08-Photovoltaics Part 2

ECEGR 4530

Renewable Energy Systems

Overview

- Solar Radiation Absorption
- Illumination Current
- PV Circuit Equivalent
- PV Cell Arrangements
- Maximum Power Point

Introduction

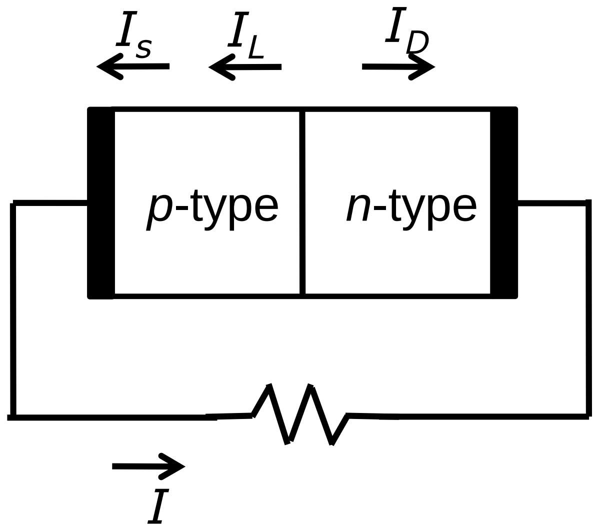
- Last lecture we described the behavior of a PV cell
  - In the dark, behaved like a diode
  - Under light, illumination current flows
- In this lecture we develop a circuit model for the PV cell and examine its power output characteristics

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

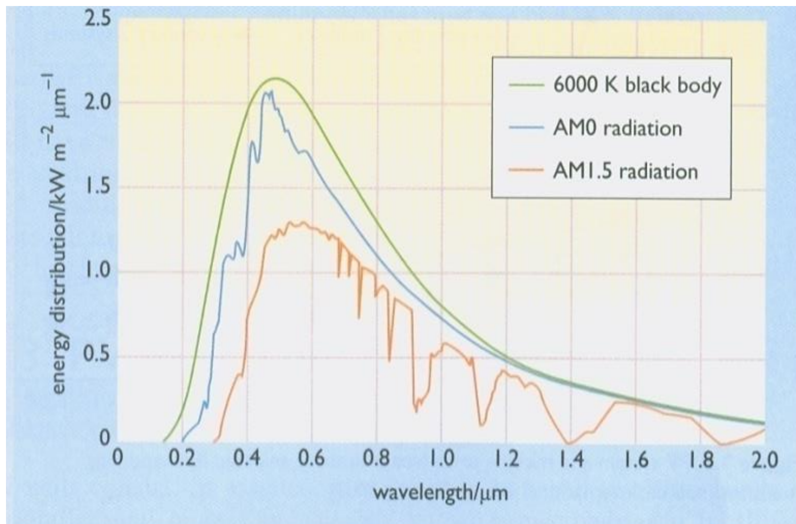


Figure 3.8 The spectral power distributions of solar radiation corresponding to Air Mass 0 and Air Mass 1.5. Also shown is the theoretical spectral power distribution that would be expected, in space, if the sun were a perfect radiator (a 'black body') at 6000 °C

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

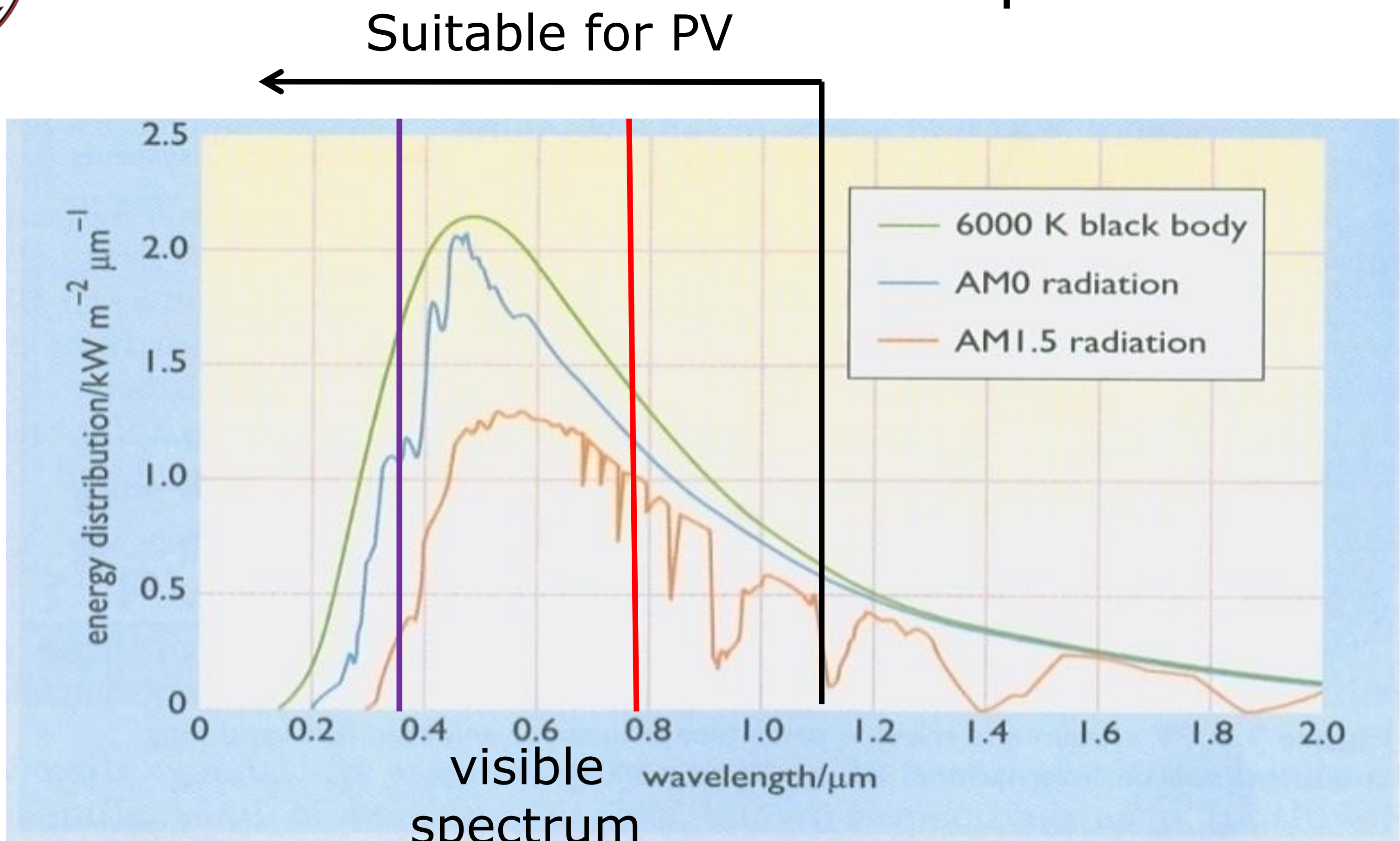


Figure 3.8 The spectral power distributions of solar radiation corresponding to Air Mass 0 and Air Mass 1.5. Also shown is the theoretical spectral power distribution that would be expected, in space, if the sun were a perfect radiator (a 'black body') at 6000 °C

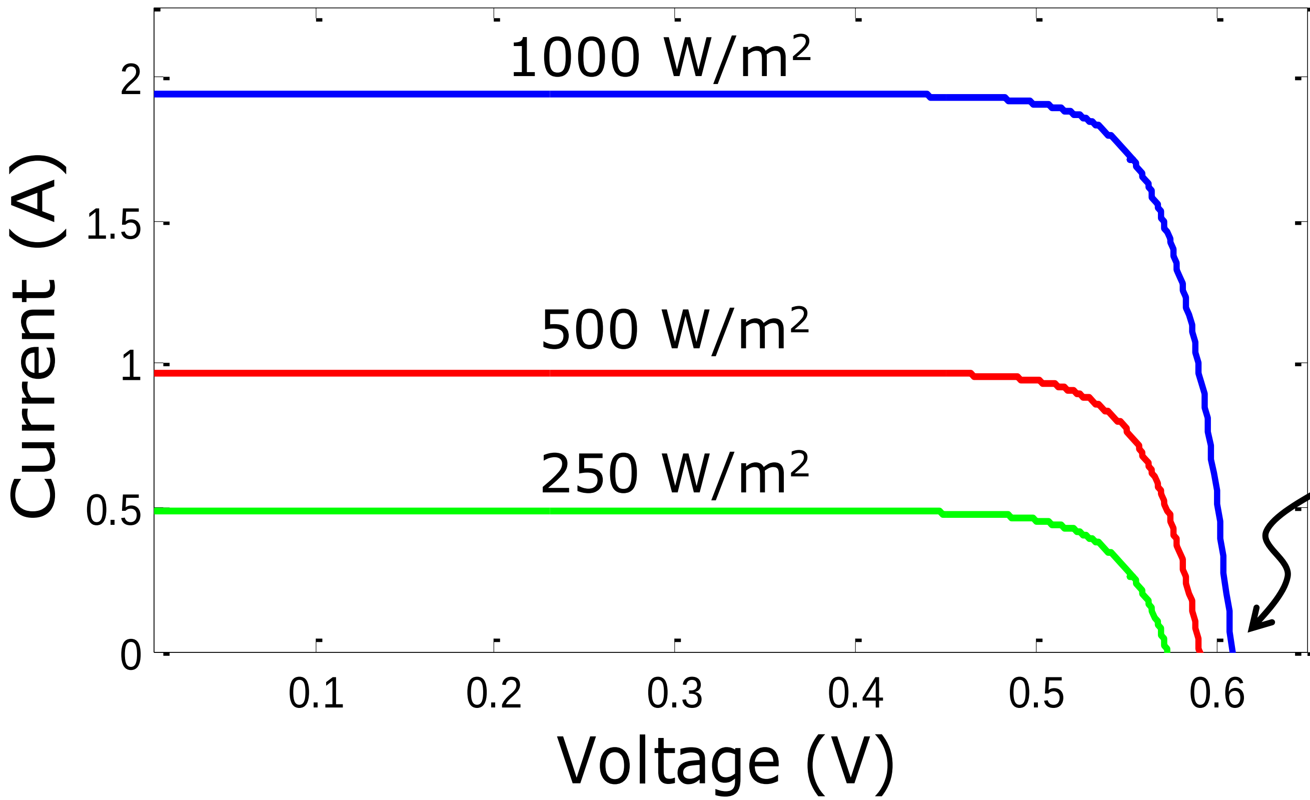
Illumination Current

- 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

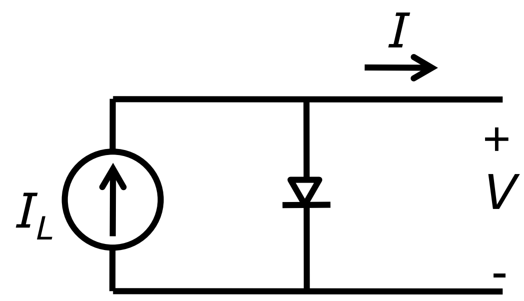
PV Circuit Equivalent

- Equivalent circuit of an ideal PV cell

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

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

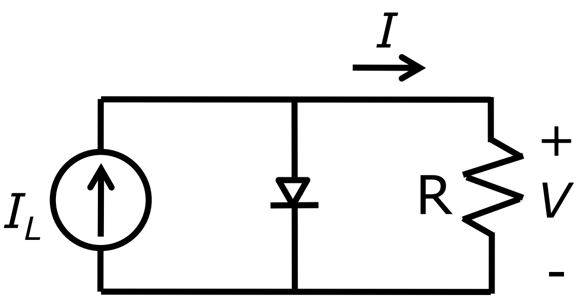
$$I_{SC} = I_L$$



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

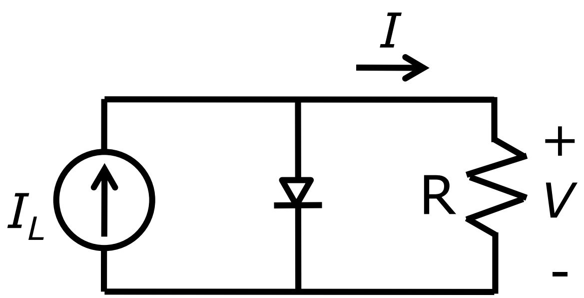
PV Circuit Equivalent

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



Exercise

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



$$V = IR$$

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

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

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)

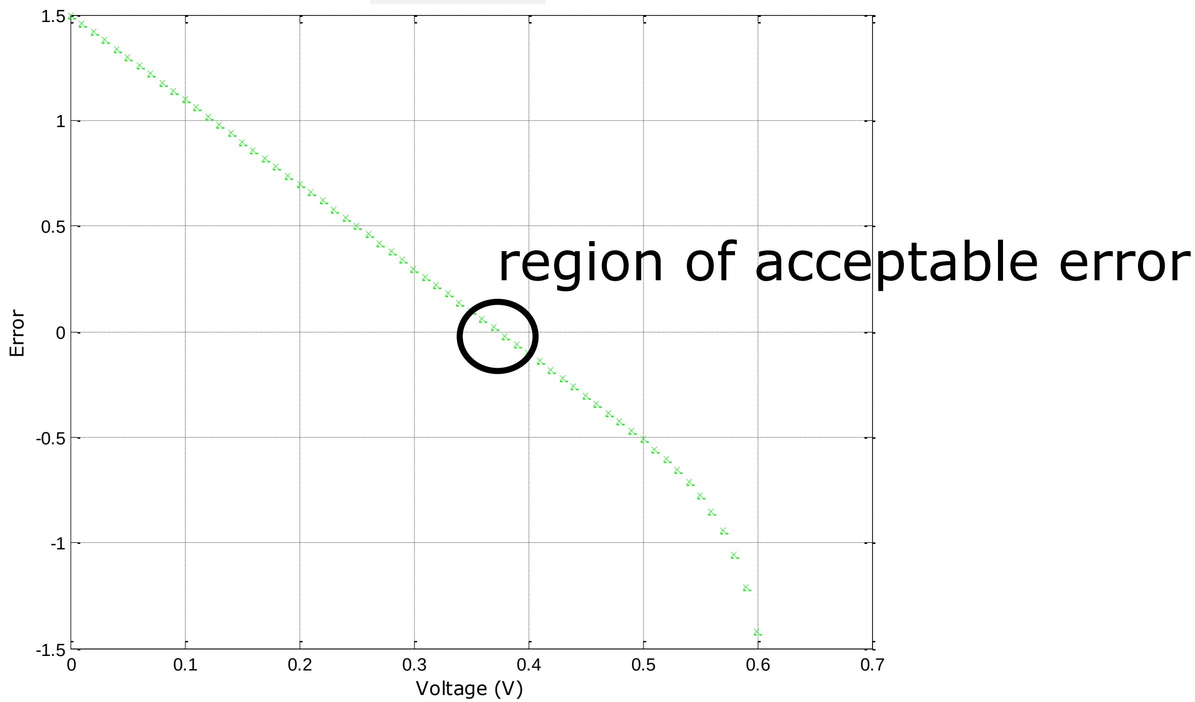
$$I = I_L - I_{Sat}\left(e^{V/V_T} - 1\right)$$

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

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

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.

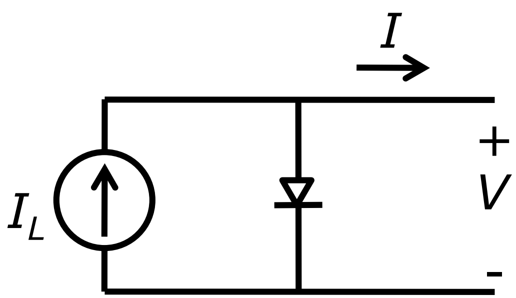


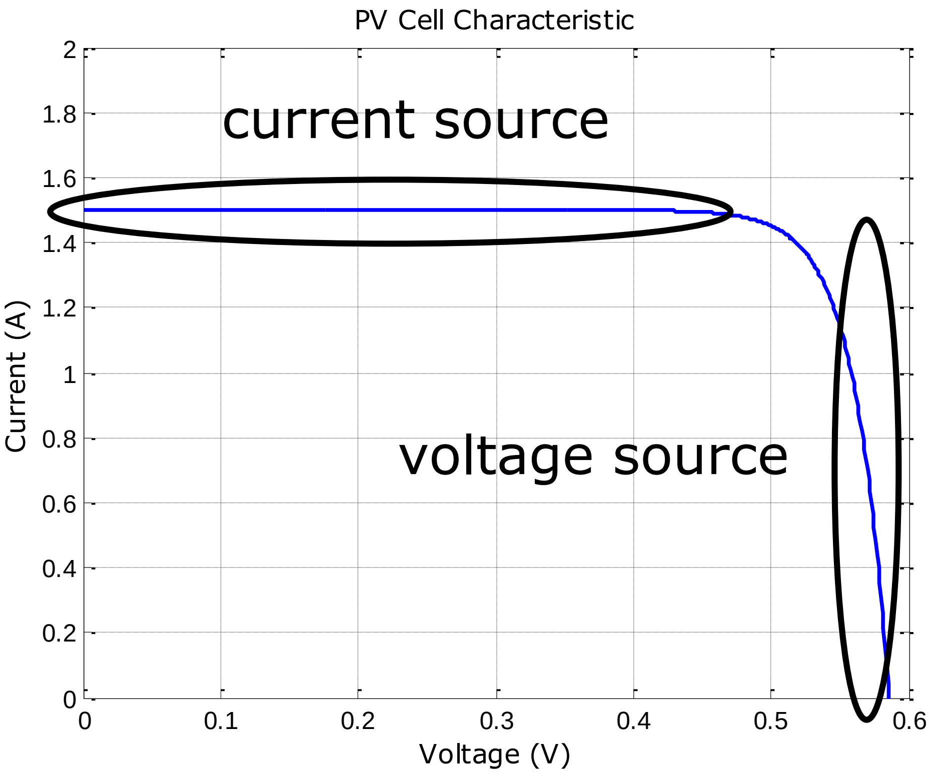
PV Circuit Equivalent

- 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

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

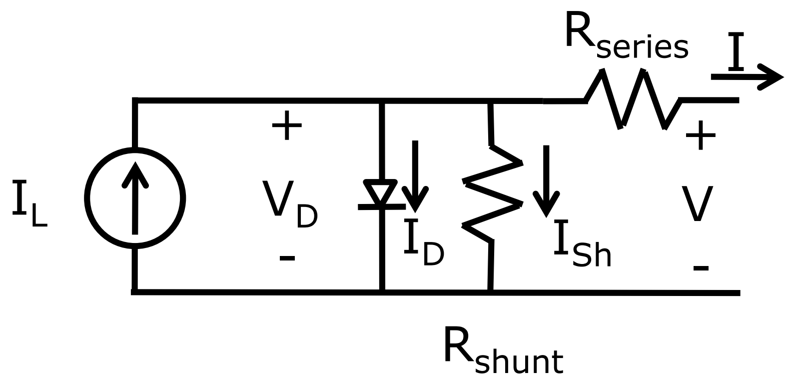
PV Circuit Equivalent





PV Circuit Equivalent

- Losses can be modeled by including shunt and series resistances



$$I = I_L - I_D - I_{sh}$$

$$I = I_L - I_{Sat}\left(e^{V_D/V_T} - 1\right) - \frac{V + IR_{series}}{R_{shunt}}$$

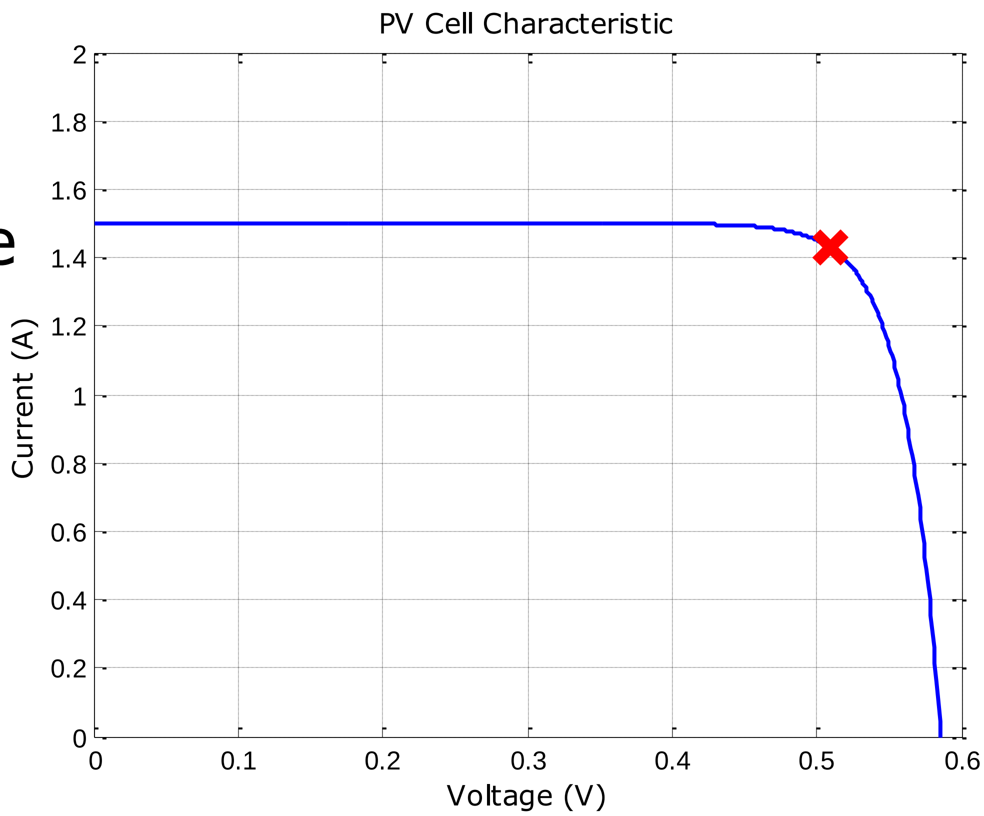
$$I = I_L - I_{Sat}\left(e^{(V+IR_{series})/V_T} - 1\right) - \frac{V + IR_{series}}{R_{shunt}}$$

PV Circuit Equivalent

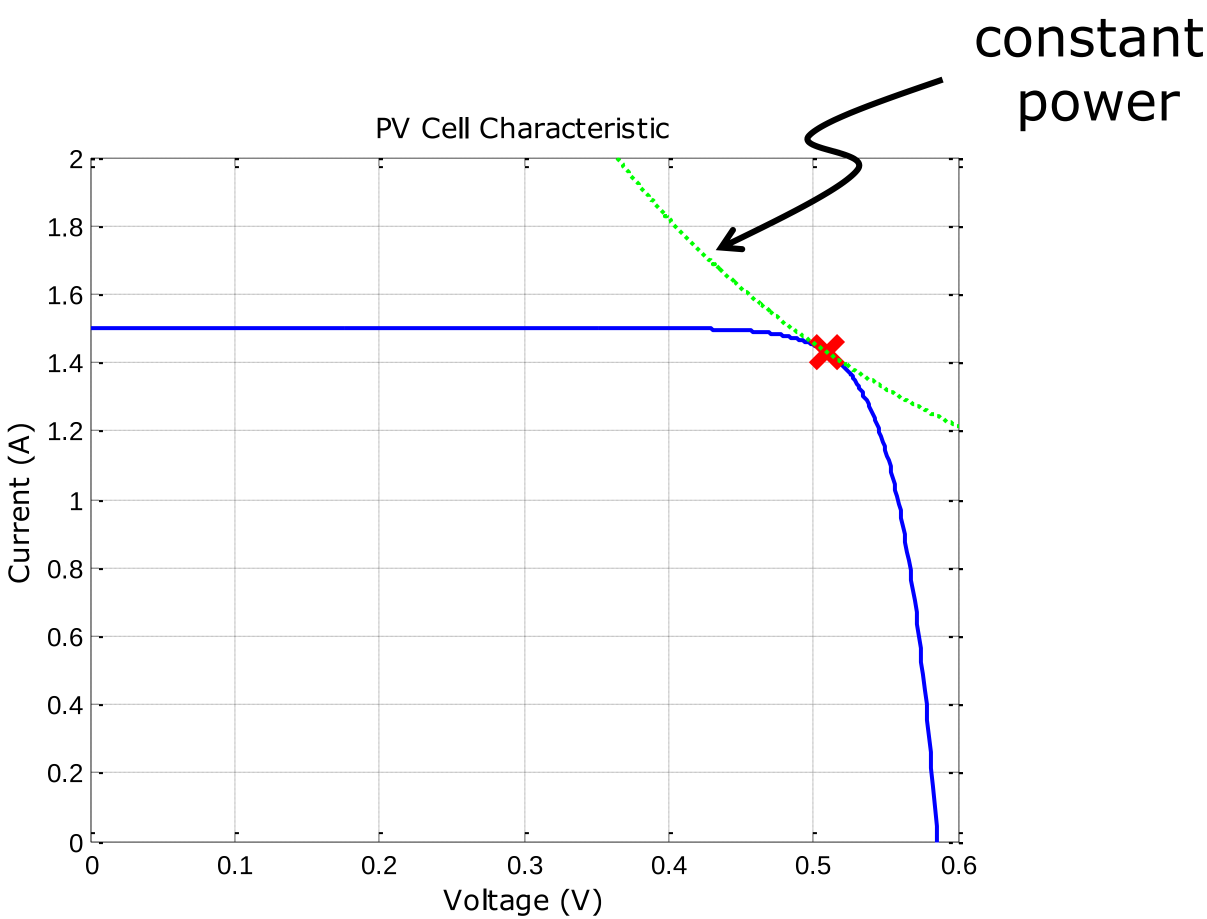
- Resistive losses in PV cells are generally small
  - R_{shunt} is large (loss ~0.1%)
  - R_{series} is small (loss ~0.3%)
- Resistances are often ignored, but if they are to be included, the circuit can be analyzed numerically

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

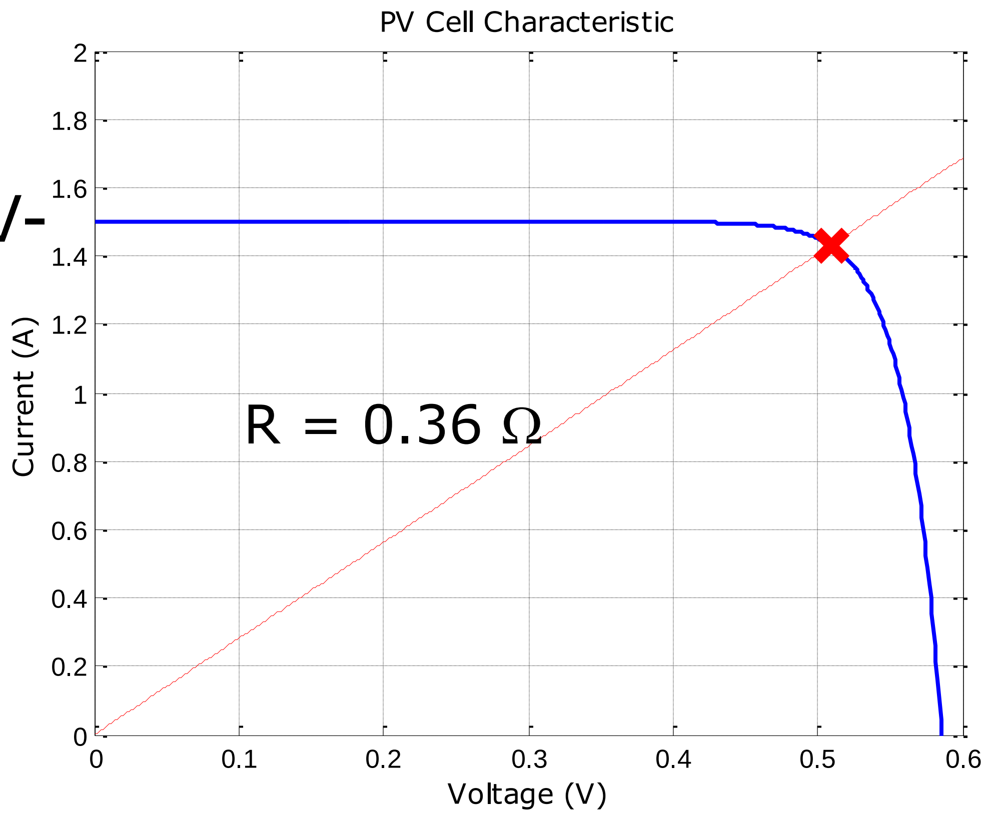


Maximum Power

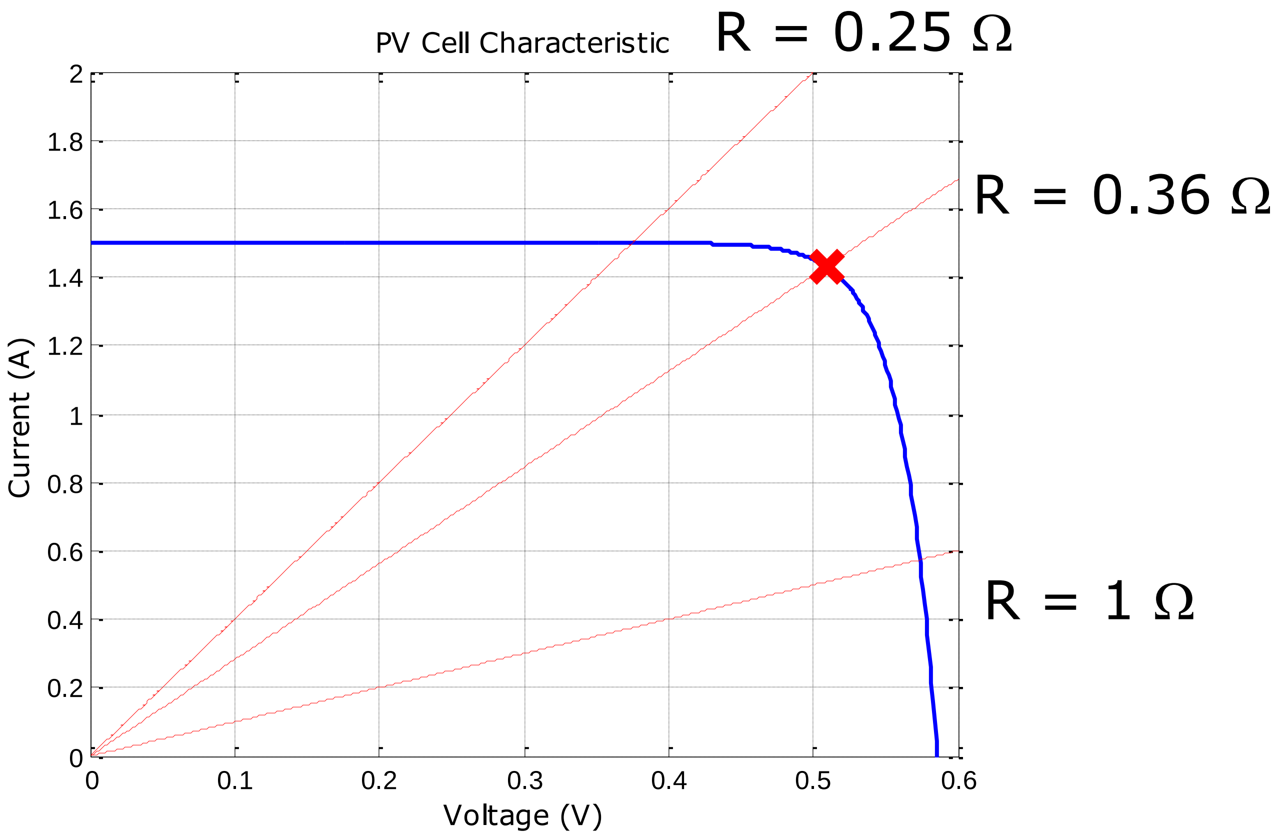


Maximum Power

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



Maximum Power

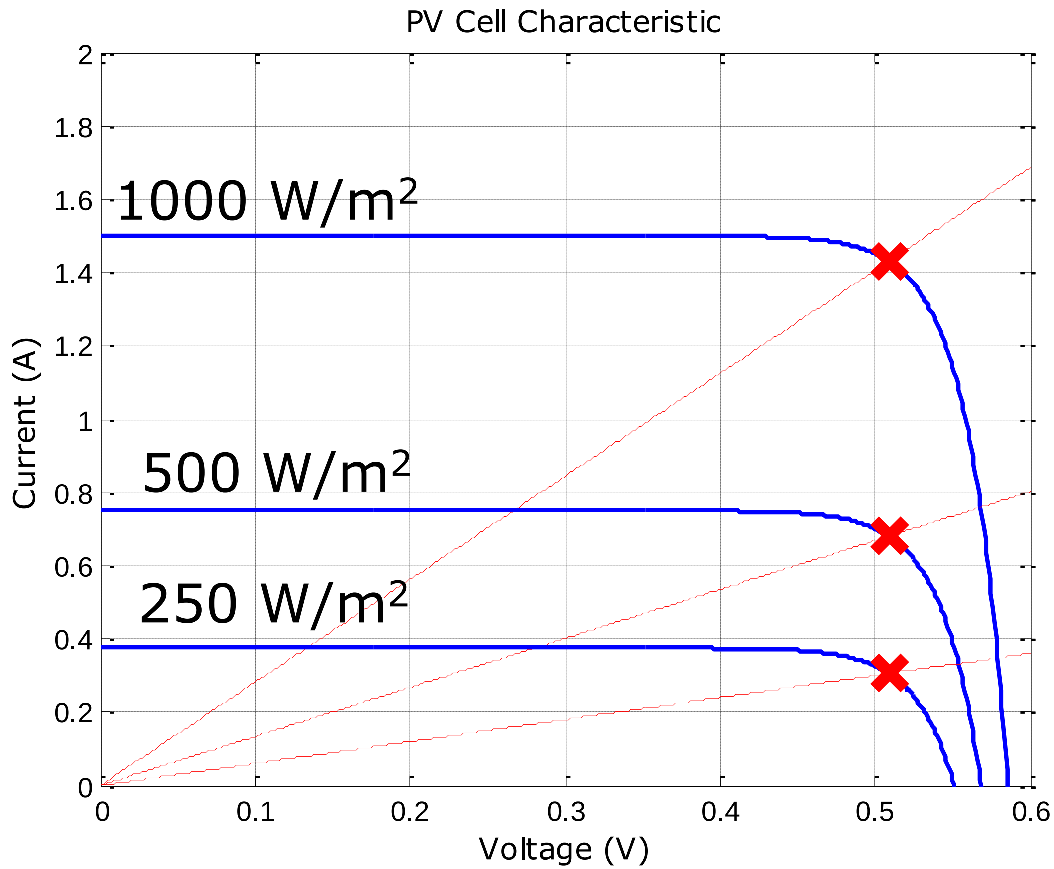


Maximum Power

- 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

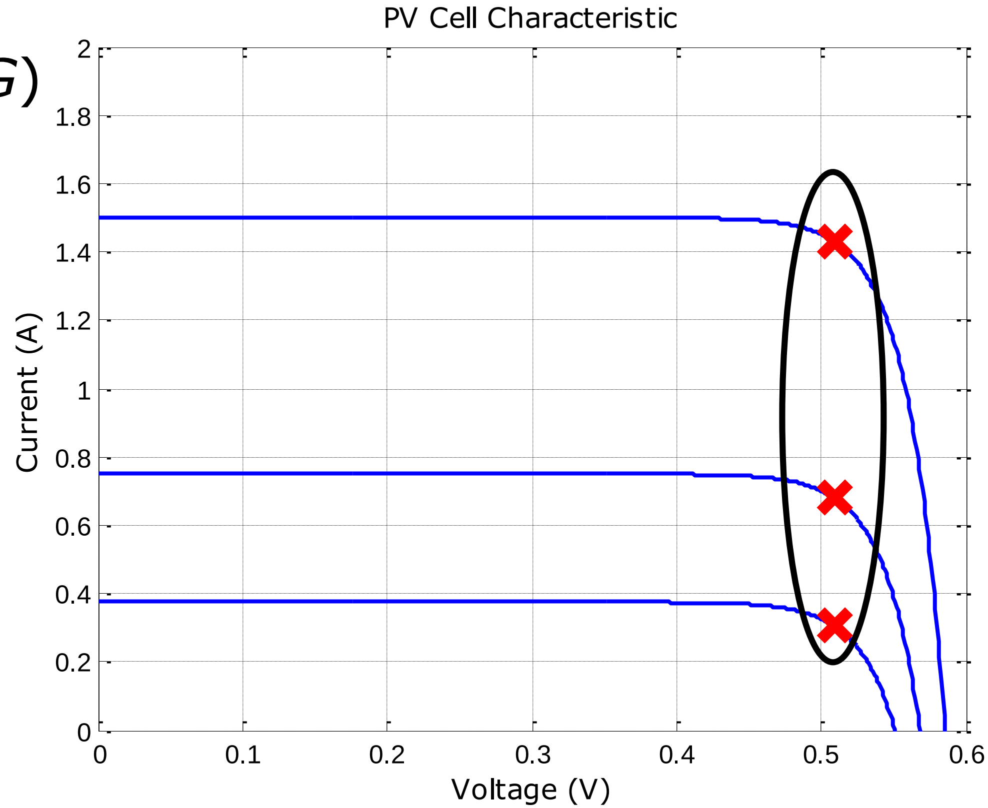
- P*, I*, V*, R* depend on illumination



Maximum Power

- Regardless of illumination amount, a <u>general rule of thumb</u>:

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

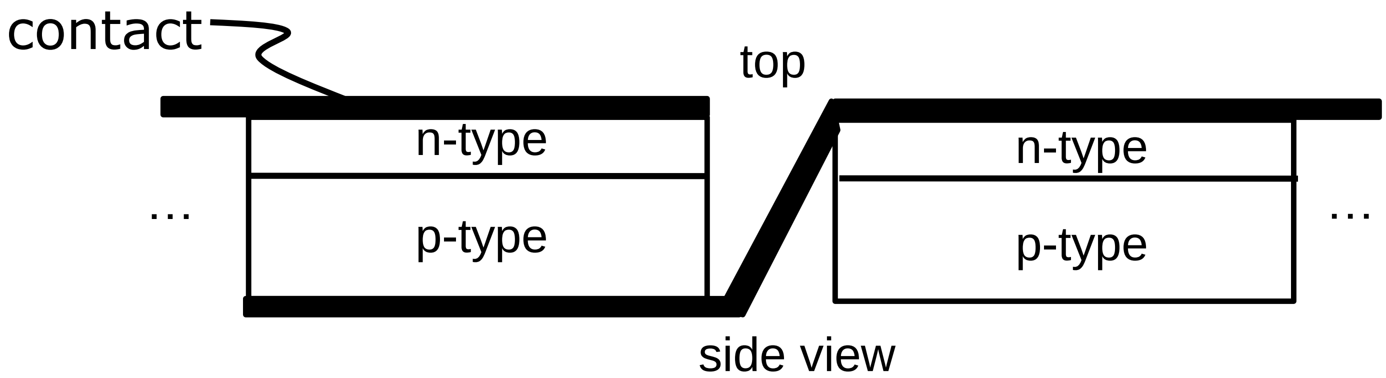


PV Cell Arrangements

- 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)

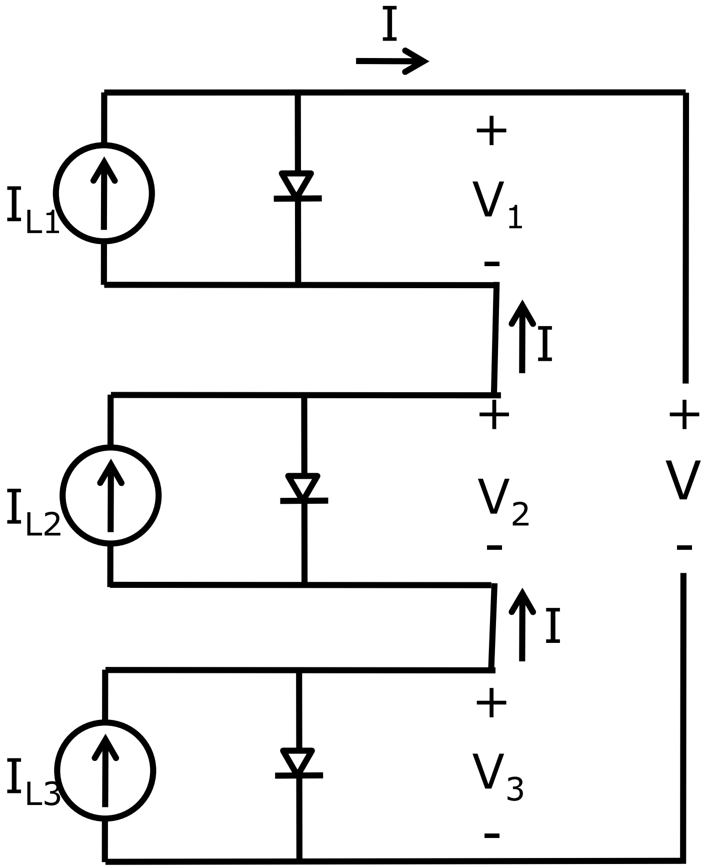


PV Cell Arrangements

- Output voltage, increased by series connection:

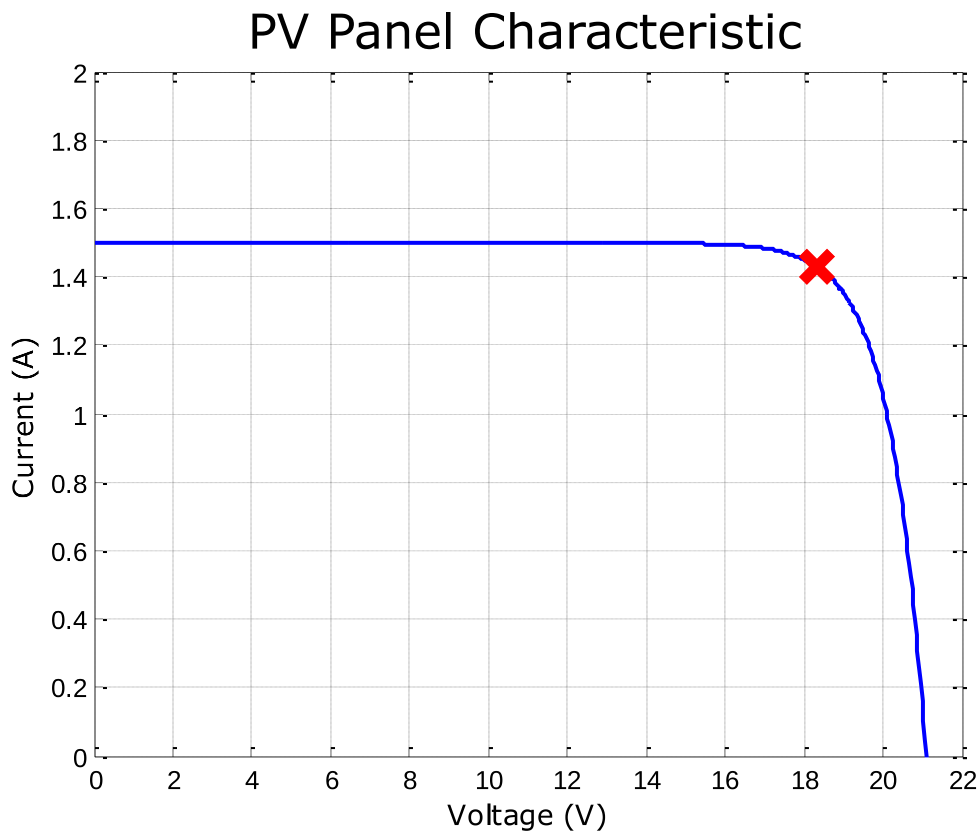
$$V = \sum_{n=1}^{N_{cells}} V_n$$

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



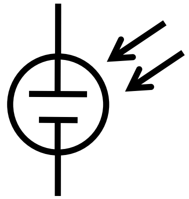
PV Cell Arrangements

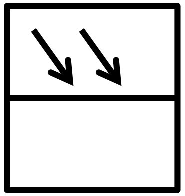
- IV characteristics can be easily aggregated
- Shape of characteristic does not change

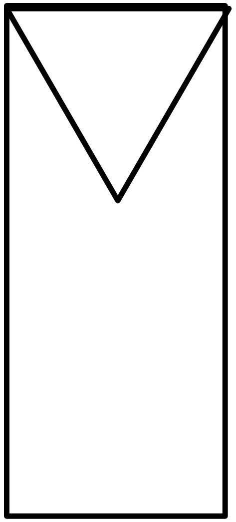


PV Cell Arrangements

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



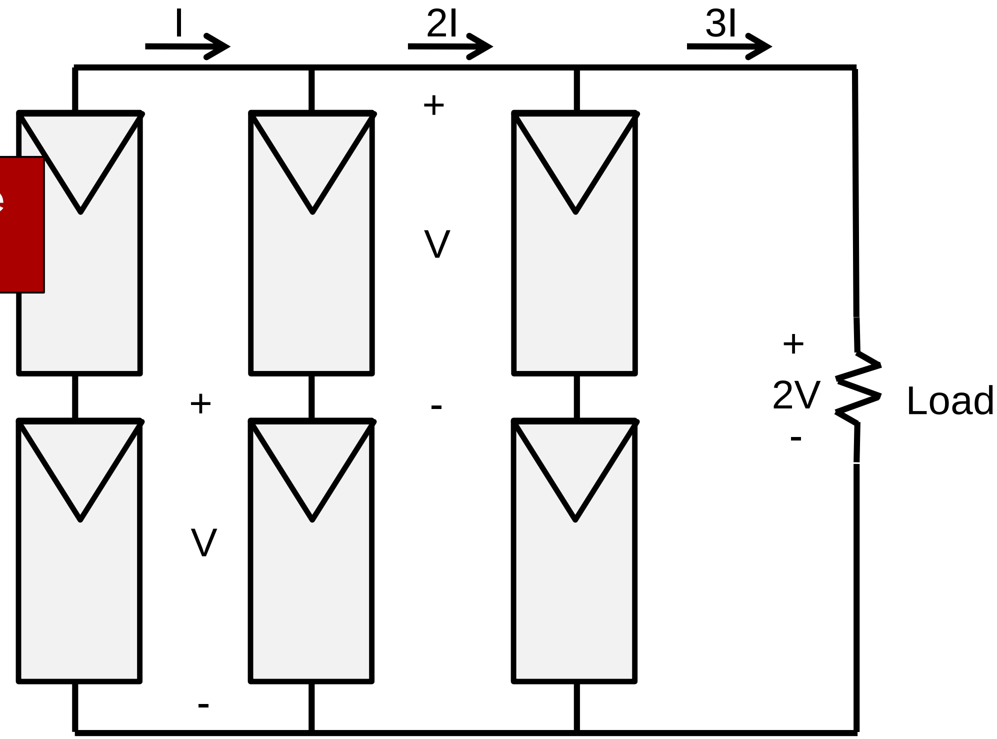




PV Module Arrangements

Series-connected PV modules are referred to as a "string"

This circuit configuration has three strings of two panels each



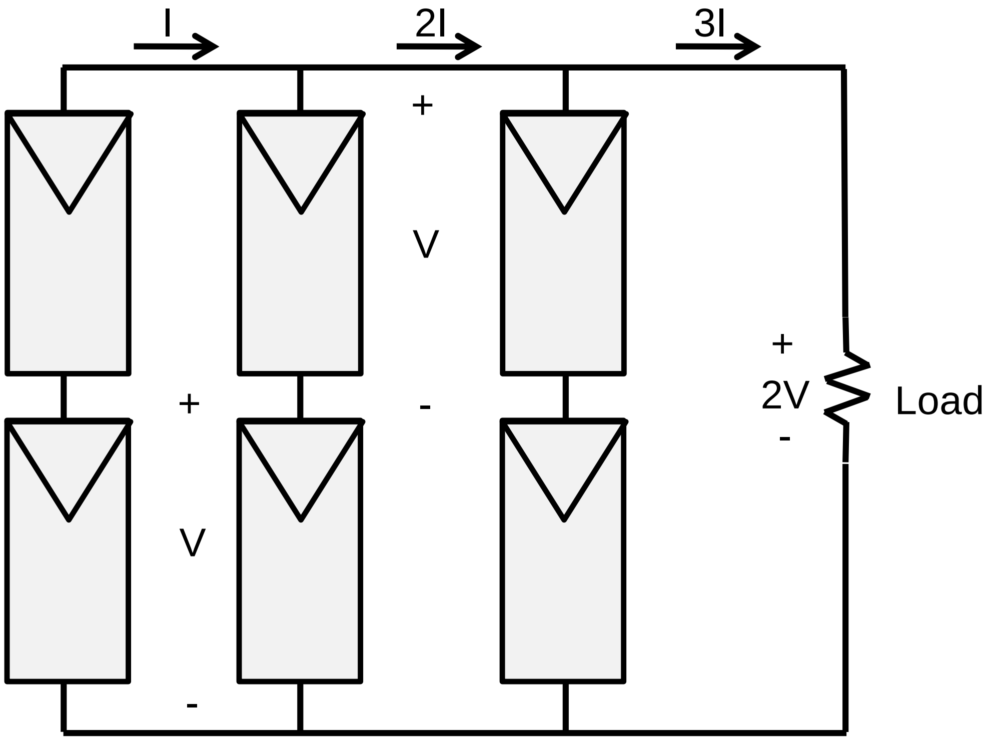
PV Module Arrangements

- The power output by each module is

  $P_m = VI$

- The power to the load is

  $P_L = 2V \times 3I = 6VI$
  $= 6\ P_m$



Exercise

The power delivered to the load of is greater if 6 PV modules are arranged in series (1 string of 6 modules) than if they are arranged in parallel (6 strings of 1 module each).

- True
- False

Exercise

The power delivered to the load of is greater if 6 PV modules are arranged in series (1 string of 6 modules) than if they are arranged in parallel (6 strings of 1 module each).

- True
- False

Series Connection: $P_L = 6V \times I = 6VI$
Parallel Connection: $P_L = V \times 6I = 6VI$

It makes no difference how the PV panels are connected (unless open or short circuited)—the same power will be delivered if the load resistance does not change

Module Configuration

If it doesn't matter how the PV modules are arranged, why not always arrange them as series (or parallel) or something else?

Parallel connections increase ampacity requirements of components and wires; series connections require components with higher voltage ratings.

Safety (high voltage), compatibility with battery voltage and desire to minimize wiring complexity and cost are also factors.