Solar Energy Technologies

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Photovoltaic Solar panels

- Physics behind Photovoltaic systems
- I-V curve
- Effect of temperature
- System calculation
- MPPT: Maximum power point tracker
- Inverter
- Charge Controller
- Grid Connected Systems
- Standalone Systems
  - Battery Charging
  - Direct Connected Load

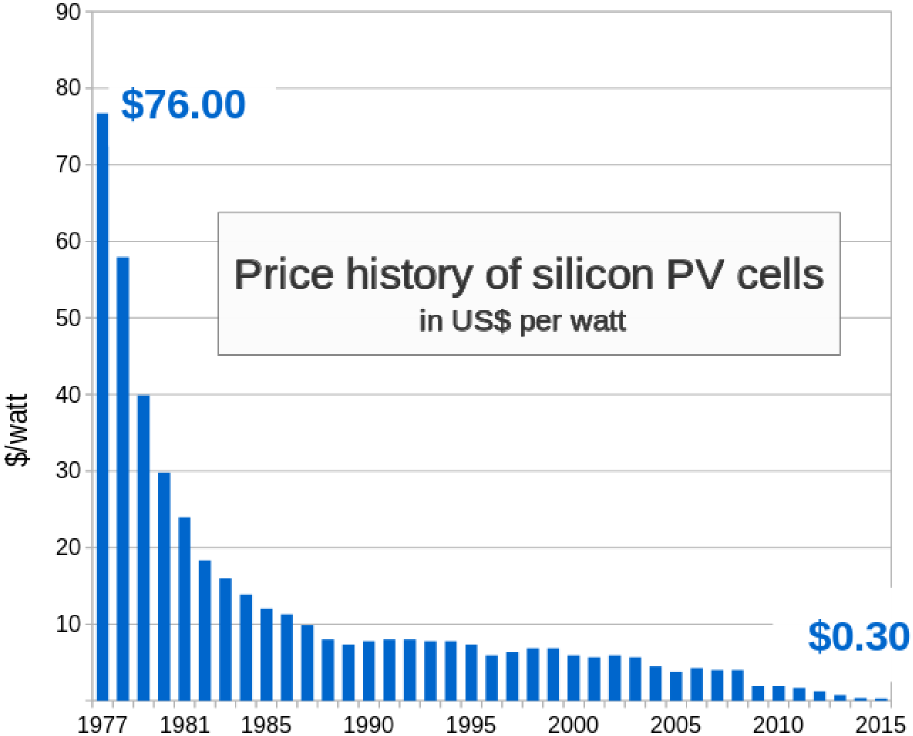
Photovoltaics (PV)

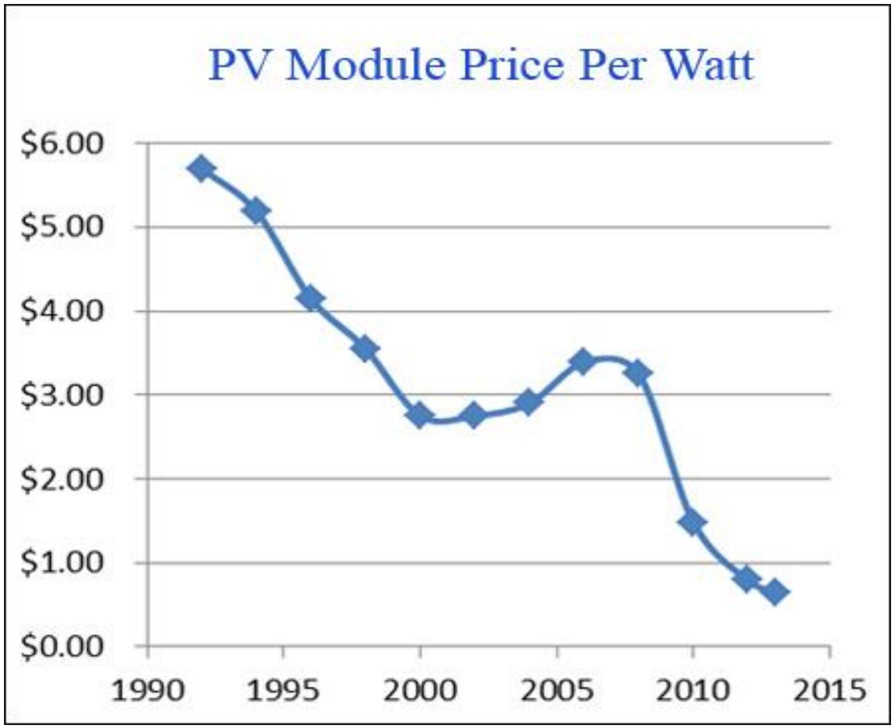
Photovoltaic panel: a device that is capable of converting the energy contained in photons of light into an electrical voltage and current.

"Sojourner exploring Mars, 1997

Rooftop PV modules on a village

PV History

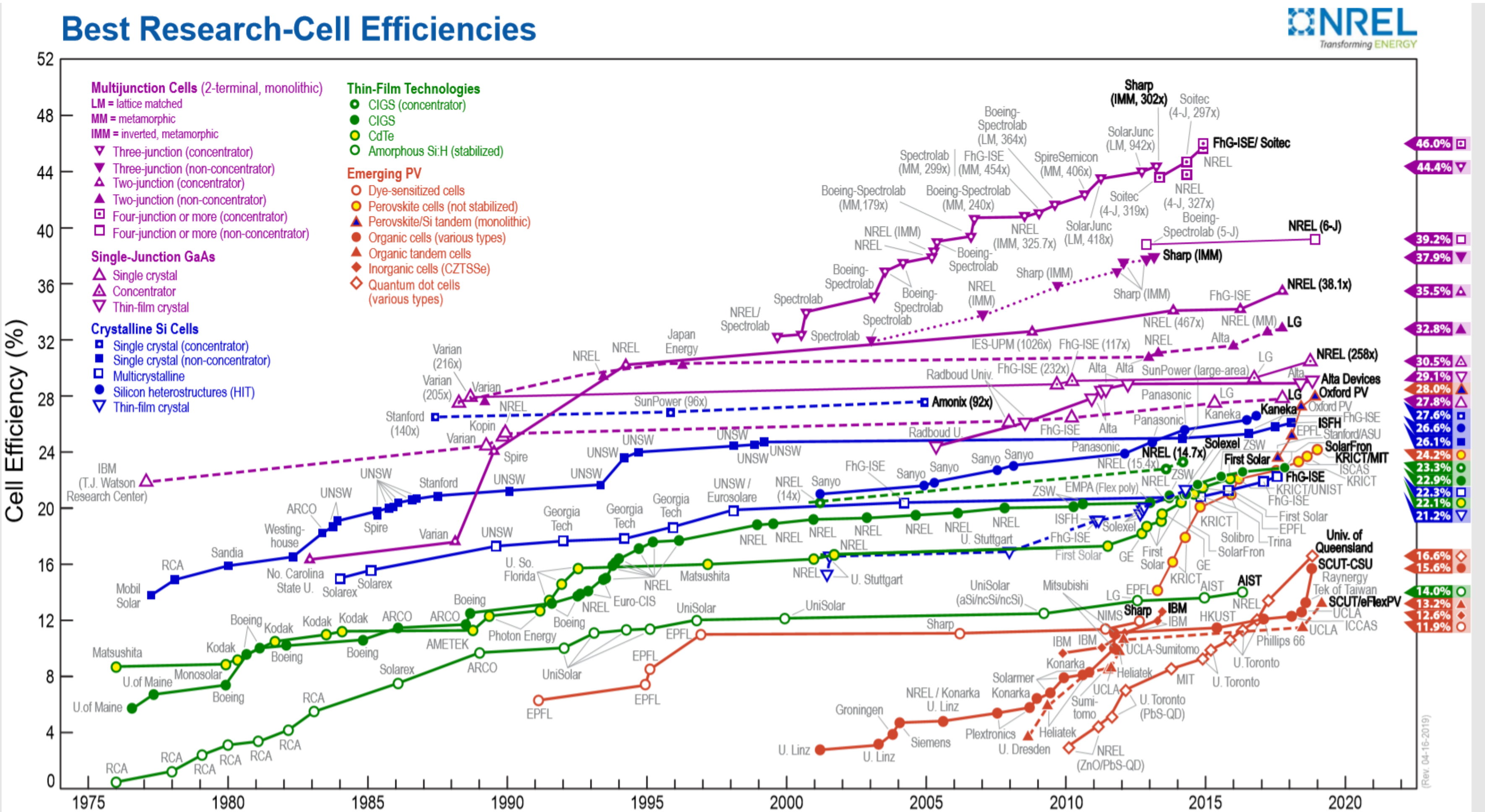




Source: Bloomberg New Energy Finance & pv.energytrend.com

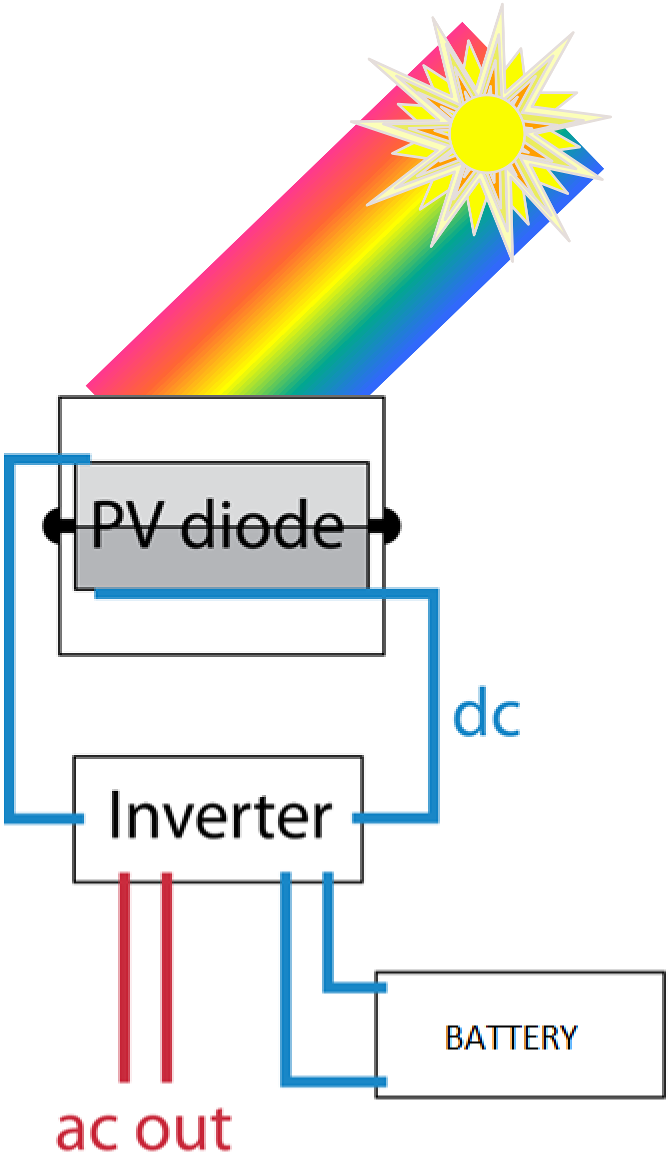
Solar cell and solar panel prices have decreased significantly in recent years!

Solar Efficiency



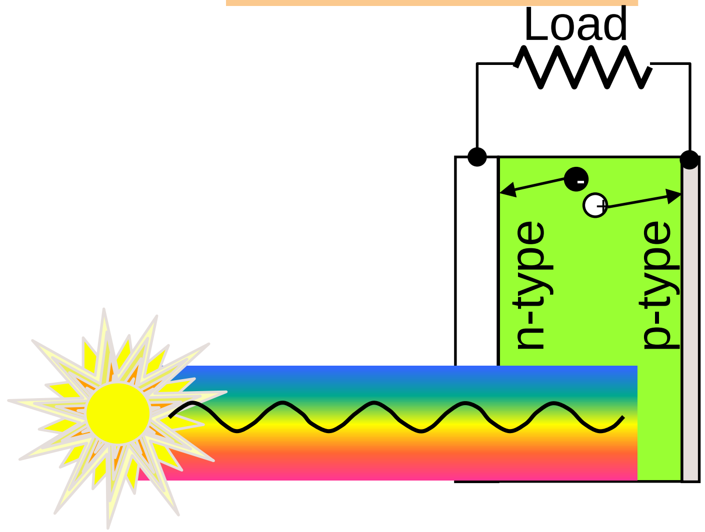
PV System Overview

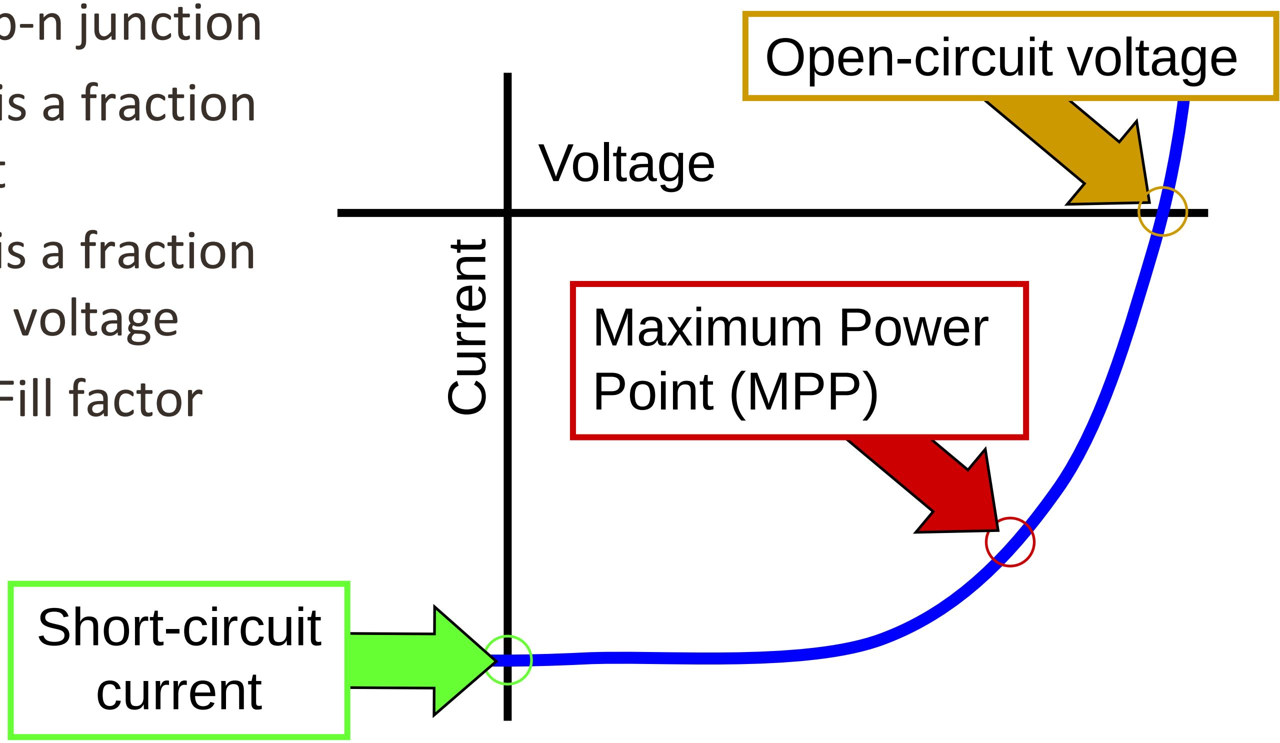
- Solar cell is a diode
- Light is coverted to DC current
- Shadows, environment & defects cause unpredictable energy generation
- Loads are unpredictable
- DC is converted to AC by an inverter
- Storage helps match generation to load



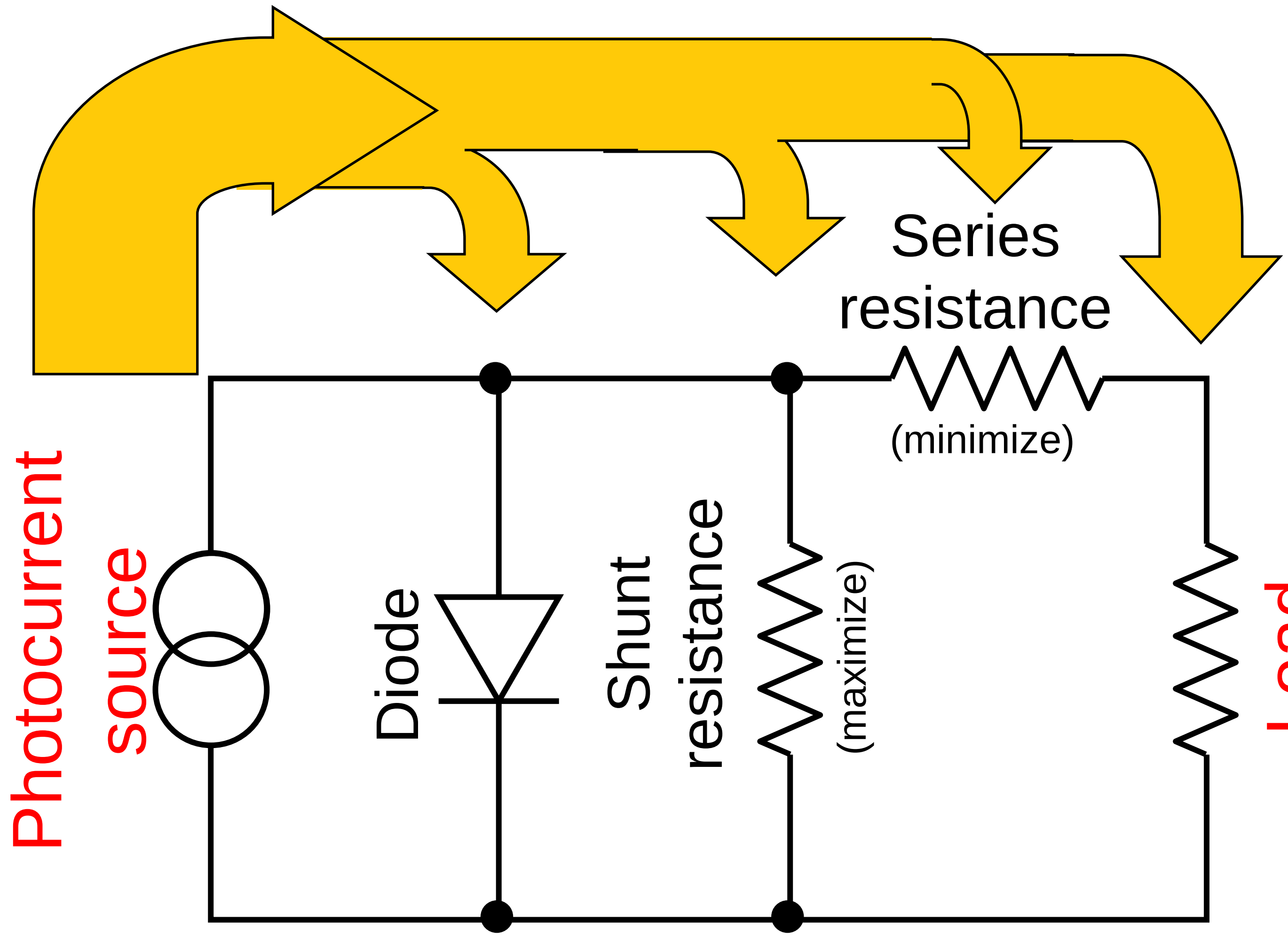
What is Solar Cell?

- Solar cells are diodes
- Light (photons) generate free carriers (electrons and holes) which are collected by the electric field of the p-n junction
- The output current is a fraction of this photocurrent
- The output voltage is a fraction of the diode built-in voltage
- Maximum power ~ Fill factor (~%80)





Standard Equivalent Circuit Model



Where does the power go?

Photons

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

$$c = \lambda v \qquad (8.1)$$

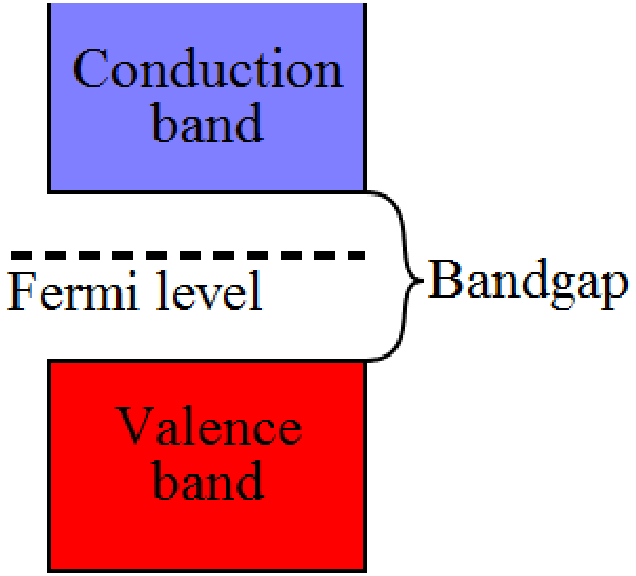
$$E = hv = \frac{hc}{\lambda} \qquad (8.2)$$

Band gap different materials and corresponding cut-off wavelength above which electron excitation doesn't occur

	Si	GaAs	CdTe	InP	Ge
Band gap (eV)	1.12	1.42	1.5	1.35	0.66
Cut-off wavelength (µm)	1.11	0.87	0.83	0.92	1.88

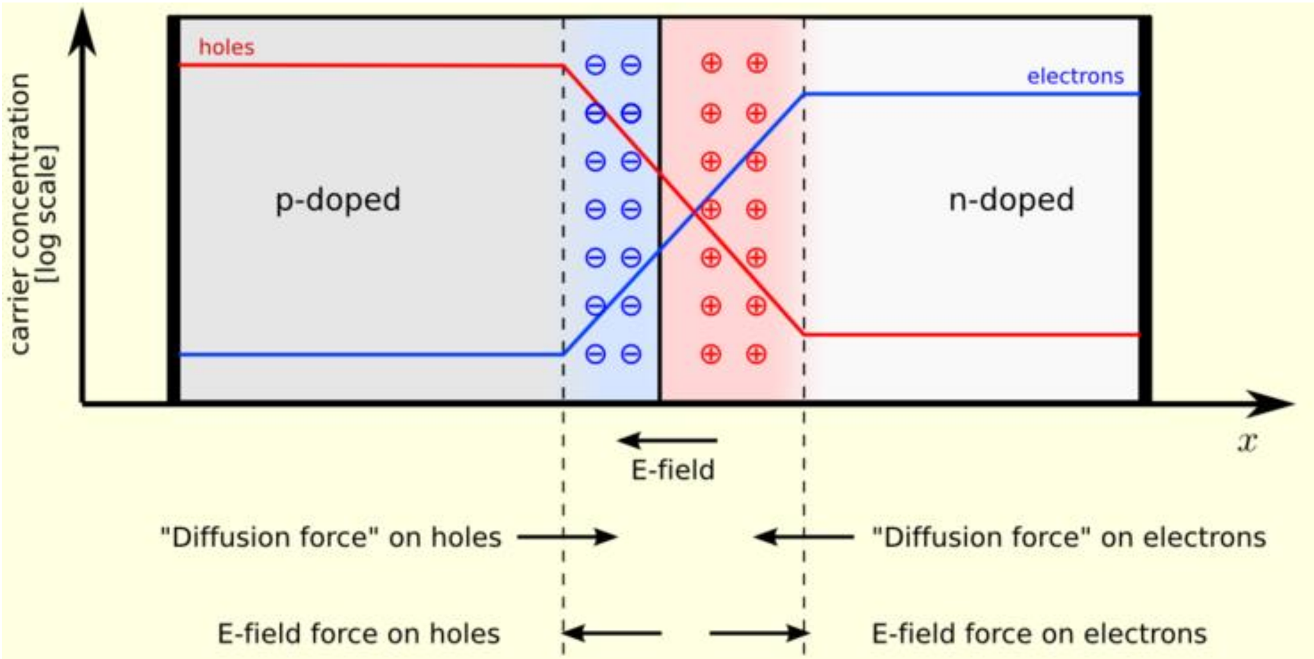
Semiconductor Energy-band Diagram

- Conduction band – top band, here electrons contribute to current flow
- Valence band –energy band where electrons are normally present
- An electron must acquire the band gap energy to jump across to the conduction band, measured in electron-volts eV
- Silicon band gap energy is 1.12 eV



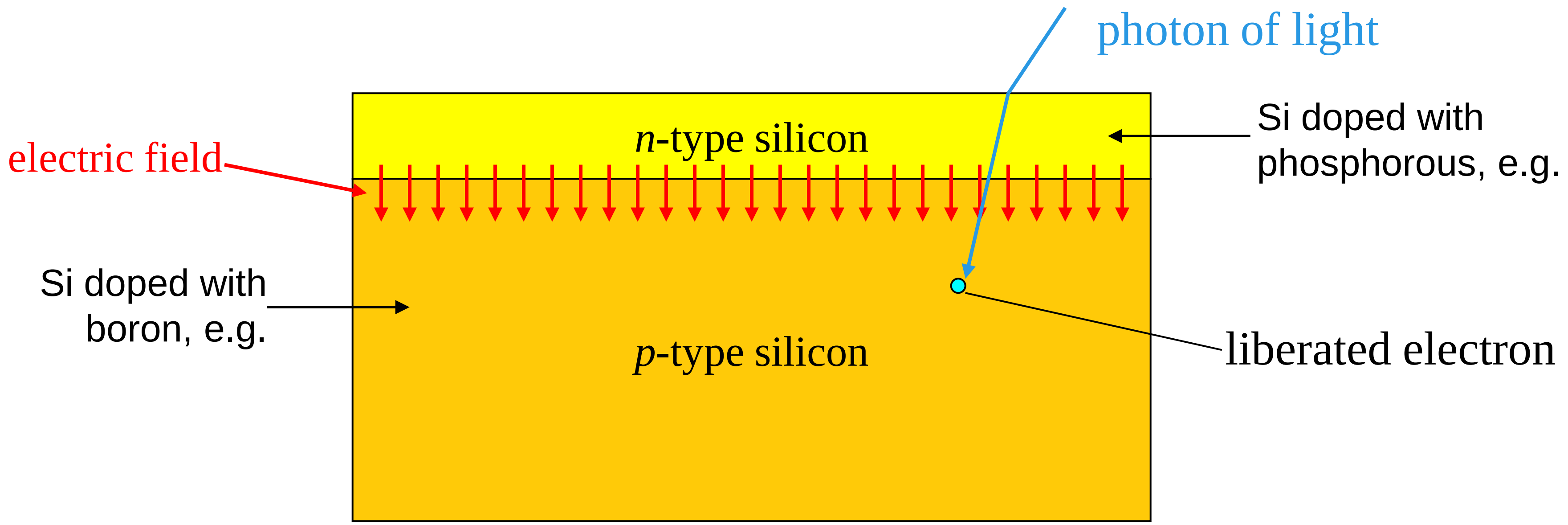
Electrons and Holes

- Photons with enough energy create electron-hole pairs in a semiconductor. Electrons create holes when they jump to the conduction band
- Electrons can move freely in the conduction band



Electrons and Holes

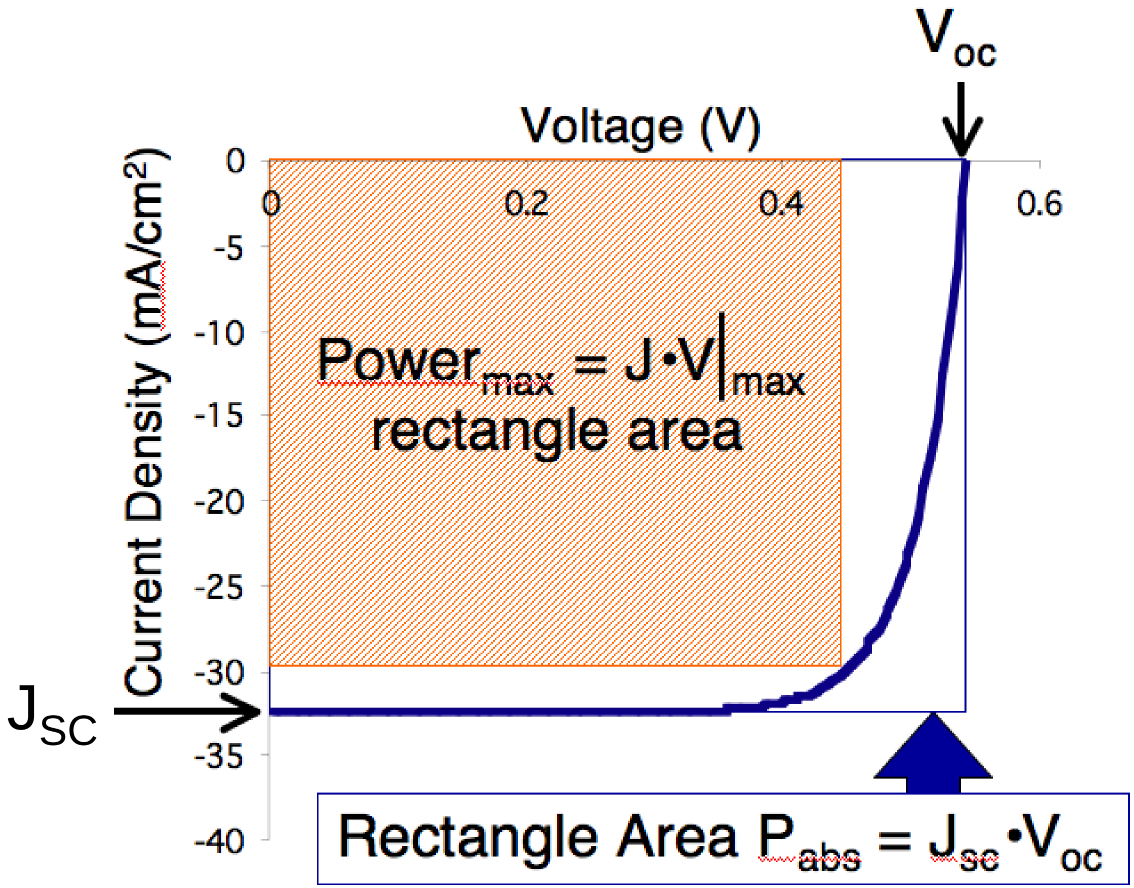
- Making a connection from an n-type semiconductor (doped with impurities with extra electrons) to a p-type material (extra holes) induces an electric field
- This field is what separates charges generated by light
- The depletion width is the region where carriers have diffused



Fill Factor

$$FF = \frac{J_{max} \bullet Vmax}{J_{sc} \bullet Voc}$$

"AM 1.5" Incident Solar Power ~100 mW/cm²



$$\text{Cell Efficiency } (\eta) = \frac{J_{sc} \bullet V_{oc} \bullet FF}{\text{Incident Power}} = \frac{J_{max} \bullet V_{max}}{\text{Incident Power}}$$

Silicon Solar Cell Max Efficiency

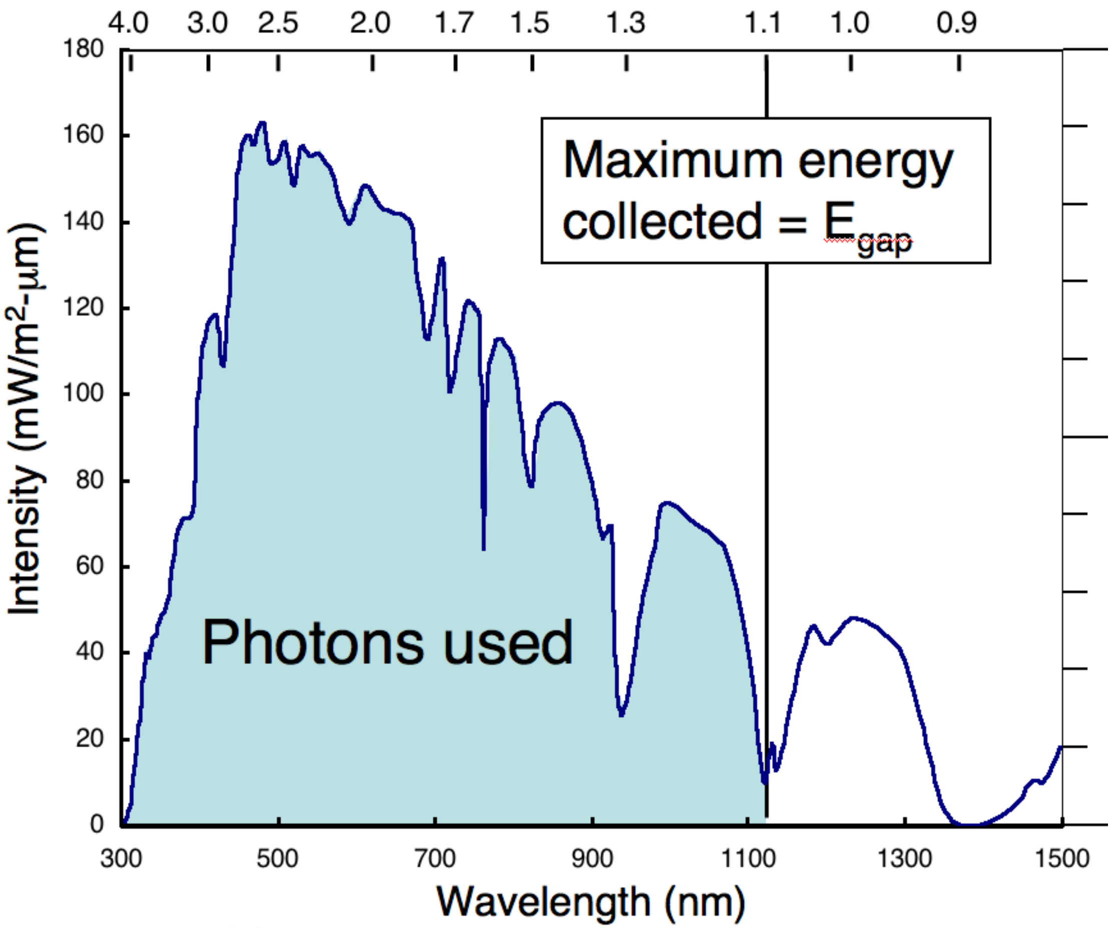
- Upper bound on the efficiency of a silicon solar cell:
- Band gap: 1.12 eV, Wavelength: 1.11 μm

- This means that photons with wavelengths longer than 1.11 μm cannot send an electron to the conduction band.

- Photons with a shorter wavelength but more energy than 1.12 eV dissipate the extra energy as heat

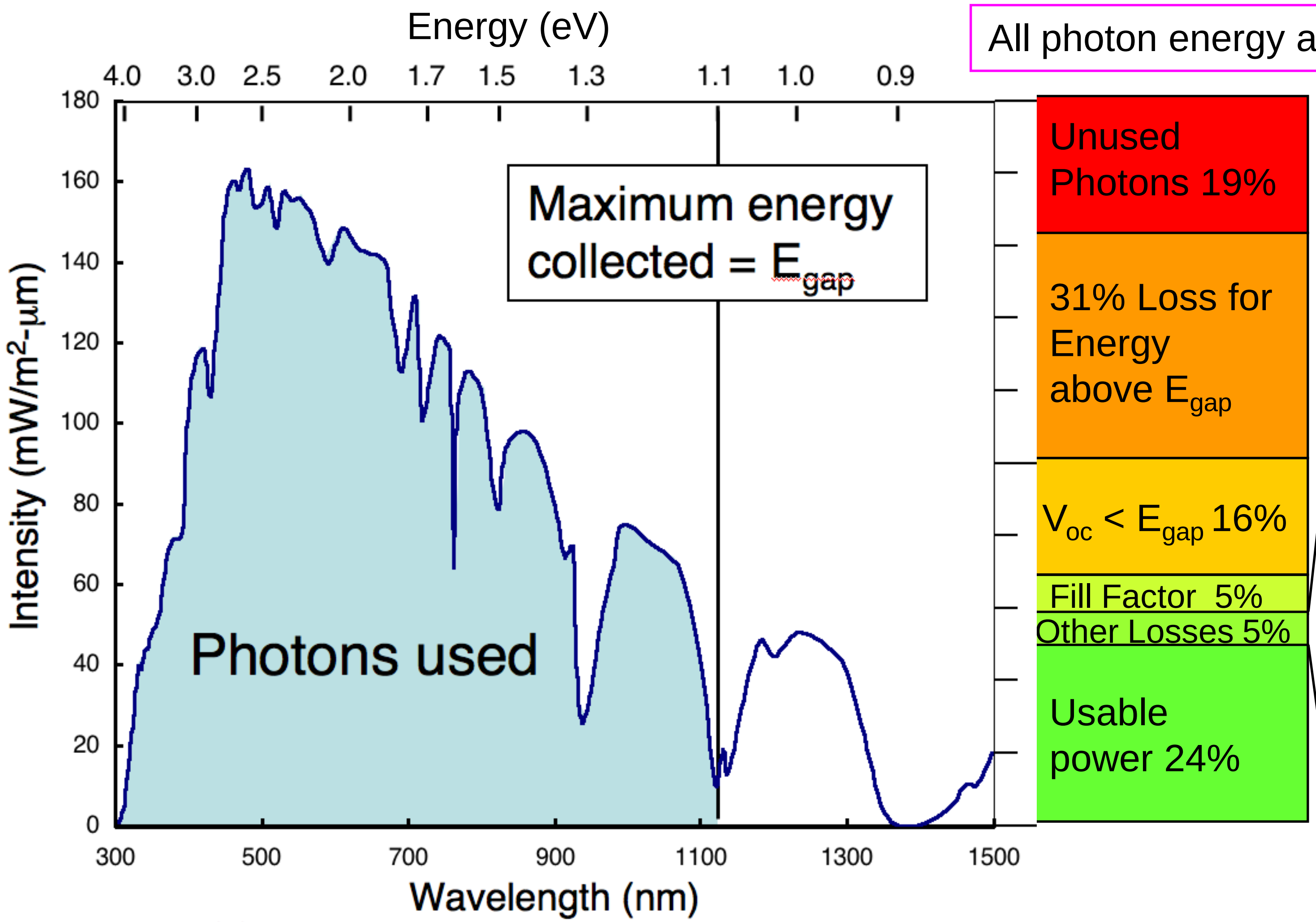
Silicon Solar Cell Max Efficiency

- For an Air Mass Ratio of 1.5, 49.6% is the maximum possible fraction of the sun's energy that can be collected with a silicon solar cell



Limitations to Solar Cell Performance

All photon energy above V_{oc} is lost.

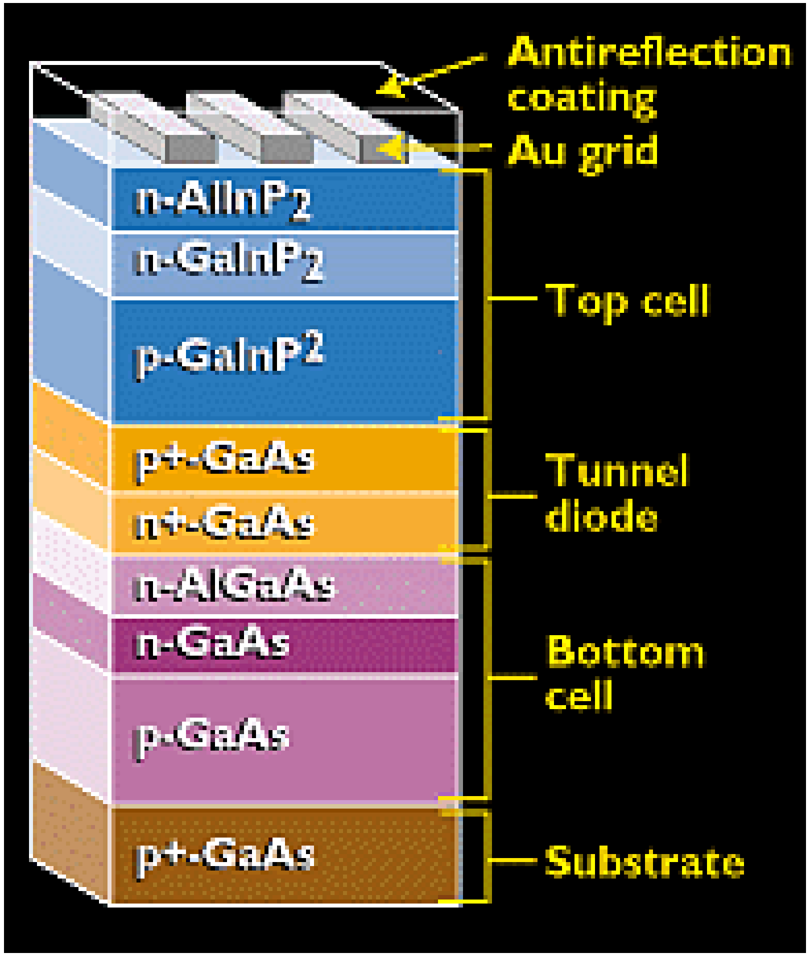


Other losses:
Absorption
Collection
Reflection
Series R
Shunts

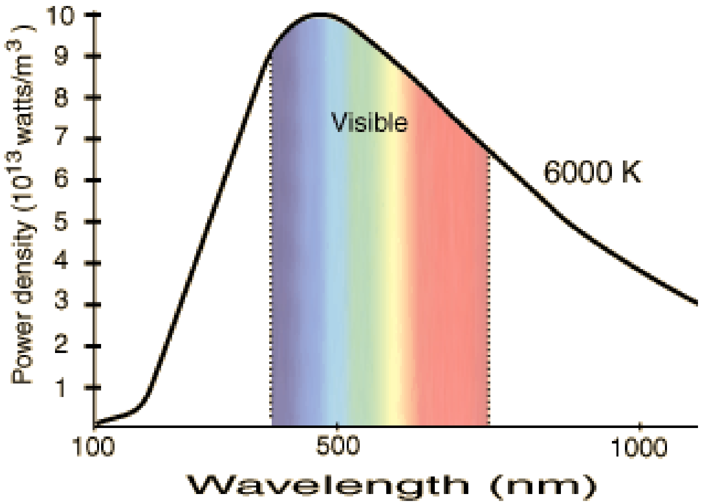
How good can the efficiency get?

- Silicon is transparent at wavelengths longer than 1.1 microns (1100 nm)
  - 23% of sunlight passes right through with no effect
- Excess photon energy is wasted as heat
  - near-infrared light (1100 nm) typically delivers only 51% of its photon energy into electrical current energy
    - roughly half the electrons stumble off in the wrong direction
  - red light (700 nm) only delivers 33%
  - blue light (400 nm) only delivers 19%
- All together, the maximum efficiency for a silicon PV in sunlight is about 23%
  - defeating “recombination loss” puts the limit in the low 30’s %

Full spectrum: multi-junction solar cells

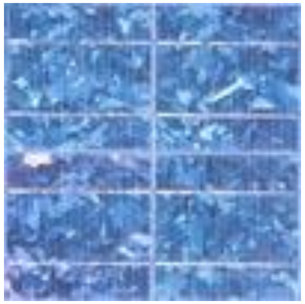


- Layers have different bandgap
- Every layer responsible for different color.

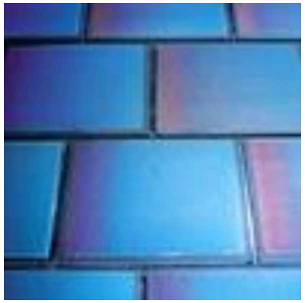


PV types

- Single-crystal silicon
  - 15–18% efficient, typically
  - expensive to make (grown as big crystal)

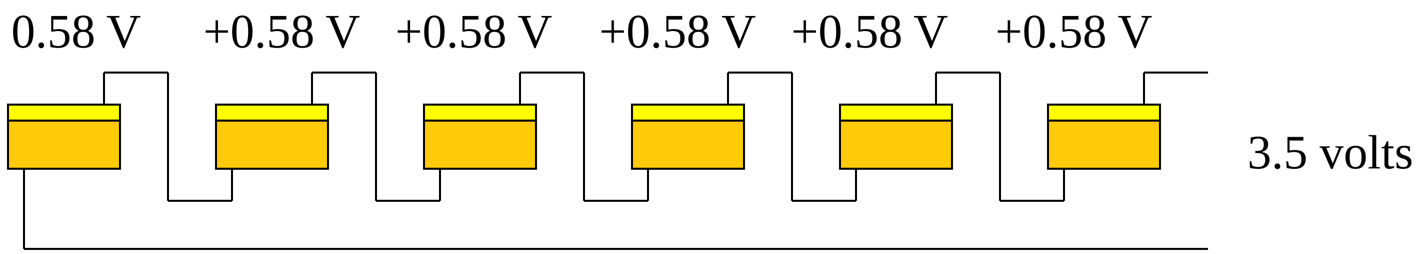


- Poly-crystalline silicon
  - 12–16% efficient, slowly improving
  - cheaper to make (cast in ingots)
- Amorphous silicon (non-crystalline)
  - 4–8% efficient
  - cheapest per Watt
  - called “thin film”, easily deposited on a wide range of surface types

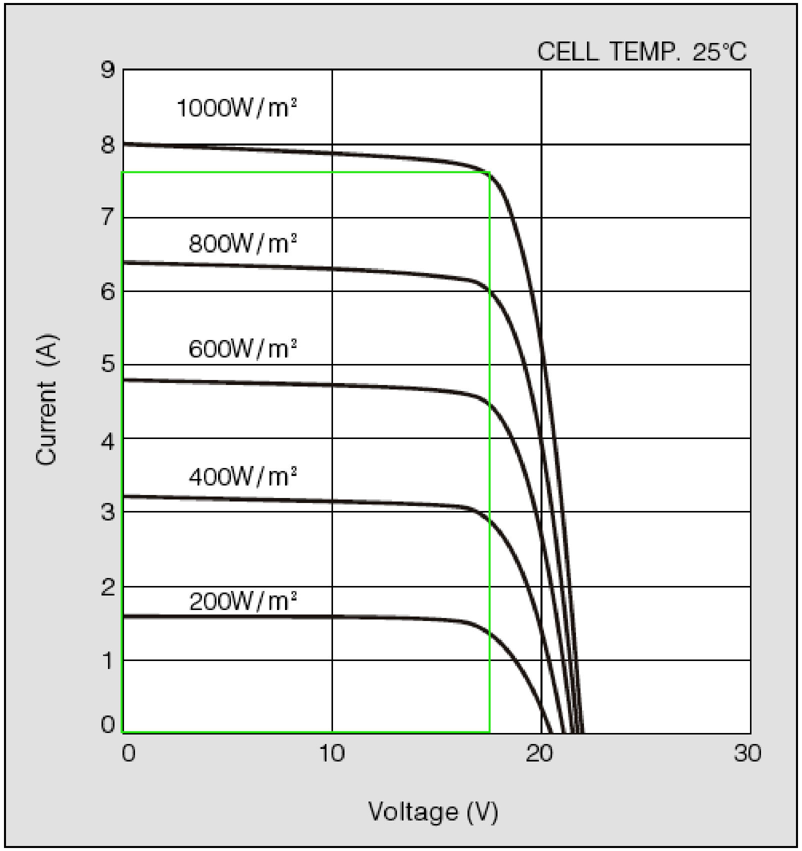


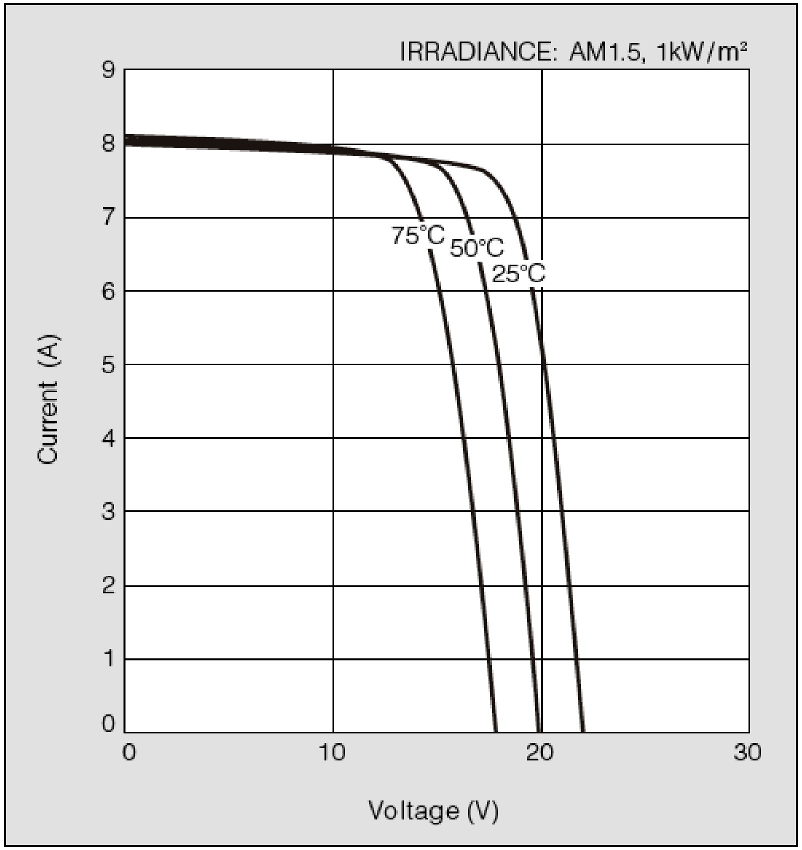
PV Cells = “Batteries”

- A single PV cell (junction) in the sun acts like a battery
  - characteristic voltage is 0.58 V
  - power delivered is current times voltage
  - current is determined by the rate of incoming solar photons
- Stack cells in series to get usefully high voltages
  - voltage ≠ power, but higher voltage means you can deliver power with less current, meaning smaller wiring, greater transmission efficiency
- A typical panel has 36 cells for about 21 V open-circuit voltage
  - but actually drops to ~16 V at max power
  - well suited to charging a nominal 12 V battery



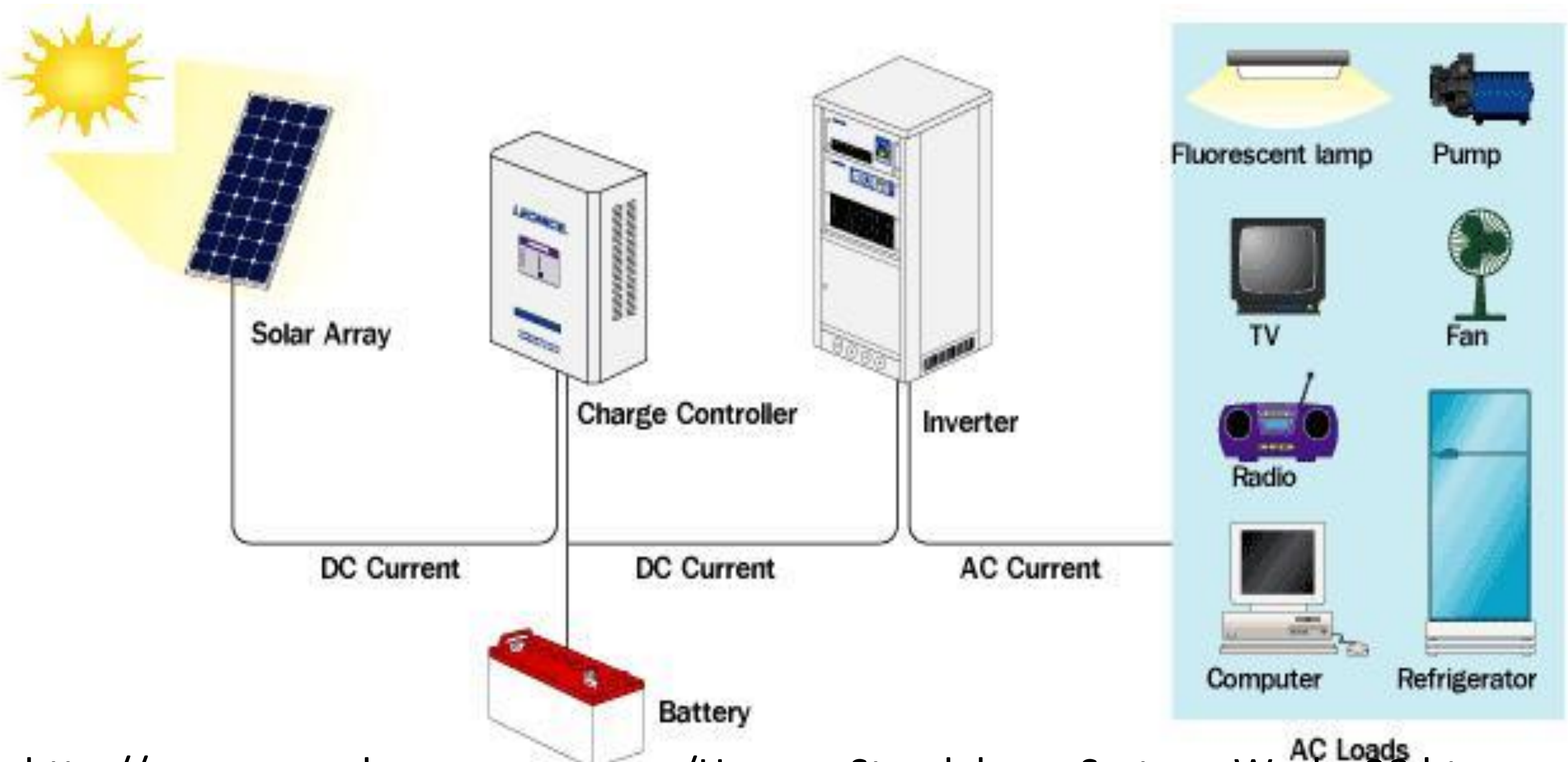
Typical I-V curves





- Typical single panel (this one: 130 W at peak power)
- Power is current times voltage, so area of rectangle
  - max power is 7.6 amps times 17.5 V = 133 W
- Less efficient at higher temperatures

Next lecture- Components of Solar Electric Systems



http://www.ecosolarenergy.com.au/How_a_Standalone_System_Works-28.htm