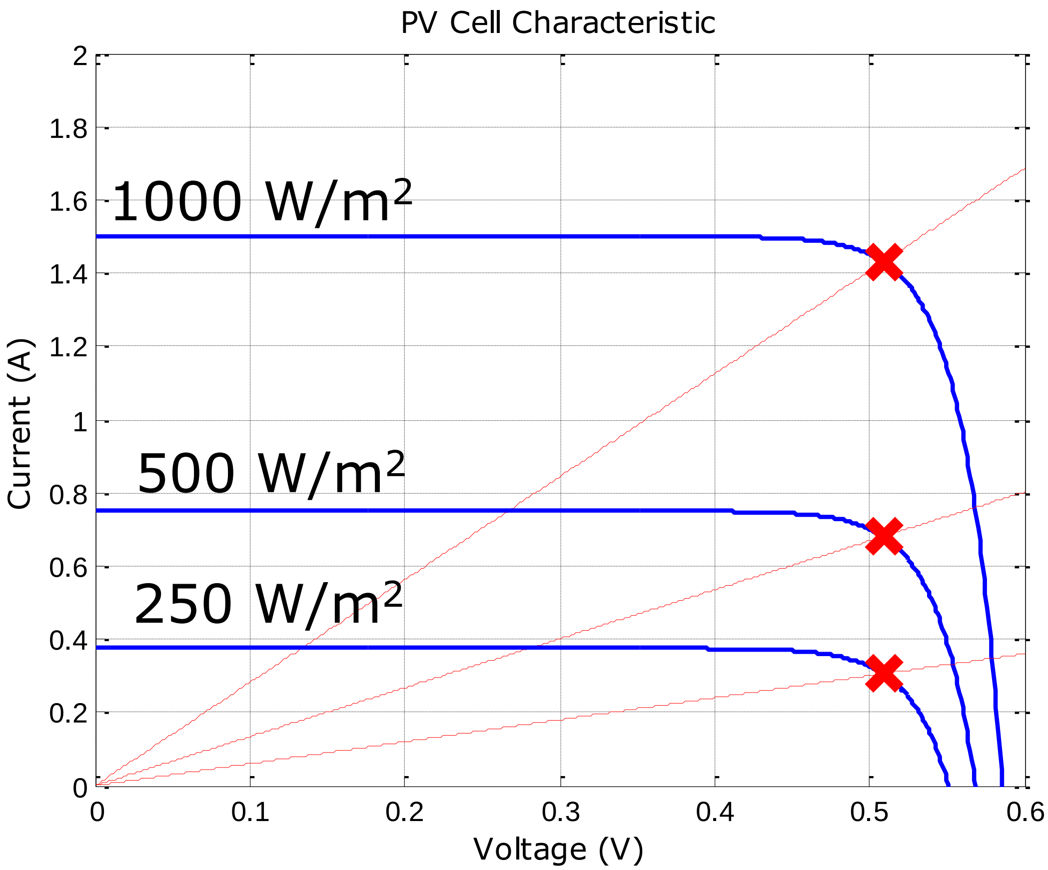


Maximum Power

- Point of maximum power output for a given irradiance, G, is known as the maximum power point (MPP)
- Let
  - $P^*(G)$: maximum power output (W)
  - $I^*(G)$: current at MPP (A)
  - $V^*(G)$: voltage at MPP (V)
  - $R^*(G)$: resistance for MPP (Ω)
- Note: * does NOT mean complex conjugate

Maximum Power

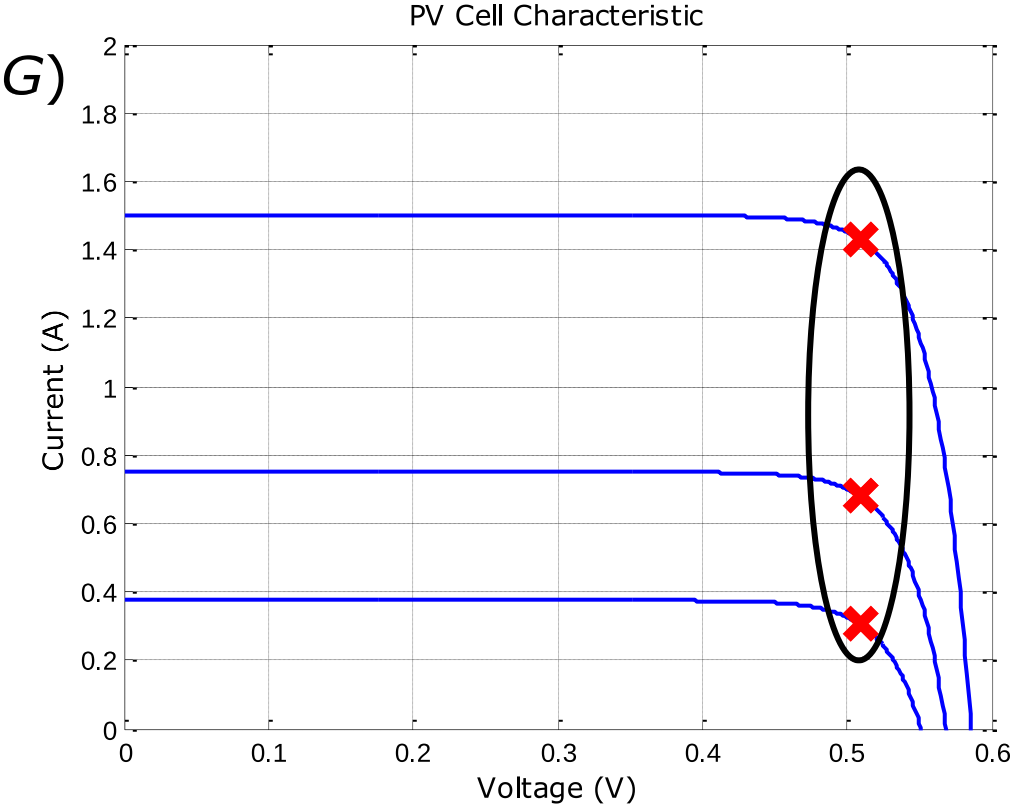
- P^*, I^*, V^*, R^* depend on illumination



Maximum Power

- Regardless of illumination amount, a general rule of thumb:

$$V^* \approx 0.8 \times V_{oc}(G)$$

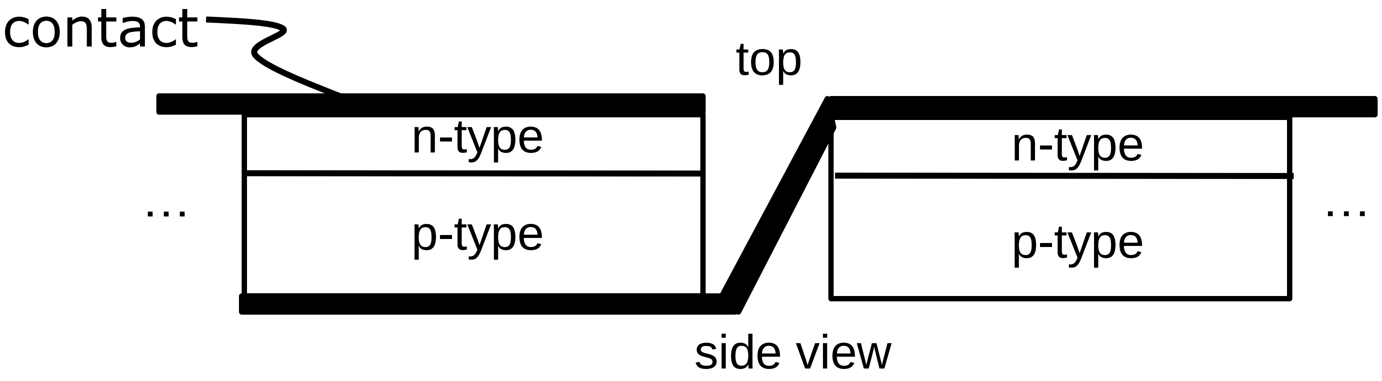


PV Cell Arrangements

- Power, voltage out of a single cell is usually not sufficient for most applications
  - $V_{oc} < 0.10$ V
  - $I_{sc} < 5$A (for cell dimension around 10cm x 10cm)
  - $P < 0.5$ W
- Multiple cells are arranged in panels (modules)
- Multiple panels are arranged in arrays

PV Cell Arrangements

- Series cell arrangement (increases voltage)

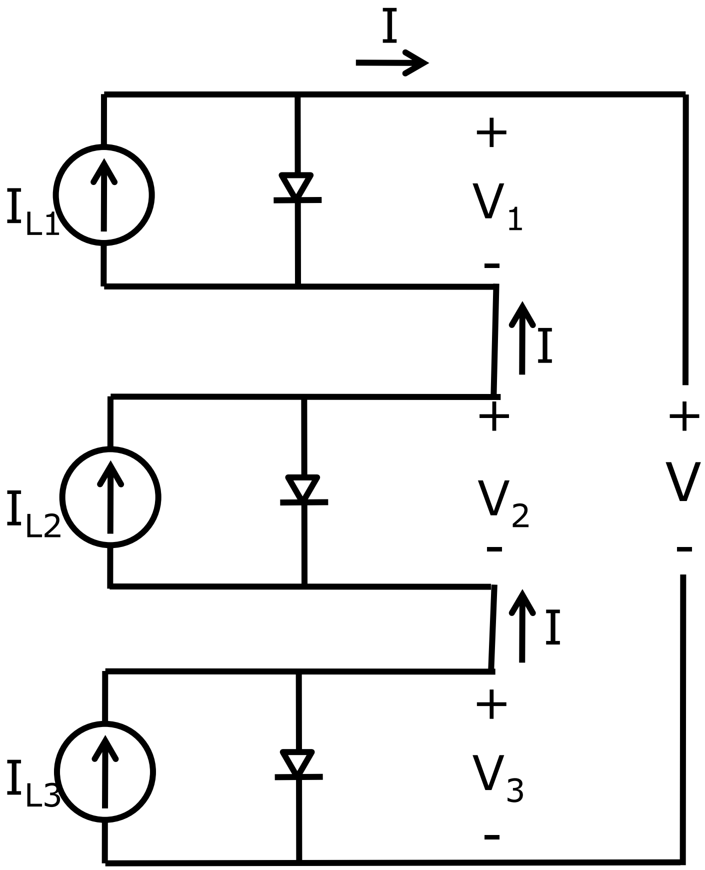


PV Cell Arrangements

- Output voltage, increased by series connection:

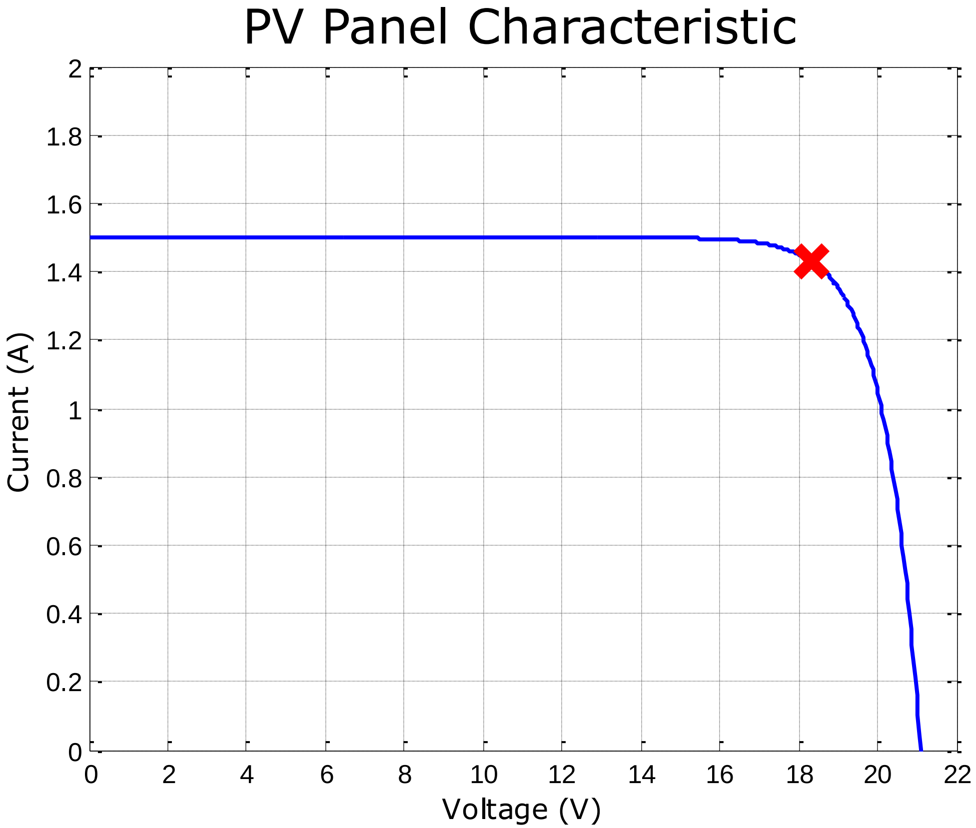
$$V = \sum_{n=1}^{N_{cells}} V_n$$

- where:
  - N_{cells}: number of cells
- Same current flows out of each cell



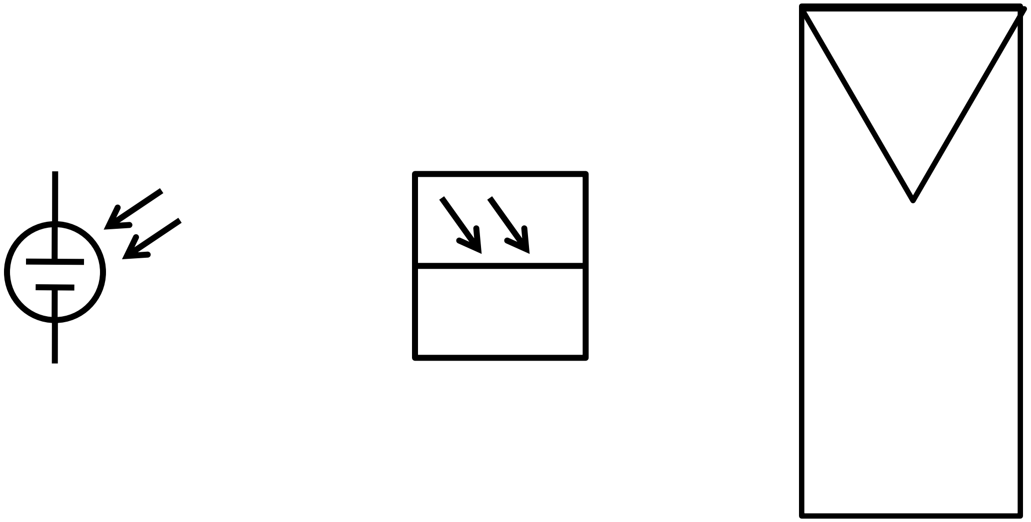
PV Cell Arrangements

- IV characteristics can be easily aggregated
- Shape of characteristic does not change

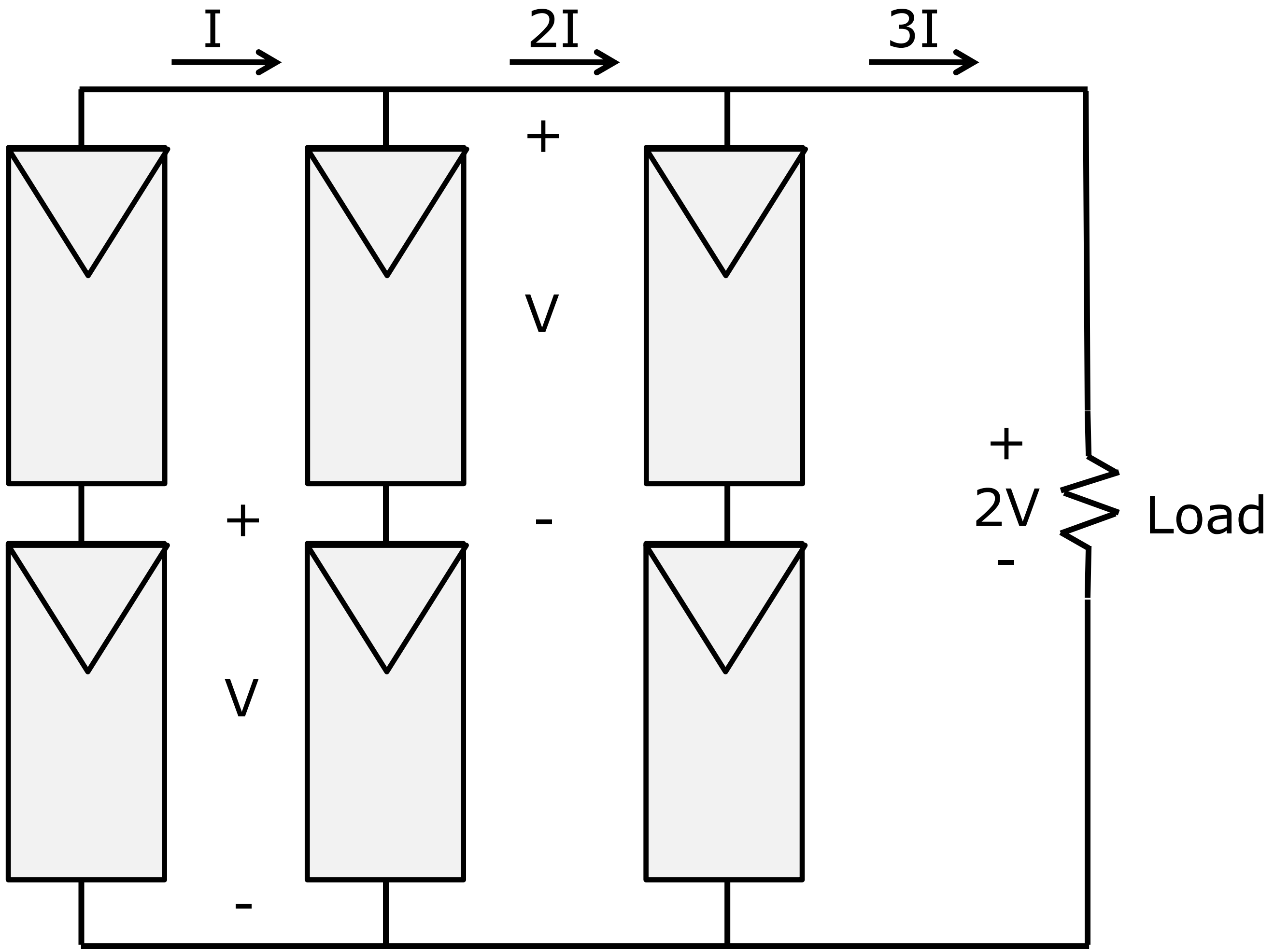


PV Cell Arrangements

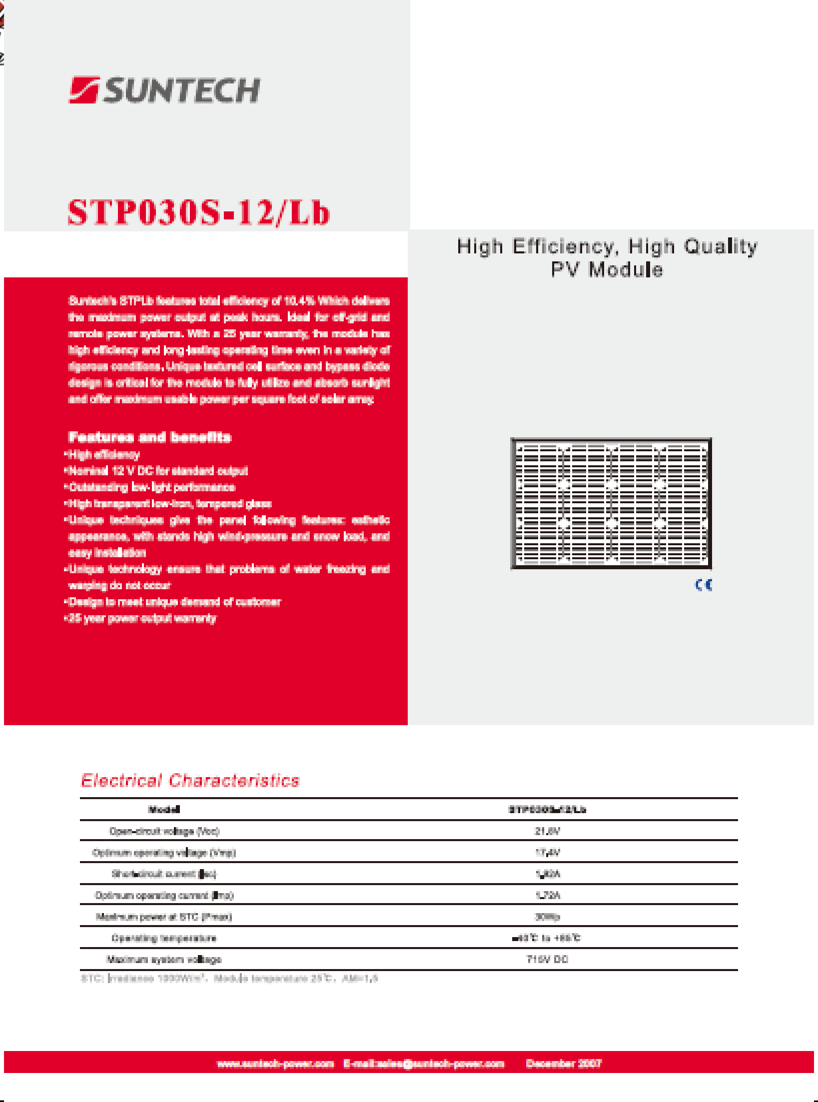
- Panel or Module: collection of PV cells
- Array: collection of PV Panels (or modules)
- Symbols:



PV Module Arrangements



PV Module Spec Sheets



SUNTECH

STP030S-12/Lb

High Efficiency, High Quality PV Module

Suntech's STPLb features total efficiency of 10.4% Which delivers the maximum power output at peak hours. Ideal for off-grid and remote power systems. With a 25 year warranty, the module has high efficiency and long-lasting operating time even in a variety of rigorous conditions. Unique textured cell surface and bypass diode design is critical for the module to fully utilize and absorb sunlight and offer maximum usable power per square foot of solar array.

Features and benefits

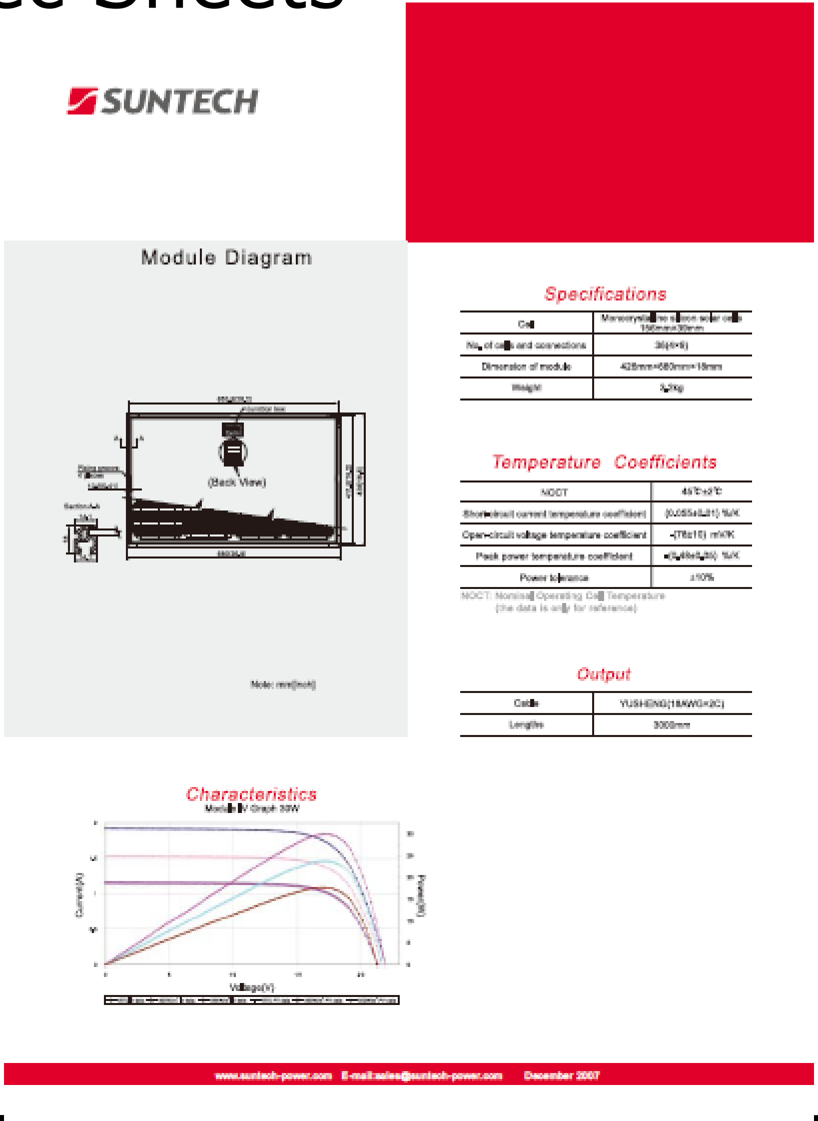
- High efficiency
- Nominal 12 V DC for standard output
- Outstanding low-light performance
- High transparent low-iron, tempered glass
- Unique techniques give the panel following features: esthetic appearance, with stands high wind-pressure and snow load, and easy installation
- Unique technology ensure that problems of water freezing and warping do not occur
- Design to meet unique demand of customer
- 25 year power output warranty

Electrical Characteristics

Model	STP030S-12/Lb
Open-circuit voltage (Voc)	21,6V
Optimum operating voltage (Vmp)	17,4V
Short-circuit current (Isc)	1,92A
Optimum operating current (Imp)	1,72A
Maximum power at STC (Pmax)	30Wp
Operating temperature	-40℃ to +85℃
Maximum system voltage	715V DC

STC: Irradiance 1000W/m², Module temperature 25℃, AM=1,5

www.suntech-power.com E-mail:sales@suntech-power.com December 2007



SUNTECH

Module Diagram

(Back View)

Note: mm(inch)

Specifications

Cell	Monocrystalline silicon solar cells 156mm×39mm
No. of cells and connections	36(4×9)
Dimension of module	425mm×680mm×18mm
Weight	3.2kg

Temperature Coefficients

NOCT	45℃±2℃
Short-circuit current temperature coefficient	(0.055±0.01) %/K
Open-circuit voltage temperature coefficient	-(78±10) mV/K
Peak power temperature coefficient	-(0.48±0.05) %/K
Power tolerance	±10%

NOCT: Nominal Operating Cell Temperature
(the data is only for reference)

Output

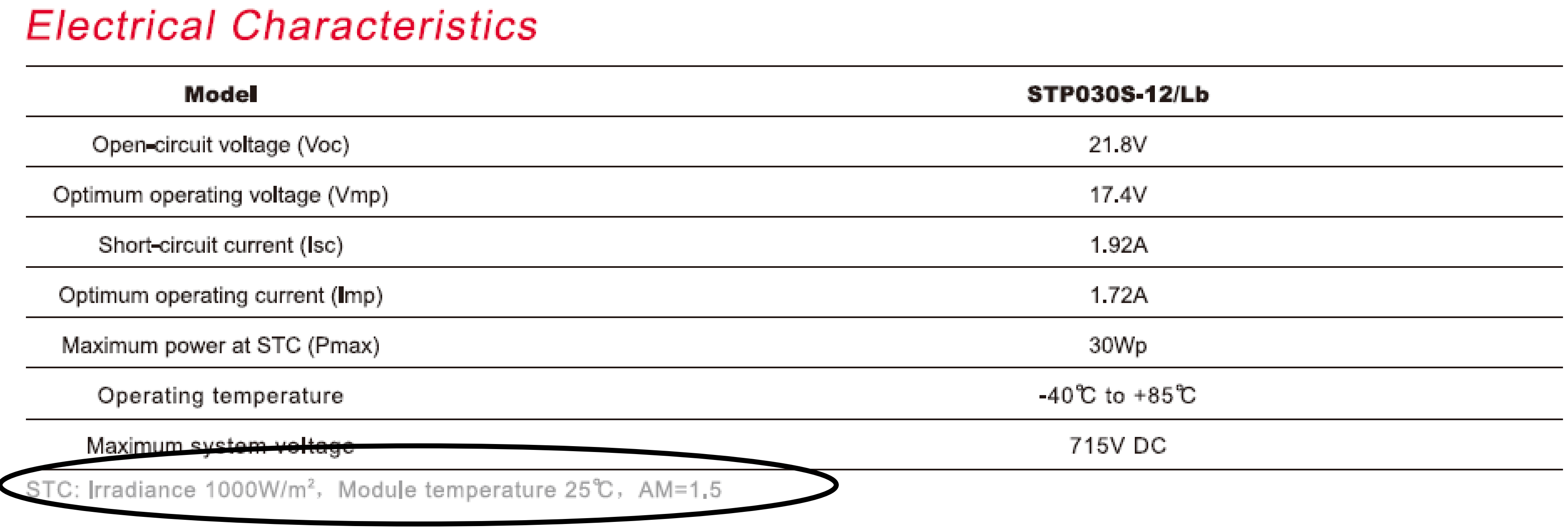
Cable	YUSHENG(16AWG×2C)
Length	3000mm

Characteristics

Module IV Graph 30W

www.suntech-power.com E-mail:sales@suntech-power.com December 2007

PV Module Spec Sheets



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STC: Irradiance 1000W/m², Module temperature 25℃, AM=1.5

Standard Test Conditions (STC)

- STC is defined as
  - Irradiance (G_{STC}): 1000 W/m^2
  - Spectral Distribution: AM 1.5
  - T_C: 25 °C
- STC rarely occur in actual PV systems
  - T_c > 25 °C (when G = 1000 W/m^2)
  - How have often does G = 1000 W/m^2 in Seattle?

Standard Test Conditions (STC)

- Is it possible for a PV panel rated at 100 W to output more than 100 W?
  - Yes
  - No

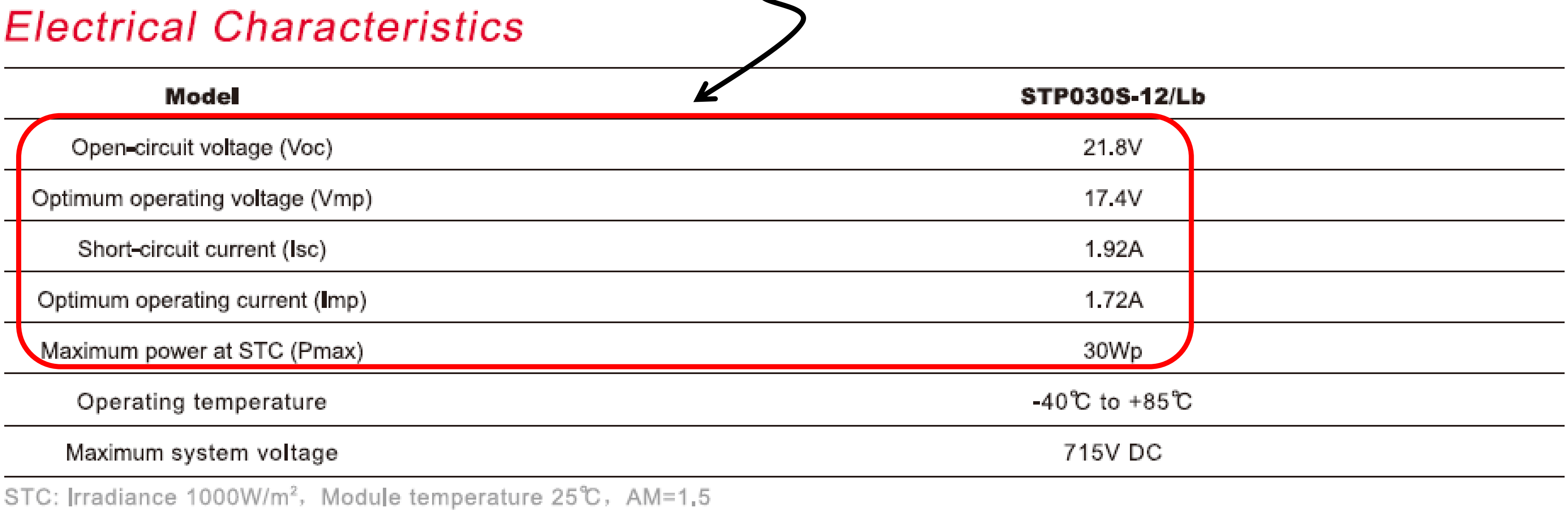
Standard Test Conditions (STC)

- Is it possible for a PV panel rated at 100 W to output more than 100 W?
  - [✓ Yes]
  - No

If irradiance, temperature and load conditions are more favorable than STC, then 100 W can be exceeded

PV Module Spec Sheets

All values referenced to STC



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Notation

- P^*_{STC} : the maximum power output under STC
  - Sometimes units are written as Wp (Watts peak)
  - Also known as the rated power
  - Possible for power to exceed P^*_{STC}
- $V_{oc,STC}$: open circuit voltage of PV module under STC (V)
- $I_{sc,STC}$: short circuit current of PV module under STC (A)

Notation

- V^*_{STC} : voltage of PV module corresponding to P^*_{STC} under STC (V)

- I^*_{STC} : current of PV corresponding to P^*_{STC} under STC (A)

Fill Factor

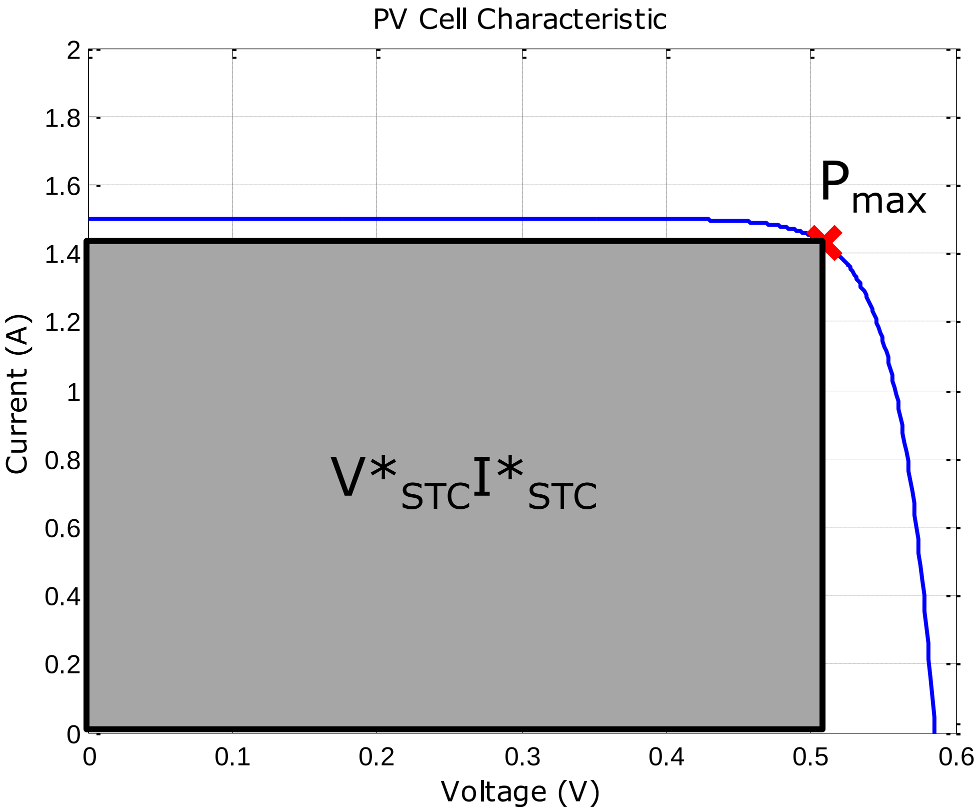
- Theoretical maximum power output of a PV cell is found by multiplying open circuit voltage with the short circuit current
- The ratio of actual maximum power to theoretical is known as the Fill Factor, and provides a metric to compare PV cell quality

Fill Factor

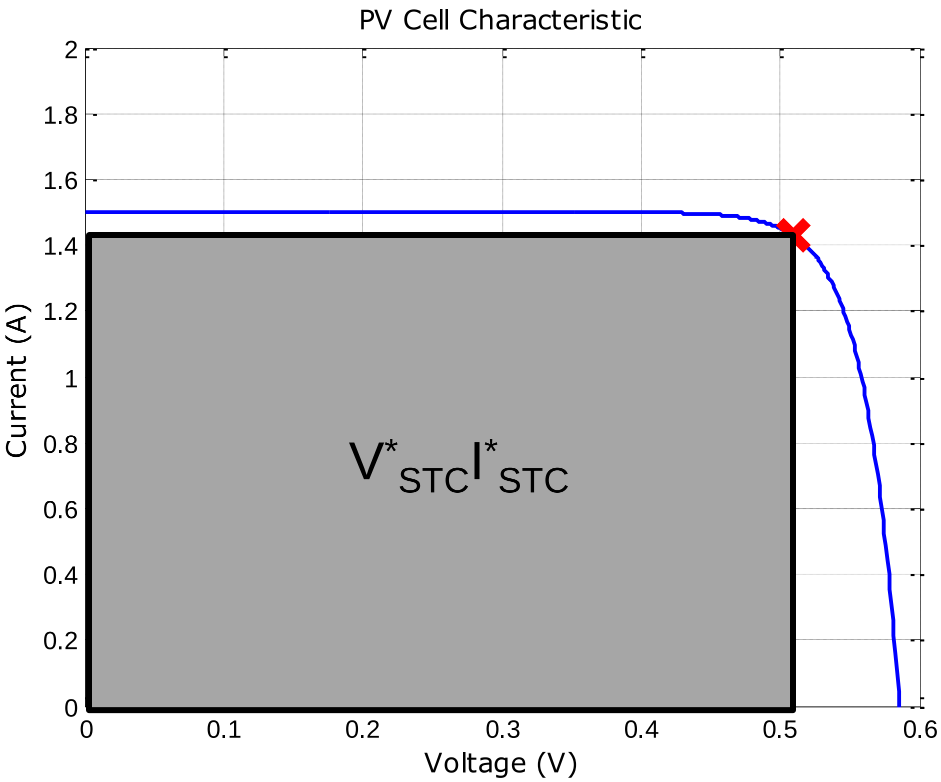
- The maximum power output of the cell is:

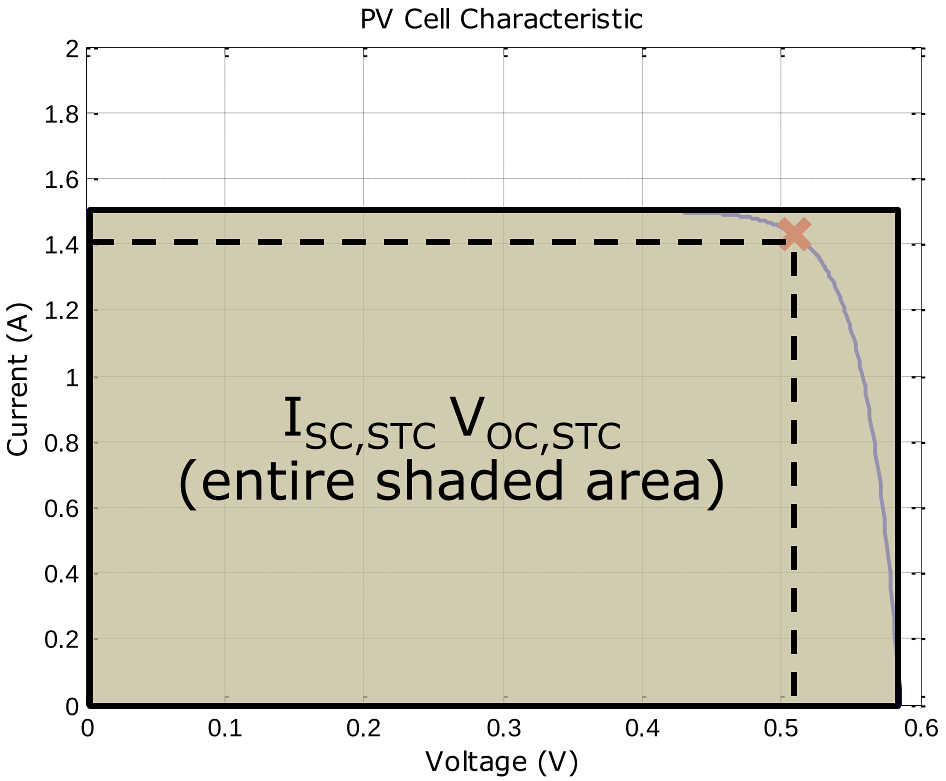
$$P^*_{STC} = I^*_{STC} V^*_{STC} = F I_{SC,STC} V_{OC,STC}$$

- Where
  - F: fill factor
- Typical value of F
  - 0.5 to 0.83



Fill Factor


PV Cell Characteristic
Current (A)
Voltage (V)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
0.1
0.2
0.3
0.4
0.5
0.6
$V^*_{STC}I^*_{STC}$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1.4
1.6
1.8
2
0
0.1
0.2
0.3
0.4
0.5
0.6
$I_{SC,STC}\,V_{OC,STC}$
(entire shaded area)

Fill Factor

- Assuming F is independent of:
    - Temperature
    - Irradiance
- MPP under various conditions can be estimated
    - Compute or measure $V_{oc}(G)$
    - Compute or measure $I_{sc}(G)$

$P^*(G) = FI_{SC}(G)V_{OC}(G)$ (assumes constant Fill Factor)

PV Array Power Output

- Another method of estimating power:

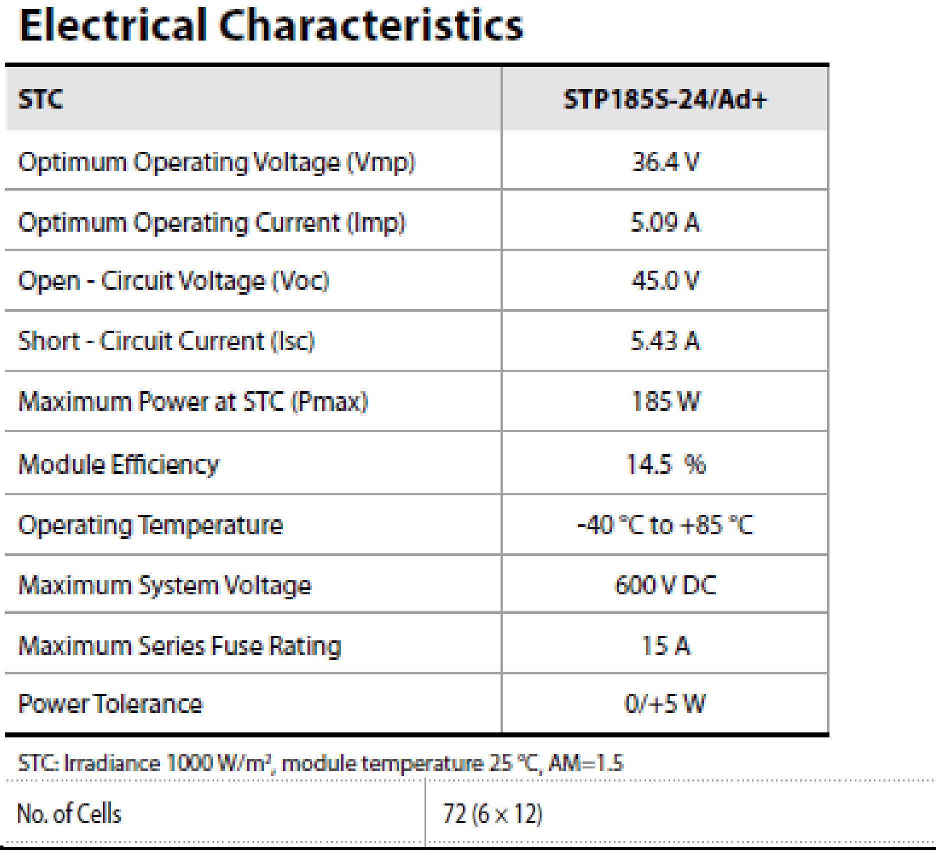
$$P^*(G) = P^*_{STC} \times \left(\frac{G}{G_{STC}} \right)$$

- Where G_{STC} = 1000 W/m^2
- Assumes:
  - Operation at MPP
  - $I^* = I^*_{STC} \times (G/G_{STC})$
  - $V^* = V_{OC}(G) = V_{oc,STC}$
- Ignores:
  - Thermal effects

PV Array Power Output

- Find the fill factor and the maximum power output of the following cell if G = 600 W/m^2. Ignore thermal effects.

$V_{OC}(600)$ is measured to be 44.04V



Electrical Characteristics

STC	STP185S-24/Ad+
Optimum Operating Voltage (Vmp)	36.4 V
Optimum Operating Current (Imp)	5.09 A
Open - Circuit Voltage (Voc)	45.0 V
Short - Circuit Current (Isc)	5.43 A
Maximum Power at STC (Pmax)	185 W
Module Efficiency	14.5 %
Operating Temperature	-40 °C to +85 °C
Maximum System Voltage	600 V DC
Maximum Series Fuse Rating	15 A
Power Tolerance	0/+5 W

STC: Irradiance 1000 W/m², module temperature 25 °C, AM=1.5

No. of Cells	72 (6 x 12)

PV Array Power Output

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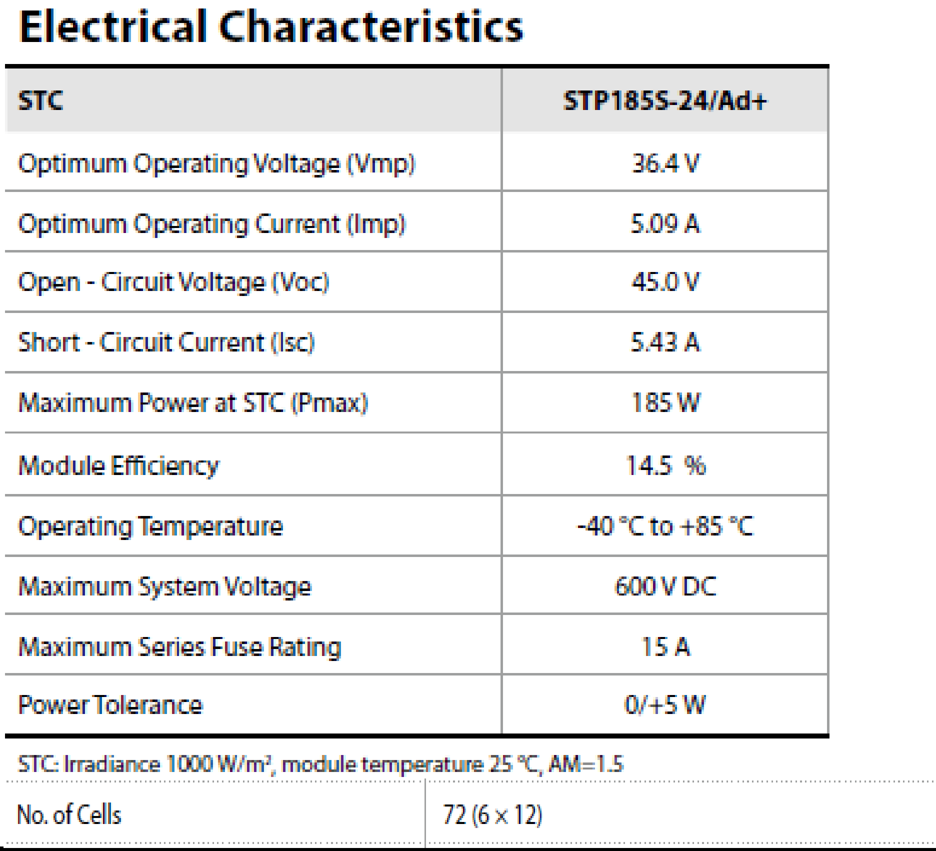

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STC: Irradiance 1000 W/m², module temperature 25 °C, AM=1.5

No. of Cells	72 (6 × 12)

$$P^*_{STC} = I^*_{STC}V^*_{STC} = FI_{SC,STC}V_{OC,STC}$$

$$F = \frac{P^*_{STC}}{I_{SC,STC}V_{OC,STC}} = \frac{185}{5.43\times 45} = 0.757$$

PV Array Power Output

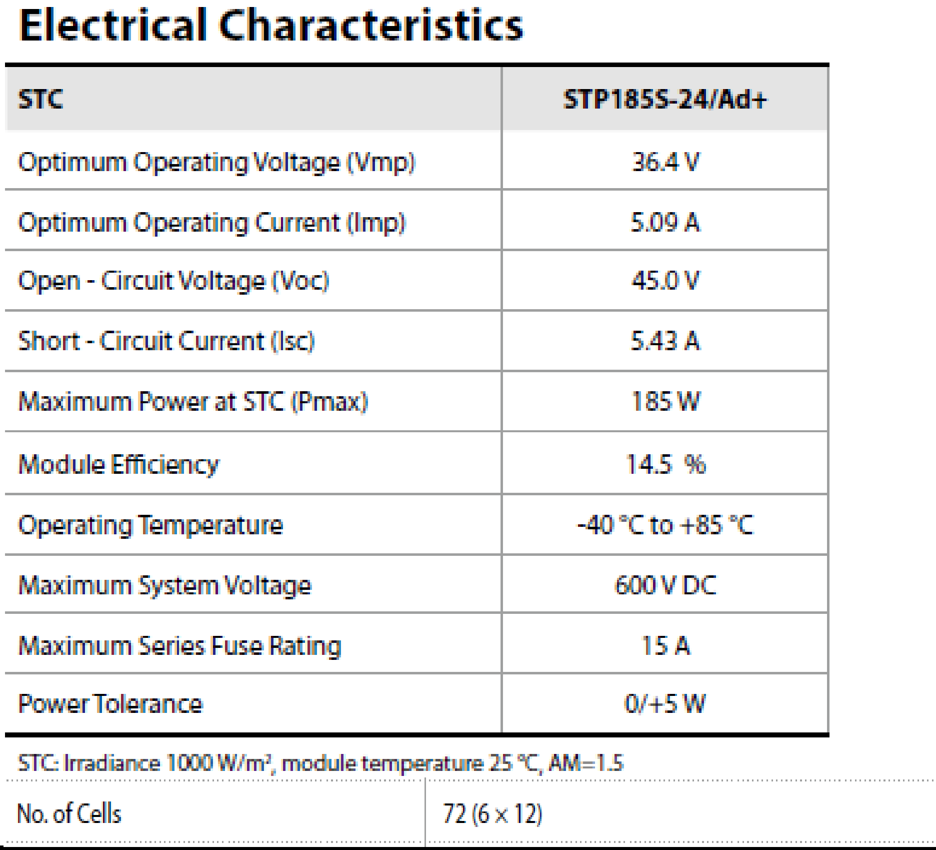
- Find the fill factor and the maximum power output of the following cell if G = 600 W/m^2. Ignore thermal effects.

$V_{OC}(600)$ is measured to be 44.04V

$$F = 0.757$$

$$I_{SC}(G) = 5.43x\left(\frac{600}{1000}\right) = 3.258A$$

$$P^{*}(G) = FI_{SC}(G)V_{OC}(G) = 108.6W$$



Electrical Characteristics

STC	STP185S-24/Ad+
Optimum Operating Voltage (Vmp)	36.4 V
Optimum Operating Current (Imp)	5.09 A
Open - Circuit Voltage (Voc)	45.0 V
Short - Circuit Current (Isc)	5.43 A
Maximum Power at STC (Pmax)	185 W
Module Efficiency	14.5 %
Operating Temperature	-40 °C to +85 °C
Maximum System Voltage	600 V DC
Maximum Series Fuse Rating	15 A
Power Tolerance	0/+5 W

STC: Irradiance 1000 W/m², module temperature 25 °C, AM=1.5

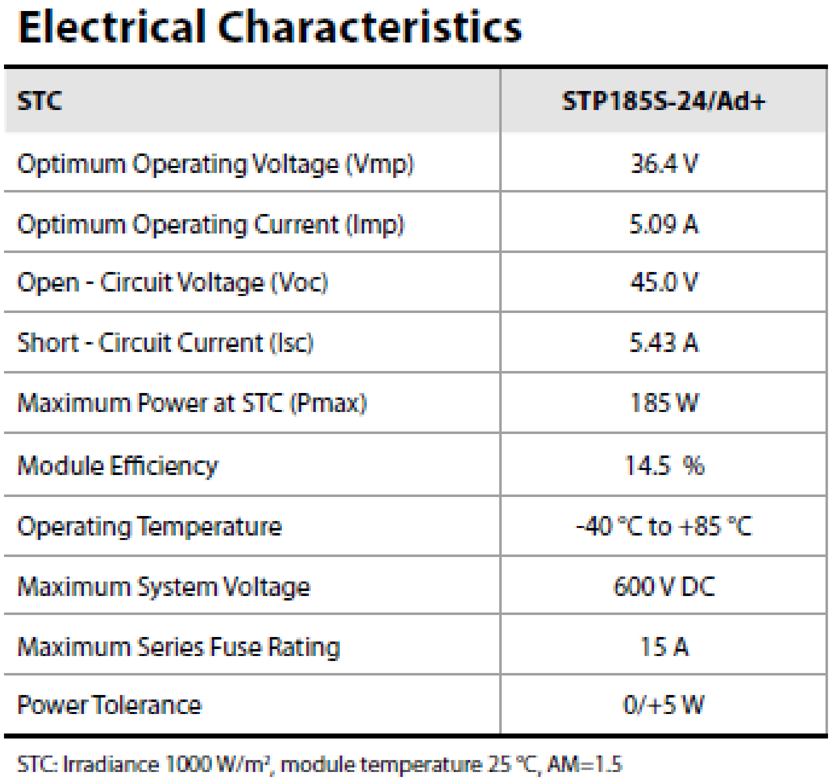
No. of Cells	72 (6 x 12)

PV Array Power Output

- Alternatively, we could estimate P*(G) for G = 600 W/m² to be:

$$P^*(G) = P^*_{STC}\left(\frac{G}{G_{STC}}\right)$$

$$P^*(600) = 185\left(\frac{600}{1000}\right) = 111 \text{ W/m}^2$$



Electrical Characteristics

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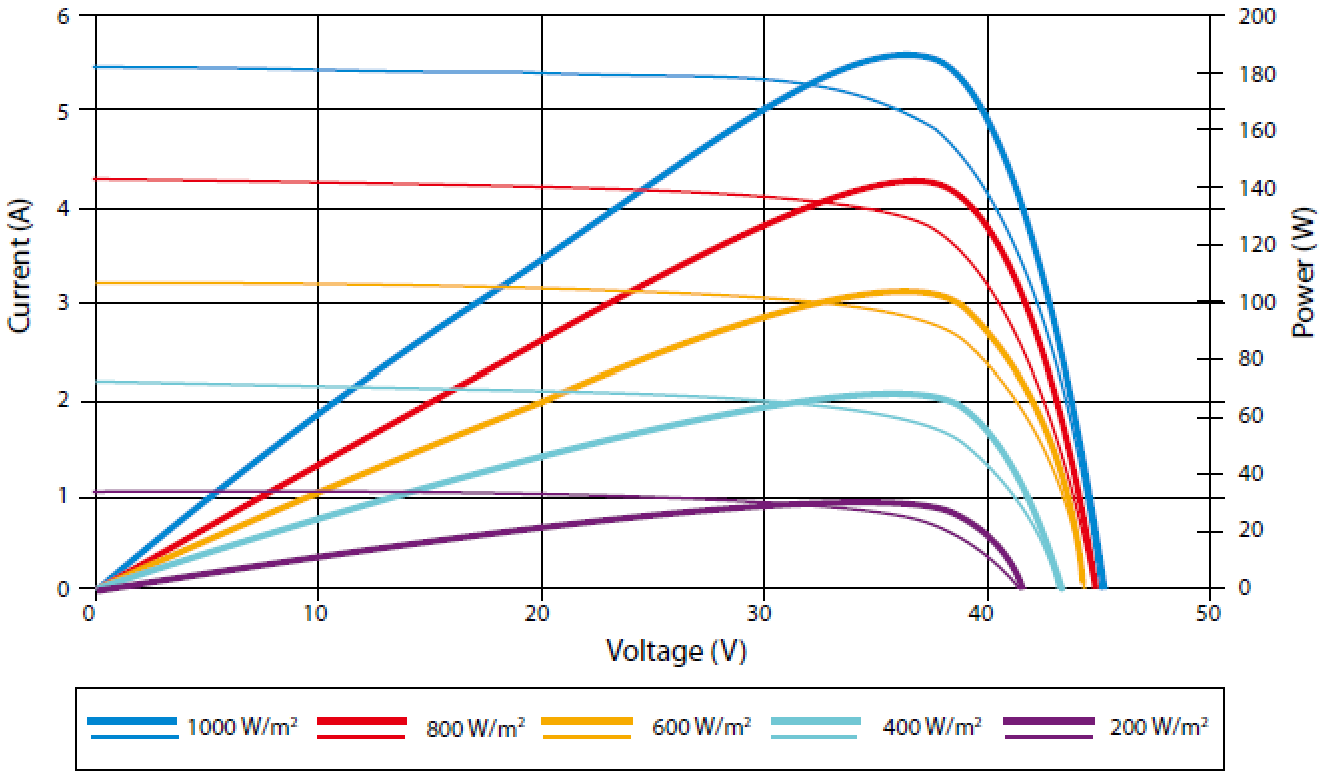
STC: Irradiance 1000 W/m², module temperature 25 °C, AM=1.5

PV Array Power Output



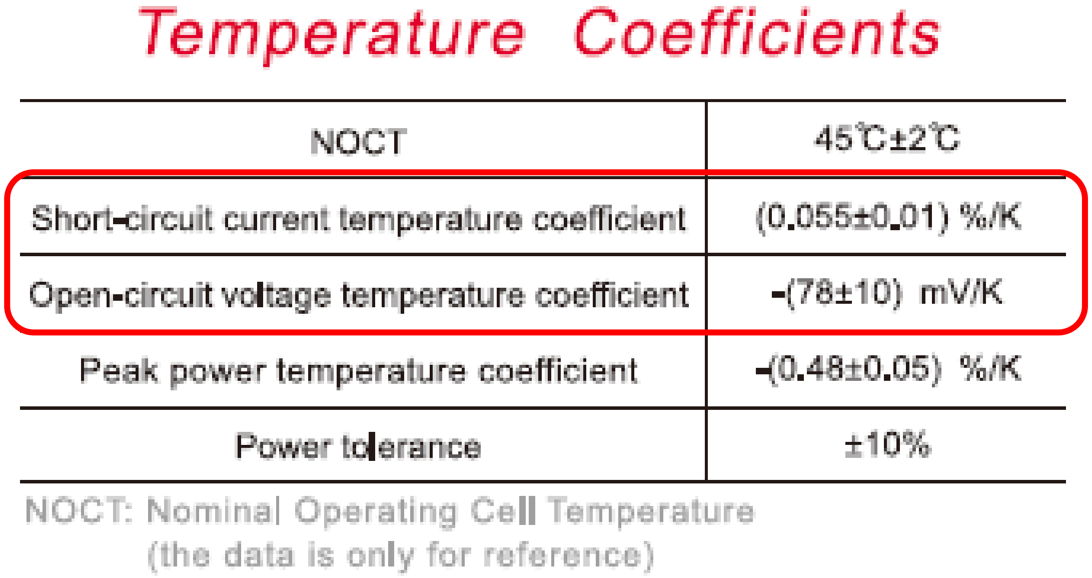
Temperature Effects

- PV cells often operate in areas of high solar irradiance and high ambient temperatures
- PV cells, like diodes, are temperature sensitive
- Effects of temperature:
    - <u>Increase</u> PV cell current
    - <u>Decrease</u> PV cell voltage

PV Module Spec Sheets

α_v: open circuit voltage temperature coefficient at STC (%/K, %/C, mV/K or mV/C)

- percent change in voltage for every degree difference in temperature from STC (25^{o} C)



Temperature Coefficients

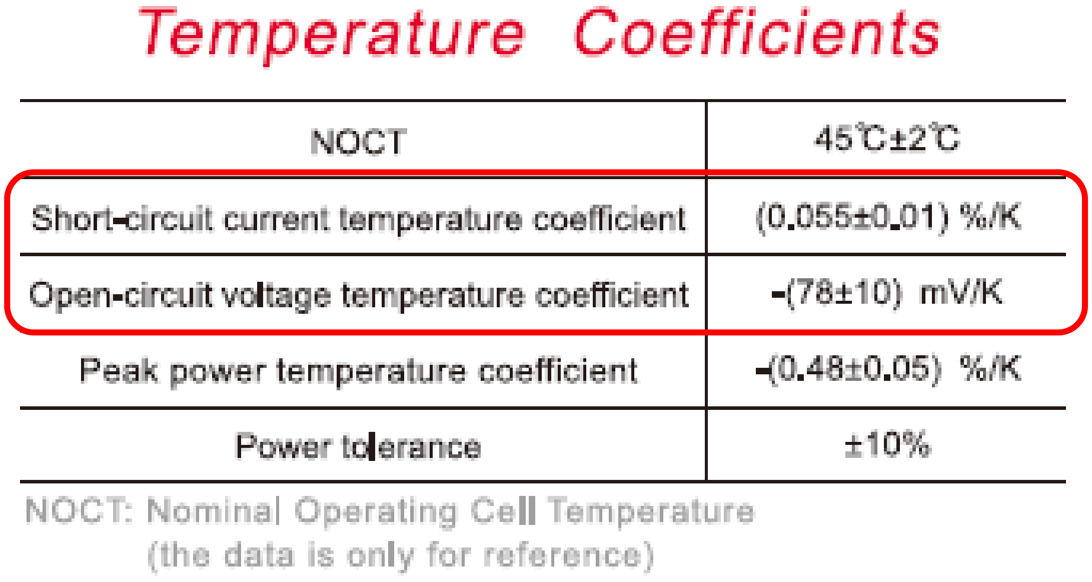
NOCT	45℃±2℃
Short-circuit current temperature coefficient	(0.055±0.01) %/K
Open-circuit voltage temperature coefficient	-(78±10) mV/K
Peak power temperature coefficient	-(0.48±0.05) %/K
Power tolerance	±10%

NOCT: Nominal Operating Cell Temperature
(the data is only for reference)

PV Module Spec Sheets

α_i: short circuit current temperature coefficient at STC (%/K or %/C)

- percent change in current for every degree difference in temperature from <u>STC</u> (25^o C)



Temperature Coefficients

NOCT	45℃±2℃
Short-circuit current temperature coefficient	(0.055±0.01) %/K
Open-circuit voltage temperature coefficient	-(78±10) mV/K
Peak power temperature coefficient	-(0.48±0.05) %/K
Power tolerance	±10%

NOCT: Nominal Operating Cell Temperature
(the data is only for reference)

Temperature Effects

- A PV panel's rated open circuit voltage is 50 V. Let α_v = -0.37 %/K. If G = 1000 W/m^2 and the panel's temperature is 30^{o}C, then:
  - Open circuit voltage changes by:

    50(-0.0037 x (30 - 25)) = -0.925V
  - V_{oc} is then: 50 – 0.925 = 49.075 V

Temperature Effects

- A PV panel's rated short circuit current is 5 A. Let α_i = 0.04 %/K. If G = 1000 W/m^2 and the panel's temperature is 30^{o}C, then:
  - Short circuit current changes by:

    5(0.0004 x (30 - 25)) = 0.01A
  - I_{sc} is then: 5 + 0.01 = 5.01 A

Temperature Effects

- Mathematically:

$$V_{OC}(T_c) = V_{OC}(25^{\circ}\mathrm{C})[1 + \alpha_v \times (T_c - 25)]$$

  - $V_{OC}(T_c)$: temperature-corrected open circuit voltage (V)
  - $V_{OC}(25^{o}C)$: open circuit voltage at $T_C = 25^{o}C$ (V)

- Important: if G = 1000 W/m^2, then
  - $V_{OC}(25^{o}C) = V_{OC,STC}$, else
  - $V_{OC}(25^{o}C)$ must be adjusted for the irradiance

Temperature Effects

- Mathematically:

  $$I_{SC}(T_c) = I_{SC}(25^\circ\text{C})[1 + \alpha_i \times (T_c - 25)]$$

  - $I_{SC}(T_c)$: temperature-corrected short circuit current (A)
  - $I_{SC}(25^\circ C)$: short circuit current at $T_C = 25^\circ C$ (A)

- Important: if G = 1000 W/m^2, then
  - $I_{SC}(25^\circ C) = I_{SC,STC}$, else
  - $I_{SC}(25^\circ C)$ must be adjusted for the irradiance

Temperature Effects

- A PV panel's rated short circuit current is 5 A. Let $\alpha_i = 0.04$ %/K. If $G = 600\ \mathrm{W/m^2}$ and the panel's temperature is 27°C, then:
    - Short circuit current at $G = 600\mathrm{W/m^2}$, $T_C = 25^{o}\mathrm{C}$:

      $I_{SC}(25^{o}\mathrm{C}) = 5 \times (600/1000) = 3\mathrm{A}$ (irradiance-adjusted current)

    - Short circuit current at $G = 600\mathrm{W/m^2}$, $T_C = 27^{o}\mathrm{C}$

      $I_{SC} = 3 \times [1 + 0.0004 \times (27-25)] = 3.0024\ \mathrm{A}$

↑

irradiance-adjusted
short circuit current

Temperature Effects

- A PV panel's rated open circuit voltage is 50V. Let α_V = -0.37 %/K. If G = 600 W/m^2 and the panel's temperature is 27^{o}C, then:
  - Open circuit voltage at G = 600W/m^2, T_C = 25^{o}C: recall from Lecture 9:

$$V_{OC} = N_{cells} \times V_T \ln\left(\frac{I_L}{I_{Sat}}\right)$$

$I_L = I_{SC} = 3A$

Let: $I_{sat} = 9.4^{-10}A$

Let there be <u>80</u> series connected cells in this panel

$V_T = 26mV$

Temperature Effects

- A PV panel's rated open circuit voltage is 50V. Let α_V = -0.37 %/K. If G = 600 W/m^2 and the panel's temperature is 27^{o}C, then:
    - Open circuit voltage at G = 600W/m^2, T_C = 25^{o}C:

$$V_{OC}(25^{o}\mathrm{C}) = 80 \times 0.026 \times \ln\left(\frac{3}{9.4^{-10}}\right) = 48.89V$$ (irradiance-adjusted voltage)

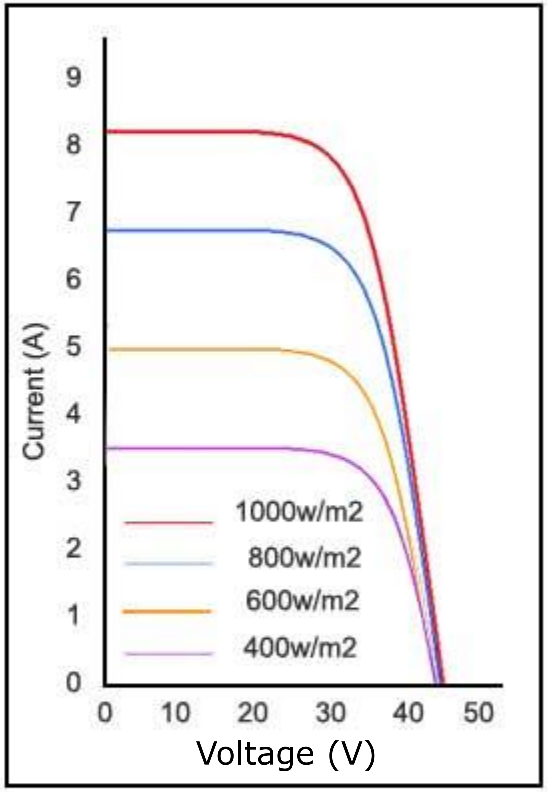
- Open circuit voltage at G = 600W/m^2, T_C = 27^{o}C

$$V_{OC} = \underset{\uparrow}{48.89} \times [1 - 0.37\times(27-25)] = 45.27\ \mathrm{V}$$

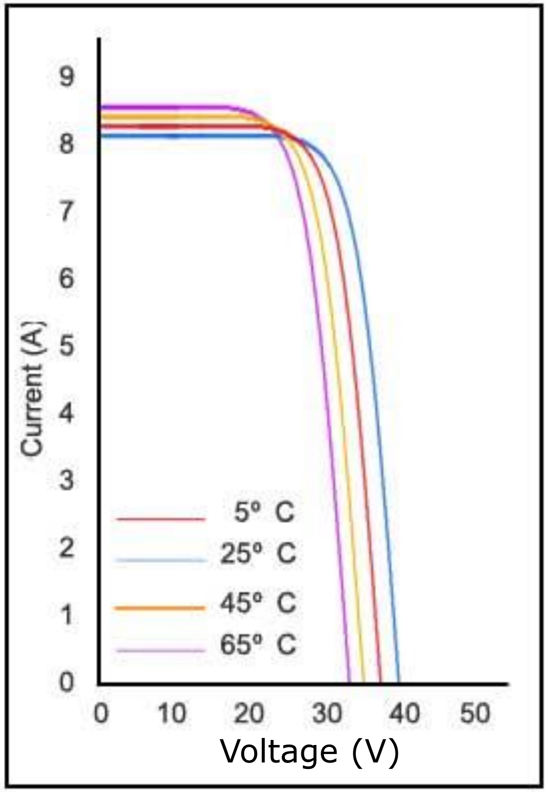
irradiance-adjusted
open circuit voltage

Irradiance/Temperature Effects

Irradiance



Temperature



Temperature Effects

- PV voltage decrease dominates current increase
- Result: percent decrease in power is approximately equal to percent decrease in voltage

PV Module Spec Sheets

α_p: power temperature coefficient at STC (%/K or %/C)

- percent change in maximum power for every degree difference in temperature from <u>STC</u> (25° C)

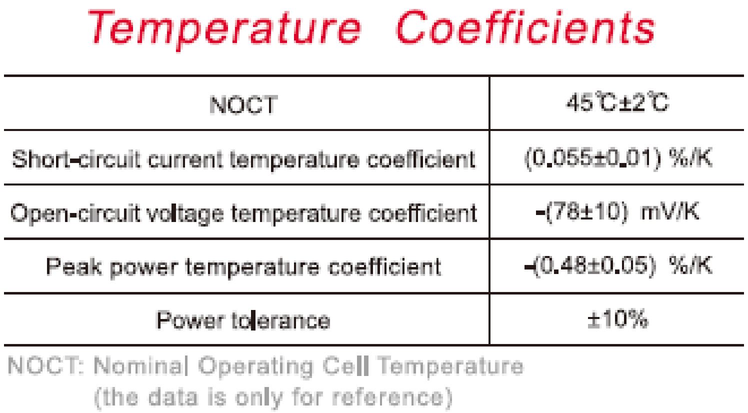
- Mathematically:

$$P^*(T_c) = P^*(25^\circ\mathrm{C})[1 + \alpha_p \times (T_c - 25)]$$

- $P^*(T_c)$: temperature-corrected maximum power point (W)
- $P^*(25^\circ\mathrm{C})$: maximum power at $T_C = 25^\circ\mathrm{C}$ (W). Must be adjusted for irradiance if G is not 1000 W/m^2

Temperature Effects

- Conversion of mV/K to %/K
  - Divide mV/K by $V_{OC,STC}$
- For a cell with
  - α_v = -78 mV/K
- With $V_{oc,STC}$ = 21.8 V
  - α_v = -0.36 %/K (much larger than α_i)



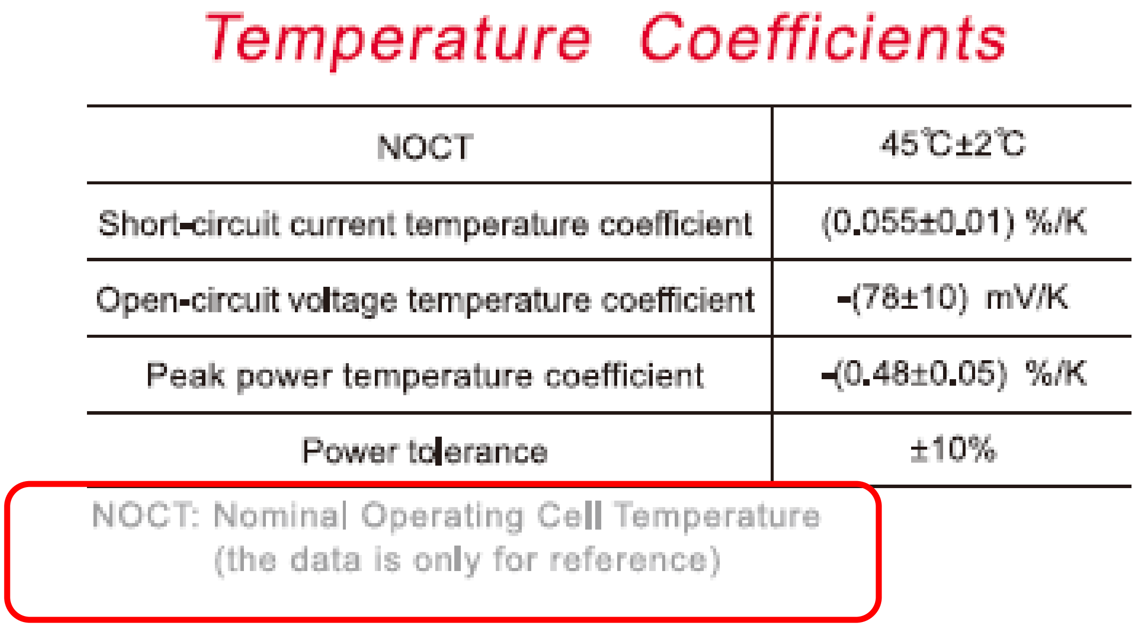
Temperature Coefficients

NOCT	45℃±2℃
Short-circuit current temperature coefficient	(0.055±0.01) %/K
Open-circuit voltage temperature coefficient	-(78±10) mV/K
Peak power temperature coefficient	-(0.48±0.05) %/K
Power tolerance	±10%

NOCT: Nominal Operating Cell Temperature
(the data is only for reference)

Temperature Effects

- To compute the change in voltage and/or current with respect to temperature, we must know the temperature of the cell



Temperature Coefficients

NOCT	45℃±2℃
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Open-circuit voltage temperature coefficient	-(78±10) mV/K
Peak power temperature coefficient	-(0.48±0.05) %/K
Power tolerance	±10%

NOCT: Nominal Operating Cell Temperature
(the data is only for reference)

Temperature Effects

- Normal Operating Cell Temperature (NOCT) is the temperature of the cell (T_C) under the following conditions:
    - G: $0.8G_{STC}$
    - Spectral Distribution: AM 1.5
    - T_{amb}: 20 ^oC
    - Wind speed: 1 m/s
    - No Load
- This is known as Standard Operating Conditions (SOC)

Temperature Effects

- Do NOT confuse SOC with STC
- STC is used to determine P^*_{STC}, etc
  - Note the difference in Temperature between NOCT and STC (20 ^oC vs 25 ^oC)
- Typical values of NOCT
  - 42 to 50 ^oC

Temperature Effects

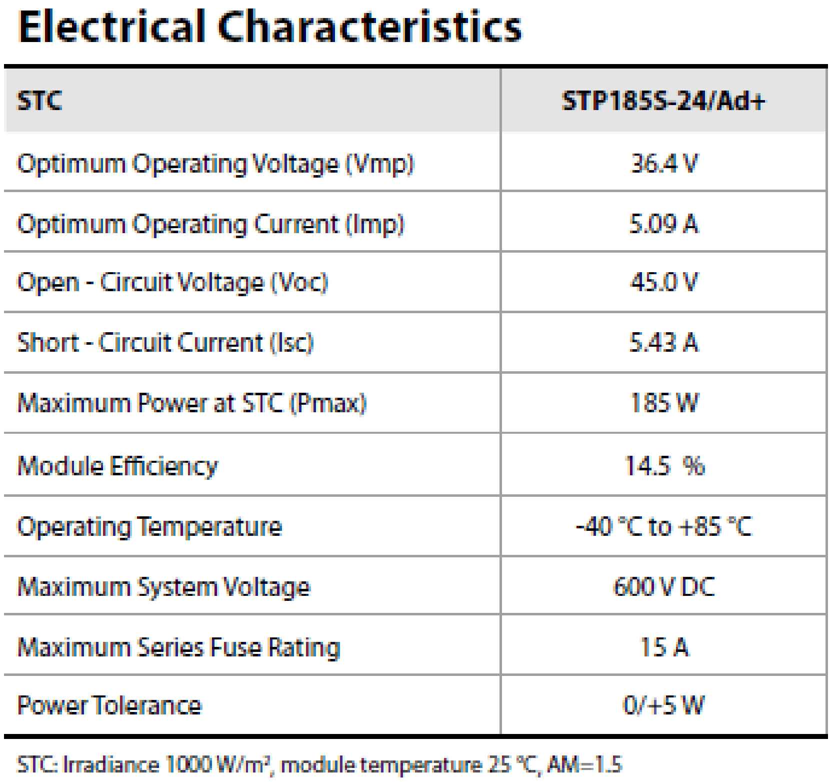
- Cell temperature is computed by:

$$T_c - T_a = \frac{NOCT - 20}{800} G$$

- Where T_a is the ambient temperature

Temperature Effects

- Consider a PV module with the nameplate values:



Electrical Characteristics

STC	STP185S-24/Ad+
Optimum Operating Voltage (Vmp)	36.4 V
Optimum Operating Current (Imp)	5.09 A
Open - Circuit Voltage (Voc)	45.0 V
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Maximum Power at STC (Pmax)	185 W
Module Efficiency	14.5 %
Operating Temperature	-40 °C to +85 °C
Maximum System Voltage	600 V DC
Maximum Series Fuse Rating	15 A
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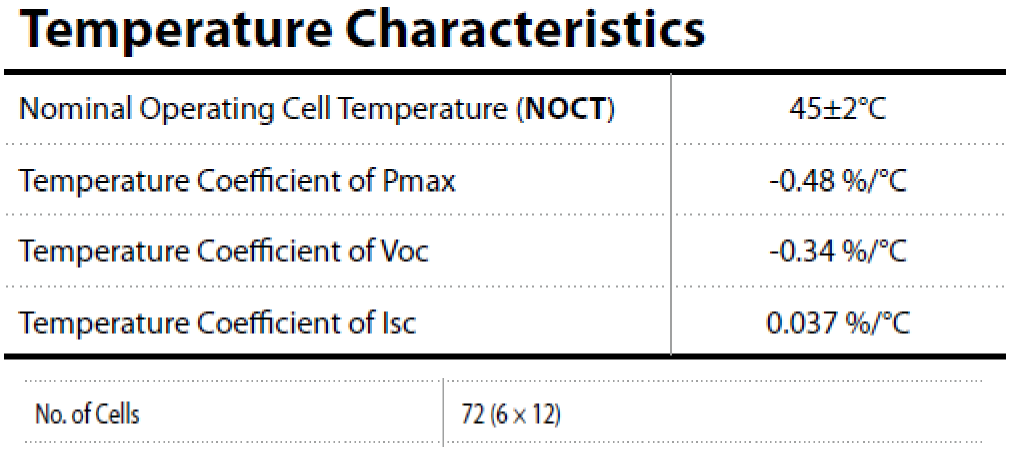
STC: Irradiance 1000 W/m^2, module temperature 25 °C, AM=1.5



Temperature Characteristics

Nominal Operating Cell Temperature (**NOCT**)	45±2°C
Temperature Coefficient of Pmax	-0.48 %/°C
Temperature Coefficient of Voc	-0.34 %/°C
Temperature Coefficient of Isc	0.037 %/°C

No. of Cells	72 (6 x 12)

Temperature Effects

- Under the following conditions:
    - G = 700 W/m^2
    - T_a = 34 ^{o}C
- Compute the open circuit voltage and short circuit current

Temperature Effects

- First compute T_c
  - NOCT = 45 °C
  - G = 700 W/m^2
  - T_a = 34 °C

$$T_c - T_a = \frac{NOCT - 20}{800} G = \frac{NOCT - 20}{800} G + T_a$$

$$T_c = \frac{45 - 20}{800} 700 + 34 = 55.9 \ ^{\circ}C$$

Temperature Effects

- Now compute I_{sc}
    - T_c = 55.9 °C
    - α_i: 0.037 %/K
    - $I_{sc,STC}$ = 5.43 A

- $I_{SC} = \underset{\underset{5.43 \text{ x } 0.7}{\uparrow}}{3.801} \text{ x } [1 + 0.00037\text{x}(55.9-25)] = 3.84 \text{ A}$

Temperature Effects

- Now compute V_{oc}
  - T_c = 55.9 ^oC
  - α_v: -0.34 %/K
  - $V_{oc,STC} = 45$ V
  - $N_{cells} = 72$
  - Assume V_t = 25 mV, $I_{sat} = 10.2^{-10}$ A
- V_{OC} = 44.4 x [1 -0.0034x(55.9-25)] = 39.32 V

$$\uparrow$$

$$N_{cells} \times V_T \ln\left(\frac{I_L}{I_{Sat}}\right)$$

PV Array Power Output

- Power output of PV array is:
  - $T_c = 55.9\ ^{o}C$
  - α_p: -0.48 %/K
  - $P^*_{STC} = 185W$

$$P^* = 129.5[1 - 0.0048(55.9 - 25)] = 110.3 \text{ W}$$

$$185\left(\frac{700}{1000}\right)$$

or could use Fill Factor method to adjust for irradiance (slide 48)

Temperature Effects

- Sometimes α_p is not known, so this approximation can be used

$$\alpha_p \approx \alpha_v \frac{V_{OC,STC}}{V^*\left(G_{STC}\right)}$$

- In the previous example:

$$\alpha_p \approx -0.0034 \frac{45}{36.4} = -0.0042$$ nameplate value: -0.0046

Comparison of Power Output

- Power as computed by various methods:

1. $P_{STC}^{*} = 185$ W
2. $P^{*} = P_{STC}^{*}\left(\frac{700}{1000}\right) = 129.5$ W   Ignoring temperature
3. $P^{*} = FV_{OC}(700)I_{SC}(700) = 118.9$ W   Using Fill factor, ignoring temp
4. $P^{*} = P_{STC}^{*}(1+\alpha_v \frac{V_{OC,STC}}{V_{mp}^{*}}(T_c - 25)) = 110.3$ W   Estimated α_p
5. $P^{*} = P_{STC}(G)(1+\alpha_p(T_c - 25)) = 112.7$ W   Actual α_p, most accurate

Comparison of Power Output

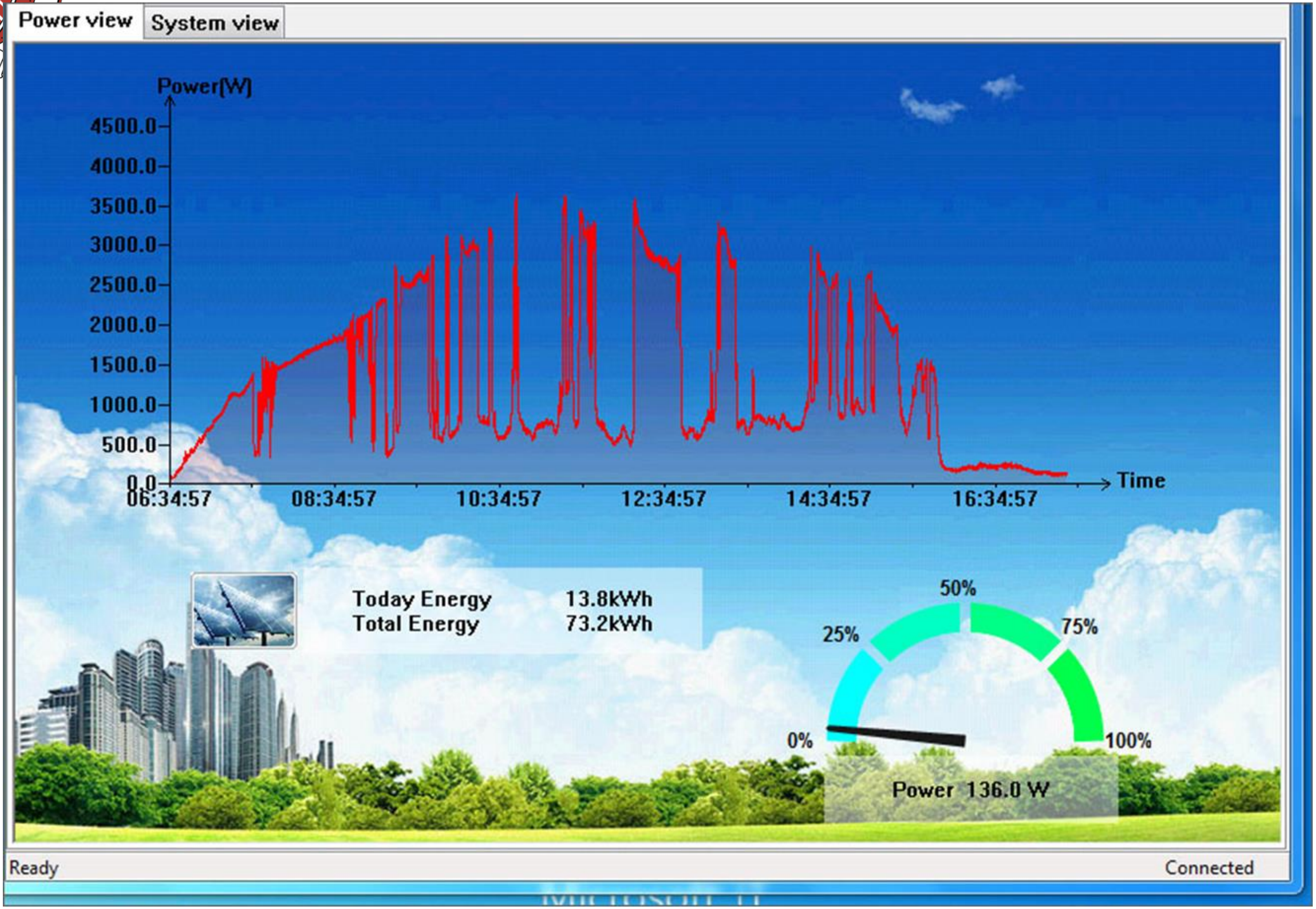
Which condition is the most favorable for PV power generation?

- Cold with high irradiance
- Hot with high irradiance
- Cold with low irradiance
- Hot with low irradiance

Comparison of Power Output

Which condition is the most favorable for PV power generation?

- [✓ Cold with high irradiance]
- Hot with high irradiance
- Cold with low irradiance
- Hot with low irradiance



Today Energy 13.8kWh
Total Energy 73.2kWh

Power 136.0 W