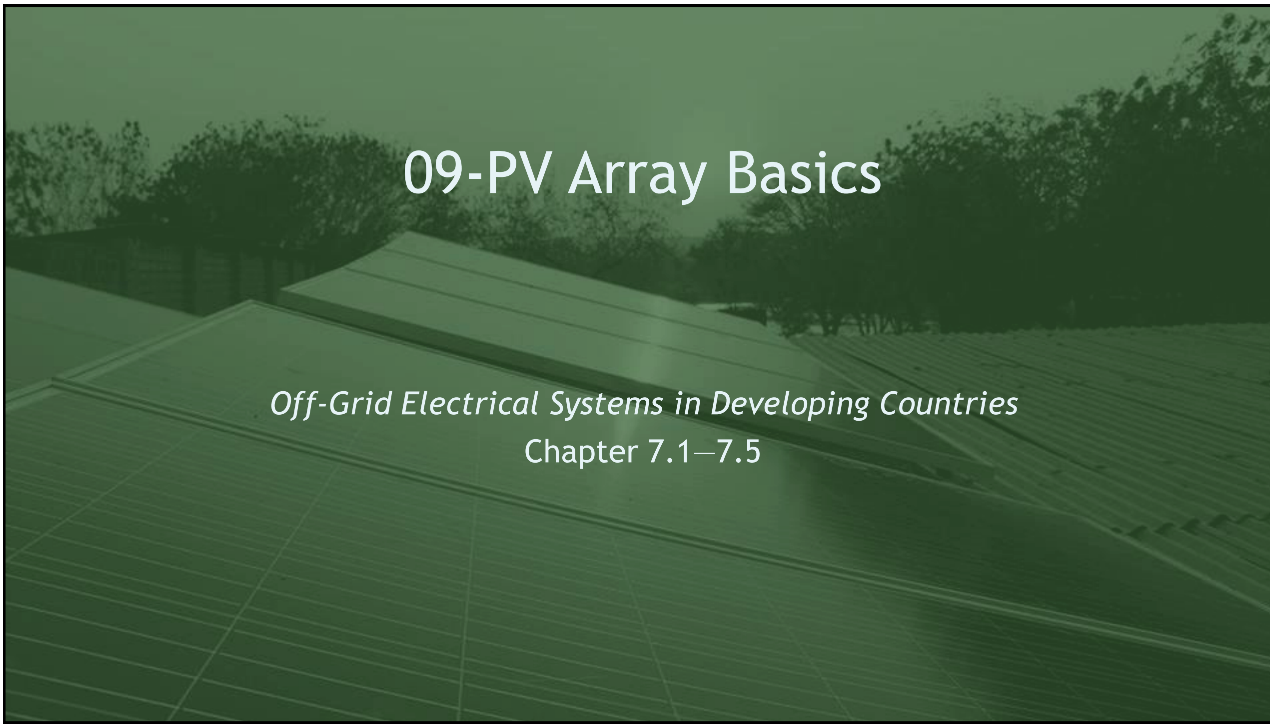


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# Learning Outcomes

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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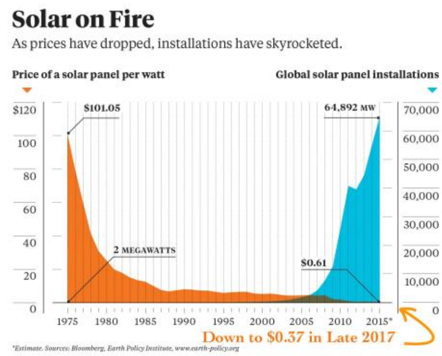
2

# 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







# The Solar Resource

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

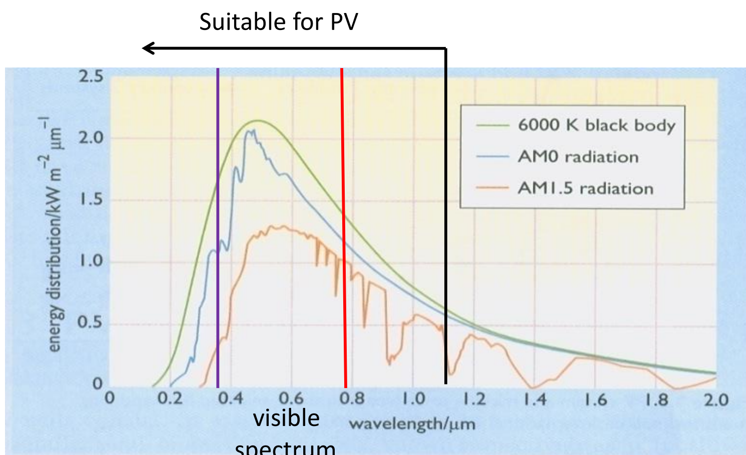



**Figure 3.8** The spectral power distributions of solar radiation corresponding to Air Mass 0 and Air Mass 1.5. Also shown is the theoretical spectral power distribution that would be expected, in space, if the sun were a perfect radiator (a 'black body') at 6000 °C

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

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# 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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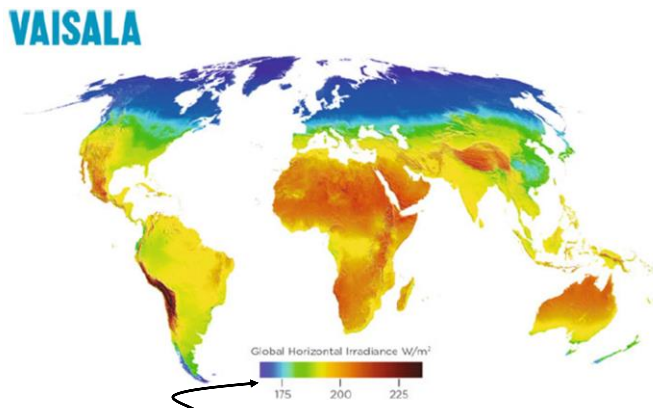
# Solar Resource




Units are average irradiance

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



7

7

# 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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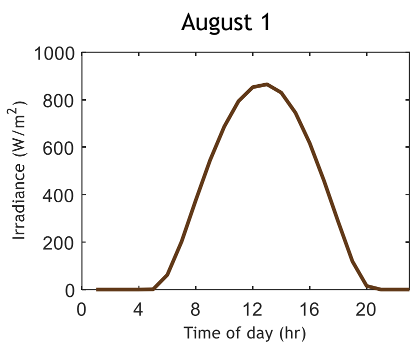
Note the peak value of irradiance



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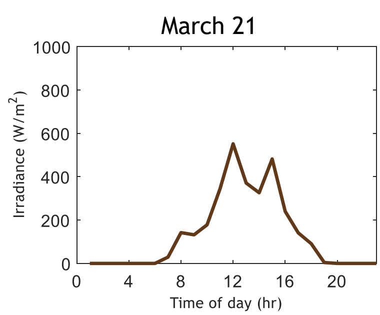
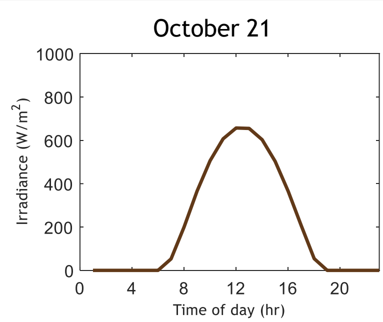
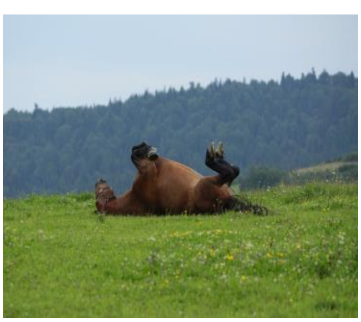
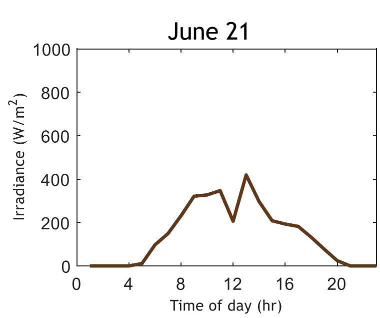
Global Horizontal Irradiance (GHI) in Seattle

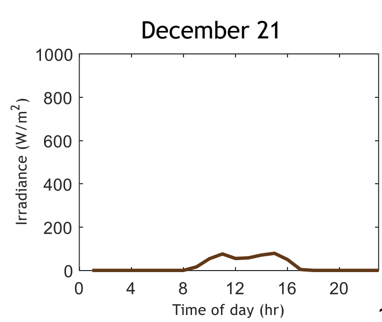




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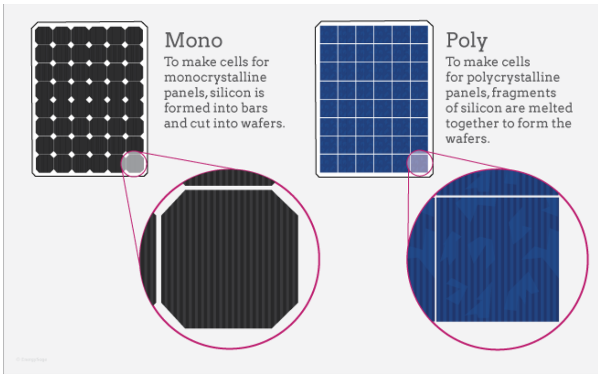
# Physical Description




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

11

11

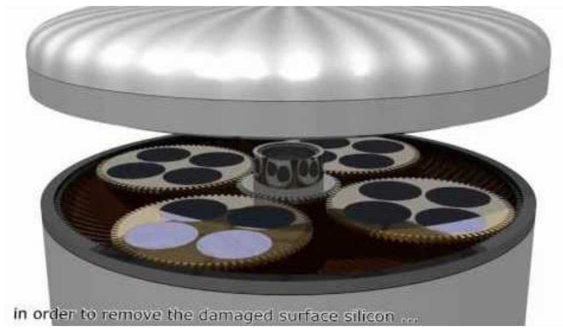
# How Polycrystalline PV Cell are Manufactured



12

12

# How Monocrystalline PV Cell are Manufactured



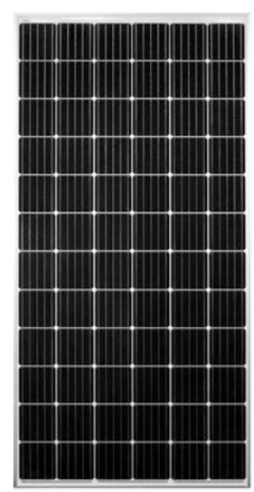



13

13

# 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 $m^2$





14

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# Basic Principles

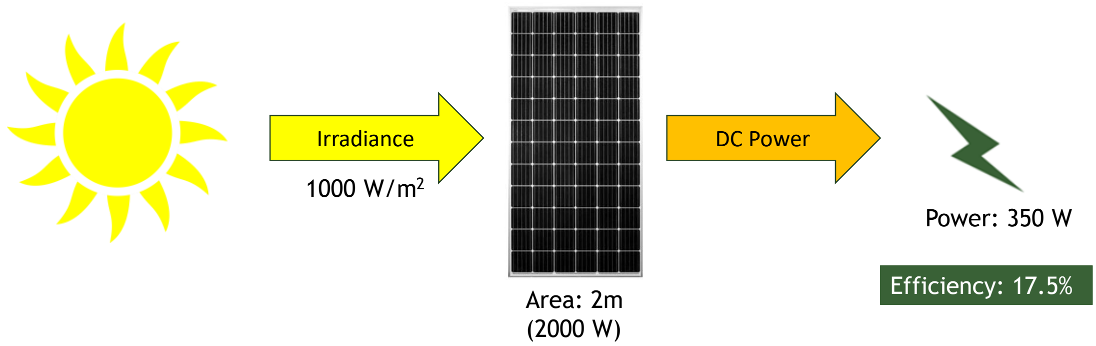
- Electricity is produced via the *photovoltaic* effect
- Power produced by PV module is approximately proportional to incident irradiance
- Power is inherently DC



16

16

# Example Efficiency







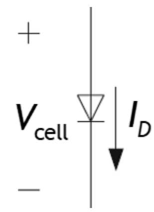



# Basic Principles

- 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

# 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)







# 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.

# 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.





# Illuminated PV Cell

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

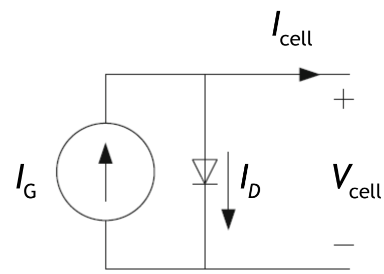
- always positive
- approx. proportional to incident irradiance, cell area, and cell efficiency
- typical range: 0.5 to 9A

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

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

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

# Ideal Circuit Model



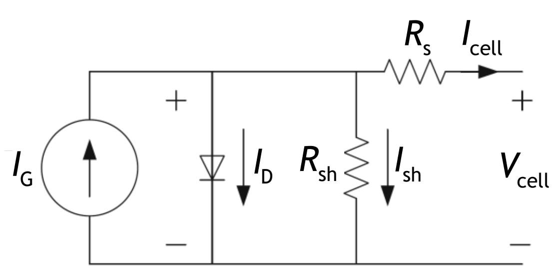

Assume PV cell is ideal unless stated otherwise



23

23

# Circuit Model with Losses (non-ideal)




See text, Chapter 7.5.1



24

24

# 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. $V_T$

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







# 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. $V_T$

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

# PV Cell Open-Circuit Voltage

Open-circuit voltage of a PV cell is computed from

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

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

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

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

Typical open-circuit voltage is between 0.6 and 0.7V







# Exercise

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

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

# Exercise

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







# Short-Circuit Current

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

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

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

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

$$I_{SC} = I_G$$

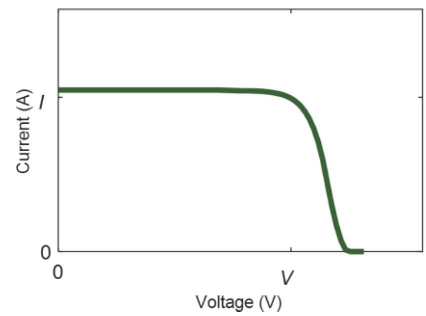
The short-circuit current is equal to the illumination current. The illumination current can be determined by shorting the PV cell and measuring the current (assuming the PV cell is ideal)

# I-V Curve

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

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

for different values of $V_{\text{cell}}$

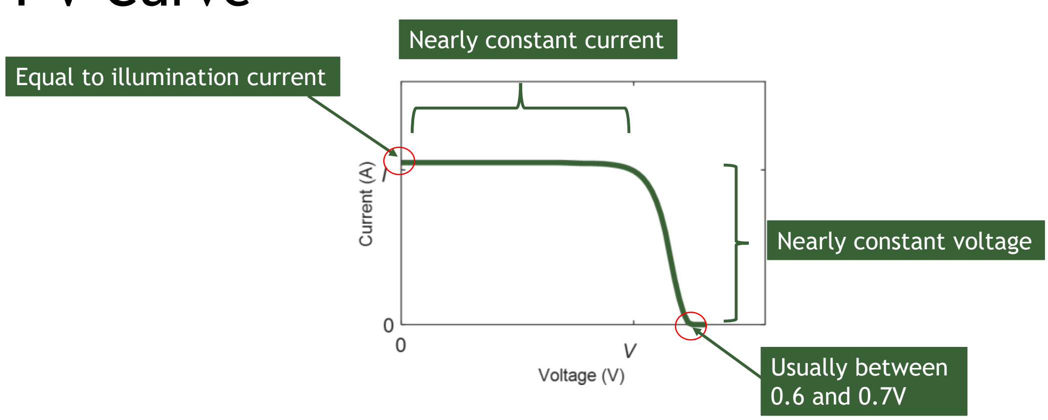





31

31

# I-V Curve



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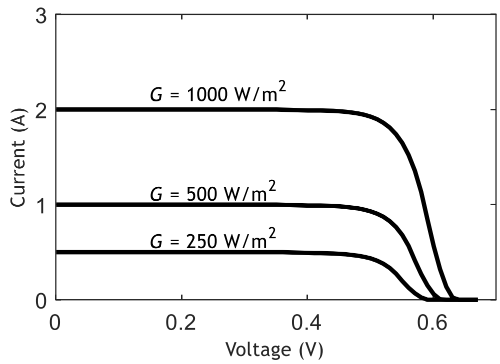
# I-V Curve at Different Irradiance

Recall that illumination current increases with irradiance



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33

# Maximum Power Point

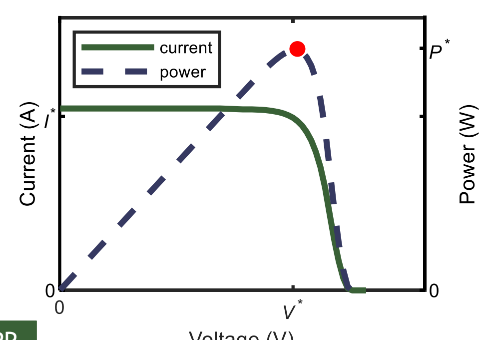
- Power output is found from

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

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

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

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



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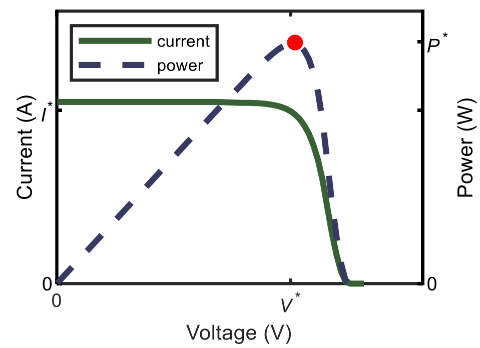
34

# 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





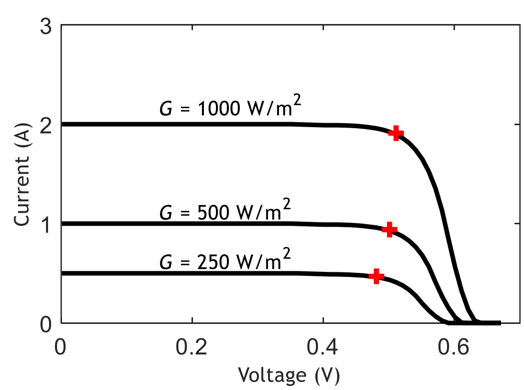



# Maximum Power Point at Different Irradiances

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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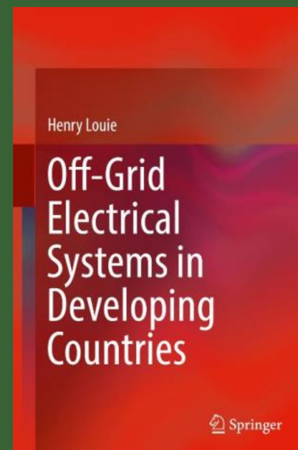


37



37