ENGR-3000:
Renewable Energy, Technology, and Resource Economics

Solar Photovoltaics

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World Learning
SIT Study Abroad

6 June 2019
Ísafjörður, Iceland

1865 THE UNIVERSITY OF MAINE

Solar Photovoltaics: Outline

- Types of Photovoltaic (PV) systems
- PV Operation and Construction
  - PV semiconductor fundamentals
- Performance and Operation Characteristics
- Advanced Designs
- Concentrating Photovoltaic (CPV) Designs
- Commercial PV Components
- Case Study: PV System Design and Installation
- Utility-Scale Systems

Space Applications

- Vanguard Satillite (1964)
  - Transmitter: 5 mW
- International Space Station
  - 2500 m^2
  - 110 kW

Terrestrial Applications

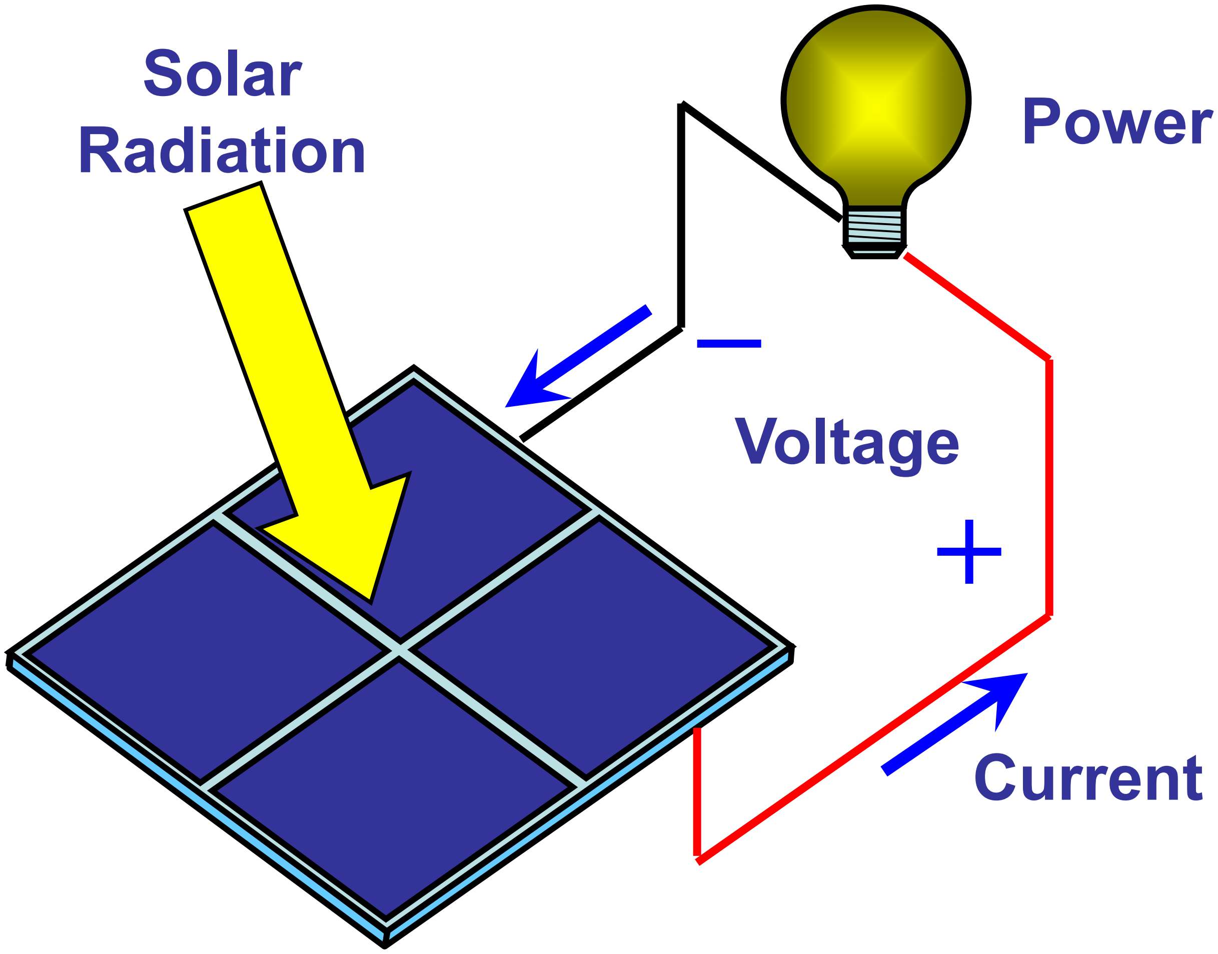
- Remote Power
  - Bangor ME
  - 160 W

- Distributed Power
  - Boston, MA
  - 28 kW

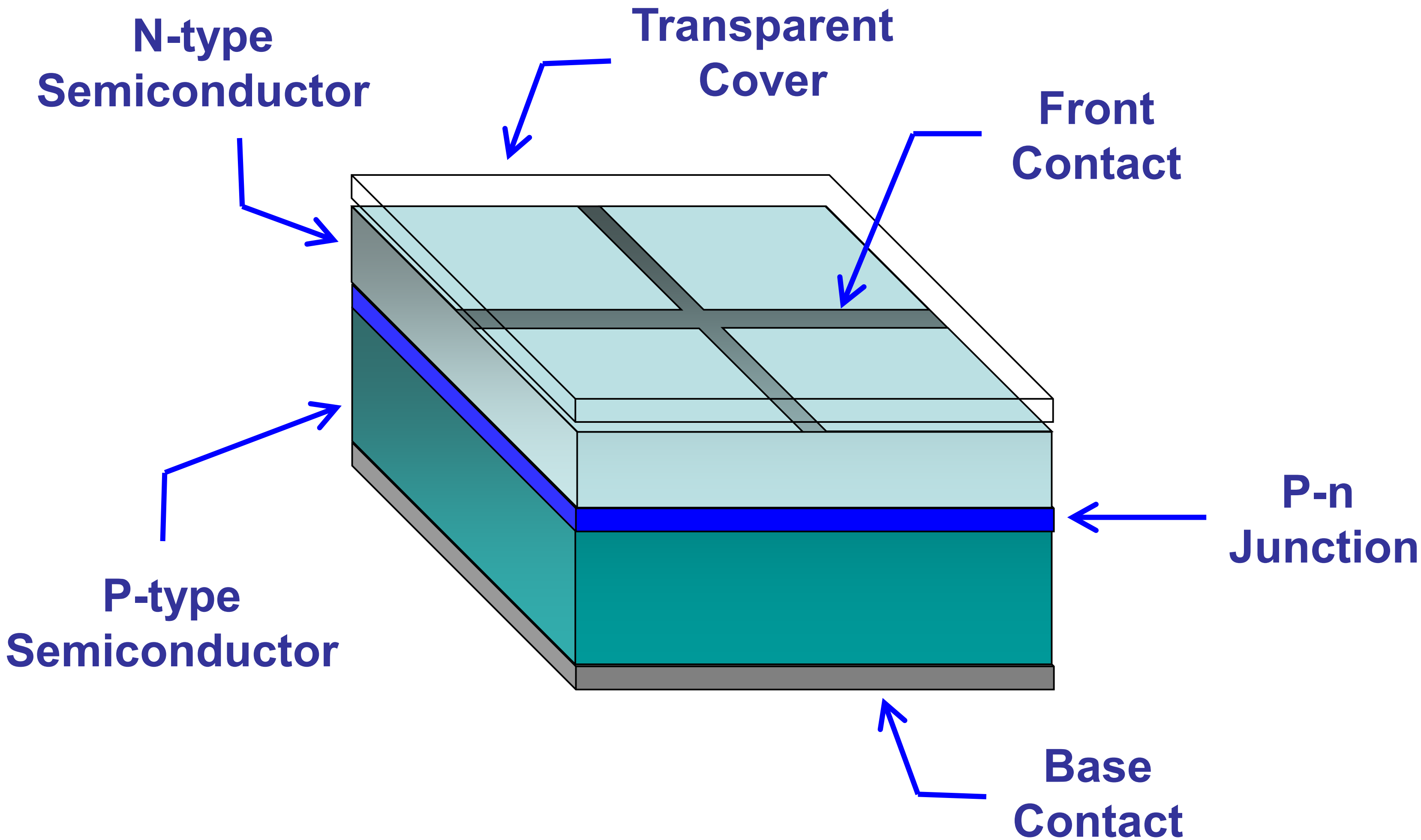
www1.eere.energy.gov/solar/

Photovoltaic Operation

- How does this work?



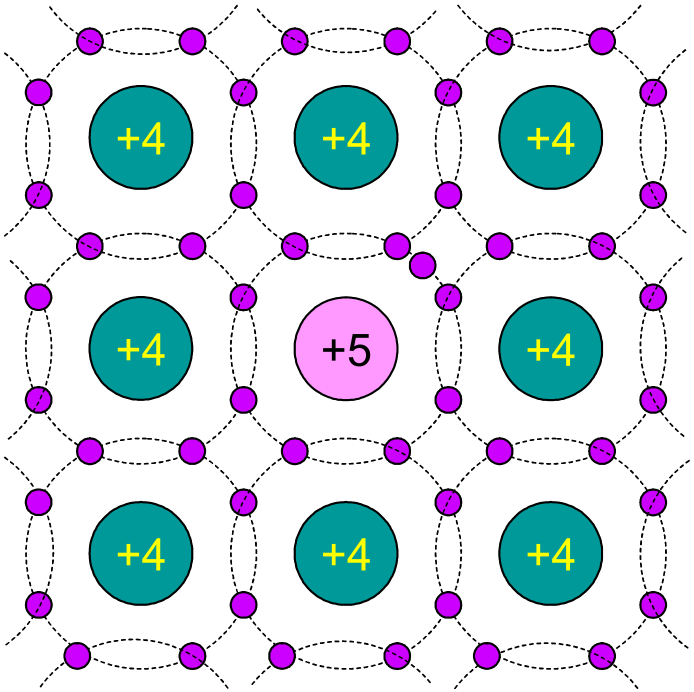
Photovoltaic Cell Construction

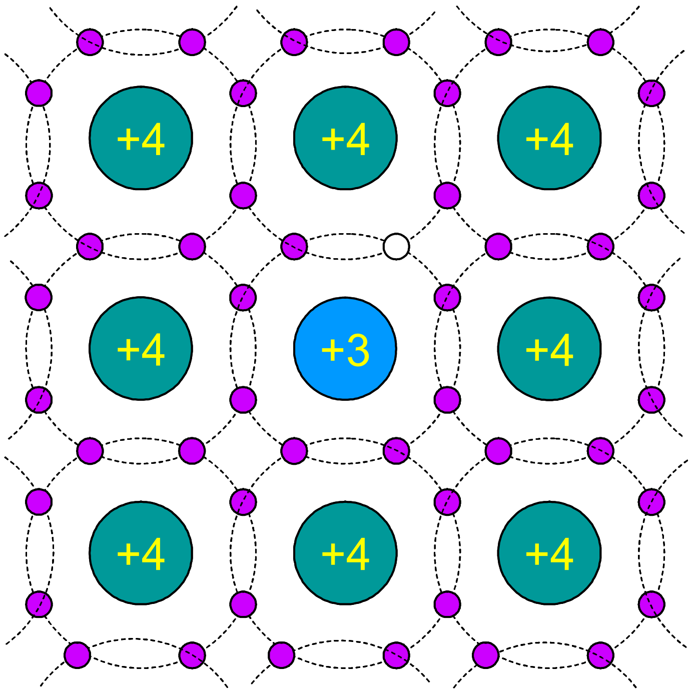


Silicon-based p and n–type doped semiconductors

- N-type semiconductor:
  - Silicon (valence = 4)
  - Group V element (valence = 5) such as phosphorous
  - Extra electron, neutral charge

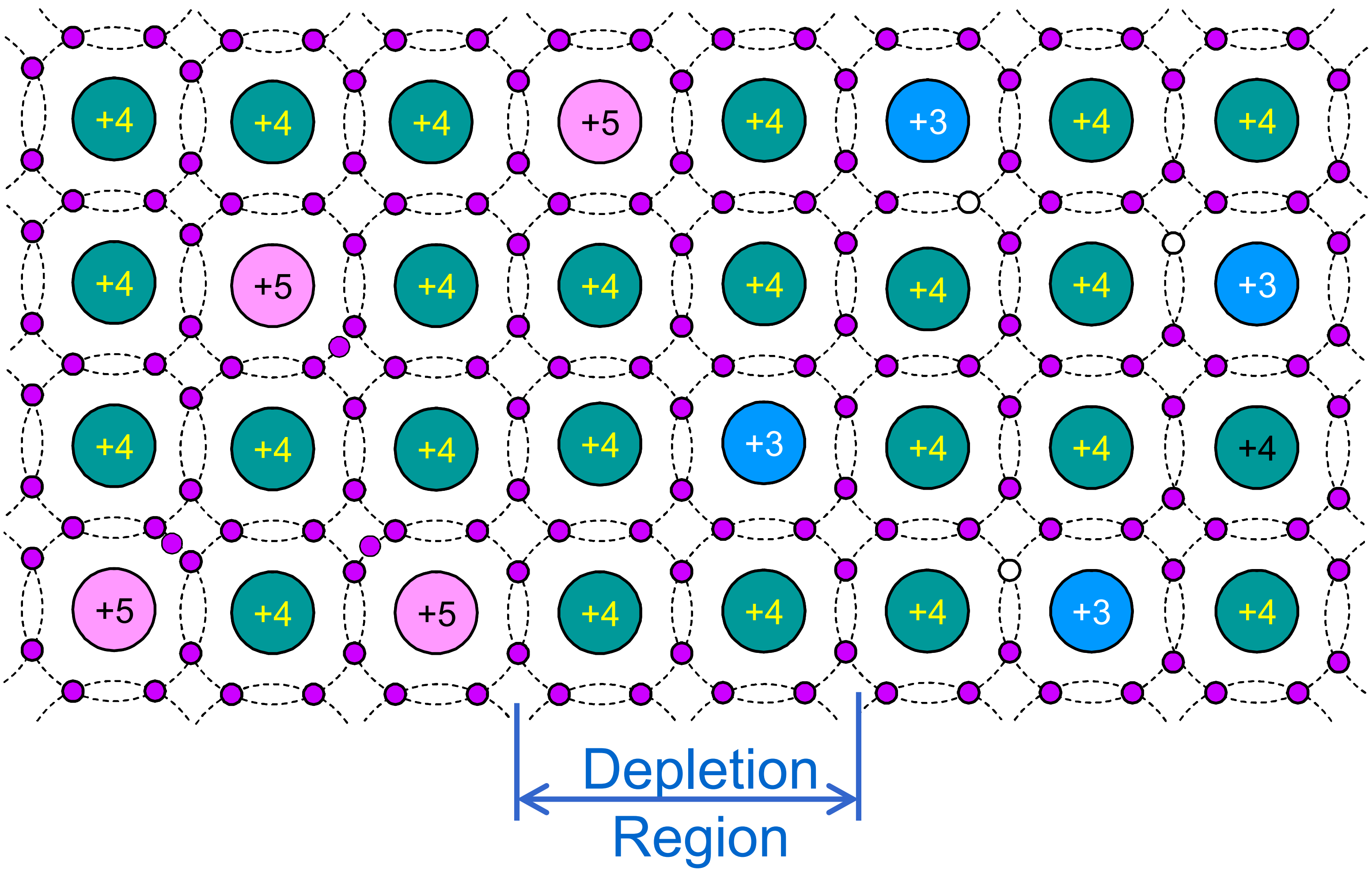
- P-type semiconductor:
  - Silicon (valence = 4)
  - Group III element (valence = 3) such as boron
  - Missing electron, neutral charge





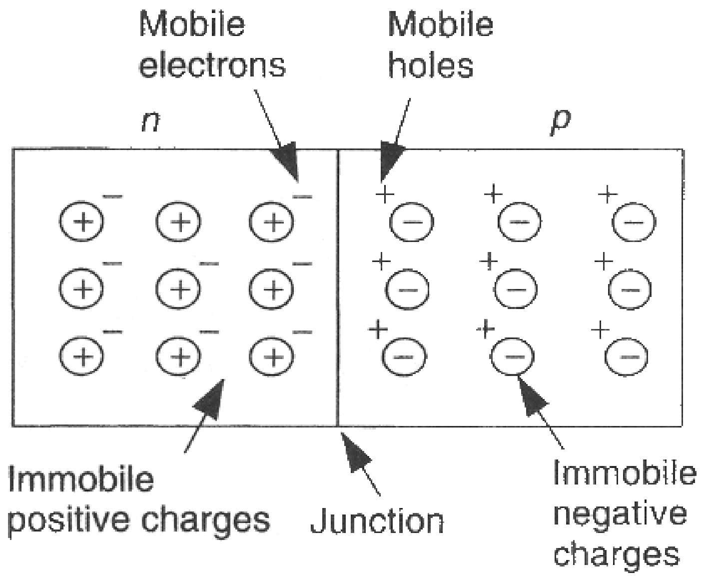
P-n junction

- N-type semiconductor
- P-type semiconductor

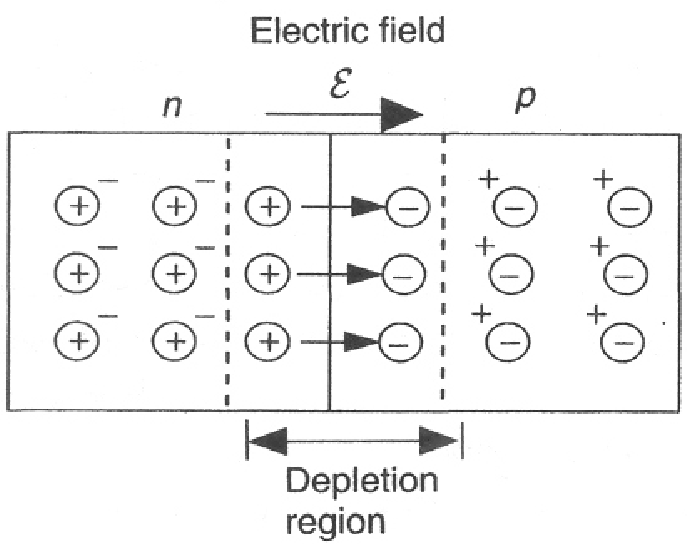


P-n junction

- Charge mobility causes a “depletion region” at the interface:
- This depletion region does not have any unpaired electrons or holes, and is not charge neutral
- The charge distribution causes an electric field, affecting charge mobility and changing the energy bands.



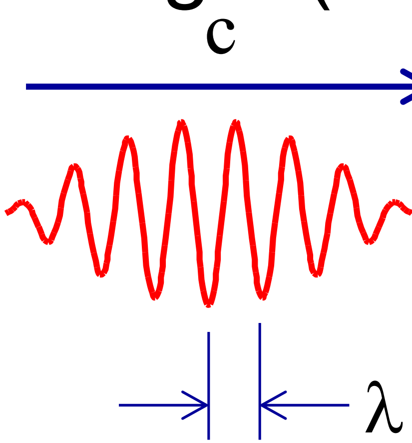
(a) When first brought together



(b) In steady-state

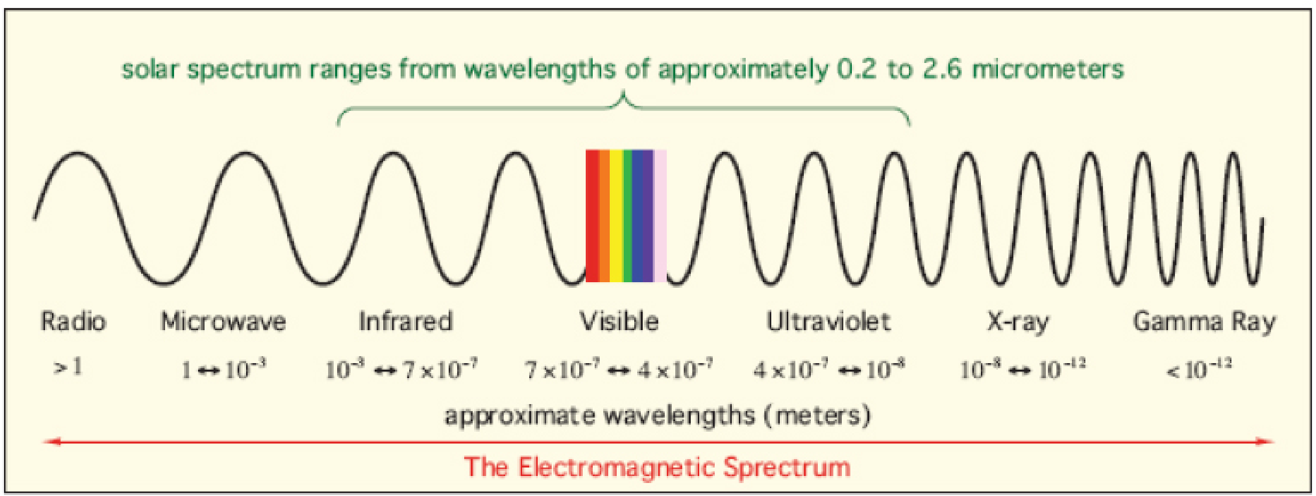
Photon Energy and Wavelength

- Photons are characterized by their wavelength (frequency) and their energy



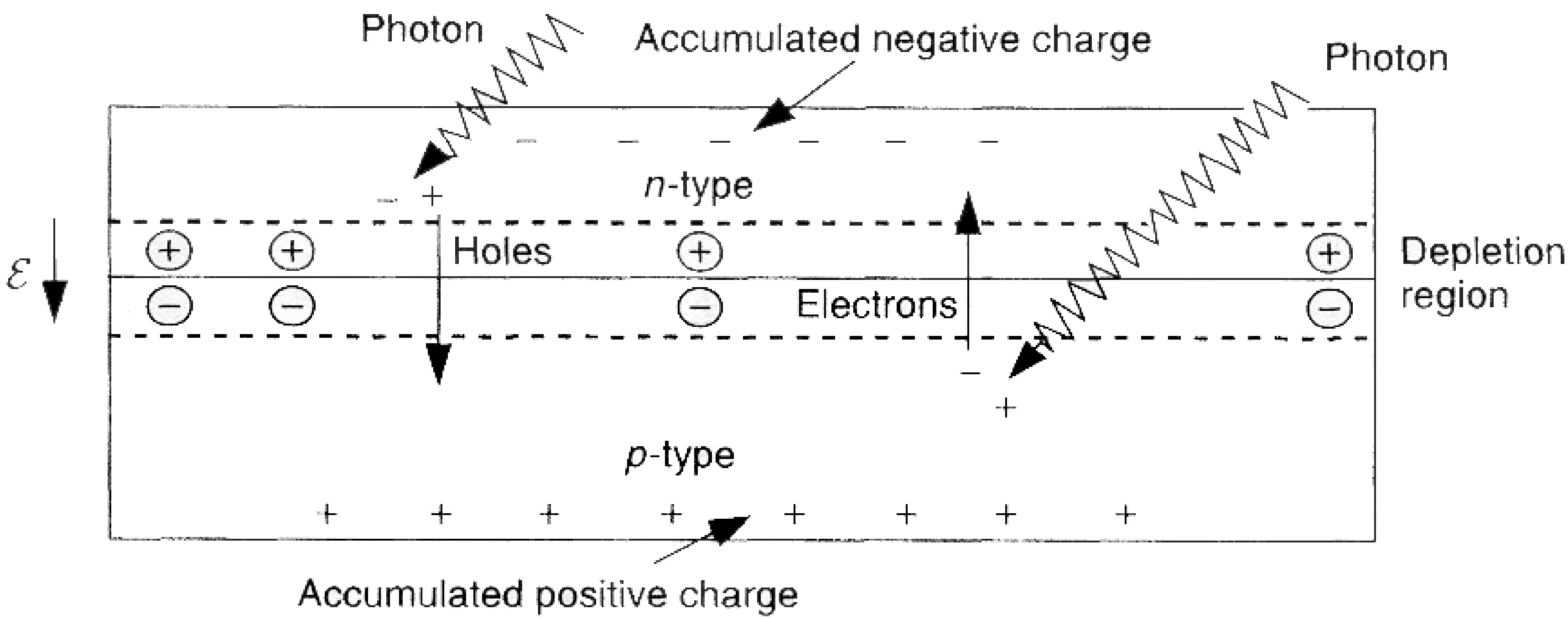
$$c = \lambda\nu$$

$$E = h\nu = \frac{hc}{\lambda}$$



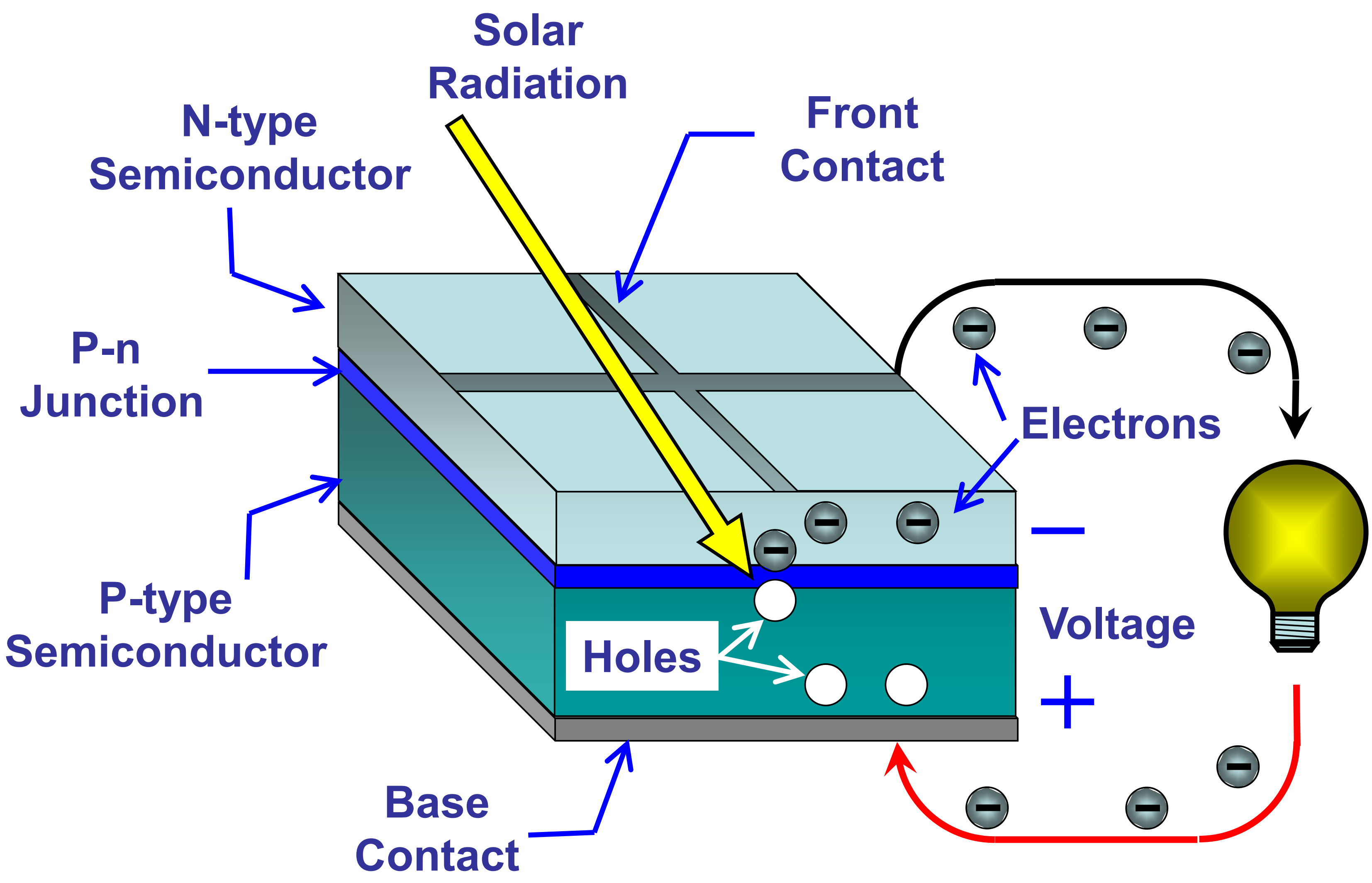
Charge migration in PV cells

- The electric field in the depletion region causes an accumulation of positive charge at the base contact, and negative charge in the top contacts:



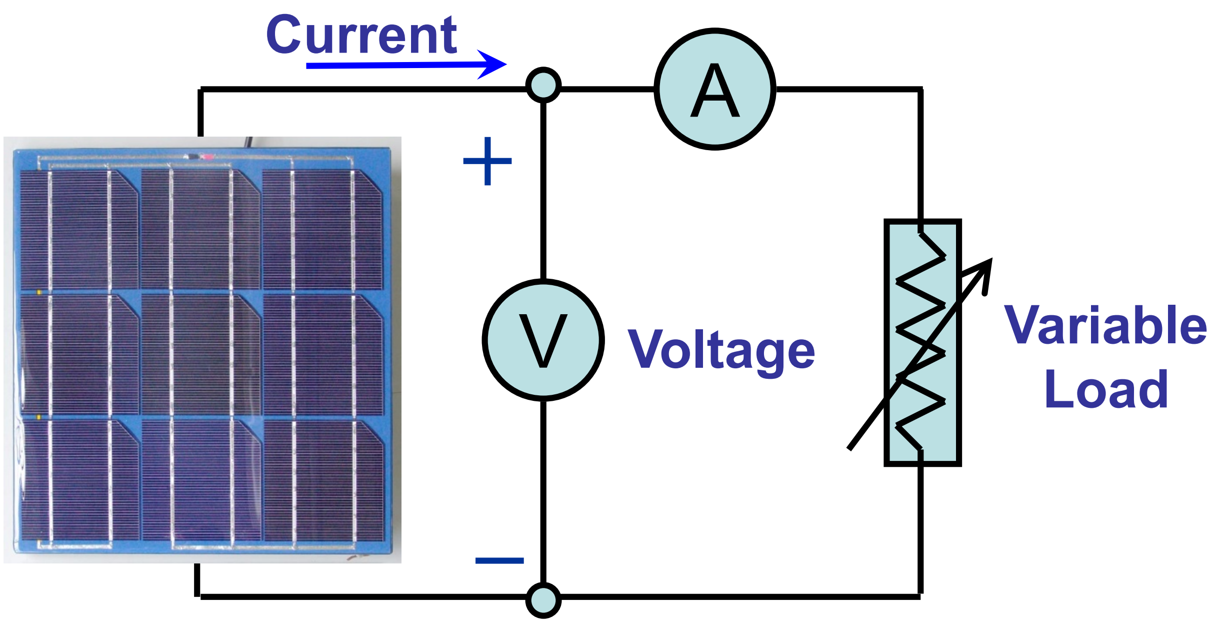
Masters, G.M., Renewable and Efficient Electric Power Systems, Wiley, 2004.

Photovoltaic Cell Operation

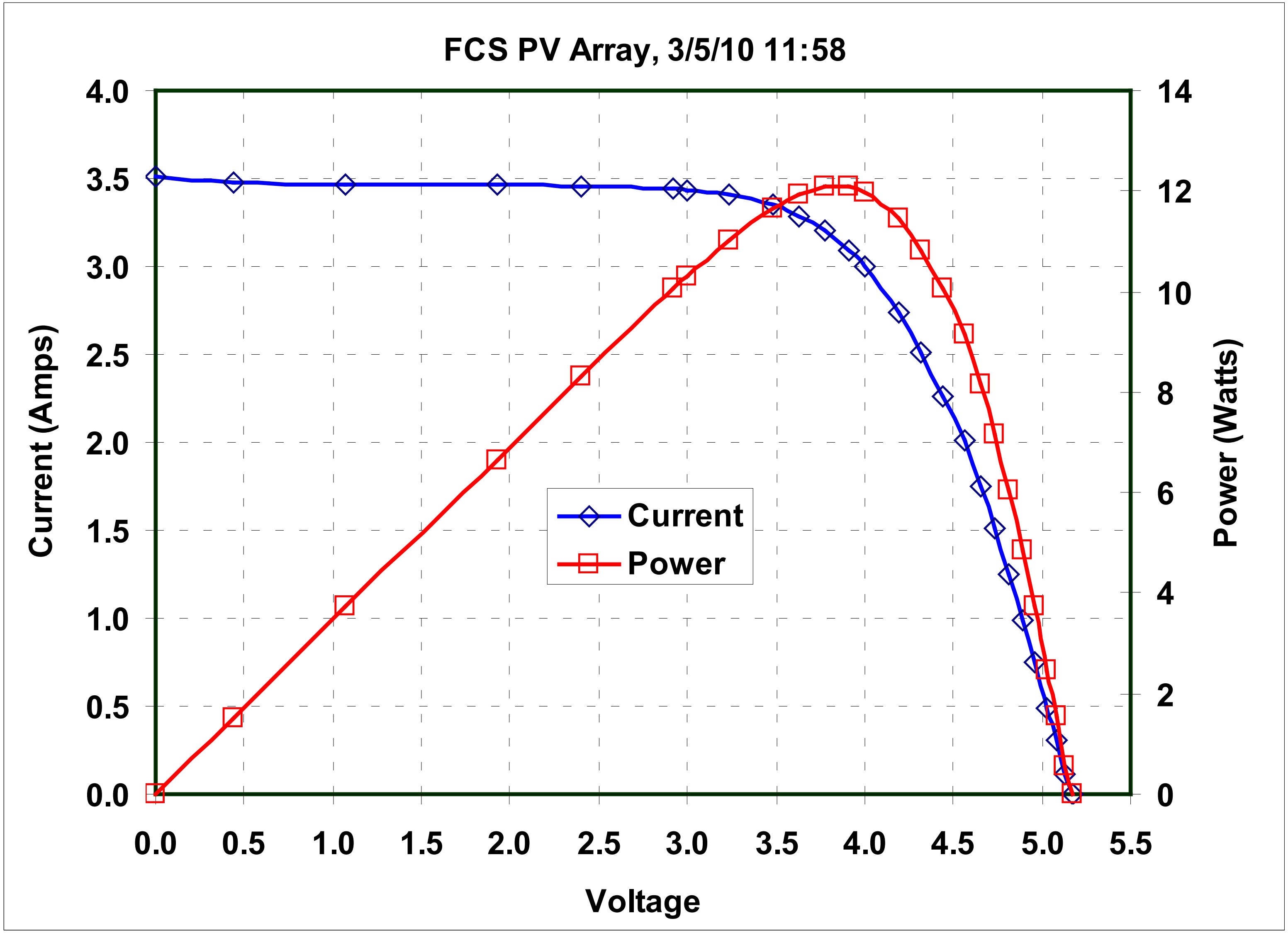


Measuring PV Module Performance

- Constant Radiation, Temperature
- Vary Resistive Load:
  - R = 0, Short Circuit (Voltage = 0, Current = Iss)
  - R = ∞, Open Circuit (Current = 0, Voltage = Voc)
- Measure Current and Voltage

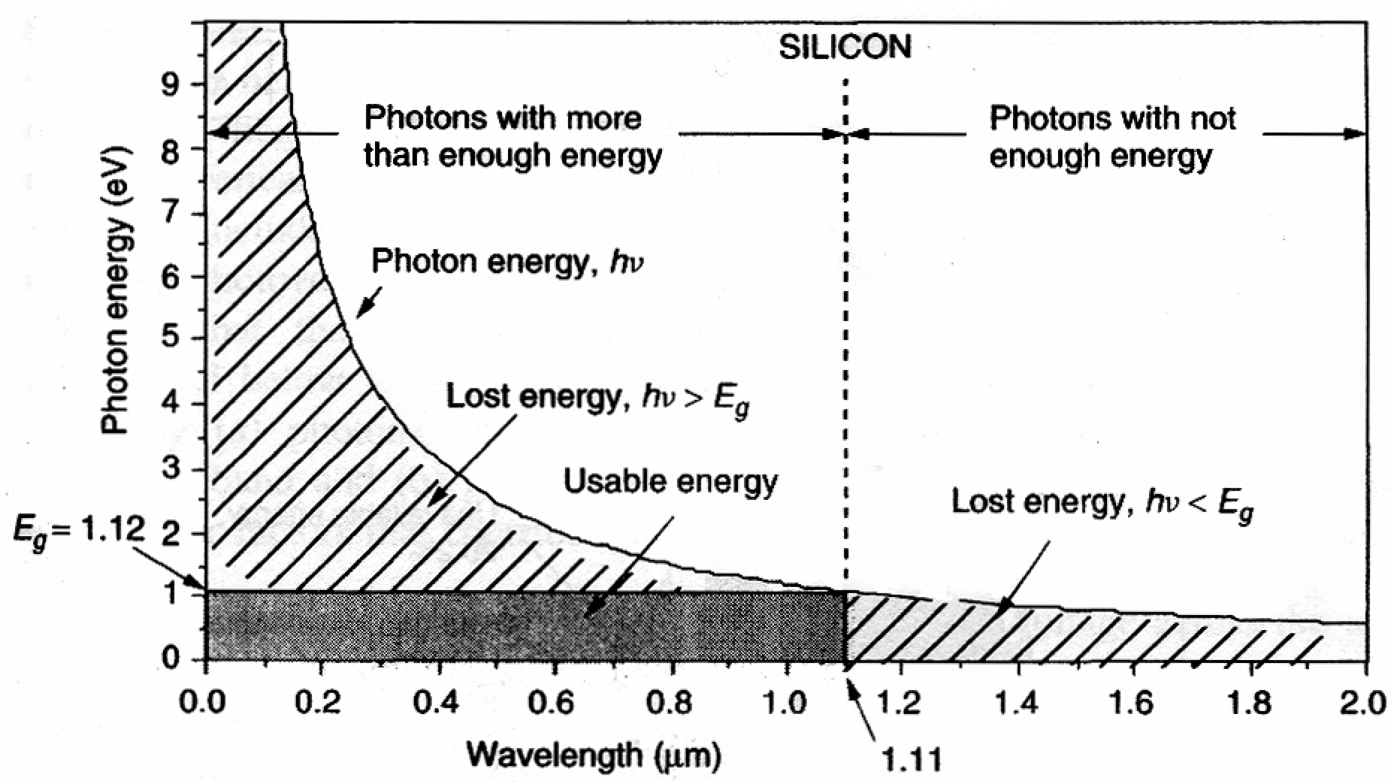


PV Module "I-V Curve"



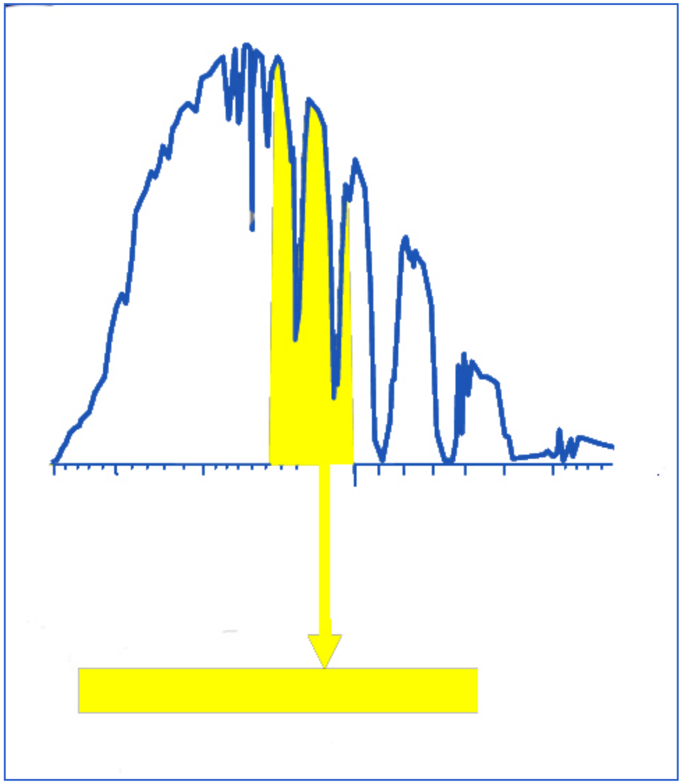
Band Gap Energy and Photon Energy

- Photons with λ > 1.11 μm do not have enough energy to promote electrons to the conduction band
- Photons with λ< 1.11 μm will promote an electron to the conduction band, but all energy > 1.12 eV is wasted.

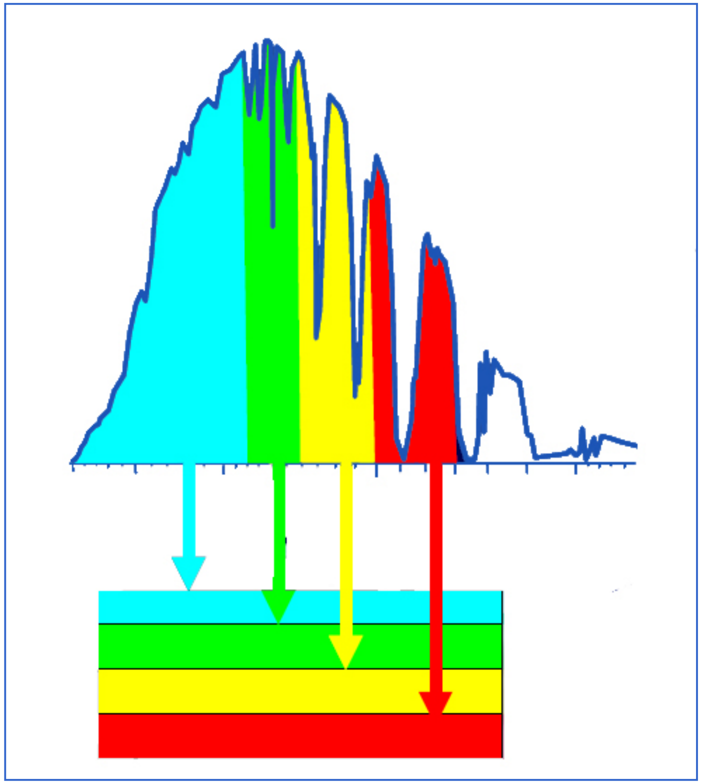


Multiple-Junction PV Cells

- Single-Junction Cell
  - Responds to a specific wavelength range of the solar spectrum

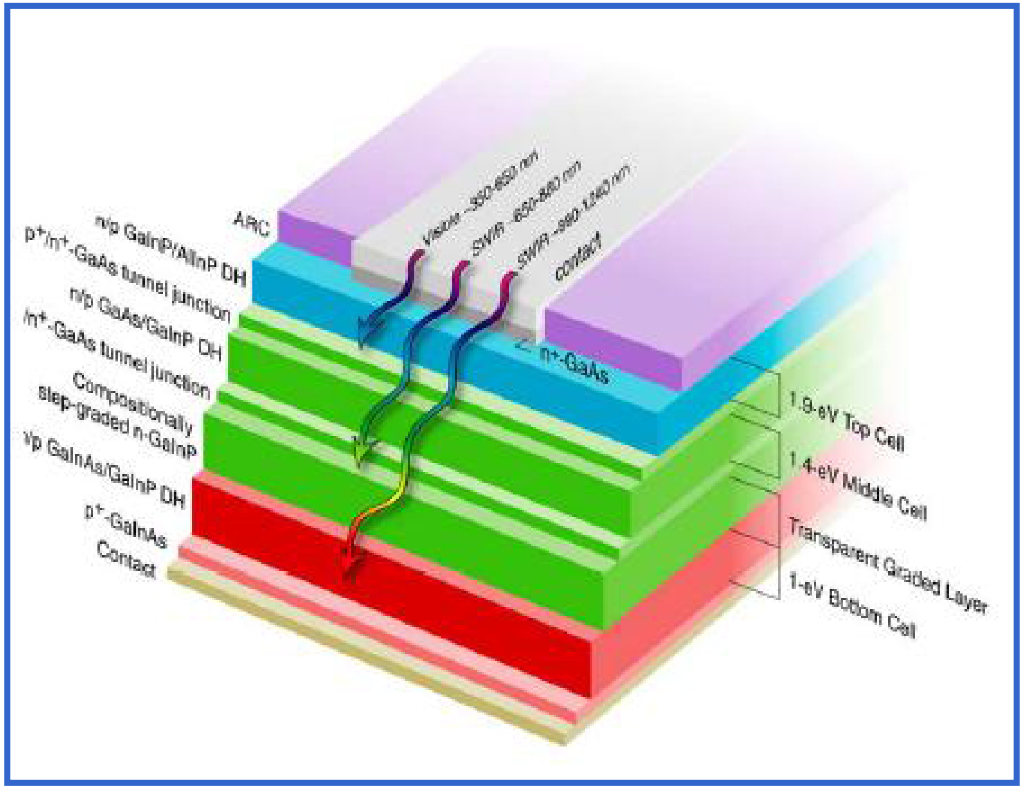


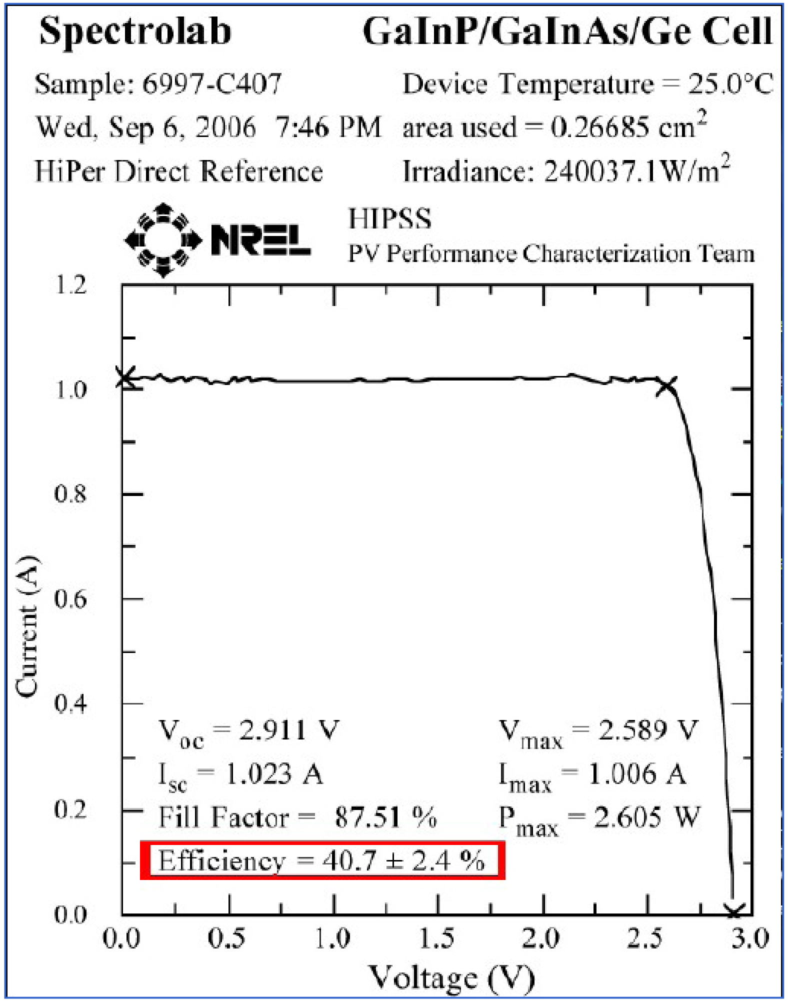
- Multiple-Junction Cell
  - Utilizes a broader range of the solar spectrum



Multi-Junction PV Cell

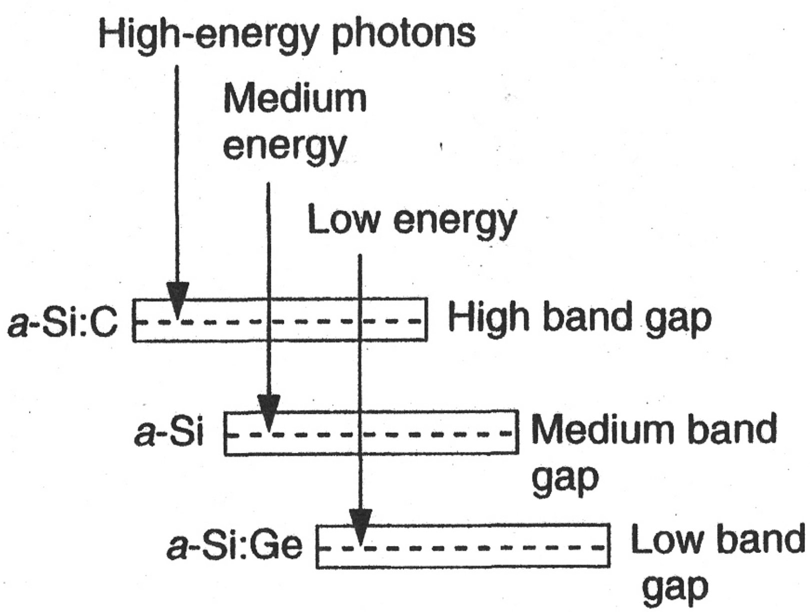
- GaInP/AlInP Top Cell: 1.9 eV
- GaAs/GaInP Middle Cell: 1.4 eV
- GaInAs/GaInP Bottom Cell: 1.0 eV

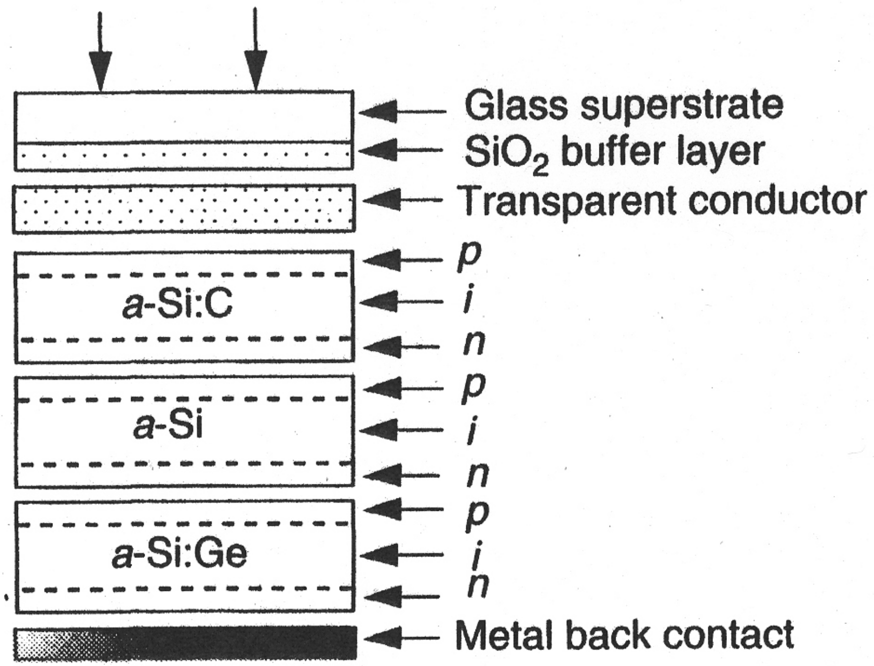




Multijunction Amorphous Silion Cell

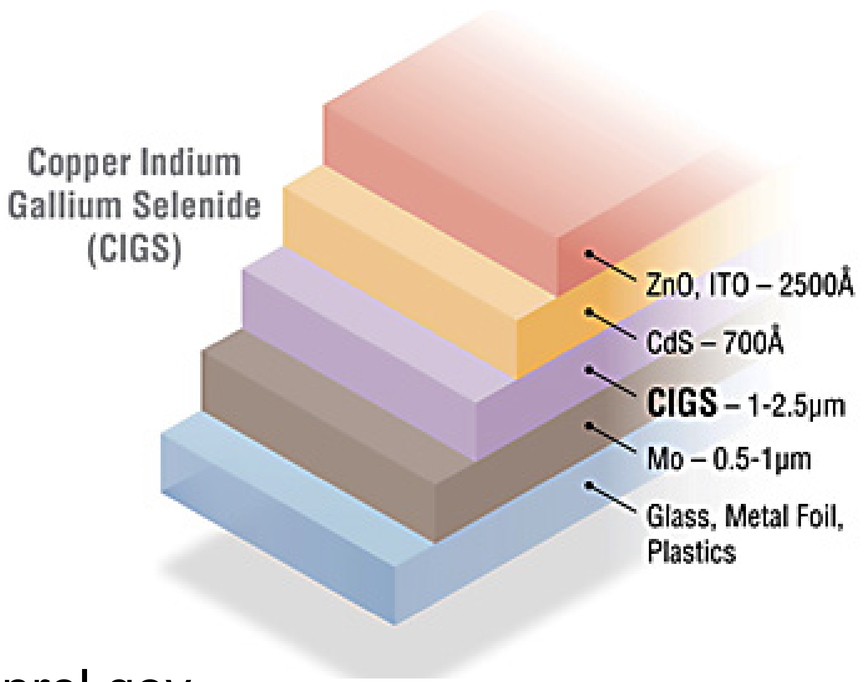
- Top layer: carbon a-Si:C (≈ 2.0 eV)
- Middle layer: a-Si:H (≈ 1.75 eV)
- Bottom layer: a-Si:H (≈ 1.3 eV)





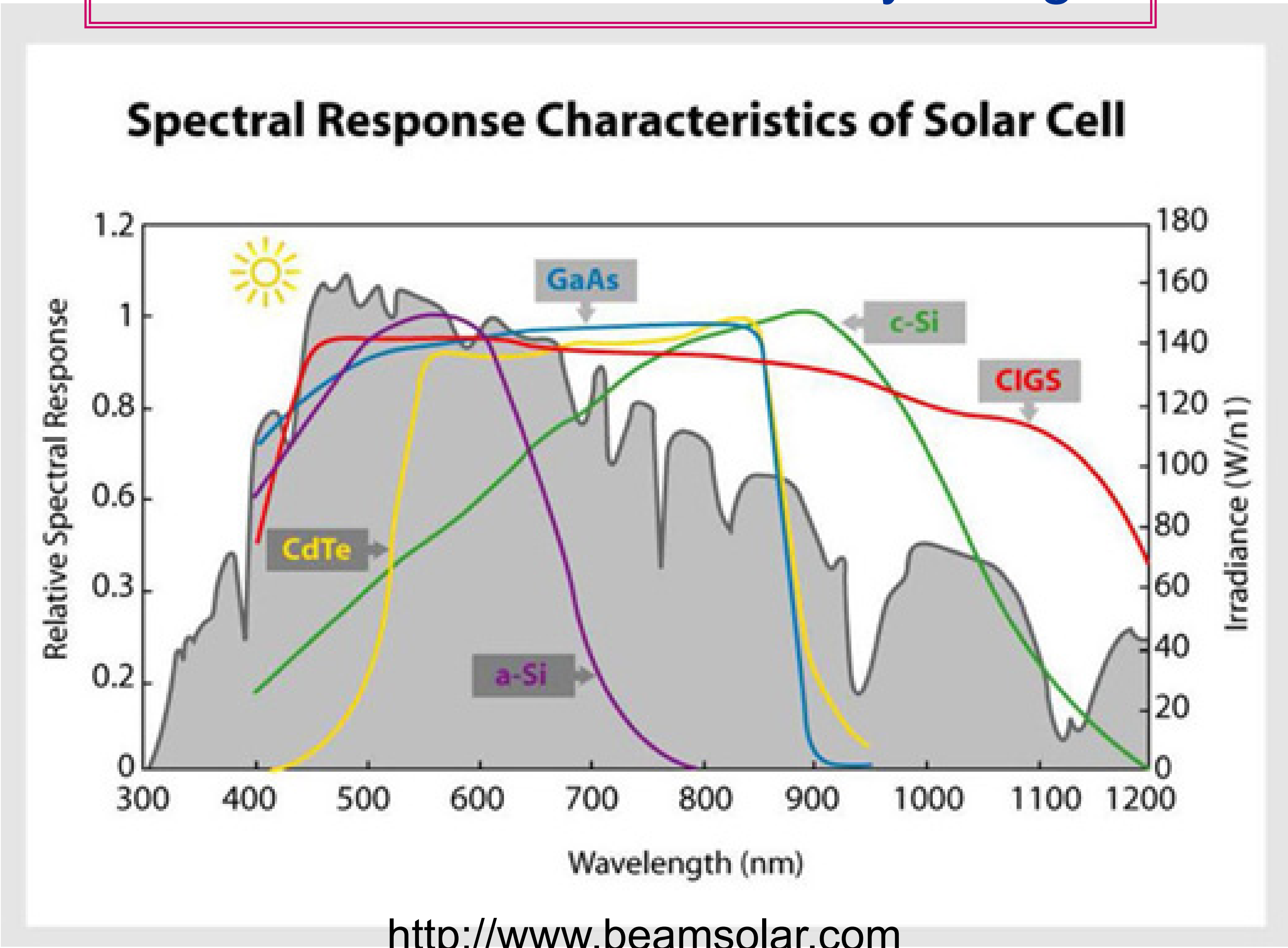
CIGS Solar Cell Technology

- Copper Indium Gallium Selenide
- Thin film solar cell, deposited on a thin substrate
- Compared to a-Si and c-Si:
  - Thinner absorber layer (1-3 μm instead of 200-300 μm)
  - 98% less semiconductor material
  - Wider absorbency range
  - Higher sensitivity to light
  - Higher efficiency



www.nrel.gov

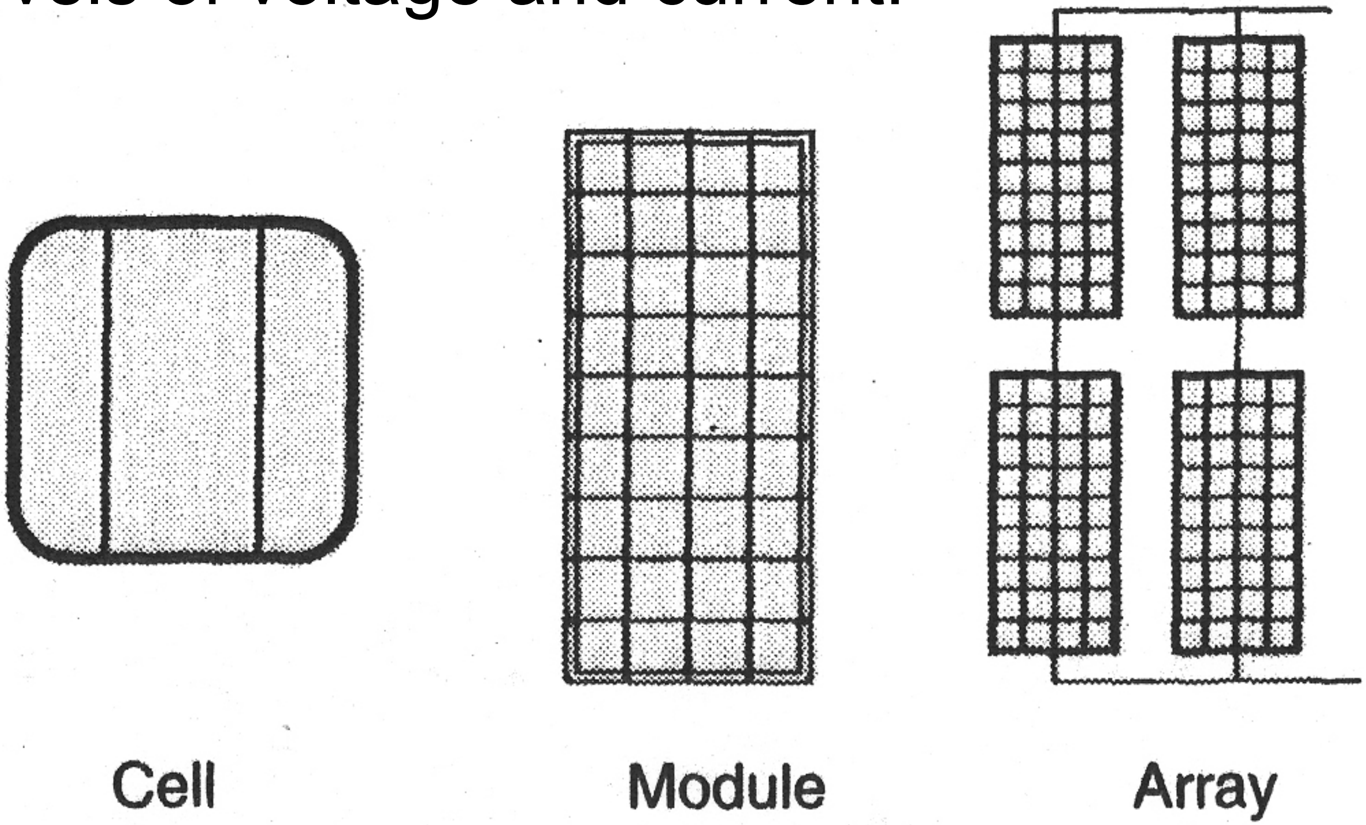
CIGS Solar Cell Absorbency Range



http://www.beamsolar.com

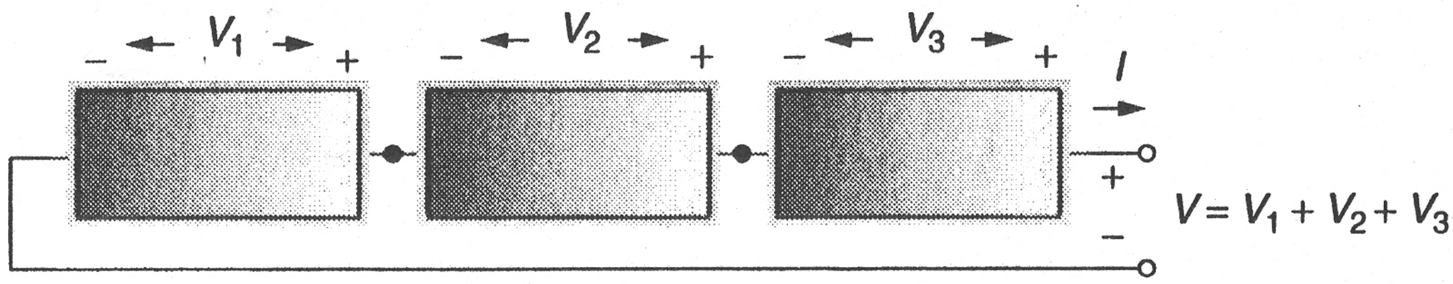
PV Cells, Modules, and Arrays

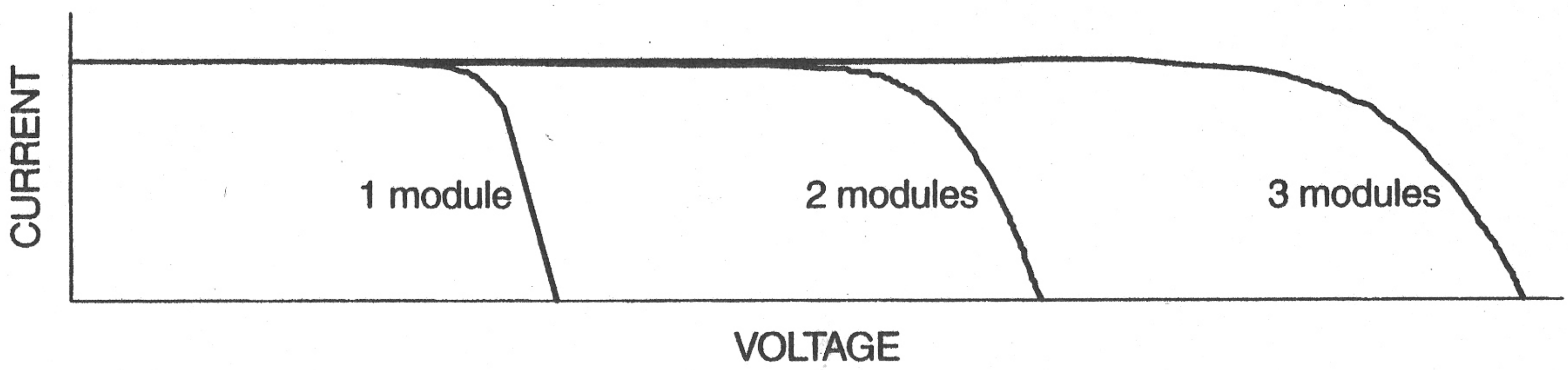
- Individual cells produce very little power, but can be combined with other cells to produce usable levels of voltage and current:



Cells added in Series

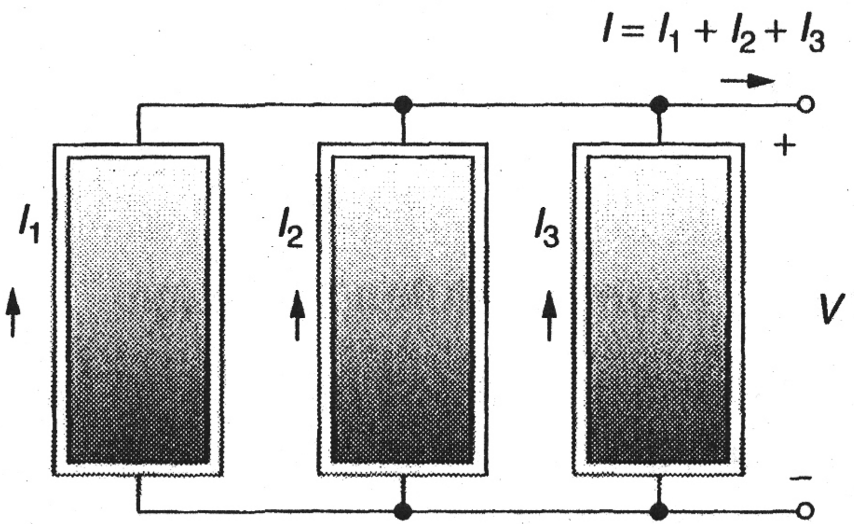
- All cells see the same current
- Cell voltages add

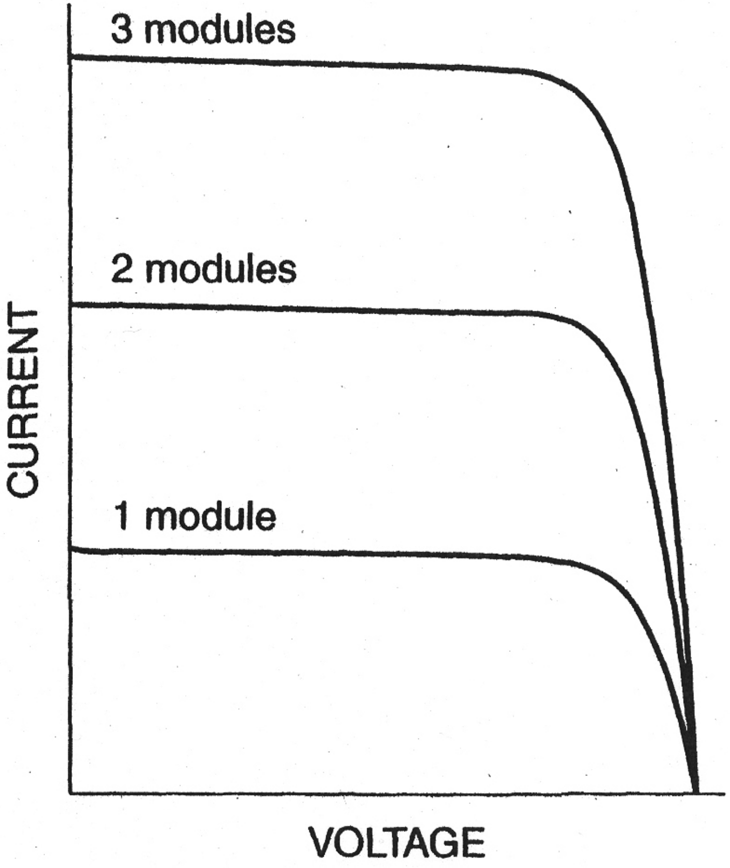




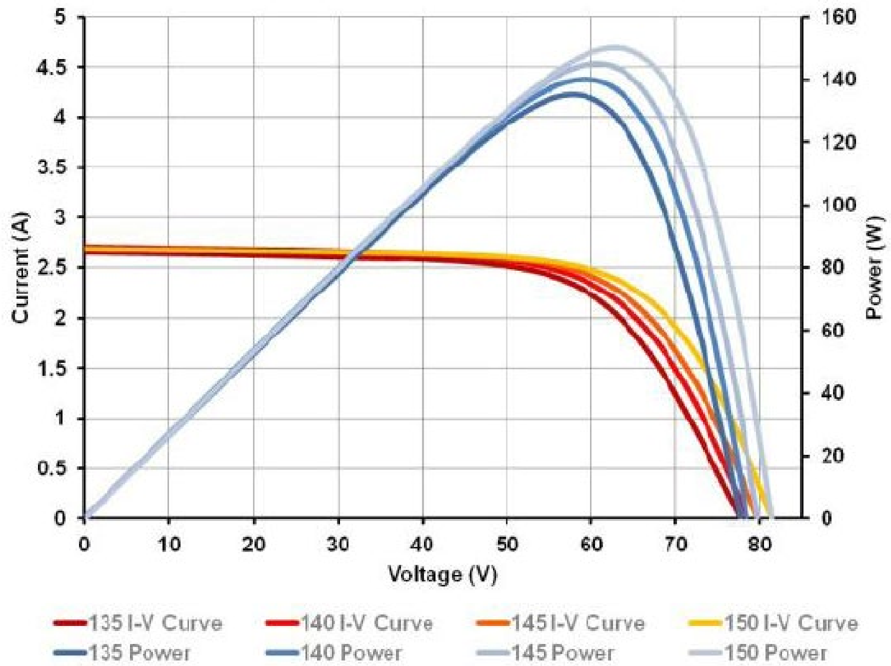
Cells Added in Parallel

- All cells see the same voltage
- Cell currents add



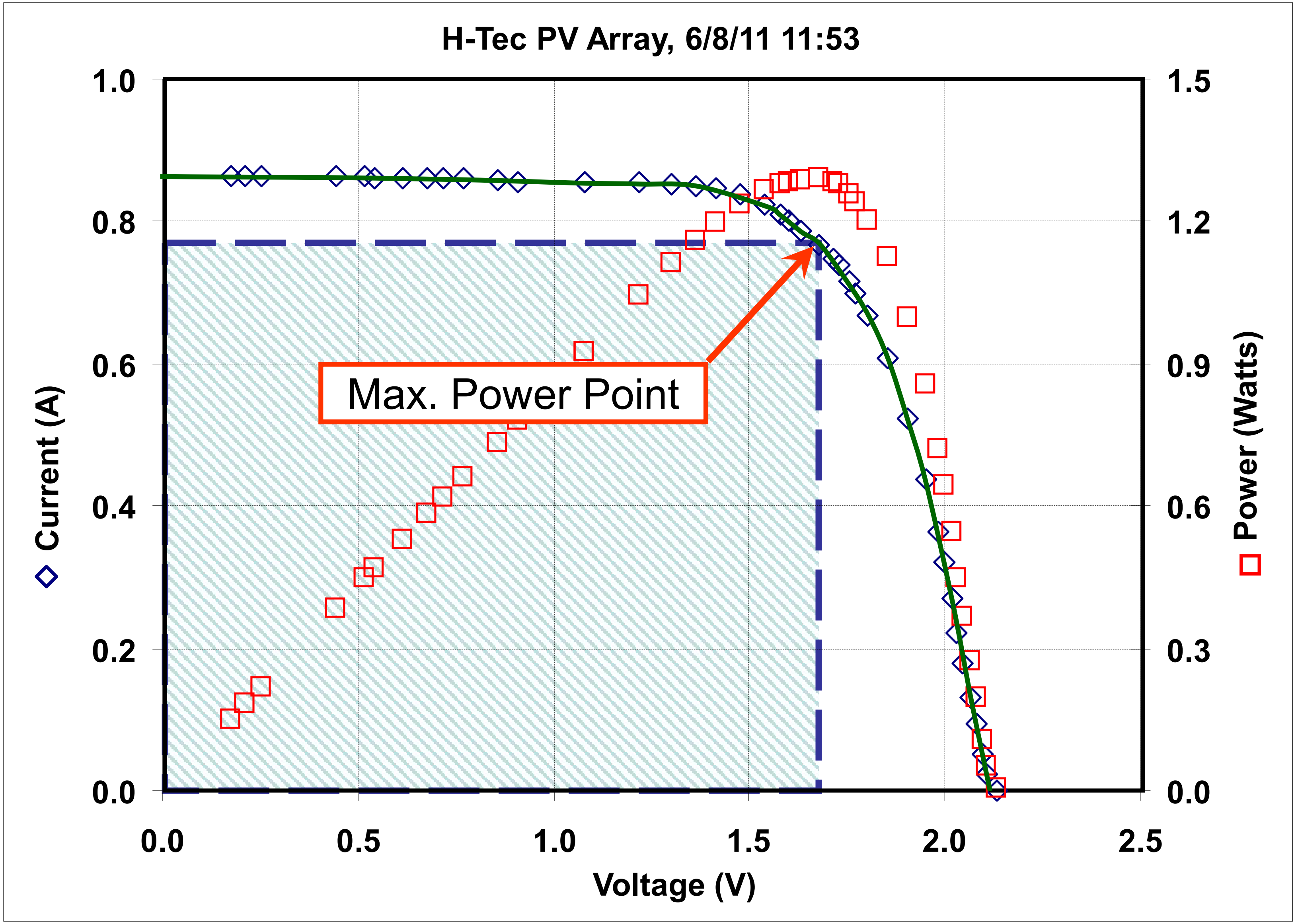


Commercial CIGS Panel Performance



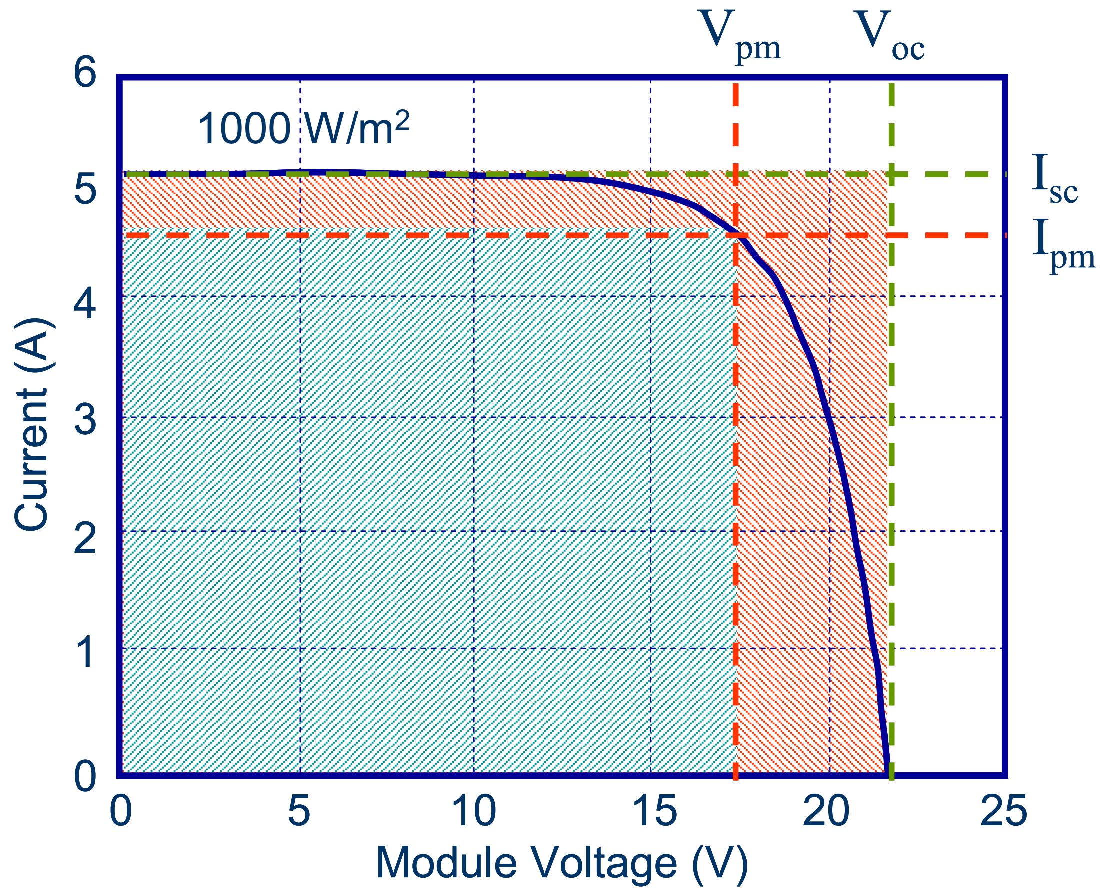
Nominal Power, PMAX (W)	135	140	145	150
Module Efficiency (%)	12.6%	13.1%	13.5%	14.0%
Vmpp (V)	58.2	59.8	61.0	62.7
Impp (A)	2.32	2.34	2.38	2.39
Voc (V)	77.4	78.8	79.6	80.8
Isc (A)	2.62	2.65	2.68	2.72

Maximum Power Point (MPP)



PV Cell Efficiency

"AM 1.5" Incident Solar Radiation ~1000 W/m²



PV Efficiency (Cell or Module):

$$\eta = \frac{\text{OutputPower}}{\text{Incident Power}} = \frac{V_{pm} \cdot I_{pm}}{(\text{AM1.5})(\text{Area})}$$

PV Current-Voltage Variation with Insolation and Temperature

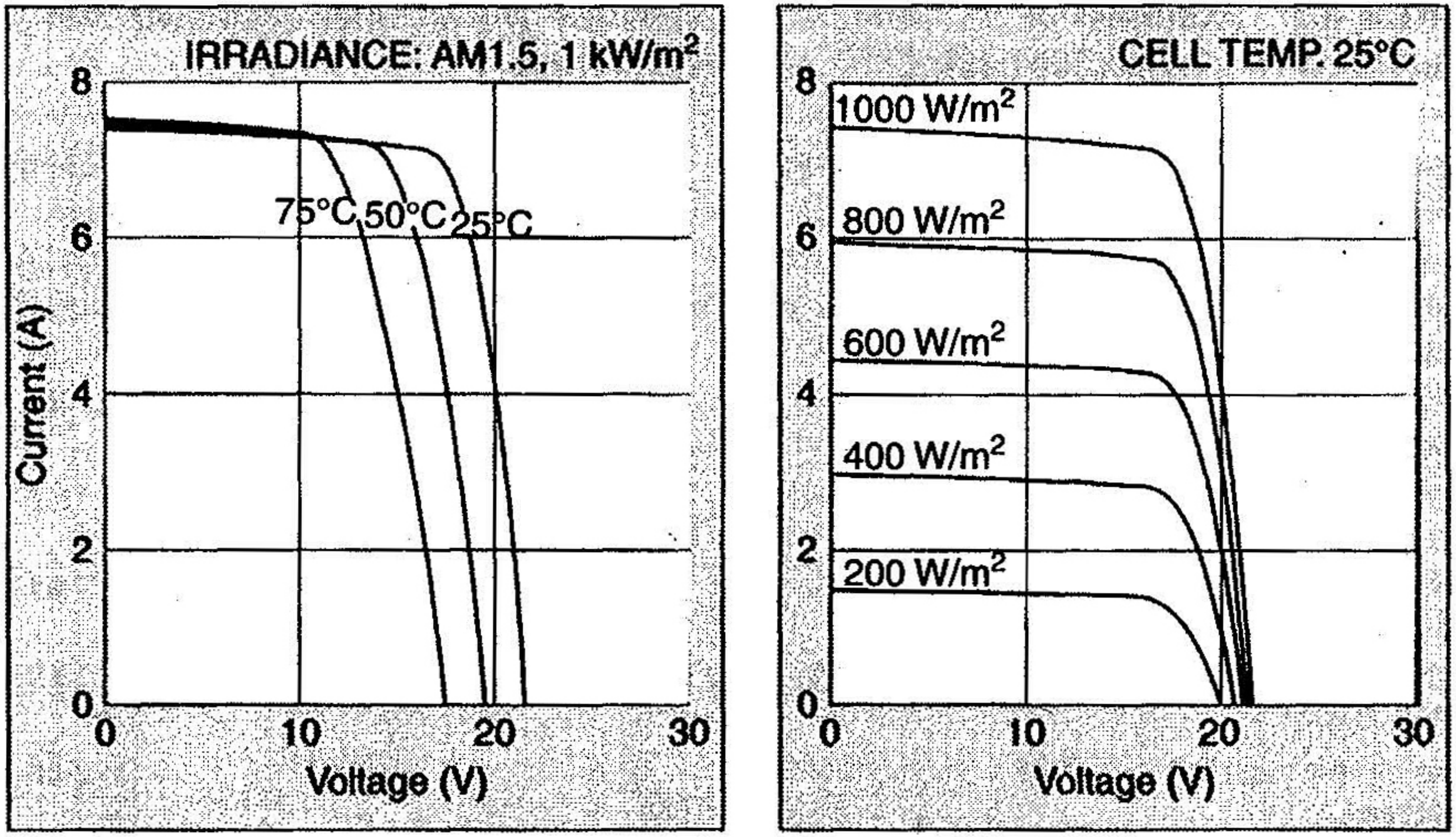
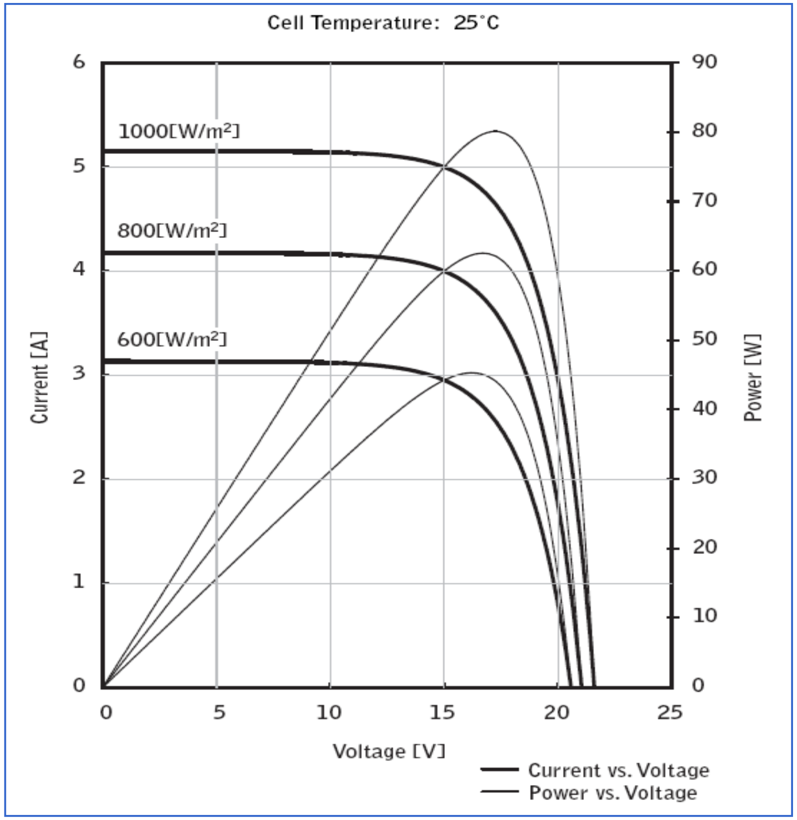


Figure 8.36 Current-voltage characteristic curves under various cell temperatures and irradiance levels for the Kyocera KC120-1 PV module.

Sharp NE-EJEA

- Electrical Characteristics
- IV Curves

Cell	Poly-crystalline silicon
No. of Cells and Connections	36 in series
Open Circuit Voltage (Voc)	21.6V
Maximum Power Voltage (Vpm)	17.3V
Short Circuit Current (Isc)	5.16A
Maximum Power Current (Ipm)	4.63A
Maximum Power (Pmax)*	80W (+10% / -5%)
Module Efficiency (ηm)	12.40%
Maximum System Voltage	600VDC
Series Fuse Rating	10A
Type of Output Terminal	Junction Box



- Dimensions: 47.28" x 21.14" x 1.81"
- Weight: 20.94 Lbs.
- Cost: $333

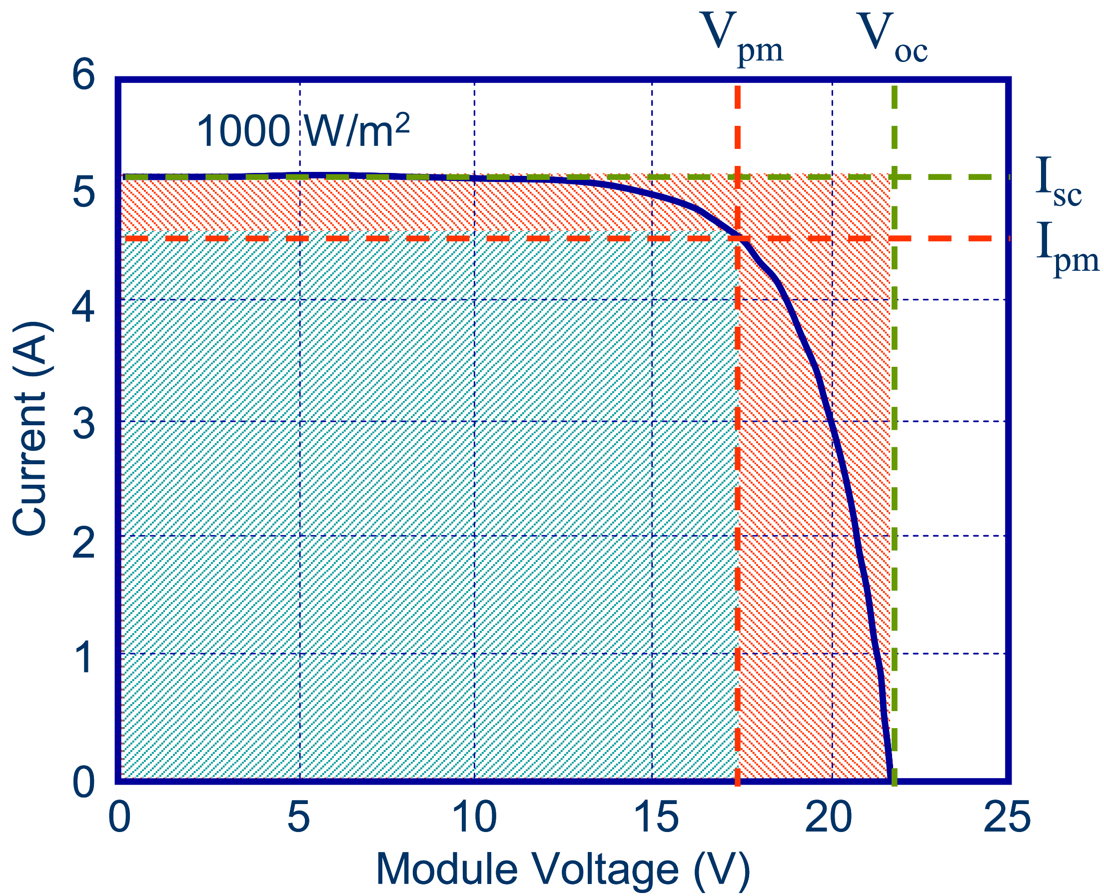
Example: Module Efficiency

$V_{pm} = 17.3V$

$V_{oc} = 21.6V$

$I_{pm} = 4.63A$

$I_{sc} = 5.16A$



- Module Area:

$$\text{Area} = (47.28\text{in})(21.14\text{in})\left(\frac{\text{m}}{39.4\text{in}}\right)^2 = 0.6448\text{m}^2$$

- Module Efficiency:

Using AM1.5 Standard Solar Irradiation = 1000 W/m^2:

$$\eta = \frac{V_{pm} \cdot I_{pm}}{\text{Incident Power}} = \frac{(17.3\text{V})(4.63\text{A})}{(1000\text{W}/\text{m}^2)(0.6448\text{m}^2)}$$

$$\eta = \frac{(80.1\text{W})}{(644.8\text{W})} = 12.4\%$$

Exercise: Module Efficiency

- Calculate the efficiency of an Evergreen ES-B-190:
- From the specification sheet:
  - Use the performance data listed under “Standard Test Conditions.”
  - Use the total area of the panel.

Stand-Alone PV System with Backup

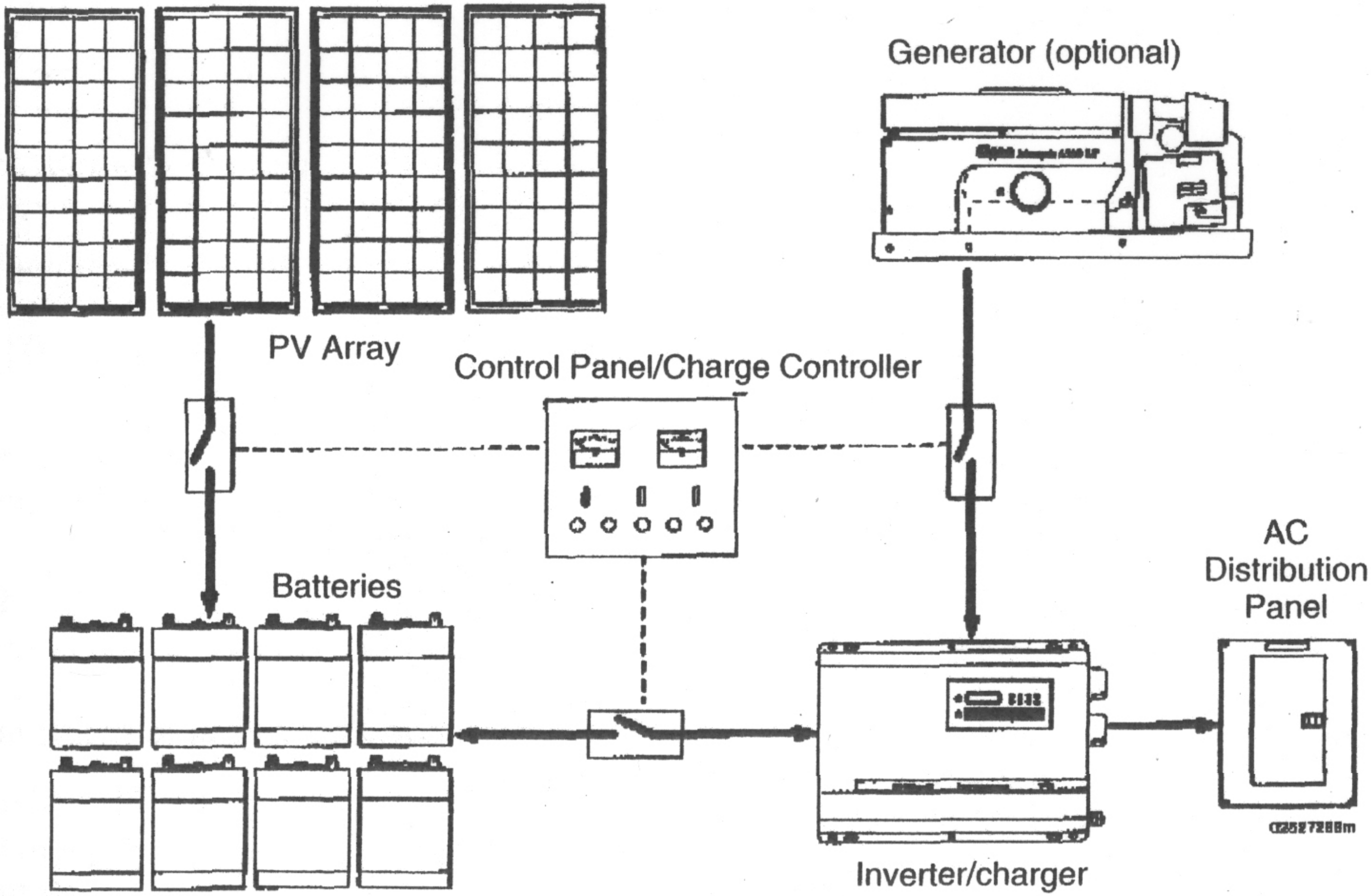


Figure 9.2 Example of a stand-alone PV system with optional generator for back-up.

<u>Renewable and Efficient Electric Power Systems</u>, G.M. Masters, Wiley, 2004

Components of Grid-Connected PV

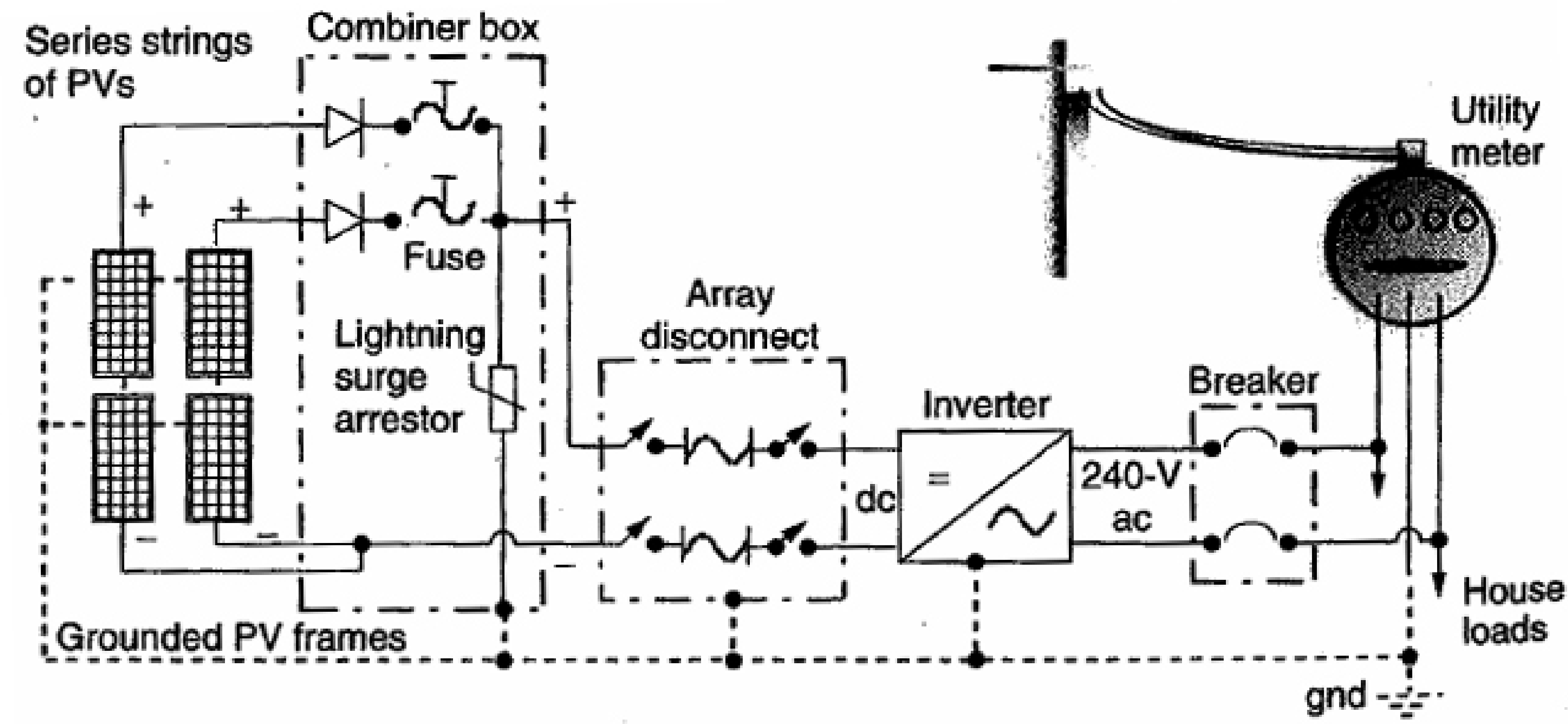


Figure 9.20 Principal components in a grid-connected PV system using a single inverter.

Grid-Connect Solar PV and Net Metering

- Energy sold to the utility can be considered a type of "energy storage."

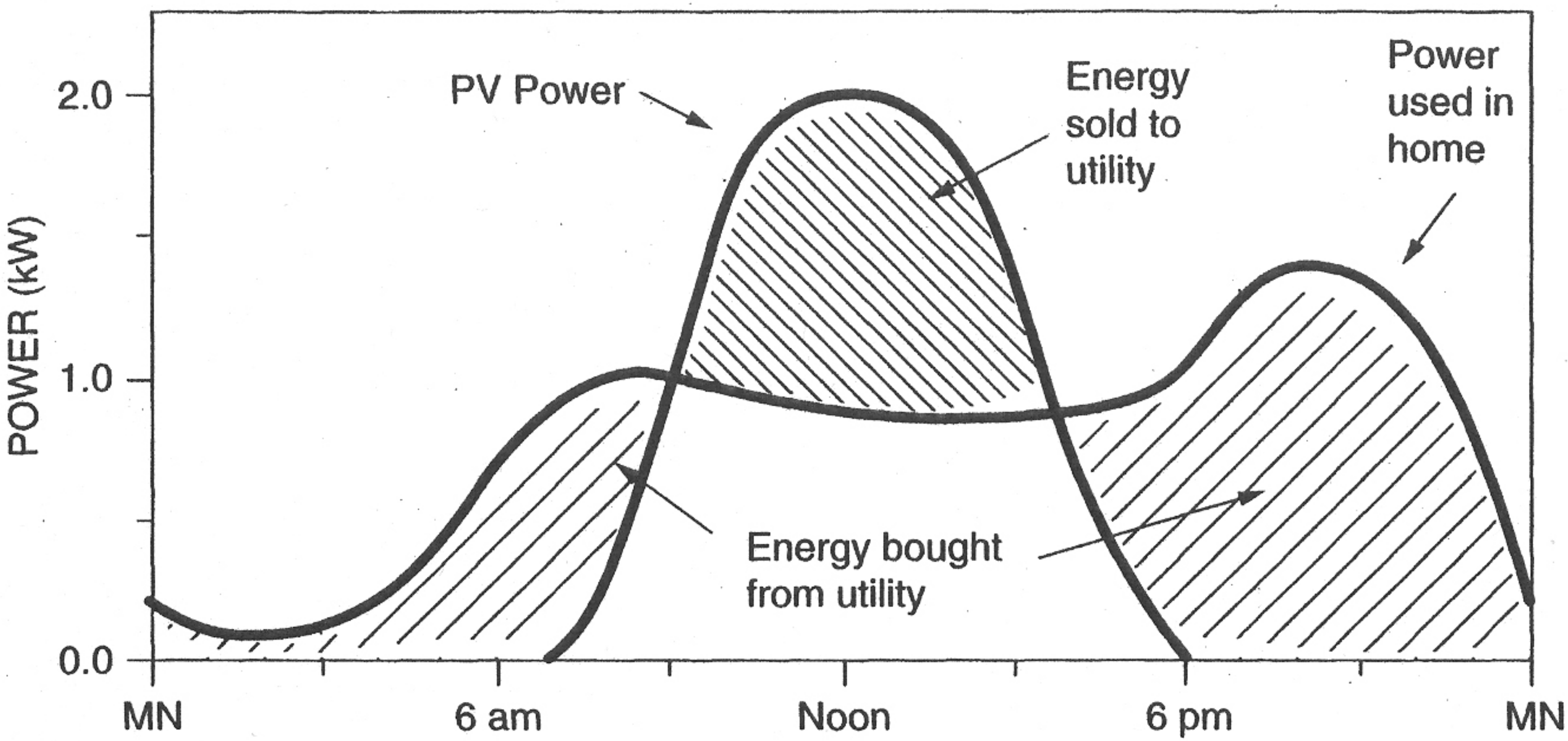


Figure 9.23 During the day, excess power from the array is sold to the utility; at night, the deficit is purchased from the utility.

<u>Renewable and Efficient Electric Power Systems</u>, G.M. Masters, Wiley, 2004

Solar Carports

- Cincinnati Zoo, OH
  - 1.6 MW installed capacity
  - 6400 solar panes, 245W each (Sunmodule© SW245)

http://solarworld-usa.com

Solar Carports

- **Stockton College, New Jersey**
  - **845 kW Installed Capacity**
  - **1212 MWh/y**
  - **500 cars**

- **Capacity Factor:**

$$CF = \frac{(1212\text{MWh/y})}{(845\text{kW})(8760\text{h/y})}$$

$$CF = \frac{(1212\text{MWh/y})}{(7402\text{MWh/y})} = 0.1637$$

Utility Power Based on Thin Film PV Technology

- 1.45 MW Solar Power Plant at Dimbach, Germany, utilizing Cadmium Telluride thin-film cells

A 1.45 MW solar power plant at Dimbach in Germany, which uses CdTe thin-film cells and was constructed in 2003–2004 by Beck Energy GmbH. Courtesy of Beck Energy GmbH.

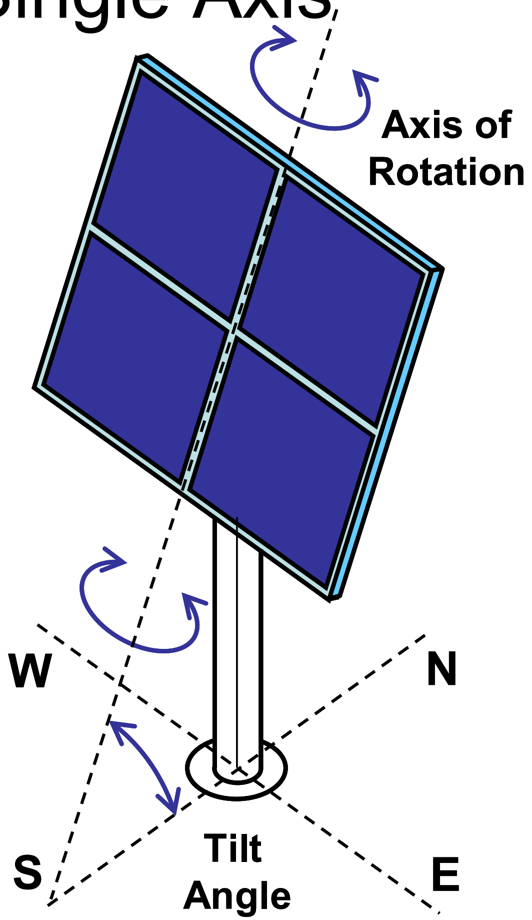
Ball, P., *MRS Bulletin*, Vol 35, Sep.2010

Tracking Systems

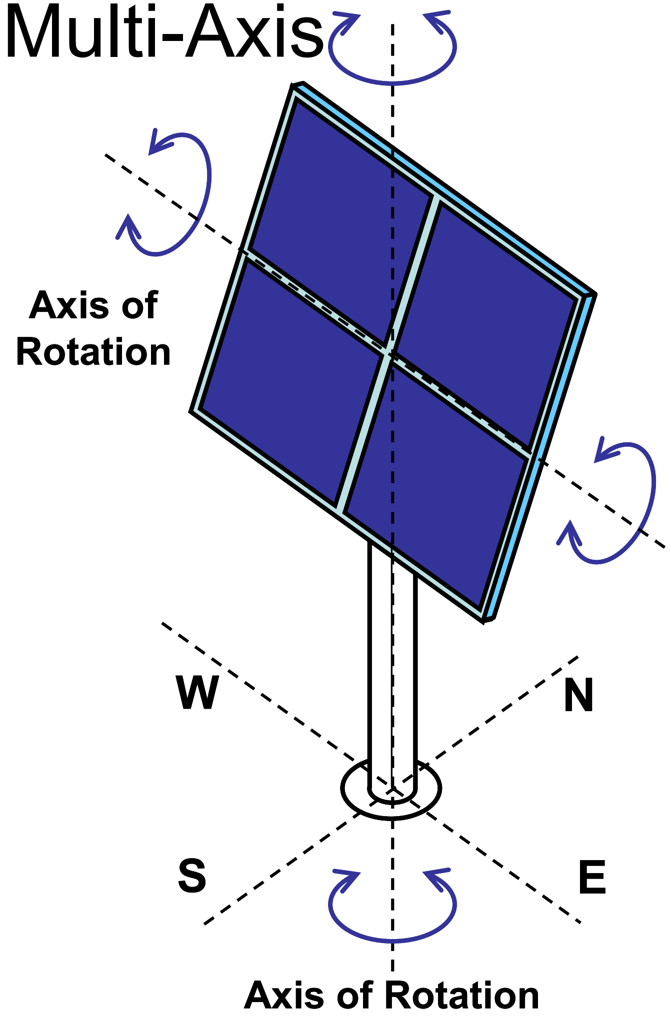
- Most residential solar systems have a fixed mount, but sometimes tracking systems are cost effective
- Tracking systems are either single axis (usually with a rotating polar mount [parallel to earth's axis of rotation), or two axis (horizontal [altitude, up-down] and vertical [azimuth, east-west]
- Ballpark figures for tracking system benefits are about 20% more for a single axis, and 25 to 30% more for a two axis

Tracking Systems

- Single Axis

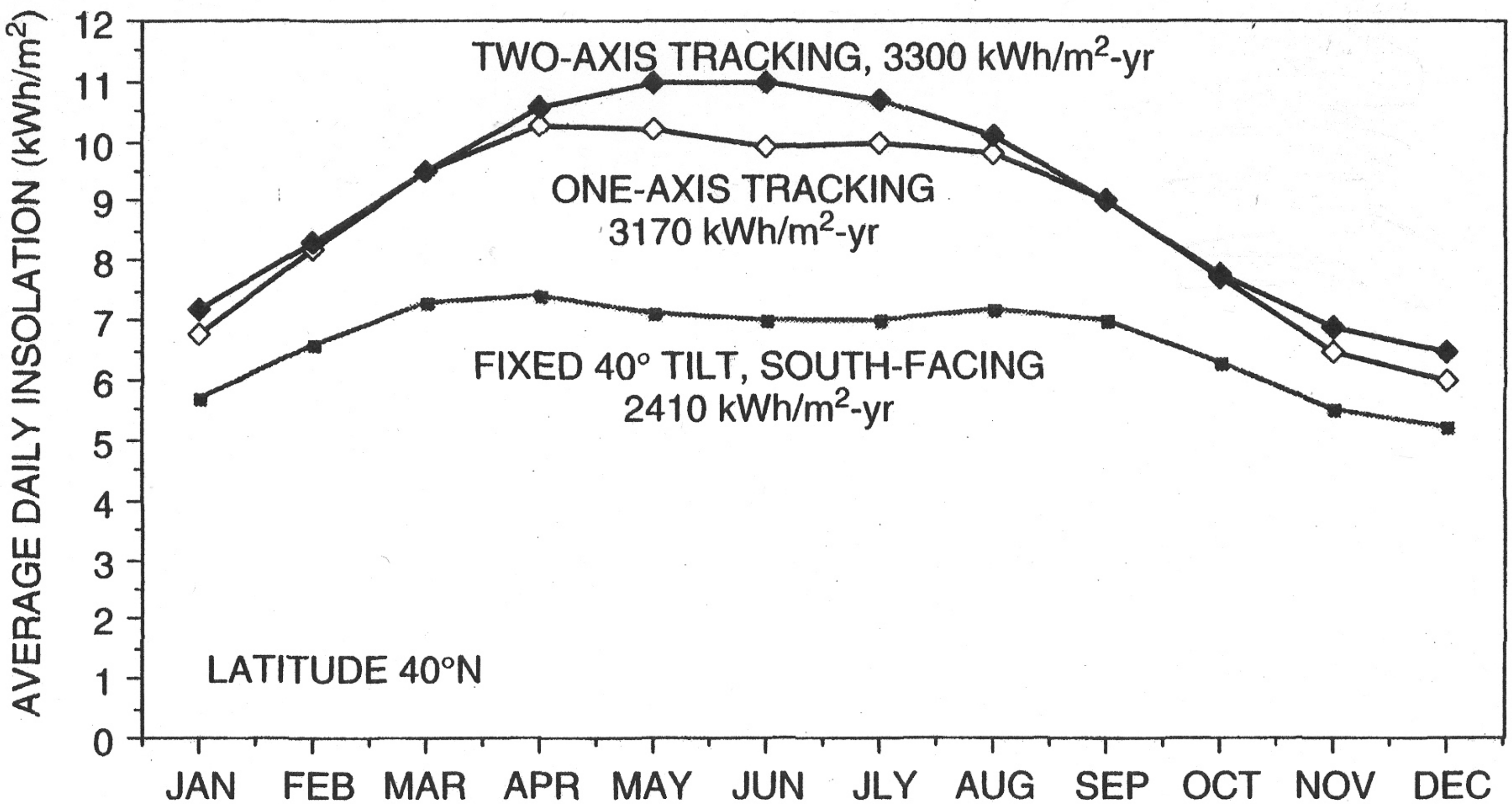


- Multi-Axis



Daily Clear Sky Insolation, w/Tracking

- Both one axis and two axis tracking yield a boost in performance.
- Two-axis tracking yields slightly better performance in summer months



Large Scale System

- Nellis Air Force Base, Nevada
- 70,000 solar panels, 14.2 MW, 32GWh/yr
- Capacity Factor = 0.25

http://energy.gov

Solar PV: Levelized Costs $/MWh

Estimated Costs for New Generation Resources: Plant Type (Capacity Factor)	Capital Cost	Fixed O&M	Variable O&M (Incl. Fuel)	Transmission Investment	Total System Levelized Cost
Solar PV (25%) AEO2011	194.6	12.1	0.0	4.0	210.7
Solar PV (25%) AEO2012	140.7	7.7	0.0	4.3	152.7
Solar PV (25%) AEO2013	130.4	9.9	0.0	4.0	144.3
Solar PV (25%) AEO2014	114.5	11.4	0.0	4.1	130.0
Solar PV (25%) AEO2015	109.8	11.4	0.0	4.1	125.3
Solar PV (25%) AEO2016	59.8	10.1	0.0	3.8	73.7
Solar PV (29%) AEO2017	51.2	8.7	0.0	3.3	63.2
Solar PV (29%) AEO2018	37.1	8.8	0.0	4.1	48.8

U.S. Energy Information Administration, Annual Energy Outlook 2011 to 2019.
www.eia.gov/forecasts/aeo/electricity_generation.cfm