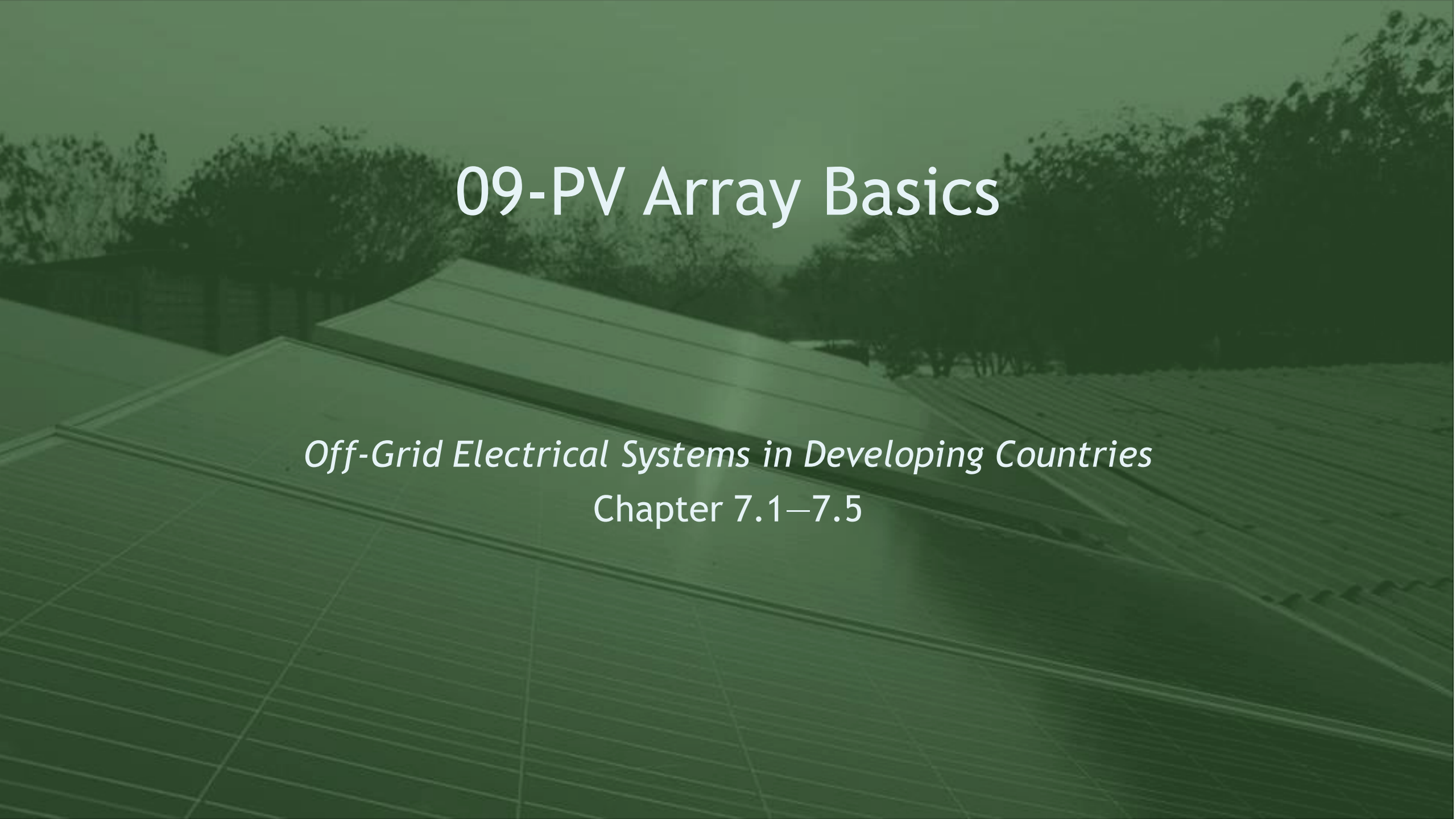

09-PV Array Basics

Off-Grid Electrical Systems in Developing Countries

Chapter 7.1—7.5

Learning Outcomes

At the end of this lecture, you will be able to:

- ✓understand the significance of PV in off-grid systems
- ✓define i*rradiance* and *insolation*
- ✓develop and analyze a circuit model of an ideal PV cell
- ✓describe and analyze the I-V curve of a PV cell and how it relates to the power produced by the cell

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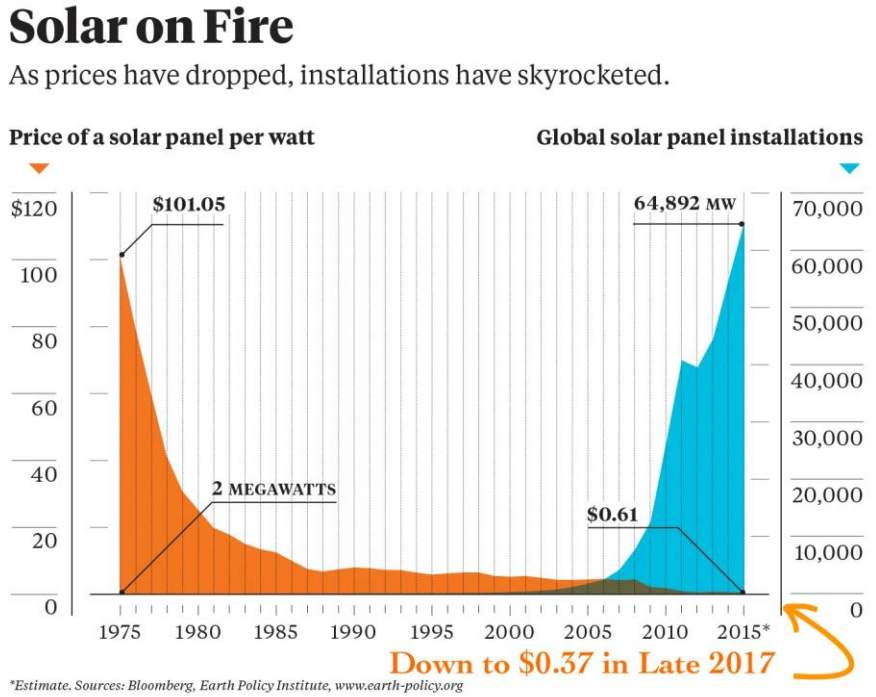
Photovoltaic (PV) Arrays

- PV arrays are commonly used in off-grid systems
- Default choice of energy conversion technology
  - Adequate sunlight in most energy-impoverished regions
  - Low data collection requirements
  - Low and falling prices



Note: prices in SSA tend to be higher

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The Solar Resource

- Energy from the sun is transferred to the earth through electromagnetic radiation
  - 3.8×10^{24} J annually (10,000 mankind's usage)
- Radiation from the sun has a wide spectral distribution, some of which is within the visible range

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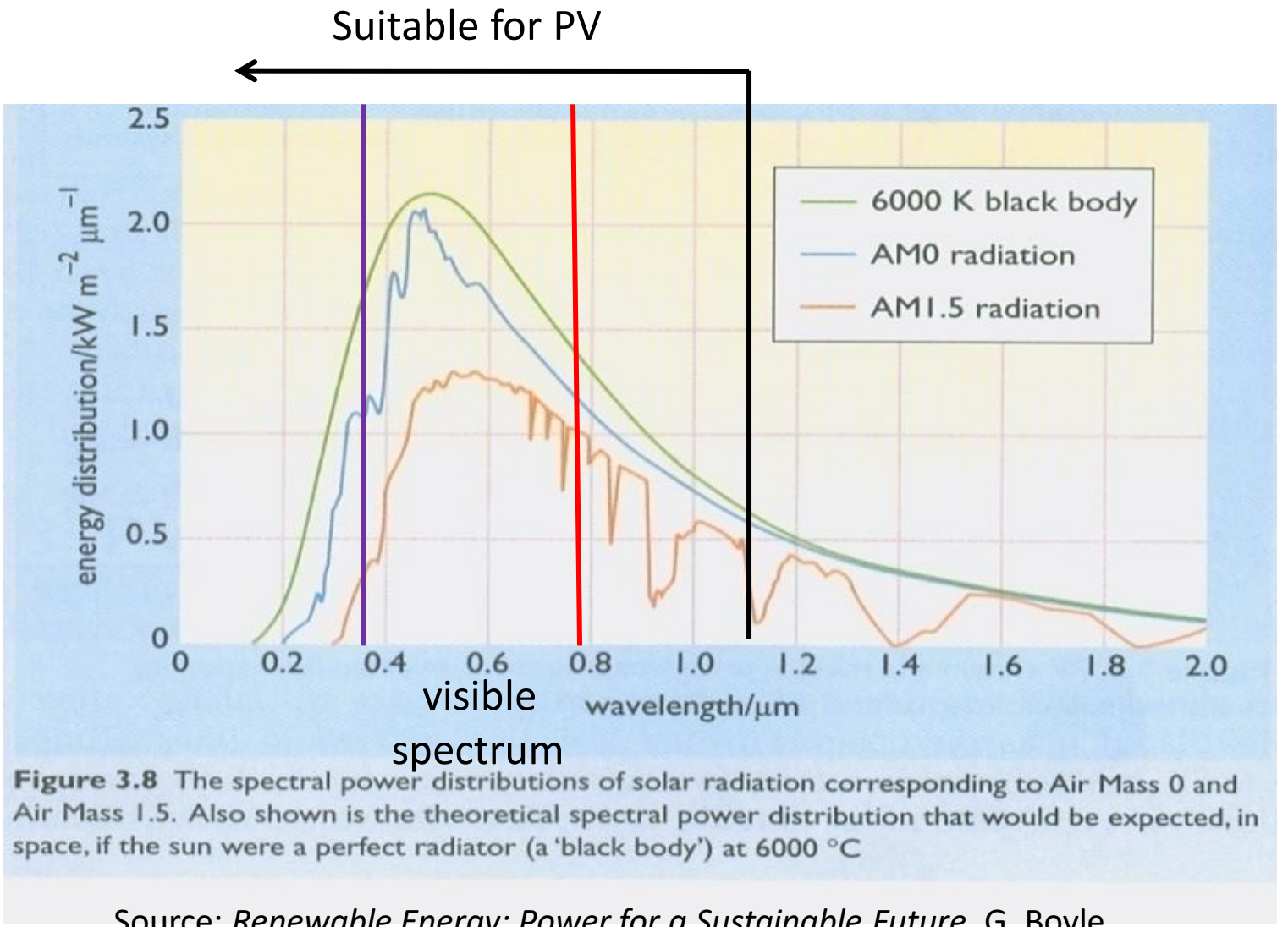

Figure 3.8 The spectral power distributions of solar radiation corresponding to Air Mass 0 and Air Mass 1.5. Also shown is the theoretical spectral power distribution that would be expected, in space, if the sun were a perfect radiator (a 'black body') at 6000 °C

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

Irradiance and Insolation

- Irradiance (*G*): density of the power produced by sunlight (W/m^2)

- Insolation (not “insulation”) (*I*): energy provided by sunlight per square meter of area over a period of time, usually per day ($kWh/m^2/day$)

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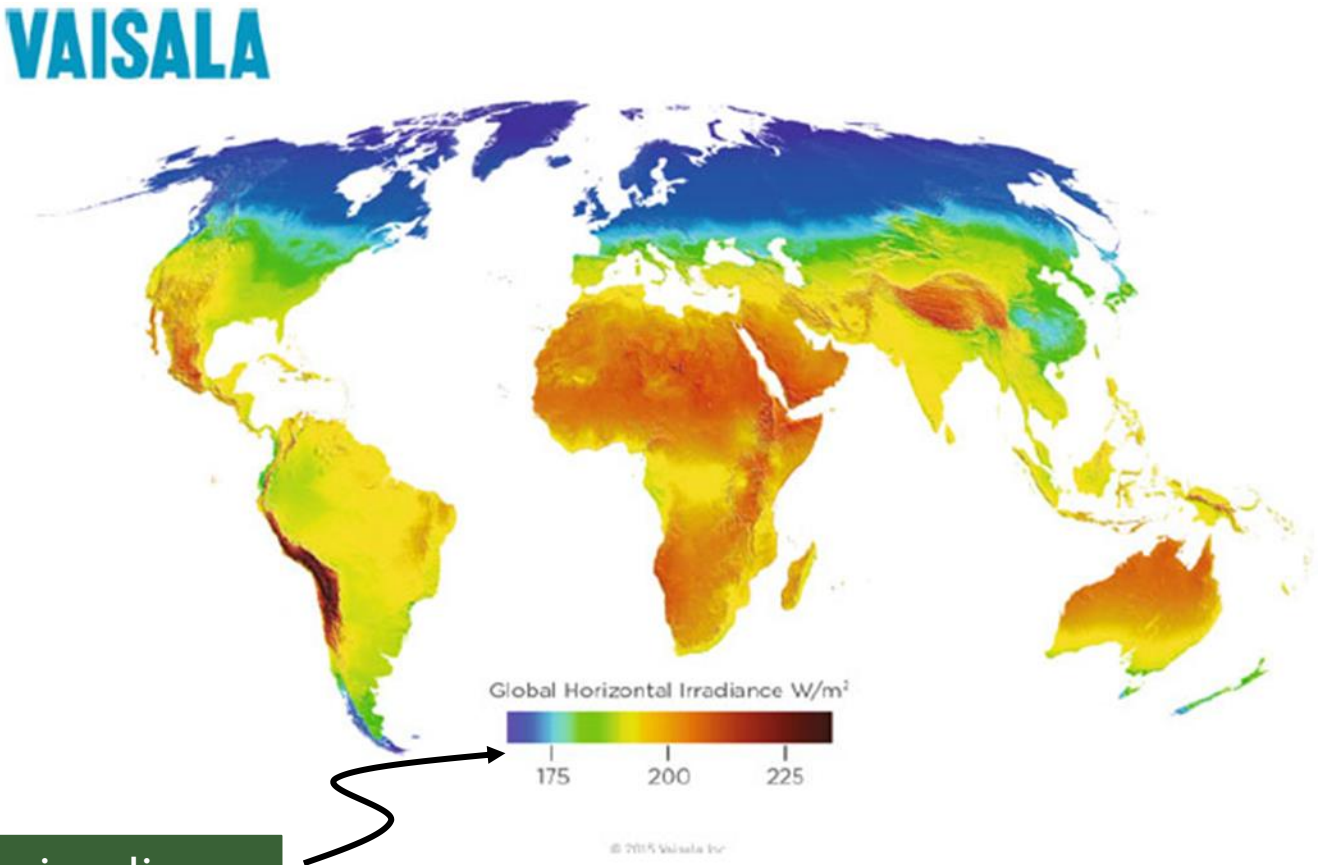
Solar Resource



Units are average irradiance

(courtesy of Viasala, Copyright (c) 2017 Vaisala)

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Typical Values

- Irradiance of 1000 W/m^2 is approximately the sunlight a horizontal surface receives on a clear sunny day in the mid-continental U.S.
- Typical insolation: 3.5 to 6 $kWh/m^2/day$

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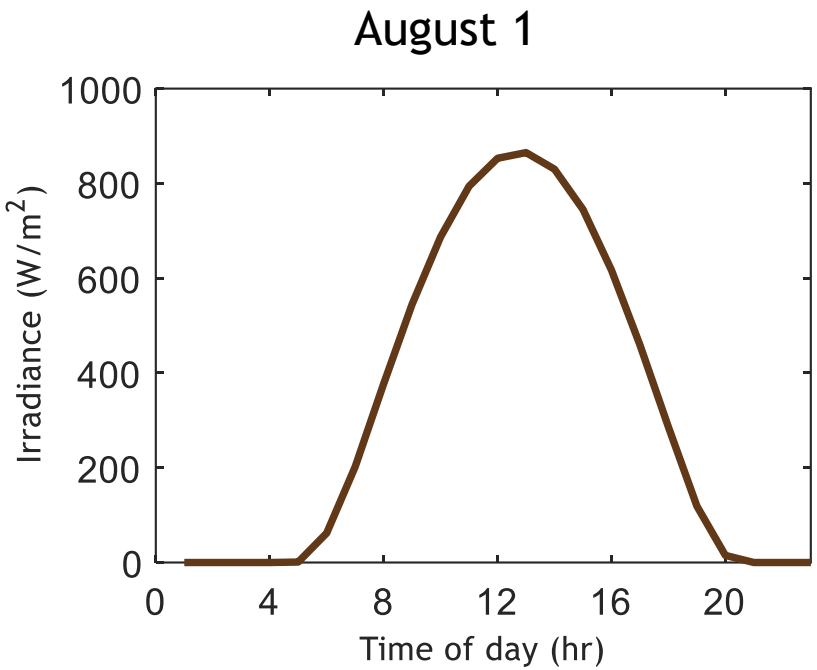
Note the peak value of irradiance



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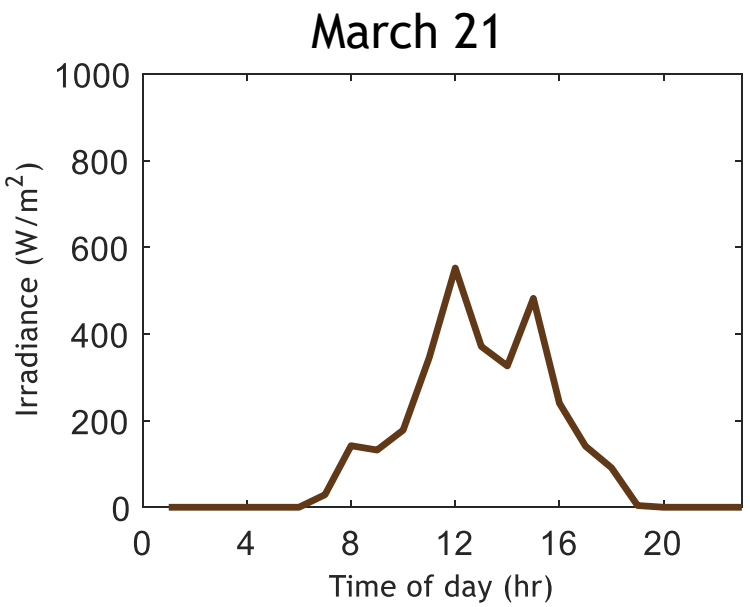
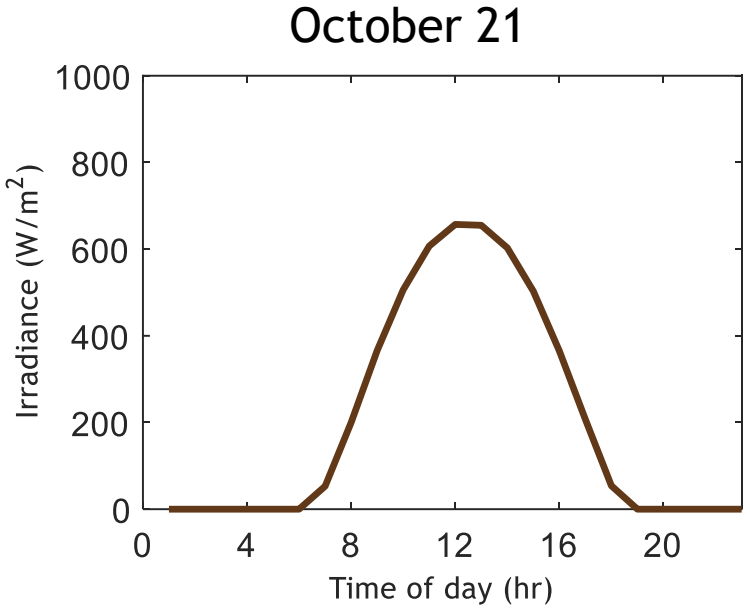
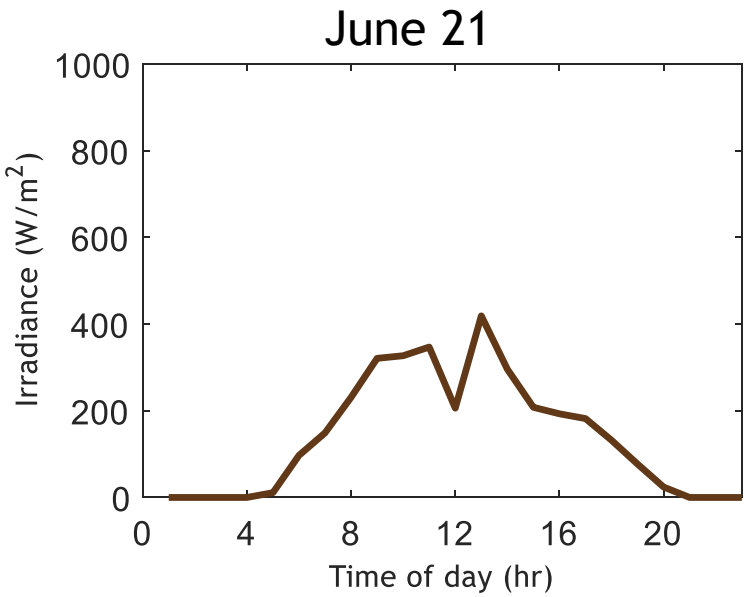
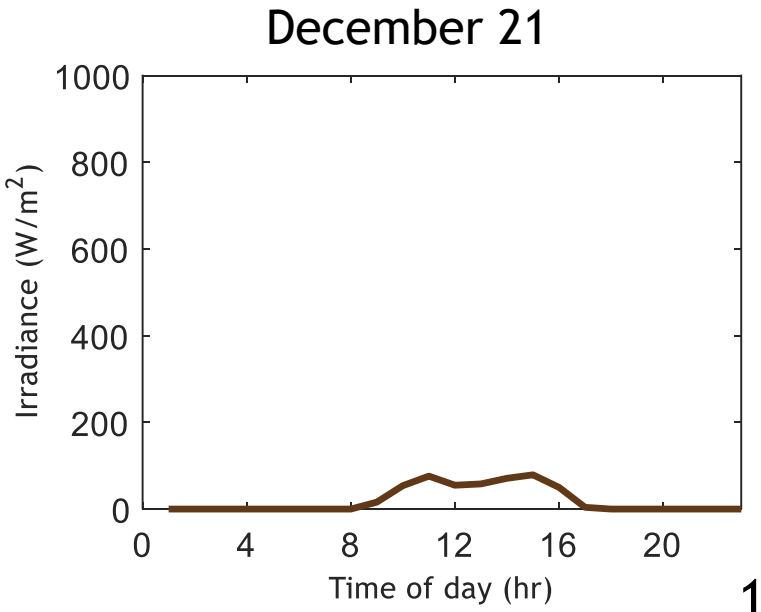
Global Horizontal Irradiance (GHI) in Seattle









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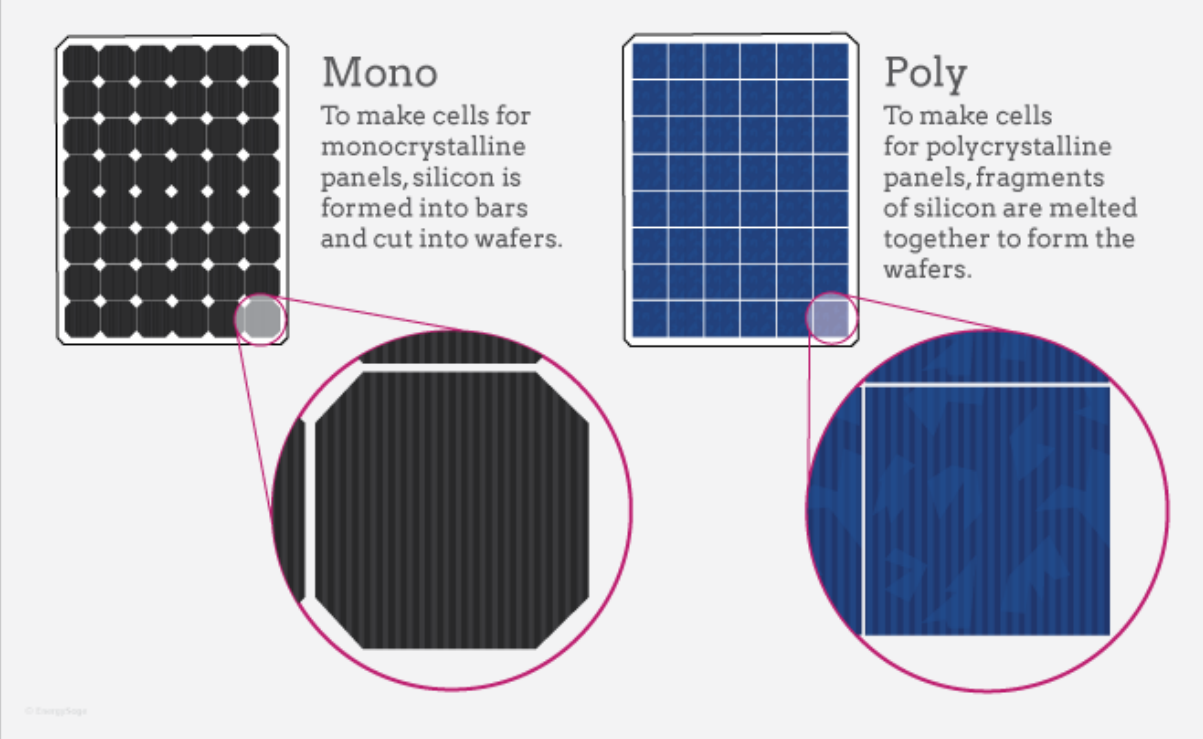
Physical Description



There are two common types of PV cells: mono-crystalline and poly-crystalline

A typical 0.156m x 0.156m (6.1in x 6.1 in) cell produces 2 to 4 W

source https://www.civicsolar.com/support/installer/articles/monocrystalline-cells-vs-polycrystalline-cells-whats-difference

How Polycrystalline PV Cell are Manufactured

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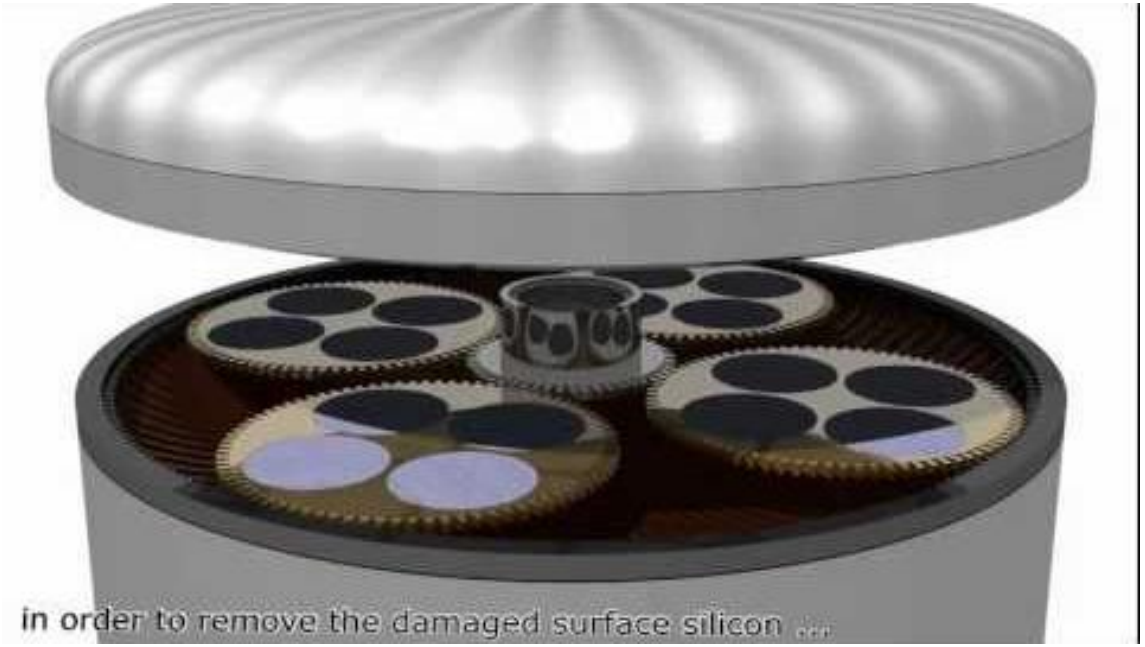
How Monocrystalline PV Cell are Manufactured



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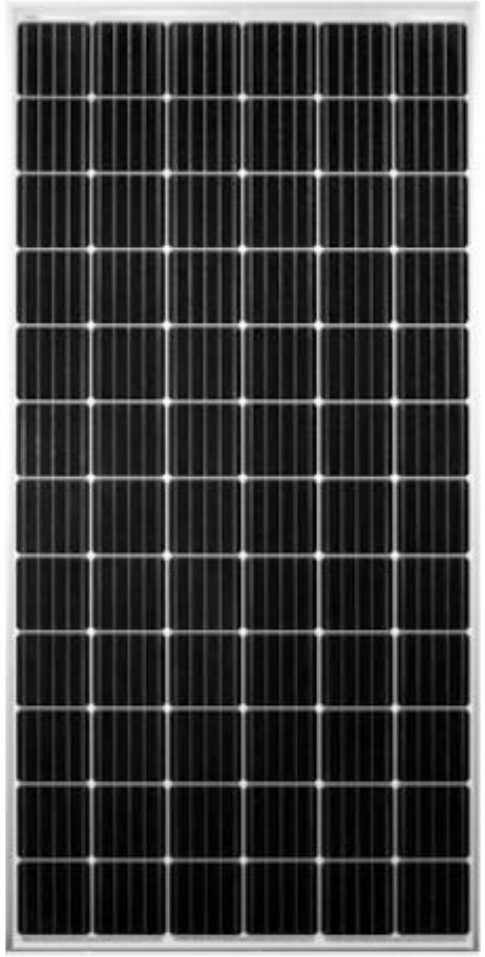
PV Modules

- PV modules are made from several cells that are connected together (in series)
- Largest modules are 300 to 400W and contain 72 series-connected cells
  - Weight ~24 kg
  - Area ~2 m^2



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Basic Principles

- Electricity is produced via the *photovoltaic* effect
- Power produced by PV module is approximately proportional to incident irradiance
- Power is inherently DC

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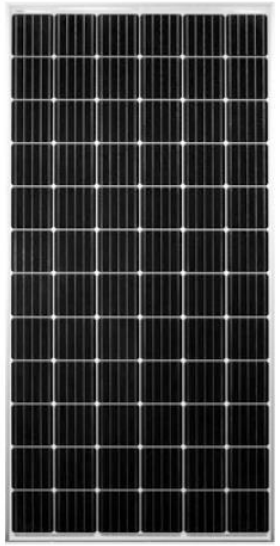
Example Efficiency

Irradiance

1000 W/m^2



Area: 2m^2
(2000 W)

DC Power

Power: 350 W

Efficiency: 17.5%

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Basic Principles

- PV cell is a p-n junction (diode)
- Recall p-n junctions are made from doped silicon crystals, which have internal built-in electric fields
- Photons from sunlight excite electrons into the conduction band, built-in field separates charge and voltage appears

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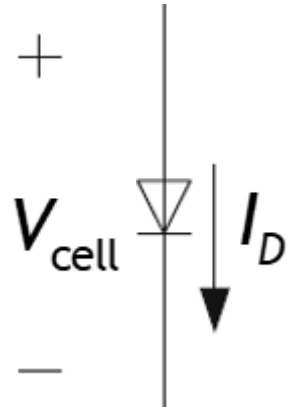
Unilluminated PV Cell

A PV cell in the dark (unilluminated) operates as a diode

$$I_D = I_0\left(e^{V_D/V_T} - 1\right)$$

$$V_T = \frac{nkT}{q}$$

Note error in book (7.2)



V_T: 25.8mV at room temperature
I_0: usually small (e.g. 10^{-9} A)

k: Boltzmann's constant (1.38 x 10^{-23} J/K)
n: ideality factor (unitless), is equal to 1 for an ideal diode
T: temperature (K)
q: charge 1.602 x 10^{-19} (C)
I_0: reverse bias saturation current (A)

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Exercise

What voltage appears across an open-circuited PV cell when it is unilluminated? Let V_t = 25.8 mV and I_0 = 10^-9 A.

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Exercise

What voltage appears across an open-circuited PV cell when it is unilluminated? Let V_t = 25.8 mV and I_0 = 10^-9 A.

$$I_D = I_0\left(e^{V_D/V_T} - 1\right)$$

$$\frac{I_D}{I_0} = \left(e^{V_D/V_T} - 1\right)$$

$$\frac{I_D}{I_0} + 1 = e^{V_D/V_T}$$

$$\ln\left(\frac{I_D}{I_0} + 1\right) = \frac{V_D}{V_T}$$

$$\ln\left(\frac{I_D}{I_0} + 1\right) V_T = V_D$$

$$\ln\left(\frac{0}{I_0} + 1\right) V_T = V_D$$

$$0 \times V_T = V_D$$

$$V_D = 0\text{V}$$

No voltage appears.

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Illuminated PV Cell

Effect of photons exciting electrons is modeled as "illumination current"

- always positive
- approx. proportional to incident irradiance, cell area, and cell efficiency
- typical range: 0.5 to 9A

$$I_{cell} = I_G - I_0\left(e^{V_{cell}/V_T} - 1\right)$$

$$I_{cell} = I_G - I_D$$

I_G: illumination current (A)
I_{cell}: current out of PV cell (A)
V_{cell}: PV cell voltage (V)

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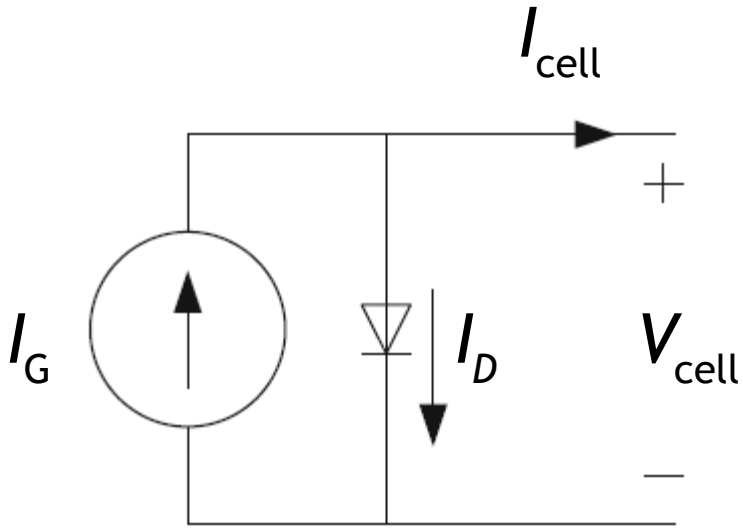
Ideal Circuit Model



Assume PV cell is
ideal unless stated otherwise

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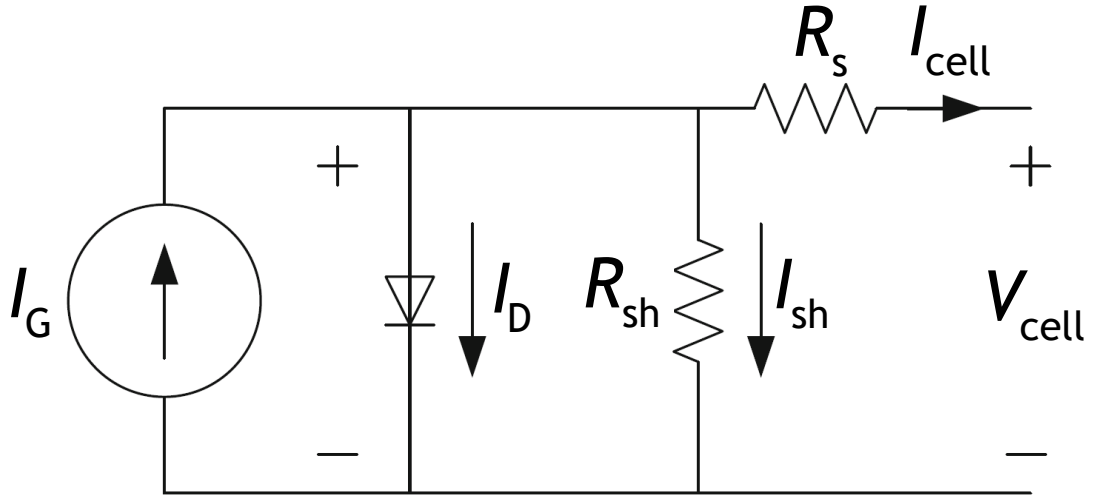
Circuit Model with Losses (non-ideal)



See text, Chapter 7.5.1

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Exercise

Which variable should be set to zero when the PV cell is operated under open-circuit conditions?

A. I_G
B. I_0
C. I_{cell}
D. V_T

$$I_{cell} = I_G - I_0\left(e^{V_{cell}/V_T} - 1\right)$$

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Exercise

Which variable should be set to zero when the PV cell is operated under open-circuit conditions?

A. I_G
B. I_0
C. I_{cell}
D. V_T

$$I_{cell} = I_G - I_0\left(e^{V_{cell}/V_T} - 1\right)$$

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PV Cell Open-Circuit Voltage

Open-circuit voltage of a PV cell is computed from

$$I_{cell} = I_G - I_0\left(e^{V_{cell}/V_T} - 1\right)$$

$$\frac{I_G - I_{cell}}{I_0} + 1 = e^{V_{cell}/V_T}$$

$$V_T \ln\left(\frac{I_G - I_{cell}}{I_0} + 1\right) = V_{cell}$$

$$V_{cell,OC} = V_T \ln\left(\frac{I_G}{I_0} + 1\right)$$

Typical open-circuit voltage is between 0.6 and 0.7V

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Exercise

Which of these affects the open-circuit voltage of a PV cell?

A. Temperature
B. Ideality factor
C. Irradiance
D. Reverse saturation current?

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Exercise

Which of these affects the open-circuit voltage of a PV cell?

A. Temperature
B. Ideality factor
C. Irradiance
D. Reverse saturation current?

$$V_{cell,OC} = V_T \ln\left(\frac{I_G}{I_0} + 1\right)$$

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Short-Circuit Current

Under short-circuit conditions V_{cell} = 0V

$$I_{cell} = I_G - I_0\left(e^{V_{cell}/V_T} - 1\right)$$

$$I_{SC} = I_G - I_0\left(e^{0/V_T} - 1\right)$$

$$I_{SC} = I_G - I_0(1-1)$$

$$I_{SC} = I_G$$

The short-circuit current is equal to the illumination current. The illumination current can be determined by shorting the PV cell and measuring the current (assuming the PV cell is ideal)

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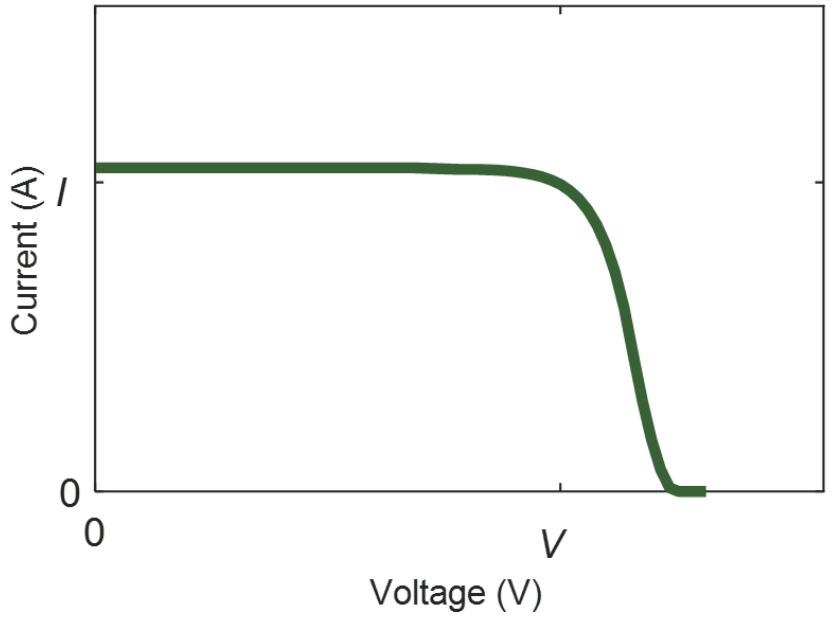
I-V Curve

The current—voltage curve of PV cell can be plotted solving

$$I_{\text{cell}} = I_{\text{G}} - I_0\left(e^{V_{\text{cell}}/V_{\text{T}}} - 1\right)$$

for different values of V_{cell}



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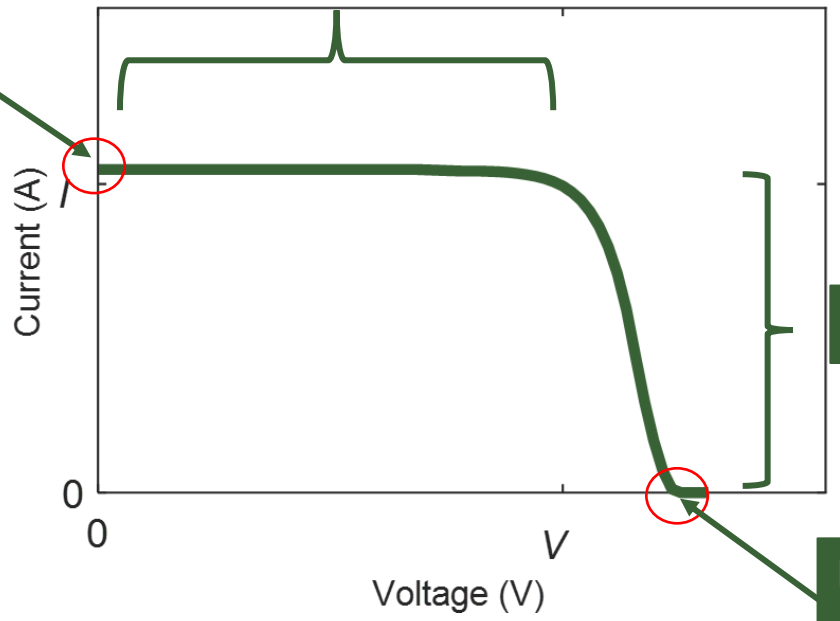
I-V Curve

Nearly constant current

Equal to illumination current



Nearly constant voltage

Usually between 0.6 and 0.7V

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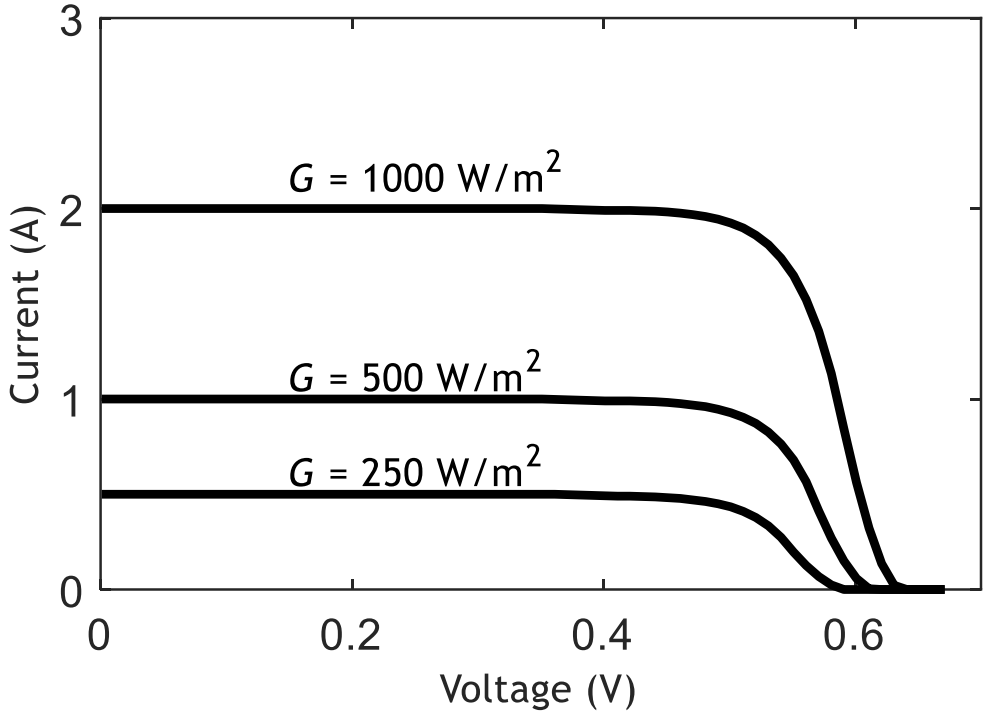
I-V Curve at Different Irradiance

Recall that illumination current increases with irradiance



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Maximum Power Point

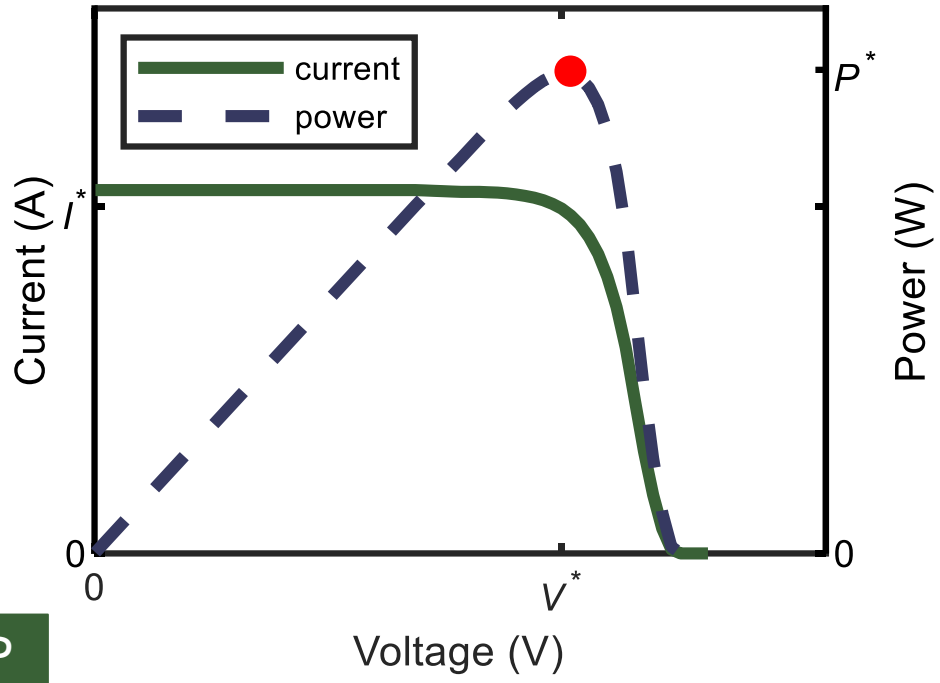
- Power output is found from

$$P_{\text{cell}} = I_{\text{cell}} V_{\text{cell}}$$

- PV arrays have a unique maximum power operating point (maximum power point, MPP)

$$P^*_{\text{cell}} = V^*_{\text{cell}} I^*_{\text{cell}}$$

here the * indicates that the values correspond to the MPP (not complex conjugate)



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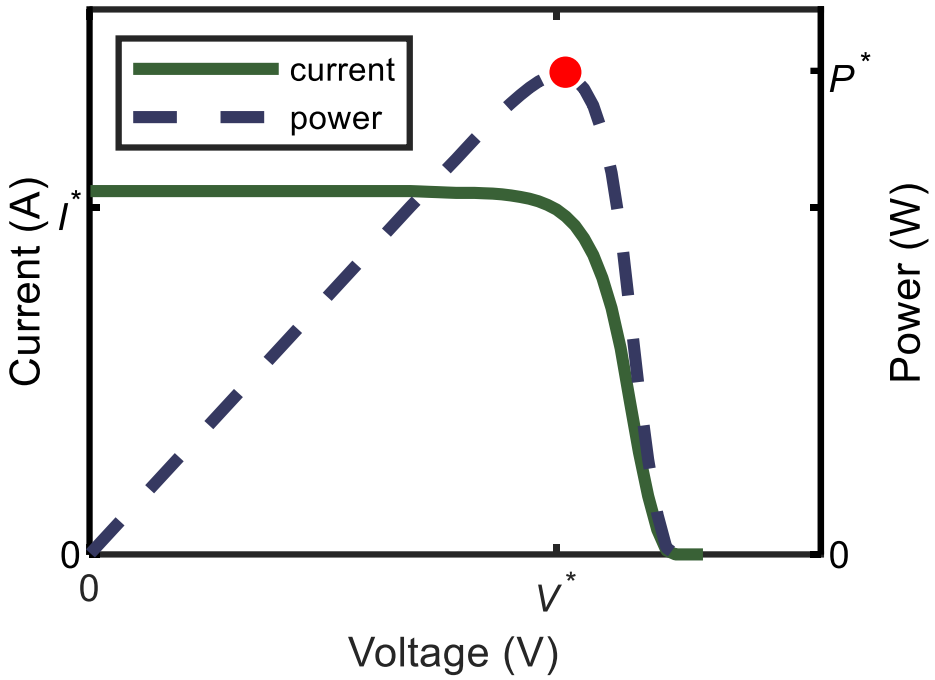
Maximum Power Point

- MPP voltage might not correspond to load impedance or battery voltage
- Use a “maximum power point tracker” to ensure PV cell (module) is operating at the maximum power point

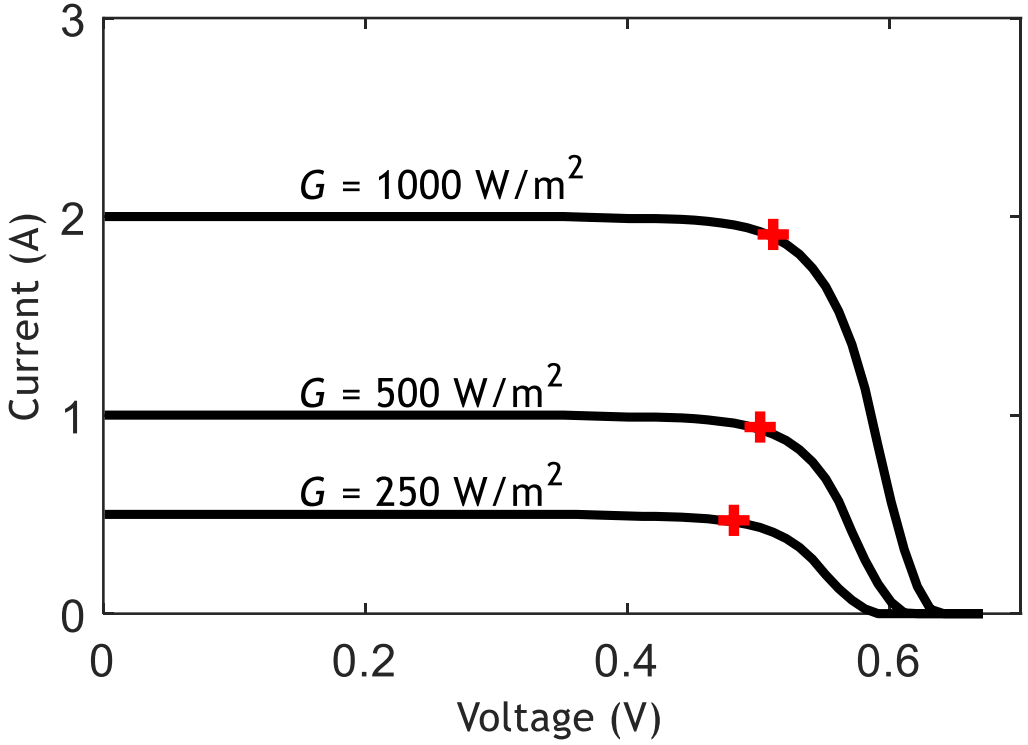


Maximum Power Point at Different Irradiances

Maximum power point voltage and current depends on the irradiance

$$P^*_{\text{cell}}(G) = V^*_{\text{cell}}(G) I^*_{\text{cell}}(G)$$

Here we show that the voltage, current, and power at the maximum power point are functions of the irradiance



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