The Florida Advanced Technological Education (FLATE) Center wishes to make available, for educational and non-commercial purposes only, materials relevant to the "EST1830 Introduction to Alternative/Renewable Energy" course comprised of images, texts, facilitator's notes, and other demonstration materials.

This instructional resource forms part of FLATE's outreach efforts to facilitate a connection between students and teachers throughout the State of Florida. We trust that these activities and materials will add value to your teaching and/or presentations.

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Introduction to Alternative and Renewable Energy

EST1830

Florida Energy Systems Consortium

FLATE
FLORIDA ADVANCED TECHNOLOGICAL EDUCATION CENTER

3. Energy Production

3.1 Renewable Energy Technologies

3.1.1 Solar Energy

3. Energy Production

- 3.1.1 Solar Energy
  - 3.1.1a Sun's Position
  - 3.1.1b Sun Path
  - 3.1.1c Sun Path Charts
  - 3.1.1d Solar Panel Positioning
- 3.1.1.1 Photovoltaics
- 3.1.1.2 Solar Thermal
  - 3.1.1.2a Low Temperature Collectors
  - 3.1.1.2b Medium Temperature Collectors
  - 3.1.1.2c High Temperature Collectors

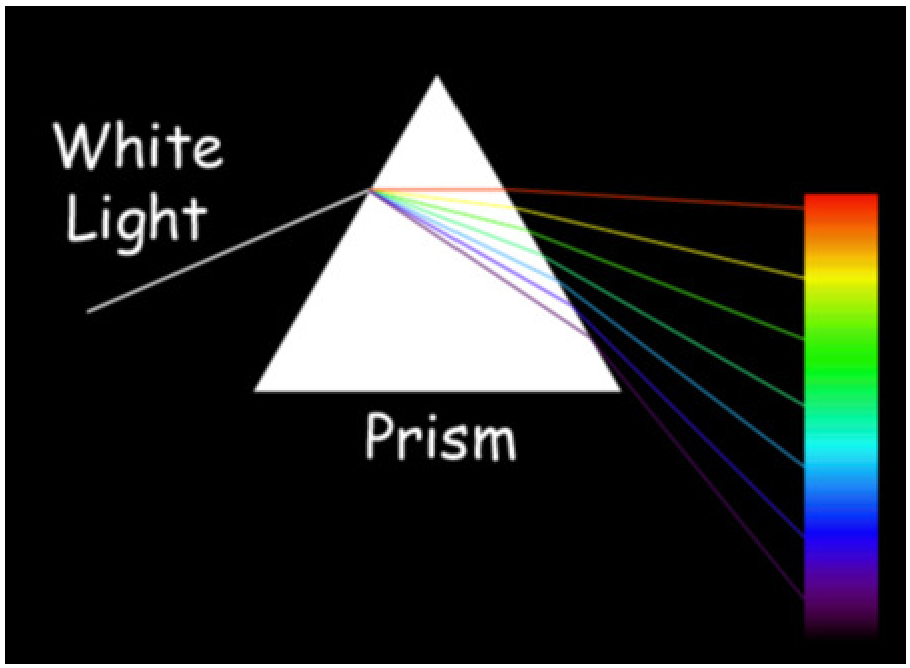
3.1.1.1 Photovoltaics

a. Review of energy in light
b. Operation of solar cells
c. Types of solar cells

Excellent resource for further study online: http://www.pveducation.org/pvcdrom

3.1.1.1a Light energy

Light from the sun is a mixture of different wavelengths. The different wavelengths that are visible to the eye show up as different colors.



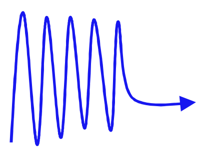
http://solarsystem.nasa.gov/deepimpact/science/spectroscopy.cfm

3.1.1.1a Light energy

Speed of light → $c = \lambda \nu$

Speed of light: c (m/s)
Wavelength: λ (m)
Frequency: ν (1/s)

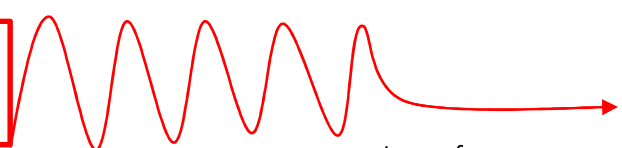
High Energy Photon for Blue Light



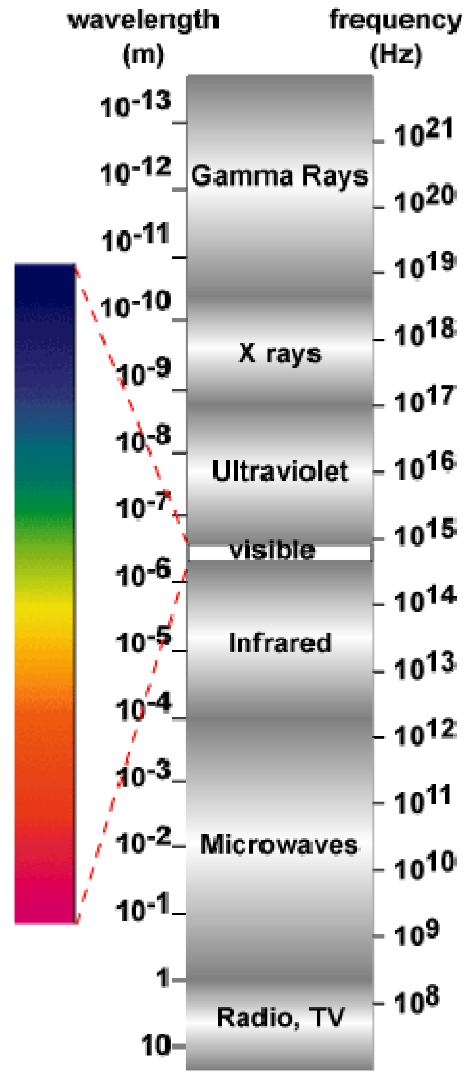
Higher frequency

Energy of a ***Photon*** $E = h\nu$ ***Or also*** $E = \frac{hc}{\lambda}$

Low Energy Photon for Red Light



Lower frequency



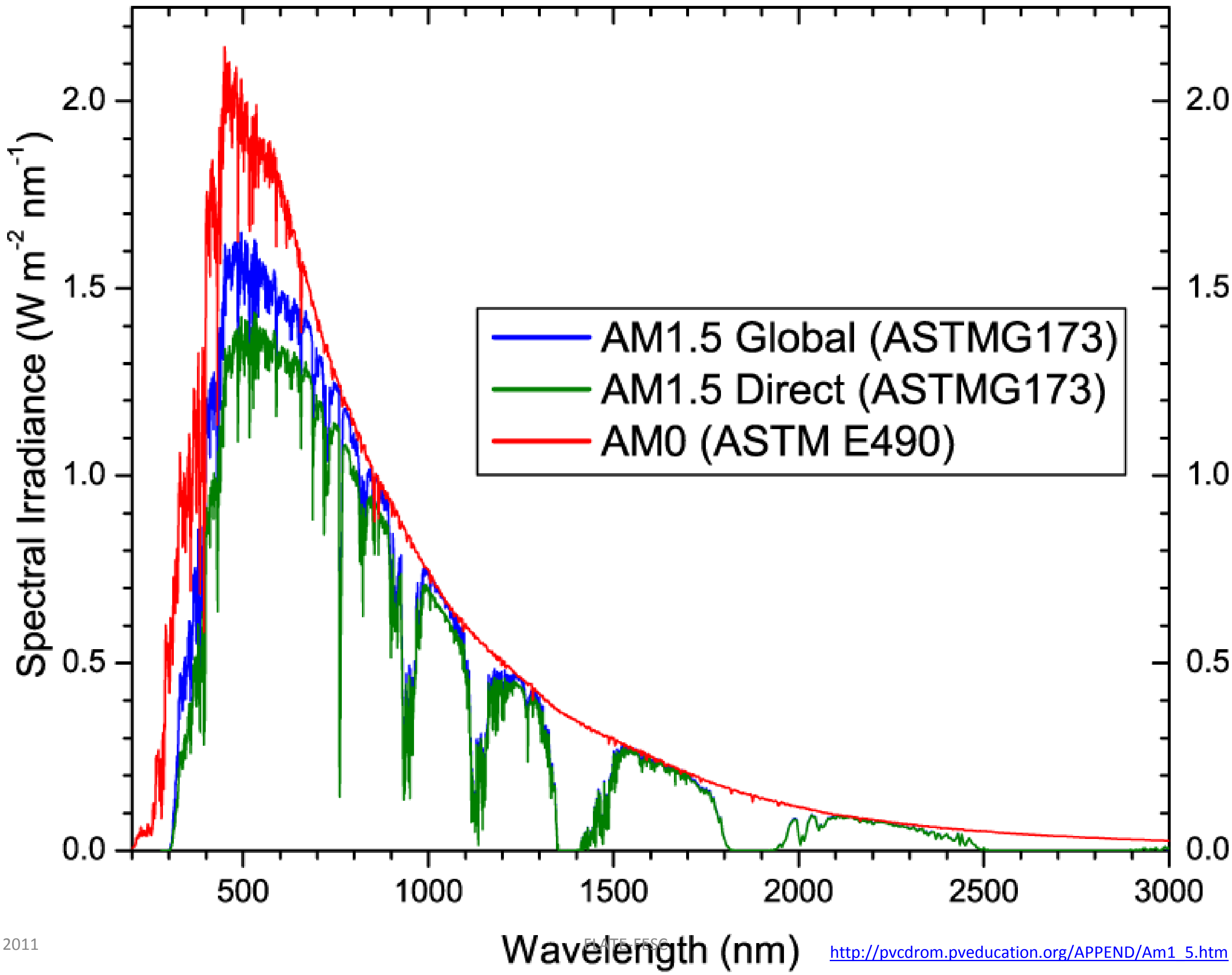
Planck's Constant: $h = 6.626 \times 10^{-34}$ Joule·second

Typically , when dealing with particles such as photons or electrons the units to use are electron volts (eV). But, we will stick to Joules.

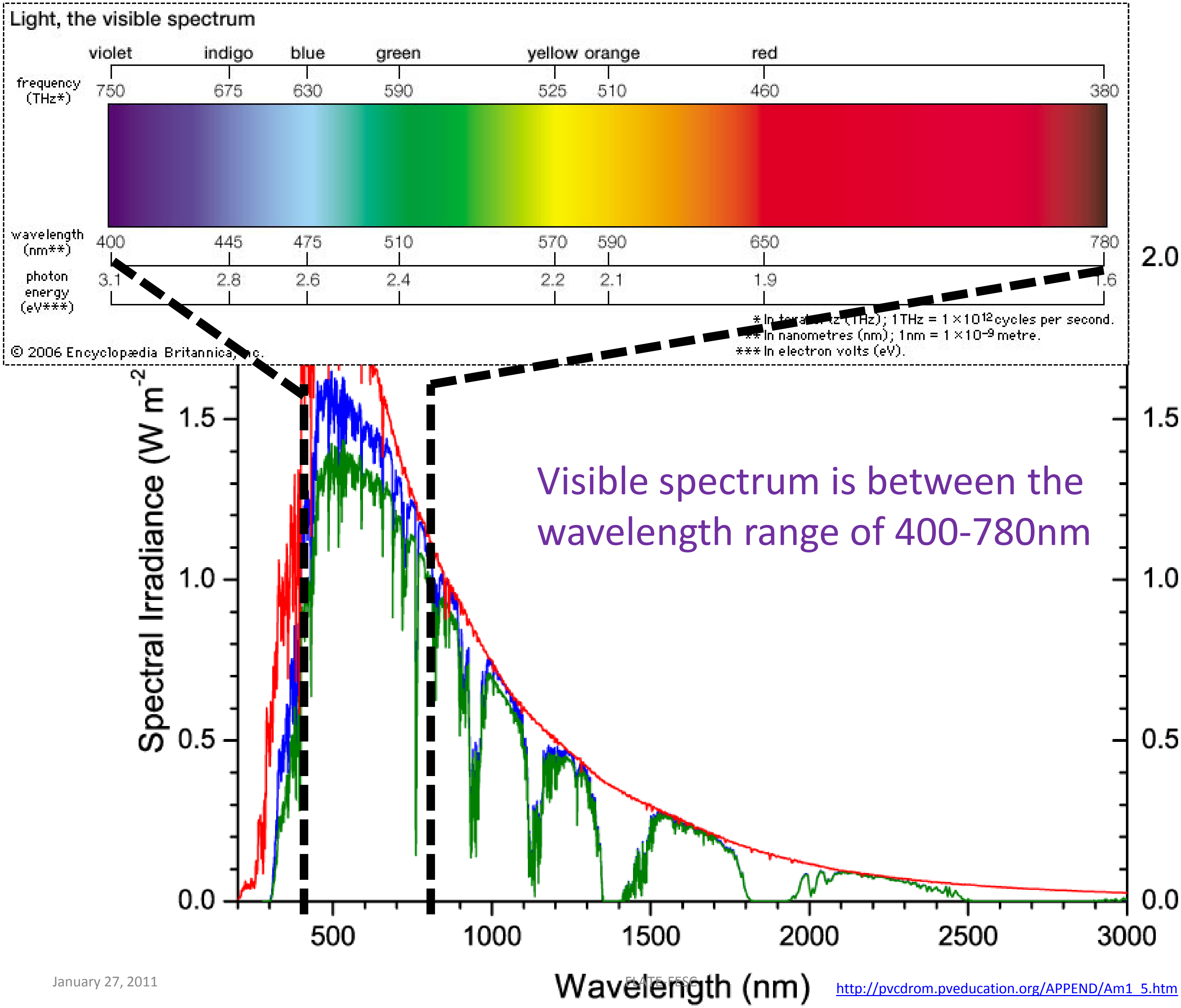
http://pvcdrom.pveducation.org/index.html

✓Remember our study of Air Mass

3.1.1.1a Air Mass



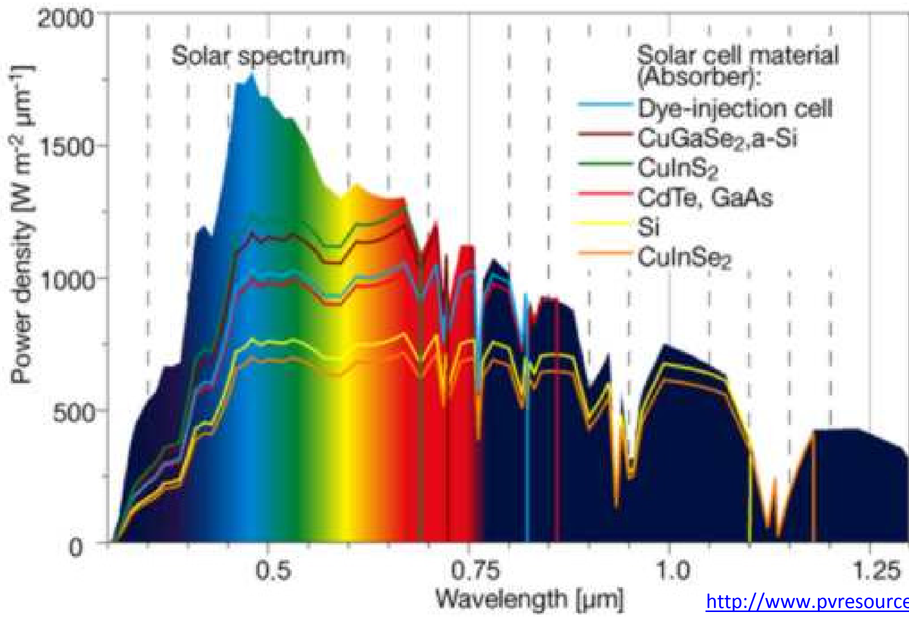
http://pvcdrom.pveducation.org/APPEND/Am1_5.htm



Visible spectrum is between the wavelength range of 400-780nm

http://pvcdrom.pveducation.org/APPEND/Am1_5.htm

3.1.1.1a Radiant energy



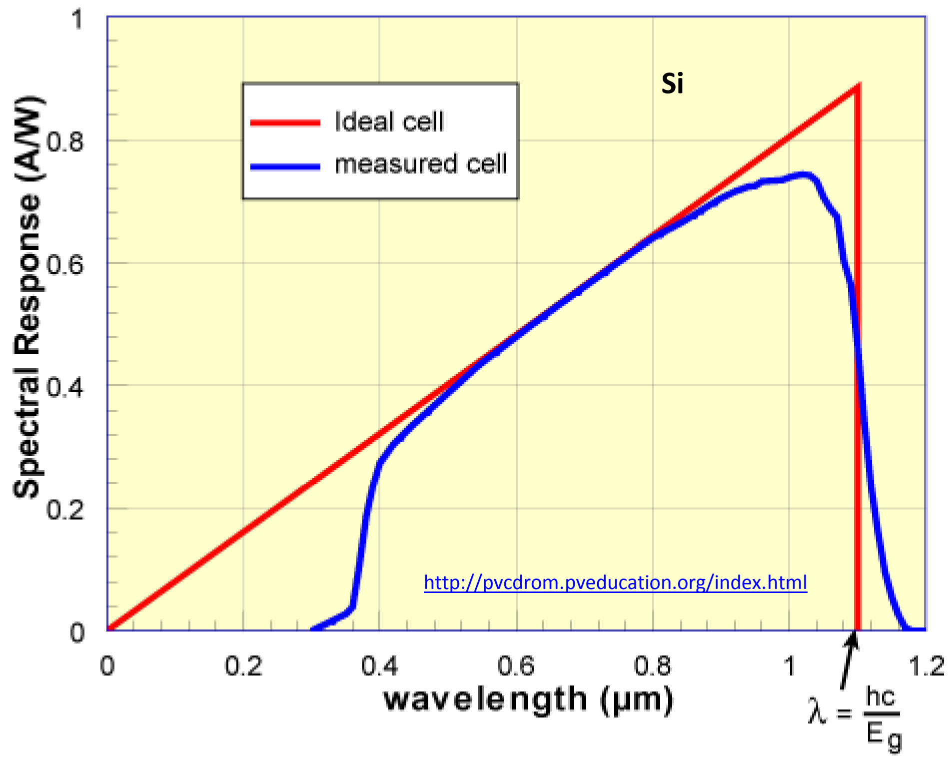
http://www.pvresources.com/en/technologies.php

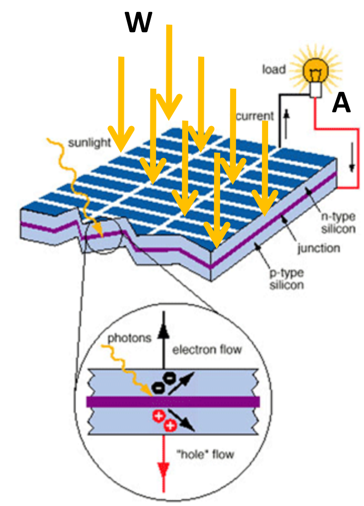
Solar cells respond differently to the different wavelengths of light. For example, **crystalline silicon (Si)** can use the entire visible spectrum, plus some part of the infrared spectrum. But energy in part of the infrared spectrum, as well as longer-wavelength radiation, is too low to produce current flow. Higher-energy radiation can produce current flow, but much of this energy is not usable. In summary, light that is too high or low in energy is not usable by a cell to produce electricity. It is transformed into heat.

http://www1.eere.energy.gov/solar/pv_cell_light.html

3.1.1.1a Radiant energy

The spectral response is the ratio of the **current** generated (A) by the solar cell to the **power** (W) incident on the solar cell.





http://www.deltaenergys.com/pvinfo.html

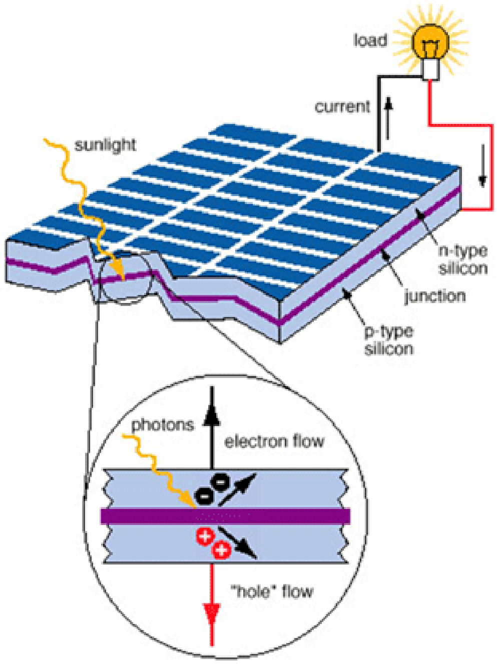
The spectral response of a silicon solar cell under glass. At short wavelengths below 400 nm the glass absorbs most of the light and the cell response is very low. At intermediate wavelengths the cell approaches the ideal. At long wavelengths the response fall back to zero.

Note: Silicon is an indirect band gap semiconductor so there is not a sharp cut off at the wavelength corresponding to the band gap (E_g = 1.12 eV).

3.1.1.1b Solar Cell Operation

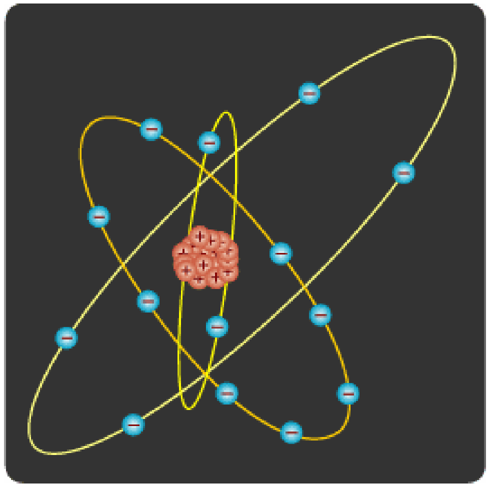
•About 80-90% of solar cells are made of **crystalline Silicon**
•These are the first generation type of solar cells.
•There are other types: Gen 2 and Gen 3 that will be mentioned briefly.

Simplified schematic of solar cell operation.

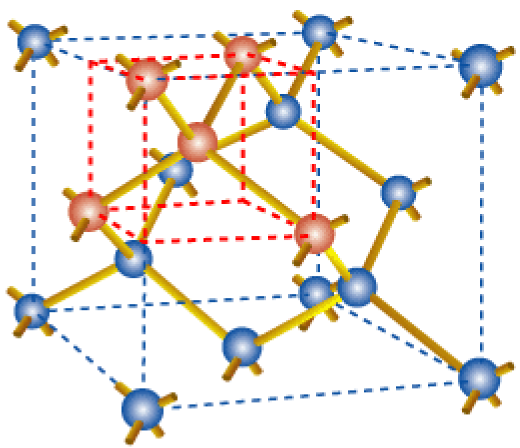


http://www.deltaenergys.com/pvinfo.html

3.1.1.1b Solar Cell Operation



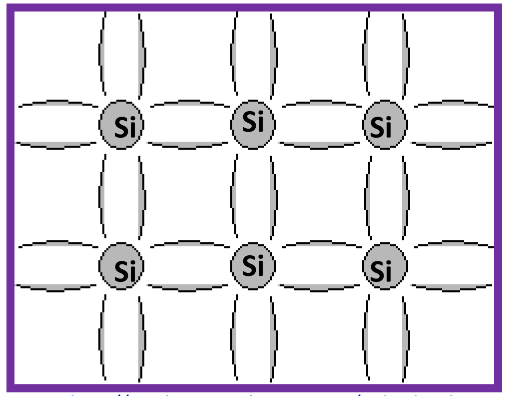
- All matter is composed of atoms, which are made up of positively charged protons, negatively charged electrons, and neutral neutrons.
- As depicted in this simplified diagram, silicon has 14 electrons.
- The four electrons that orbit the nucleus in the outermost "valence" energy level are given to, accepted from, or shared with other atoms.



http://www1.eere.energy.gov/solar/atomic_description.html

- Large numbers of silicon atoms bond with each other by means of their valence electrons to form a crystal.
- In a crystalline solid, each silicon atom normally shares one of its four valence electrons in a covalent bond with each of four neighboring silicon atoms.
- The solid thus consists of basic units of five silicon atoms: the original atom plus the four other atoms with which it shares valence electrons.

3.1.1.1b Solar Cell Operation

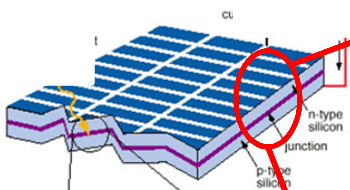


http://pvcdrom.pveducation.org/index.html

Schematic of covalent bonds in a Silicon crystal lattice

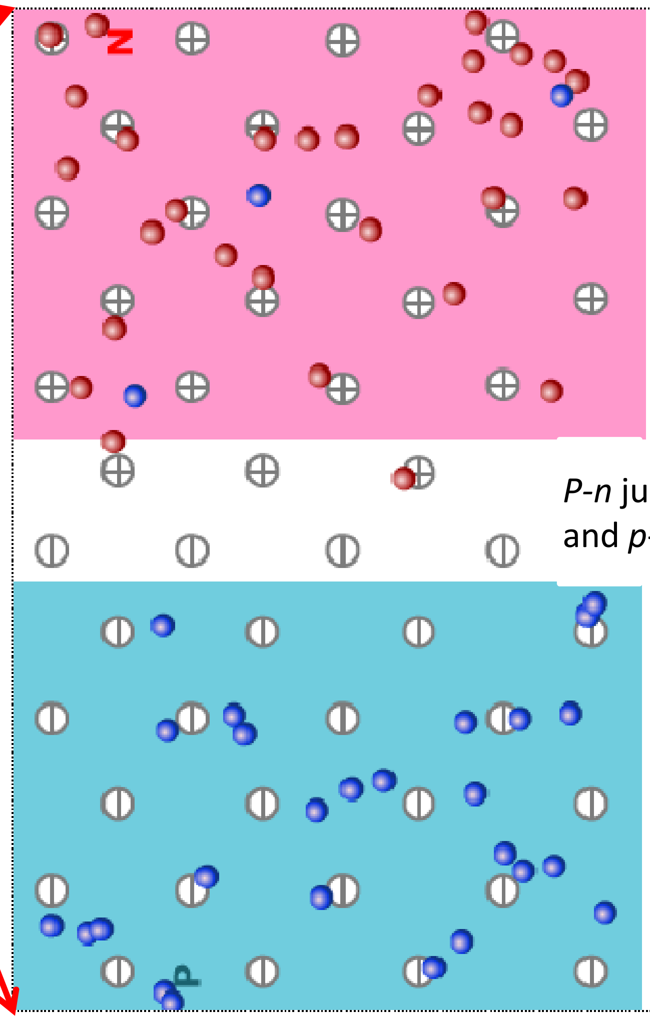
- Solar Cells are made of semi-conductor material, meaning that the material doesn't have the conductivity of metals but it is also not insulating material .
- The atomic characteristics are such that electrons "straddle" between the conductor and insulator states.
- External energy is needed to move the electrons into a conductive state.
- In the case of solar cells, this external energy is provided by ***Photons*** from sunlight.
- When the electron gets "knocked" into the conductive state (or free state), it leaves a space in the covalent bond which could be thought of as a hole.
- Many free electrons are what create electric currents when connected to a load.
- Electrons have negative charge **(-)**
- Holes have positive charge **(+)**

3.1.1.1b Solar Cell Operation



http://www.deltaenergys.com/pvinfo.html

P-N Junction



The *n*-type (negative) region has a high **electron** concentration..this is due to doping with electron donor elements.

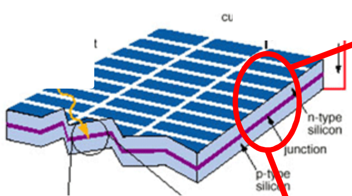
P-n junctions are formed by joining *n*-type and *p*-type semiconductor materials.

The *p*-type (positive) region has a high **hole** concentration…this is due to doping with electron acceptor elements.

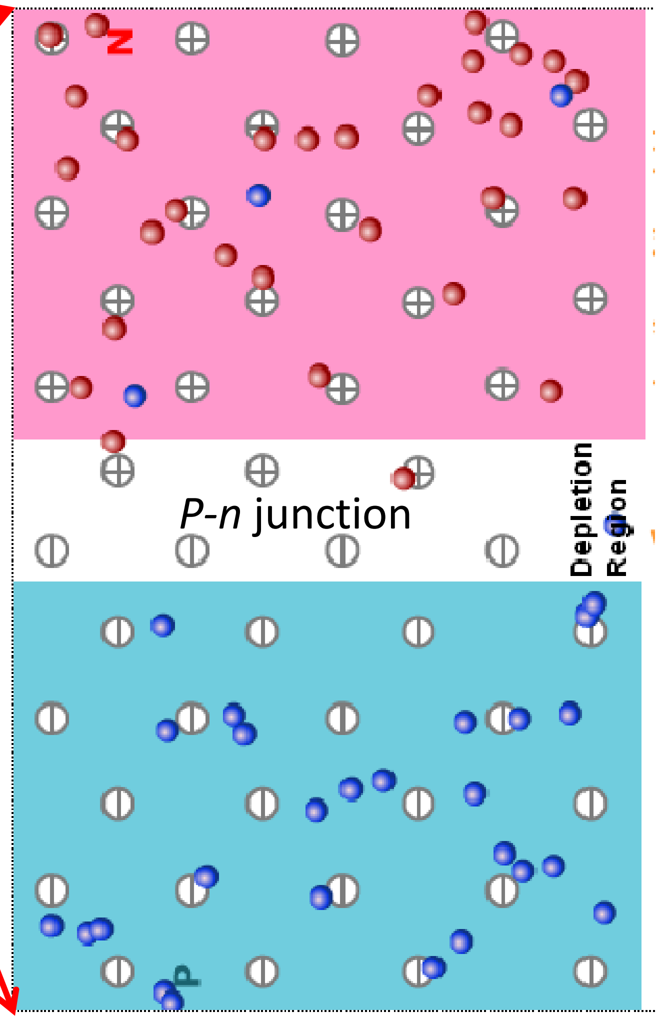
http://www.pveducation.org/pvcdrom/pn-junction/pn-junction-diodes

3.1.1.1b Solar Cell Operation

P-N Junction



http://www.deltaenergys.com/pvinfo.html



On the *n*-type side, positive ion cores are exposed

electrons diffuse from the *n*-type side to the *p*-type side

An electric field Ê forms between the positive ion cores in the *n*-type material and negative ion cores in the *p*-type material.

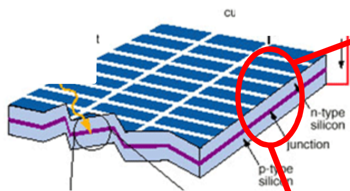
holes flow by diffusion from the *p*-type side to the *n*-type side

On the *p*-type side, negative ion cores are exposed

in a *p-n* junction, when the electrons and holes move to the other side of the junction, they leave behind exposed charges on dopant atom sites, which are fixed in the crystal lattice and are unable to move

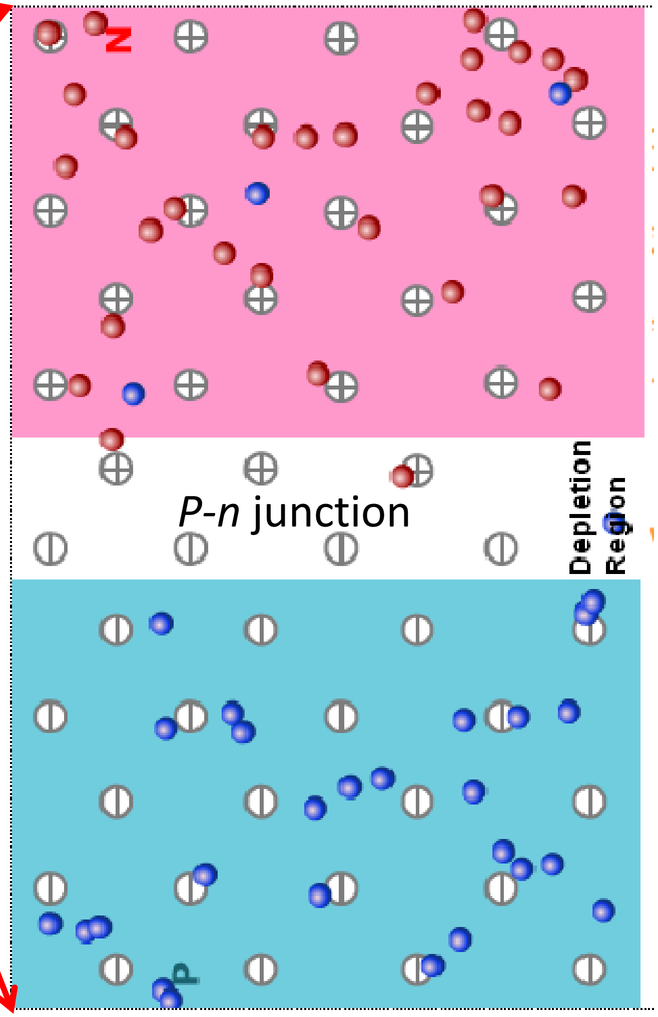
http://www.pveducation.org/pvcdrom/pn-junction/pn-junction-diodes

3.1.1.1b Solar Cell Operation



http://www.deltaenergys.com/pvinfo.html

P-N Junction



On the *n*-type side, positive ion cores are exposed

electrons diffuse from the *n*-type side to the *p*-type side

A "built in" potential V_{bi} due to $\hat{E}$ is formed at the junction

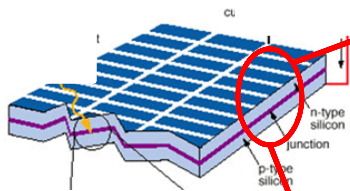
holes flow by diffusion from the *p*-type side to the *n*-type side

On the *p*-type side, negative ion cores are exposed

In equilibrium, the net current from the device is zero.

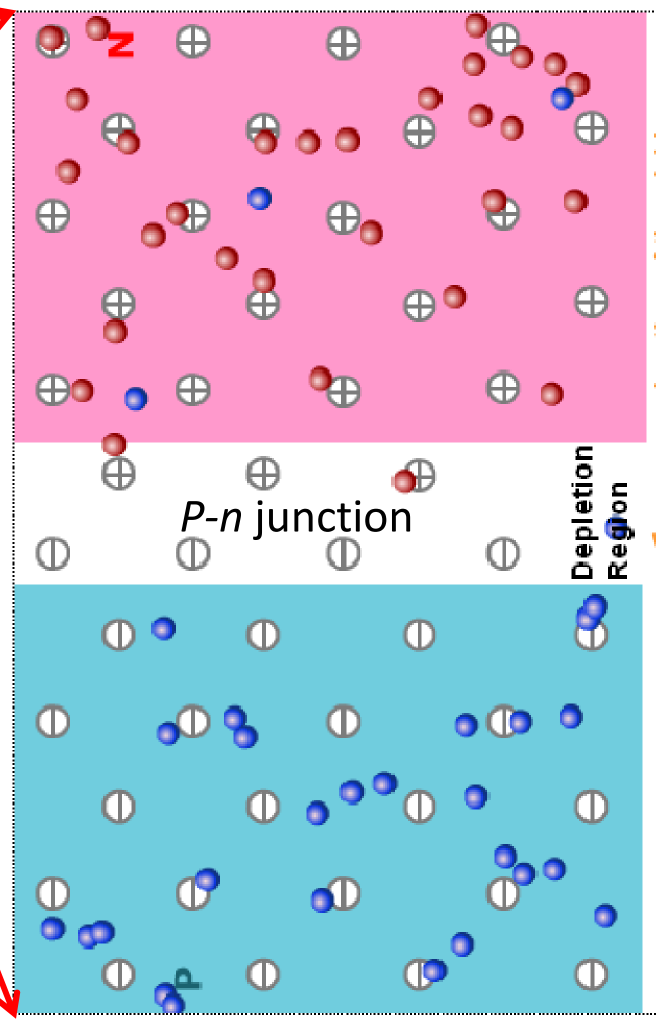
http://www.pveducation.org/pvcdrom/pn-junction/pn-junction-diodes

3.1.1.1b Solar Cell Operation



http://www.deltaenergys.com/pvinfo.html

P-N Junction



In equilibrium, the net current from the device is zero.

Zero voltage with no light.

Electrons in the *n*-type region "want" to continue to recombine with the holes in the *p*-type region. (-)(+)

But, the electric field in the depletion region prevents recombination.

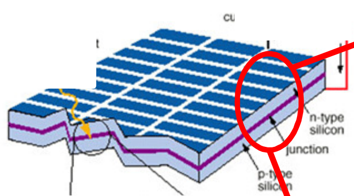
However, there are still some electrons or holes that go across the depletion region through diffusion or drift.

The electron drift and diffusion current exactly balance out (if they did not there would be a net buildup of electrons on either one side or the other of the device).

Similarly, the hole drift and diffusion current also balance each other out.

http://www.pveducation.org/pvcdrom/pn-junction/pn-junction-diodes

3.1.1.1b Solar Cell Operation

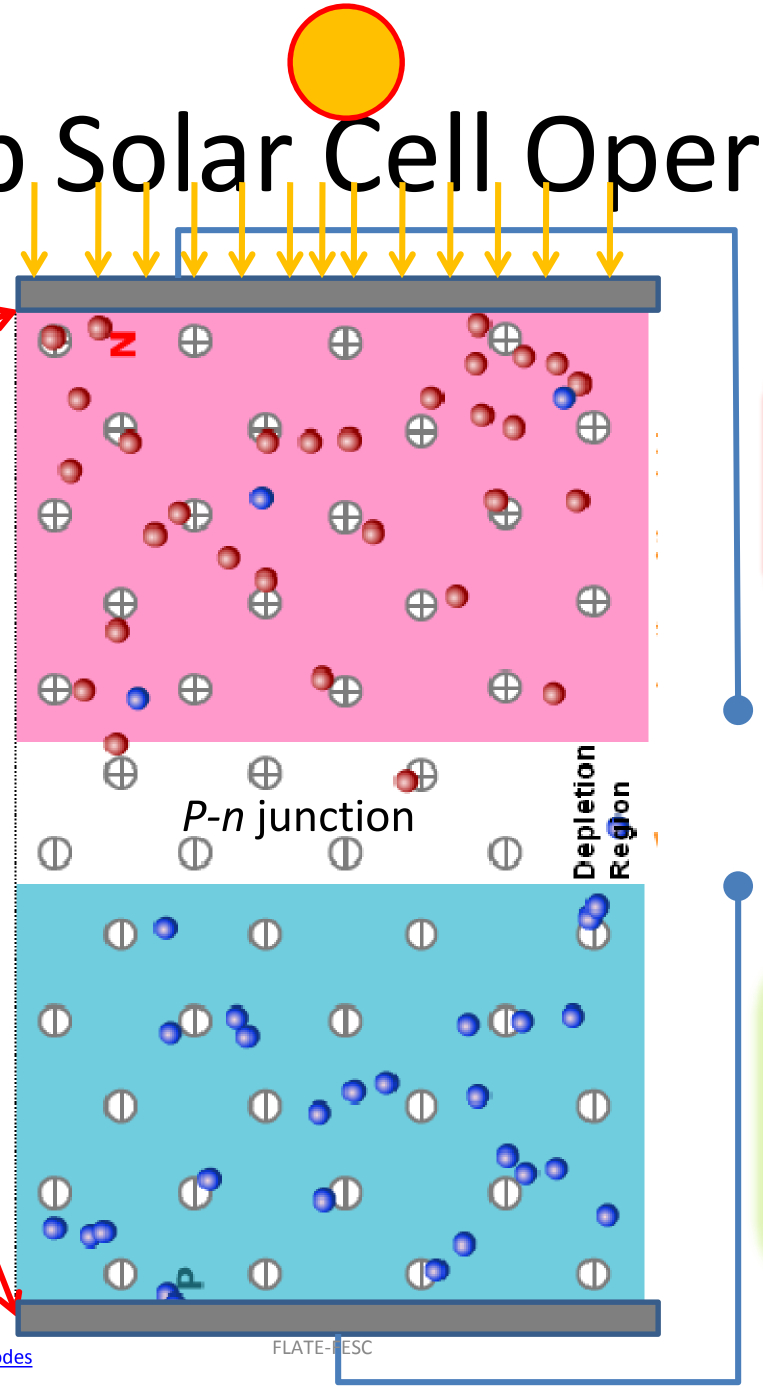


http://www.deltaenergys.com/pvinfo.html

The Photovoltaic Effect

Light generates extra carriers.

The collection of light-generated carriers does not by itself give rise to power generation. In order to generate power, a voltage must be generated as well as a current.

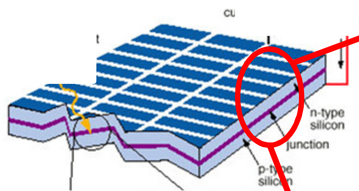


1. As we learned before, when photons from sunlight hit the solar cell, valence electrons are "knocked" free to become conductive.

2. The collection of light-generated carriers causes an increase in the number of electrons on the *n*-type side of the *p-n* junction and a similar increase in holes in the *p*-type material

http://www.pveducation.org/pvcdrom/pn-junction/pn-junction-diodes

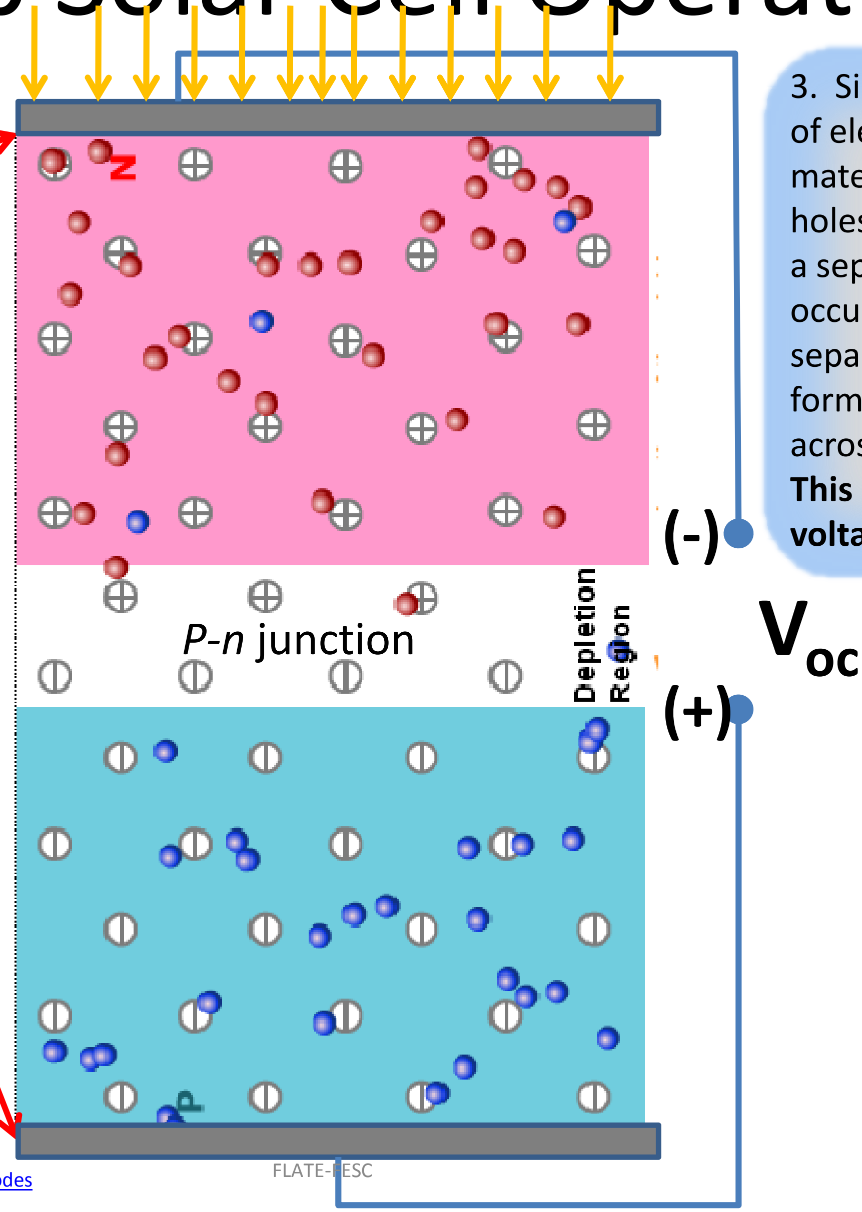
3.1.1.1b Solar Cell Operation



http://www.deltaenergys.com/pvinfo.html

The Photovoltaic Effect

Light generates extra carriers.

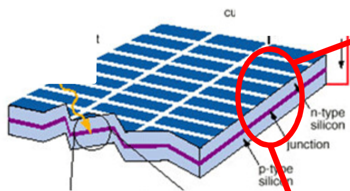


3. Since there is an excess of electrons in the n-type material and an excess of holes in the p-type material a separation of charges occurs. That charge separation leads to the formation of a voltage across the *P-n* junction. **This is the open circuit voltage: V_{oc}**

This is DC voltage!!

http://www.pveducation.org/pvcdrom/pn-junction/pn-junction-diodes

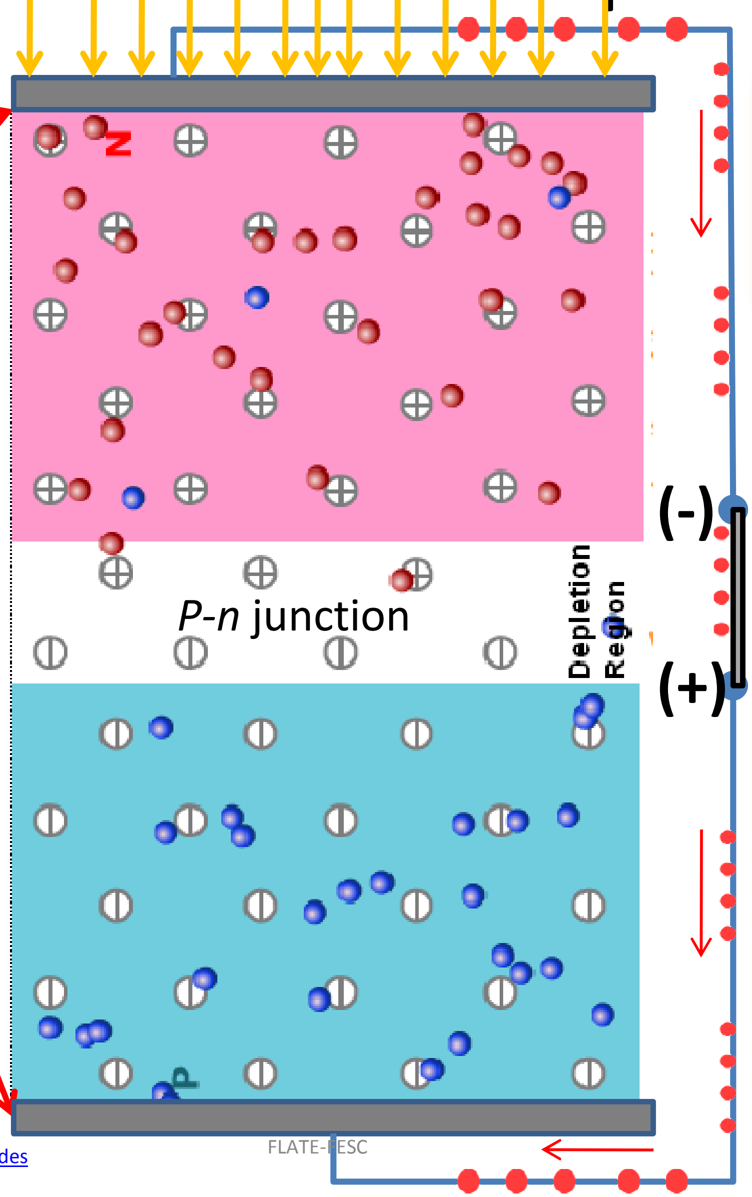
3.1.1.1b Solar Cell Operation



http://www.deltaenergys.com/pvinfo.html

The Photovoltaic Effect

Light generates extra carriers.



I_{sc}

4. When the terminals are connected, a current flows proportional to the light intensity. **This is the short-circuit current: I_{sc}**

- Voltage is Zero
- This is also maximum current from solar cell.

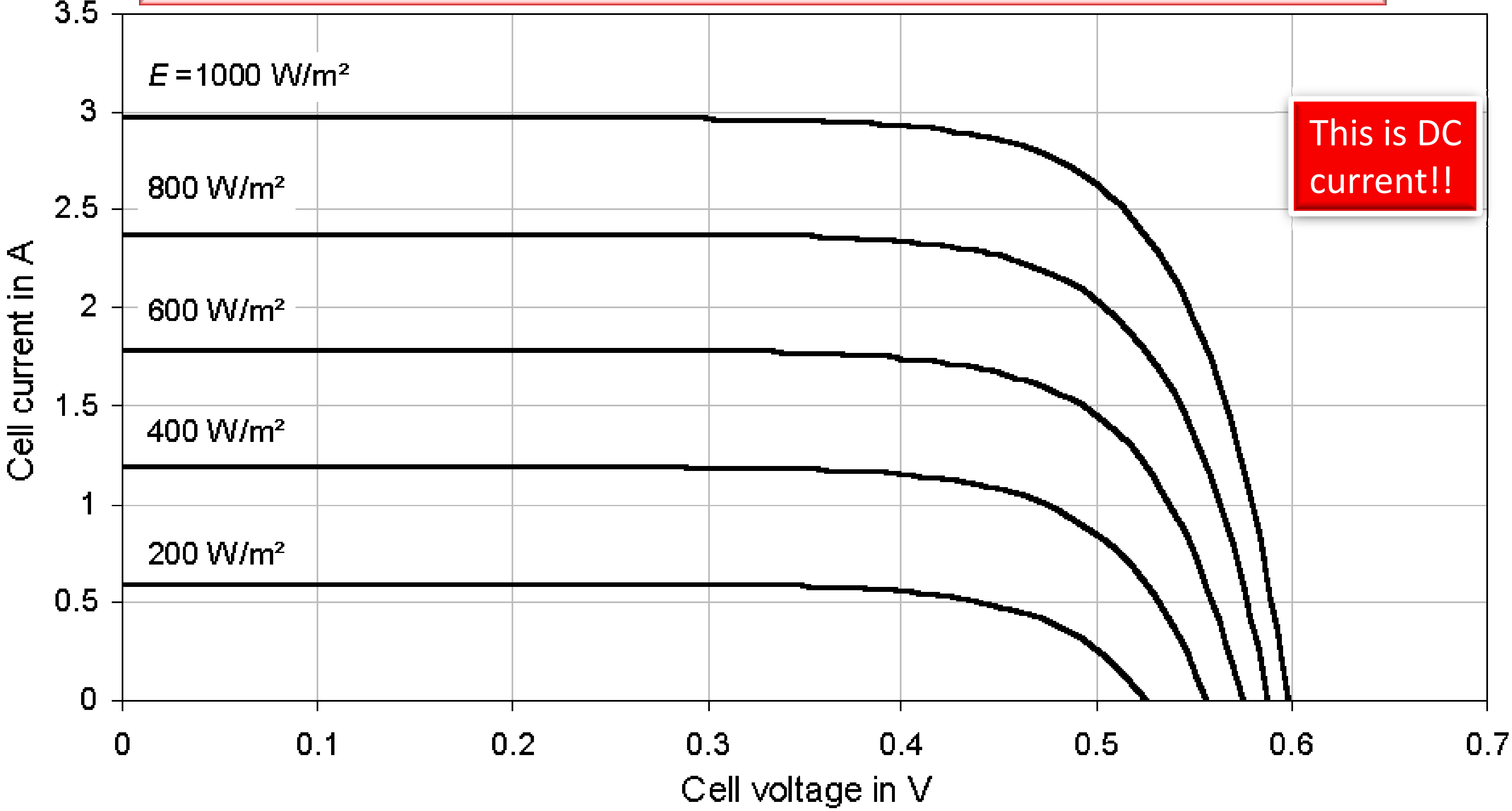
This is DC current!!

Electrons recombine with holes to complete the circuit.

http://www.pveducation.org/pvcdrom/pn-junction/pn-junction-diodes

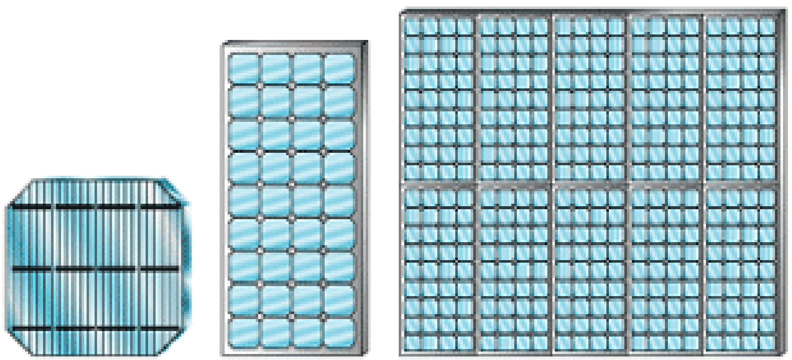
3.1.1.1b Solar Cell Operation

Influence of irradiance on the I-V Characteristics of a Solar Cell at T=25ºC



Volker Quaschning - Understanding Renewable Energy Systems - Earthscan, London, 2005

3.1.1.1b Solar Cell Operation

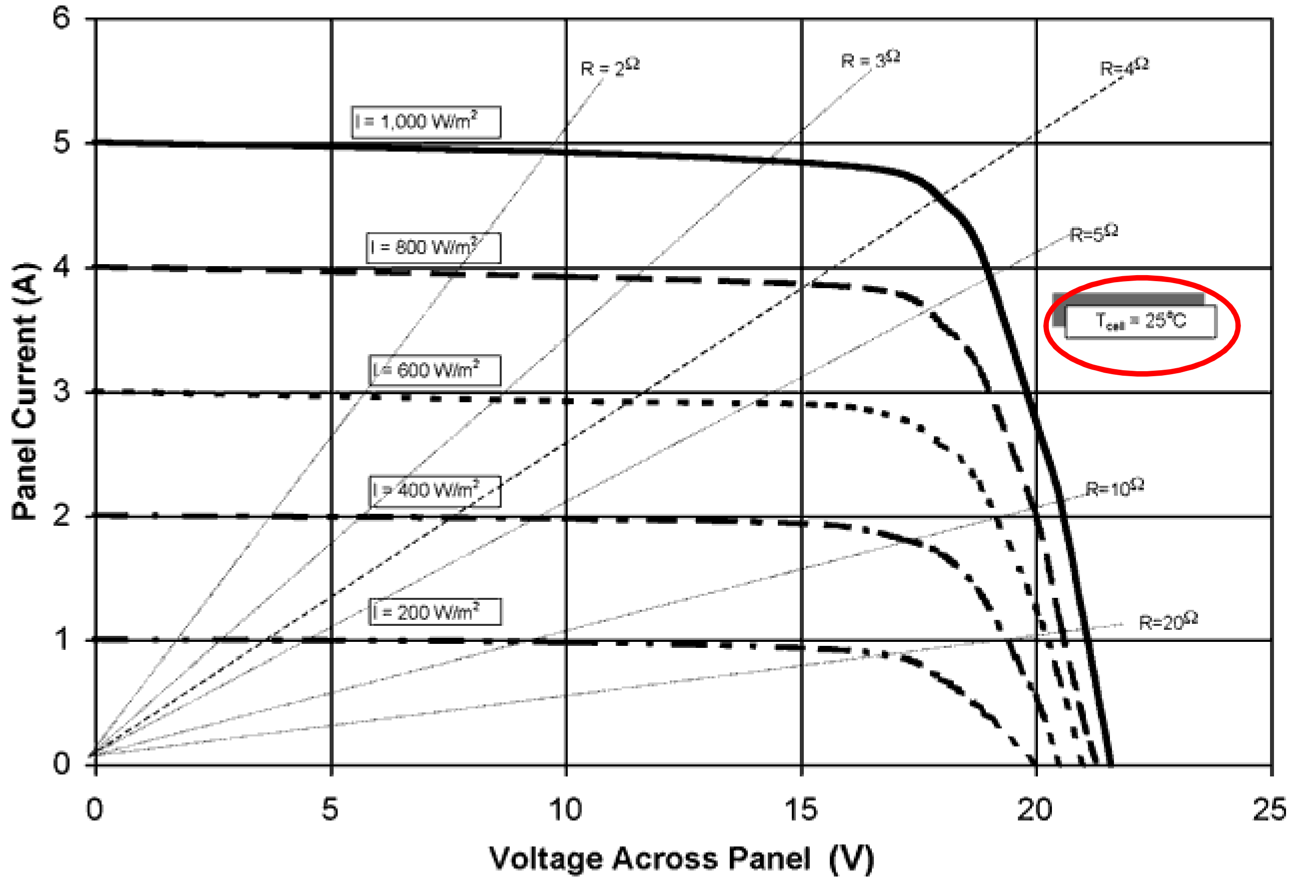


http://www.solar-electric.com/solar_photo_gallery.htm

The basic photovoltaic or solar cell typically produces only a small amount of power. To produce more power, cells can be interconnected to form modules (also called panels), which can in turn be connected into arrays to produce yet more power. Because of this modularity, PV systems can be designed to meet any electrical requirement, no matter how large or how small.

http://www1.eere.energy.gov/solar/atomic_description.html

3.1.1.1b Solar Cell Operation



This is DC current!!

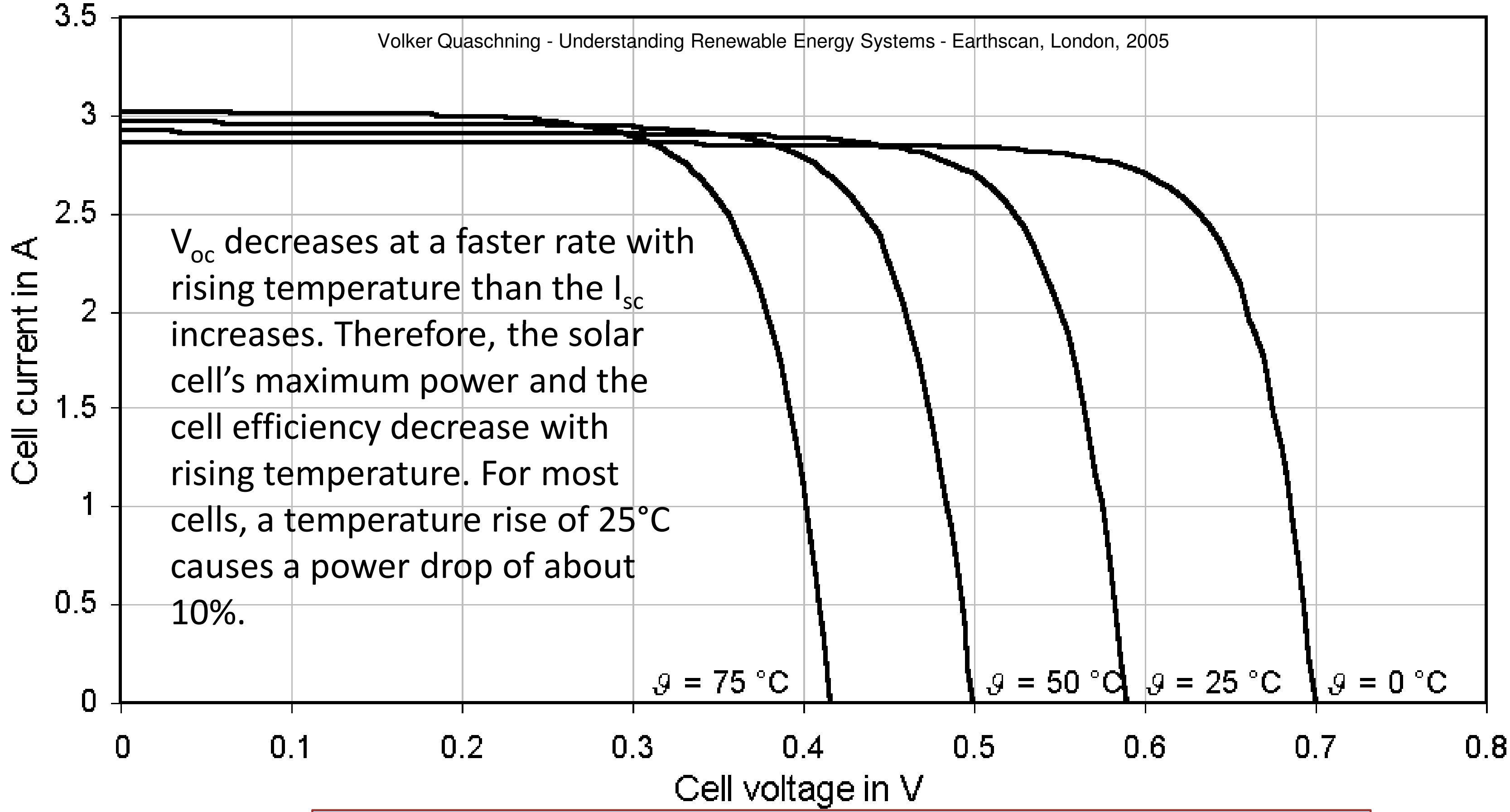
Don't pay attention to the resistance lines.

A single silicon photovoltaic cell produces an open-circuit voltage of slightly over 0.55 volts. The voltage produced by a photovoltaic panel is a function of how many cells are connected in series. In the case of the panel described above, there must be about 36 photovoltaic cells connected in series in order to produce over 20 volts.

http://www.powerfromthesun.net/chapter5/Chapter5Word.htm

3.1.1.1b Solar Cell Operation

Influence of Temperature on the I-V Characteristics of a Solar Cell

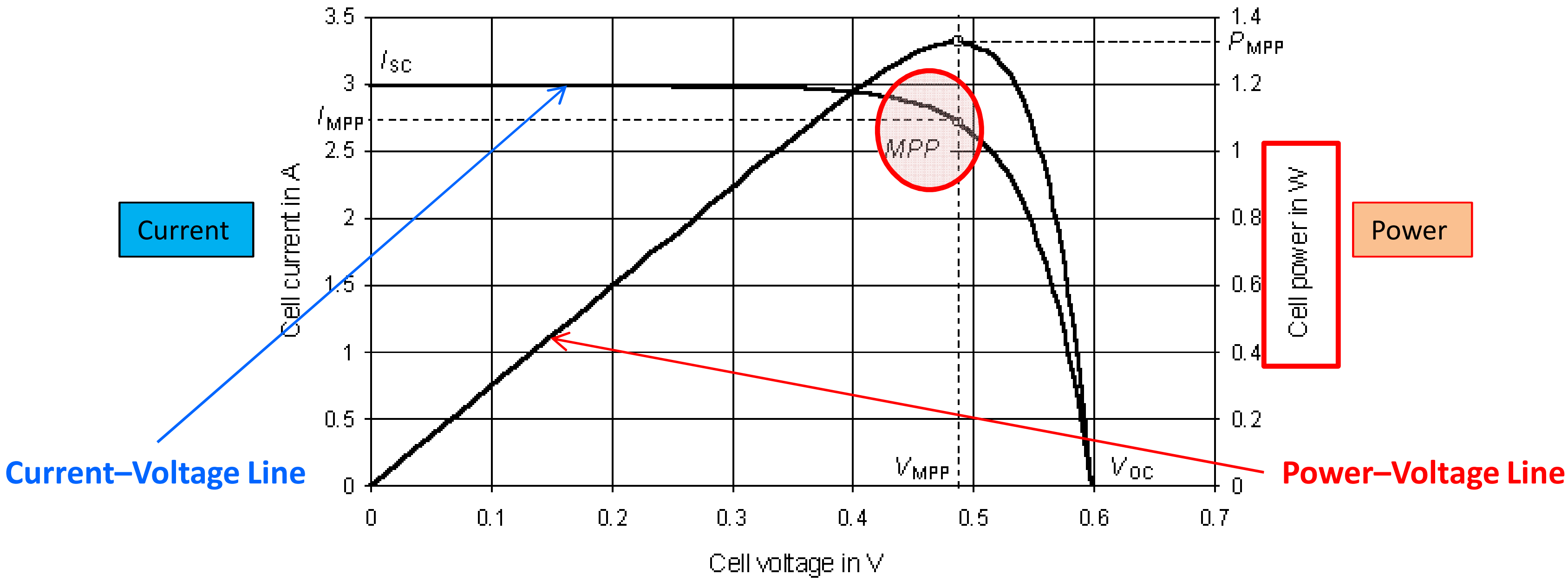


V_{oc} decreases at a faster rate with rising temperature than the I_{sc} increases. Therefore, the solar cell's maximum power and the cell efficiency decrease with rising temperature. For most cells, a temperature rise of 25°C causes a power drop of about 10%.

Unfortunately, the higher the temperature of the cell, the lower the voltage output. Cold, Sunny days are the best.

3.1.1.1b Solar Cell Operation

The solar cell generates its maximum power at a certain voltage



- ❑This graph shows the **current–voltage** and **power–voltage** characteristics.
- ❑It shows clearly that the power curve has a point of maximum power called the 'maximum power point', MPP.
  - •The maximum power point voltage, V_{MPP}, is less than V_{oc}
  - •The current I_{MPP} is lower than I_{sc}.
  - •At the MPP, current and voltage have nearly the same relation to irradiance and temperature as the short circuit current and open circuit voltage.

Volker Quaschning - Understanding Renewable Energy Systems - Earthscan, London, 2005

3.1.1.1b Solar Cell Operation

The solar cell generates its maximum power at a certain voltage

- To make solar cells and modules comparable, MPP power is measured under standard test conditions (STC):
  - Irradiance at 1000 W/m2 : Temperature of 25°C: Air mass (AM) 1.5.
  - Power generated by the solar modules in real weather conditions is usually lower, hence STC power has the unit W_p (Watt peak). This is the rating you will typically see on commercial solar cells.
- In terms of dependence on irradiance, the current dominates the device's behavior, so that the MPP power is nearly proportional to the irradiance.
- Solar cell efficiency is the ratio of the maximum electrical solar cell power to the radiant power on the solar cell area.

$$\eta = P_{MPP}/E*A$$

where E=irradiance; A=solar cell area

  - Commercial crystalline solar cells now reach efficiencies up to almost 20%, but in the laboratory, efficiencies of more than 25% are possible.
  - Efficiencies of thin-film solar cells are lower.

Volker Quaschning - Understanding Renewable Energy Systems - Earthscan, London, 2005

3.1.1.1b Solar Cell Operation

The solar cell generates its maximum power at a certain voltage

- So we have seen that
  - P_{MPP} is nearly proportional to the irradiance, so that
  - Solar cell efficiency is the ratio of maximum power point power to irradiance.
- But,
  - Maximum power point voltage varies with irradiance and temperature. So that efficiency varies.
- One solution: **Maximum Power Point Tracker**

http://www.ee.uconn.edu/SeniorDesign/projects/ecesd129/

3.1.1.1b Solar Cell Operation

The solar cell generates its maximum power at a certain voltage

- Maximum Power Point Tracker
  - High efficiency DC to DC converter which operates by taking the DC input current, changing it to AC, running it through a transformer (usually a toroid, a doughnut looking transformer), and then rectifying it back to DC.
  - It tracks the instantaneous power by continually measuring the voltage and current through a microprocessor
  - Uses this information to dynamically adjust the load so the maximum power is *always* transferred, regardless of the variation in temperature and irradiance.
  - The microprocessor tries to maximize the watts delivered to the load from the solar panel by controlling the step down ratio to keep the solar panel operating at its Maximum Power Point.
  - A load that may represent an end-user, or an energy storage element, or a power grid-interface.

Outback Power FLEXmax 80 MPPT Solar Charge Controller

Maximum Solar Array: 12 VDC systems 1250 Watts / 24 VDC systems 2500 Watts / 48 VDC systems 5000 Watts / 60 VDC Systems 7500 Watts

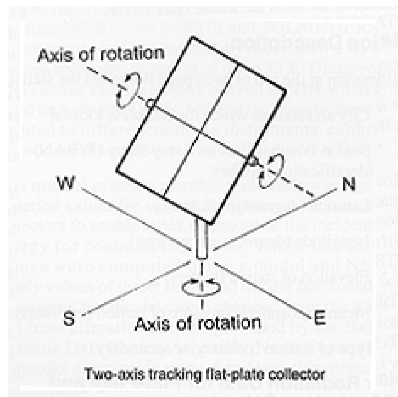
http://store.solar-electric.com/oufl80sochco.html

3.1.1.1b Solar Operation

Another way to maximize power is to maximize irradiance by having the panels (or arrays) track the sun. This is Panel/Array Tracking.

These are mainly used in commercial applications.

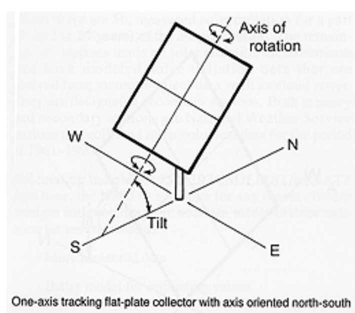
Azimuth-Altitude Dual Axis Tracker
- 2 axis solar tracker, Toledo, Spain
http://en.wikipedia.org/wiki/Solar_tracker

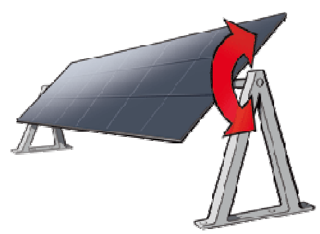


Horizontal Single Axis Trackers
http://en.wikipedia.org/wiki/Solar_tracker

Two Axis Tracker, Alamosa, CO
http://www.nrel.gov/data/pix/searchpix.php

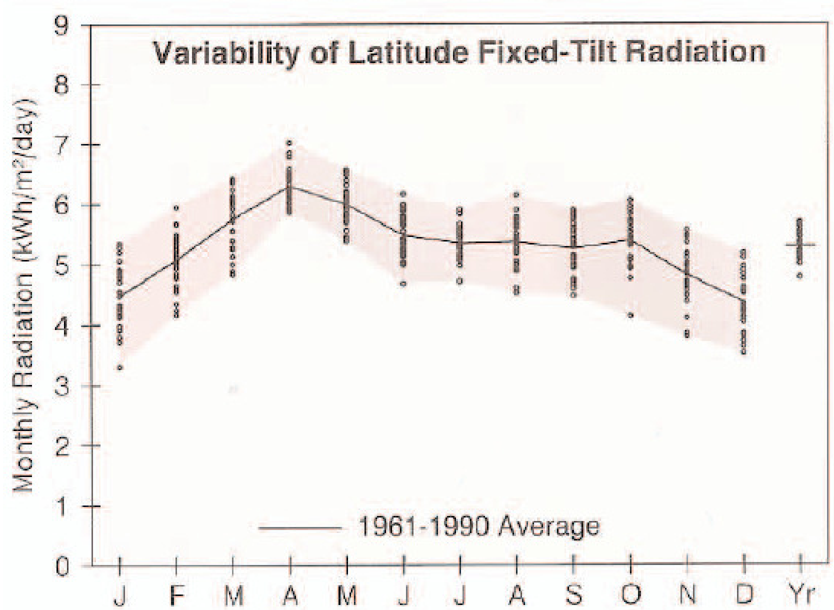
Single Axis Trackers





One Axis Tracker, Alamosa, CO
http://www.nrel.gov/data/pix/searchpix.php

3.1.1.1b Irradiation Data



Tampa, FL

WBAN NO. 12842

LATITUDE: 27.97° N
LONGITUDE: 82.53° W
ELEVATION: 3 meters
MEAN PRESSURE: 1018 millibars

STATION TYPE: Secondary

http://rredc.nrel.gov/solar/pubs/redbook/PDFs/FL.PDF

Solar Radiation for 1-Axis Tracking Flat-Plate Collectors with a North-South Axis (kWh/m²/day), Uncertainty ±9%

Axis Tilt (°)		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
0	Average	4.5	5.5	6.8	8.3	8.3	7.5	7.1	6.8	6.2	6.0	4.9	4.2	6.3
	Min/Max	3.3/5.4	4.3/6.6	5.5/7.9	7.5/9.4	7.1/9.4	6.0/8.8	6.0/8.1	5.6/8.1	5.2/7.2	4.4/6.8	3.9/5.8	3.3/5.2	5.6/6.9
Latitude -15	Average	5.0	5.9	7.2	8.4	8.2	7.4	7.1	6.9	6.5	6.4	5.4	4.8	6.6
	Min/Max	3.5/6.0	4.6/7.1	5.8/8.3	7.7/9.6	7.1/9.3	5.9/8.7	6.0/8.0	5.7/8.2	5.3/7.5	4.7/7.3	4.2/6.4	3.7/5.8	5.8/7.2
Latitude	Average	5.4	6.3	7.3	8.4	8.0	7.1	6.8	6.8	6.5	6.7	5.9	5.2	6.7
	Min/Max	3.8/6.6	4.9/7.6	5.9/8.5	7.6/9.6	6.9/9.1	5.7/8.4	5.7/7.7	5.6/8.0	5.3/7.6	4.8/7.7	4.5/6.9	4.0/6.4	5.9/7.3
Latitude +15	Average	5.6	6.4	7.3	8.1	7.5	6.6	6.3	6.4	6.4	6.8	6.1	5.5	6.6
	Min/Max	3.9/7.0	4.9/7.8	5.8/8.5	7.3/9.2	6.4/8.5	5.3/7.8	5.3/7.2	5.3/7.6	5.2/7.4	4.8/7.8	4.6/7.3	4.2/6.8	5.8/7.2

Solar Radiation for 2-Axis Tracking Flat-Plate Collectors (kWh/m²/day), Uncertainty ±9%

Tracker		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
2-Axis	Average	5.7	6.4	7.4	8.5	8.3	7.6	7.2	6.9	6.5	6.8	6.1	5.6	6.9
	Min/Max	3.9/7.1	5.0/7.8	5.9/8.5	7.7/9.7	7.2/9.4	6.0/8.9	6.0/8.1	5.7/8.2	5.4/7.6	4.9/7.8	4.6/7.3	4.3/7.0	6.1/7.6

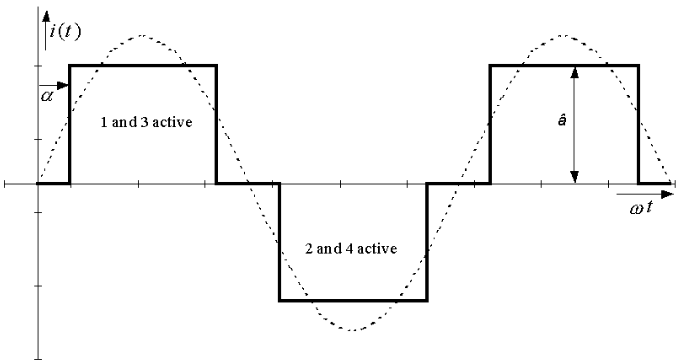
3.1.1.1b Solar Cell Operation

- We have seen that solar cells generate DC current/voltage.
- But, most commercial appliances use AC current/voltage.
- Inverters must be used.
- Most have MPP tracking capability.

http://www.aegps.com/en/products/SolarInverters

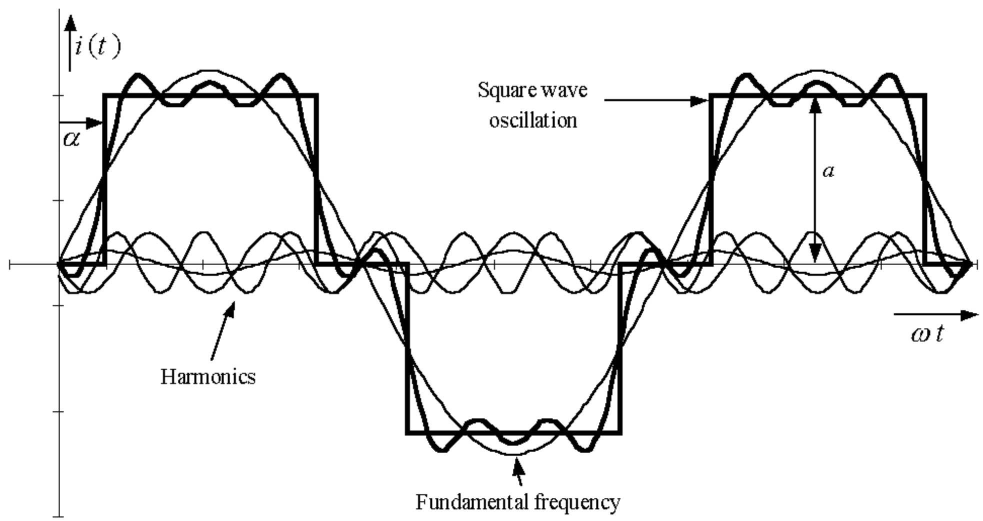
MODEL	Protect PV 25	Protect PV 33
DC INPUT		
Nominal DC voltage	640 VDC	640 VDC
Max. PV open voltage	800 VDC	800 VDC
MPPT-range	300–800 VDC	300–800 VDC
Working range	200–800 VDC	200–800 VDC
Number of MPP Tracker	6	9
Input current	13 A/MPPT	13 A/MPPT
AC OUTPUT		
Output power	25000 W	33000 W
Operational voltage	400 V x3, –15 % +10 %	400 V x3, –15 % +10 %
Operational Frequency	50 Hz	50 Hz
Current distortion	< 3 %	< 3 %
Power Factor (cos φ)	~ 1	~ 1

3.1.1.1b Solar Cell Operation



Mimics AC current by using square waves.

A reasonable AC current is obtained through superposition of square waves, but it is not perfect.



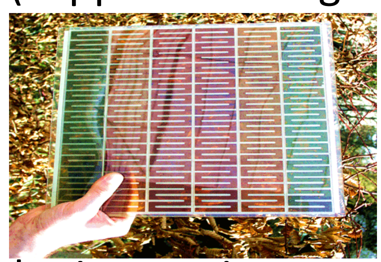
DC to AC Inverters modify DC signals, which are constant, to AC signals, which as we have seen vary in a sinusoidal pattern.

Volker Quaschning - Understanding Renewable Energy Systems - Earthscan, London, 2005

3.1.1.1c Types of Solar Cells

- **First Generation**
  - Single crystal; multicrisytalline Silicon
  - These solar cells, using silicon wafers, account for 86% of the solar cell market.
  - High efficiency, long life
  - But, high material and manufacturing costs
  - Fragile and Rigid
- **Second Generation**
  - Thin-film solar cells, are significantly cheaper to produce than first generation cells but have lower efficiencies
  - Amorphous Si, CdTe, CIGS (copper indium gallium selenide)
  - Flexible

- **Third Generation**
  - Still in research phase
  - Do not need P-n junction
  - Wide range of potential solar innovations
    - Organic and dye sensitized (Grätzel cells)
    - Polymer solar cells
    - Nanocrystalline solar cells

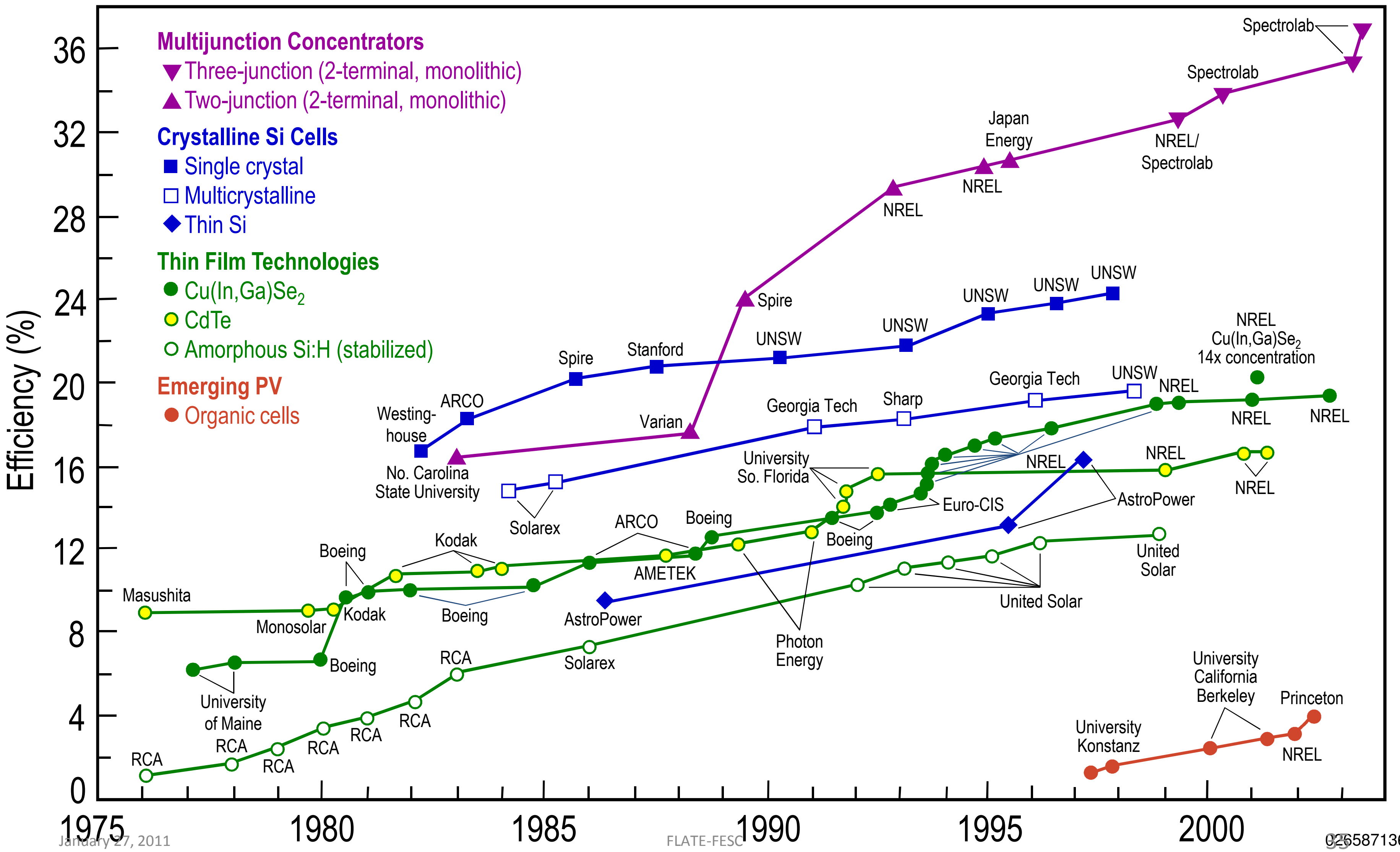


Light absorbing dye attached to nanoscale titania.

3.1.1.1c Types of Solar Cells

AS OF 5/27/10

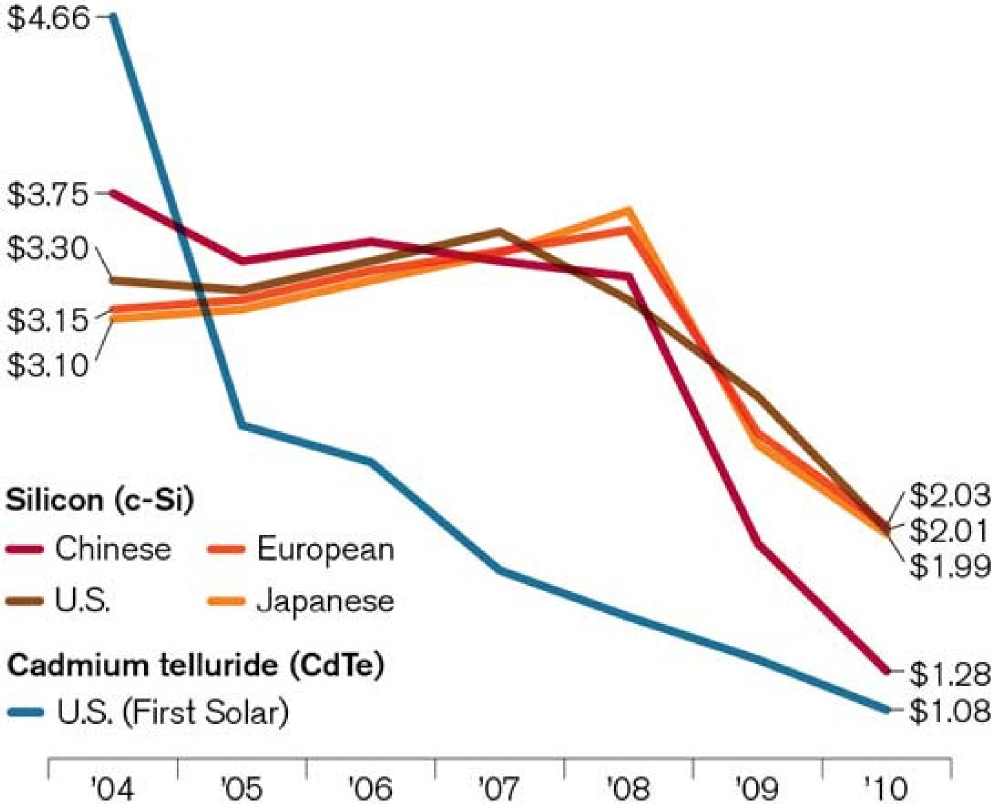
Best Research-Cell Efficiencies



3.1.1.1 Photovoltaic Cost Trends

Cost per watt*

Source: Bullis, Kevin, *Technology Review*, Vol. 113, Solar's Great Leap Forward No. 4, July/August 2010.



Source: Photon Consulting

**For the lowest-cost manufacturers in each country* Credit: Tommy McCall

Today the solar panels themselves account for less than half the total cost of the technology.

Additional costs are:

- Installation costs
- inverters
- sales and marketing by installers
- and financing.

3.1.1.1 Photovoltaics

a. Review of energy in light
b. Operation of solar cells
c. Types of solar cells

Excellent resource for further study online: http://www.pveducation.org/pvcdrom