PV System Components

- PV modules each containing many PC cells. Connected in series or parallel **arrays.**
- Charge Controllers – Optimally charges **a storage battery** for an *off-grid* system, or…
- Grid-tie Inverters – Most residential apps. Converts solar DC to AC synchronized with utility power, to push power back into the grid.

- Balance of System (BOS)

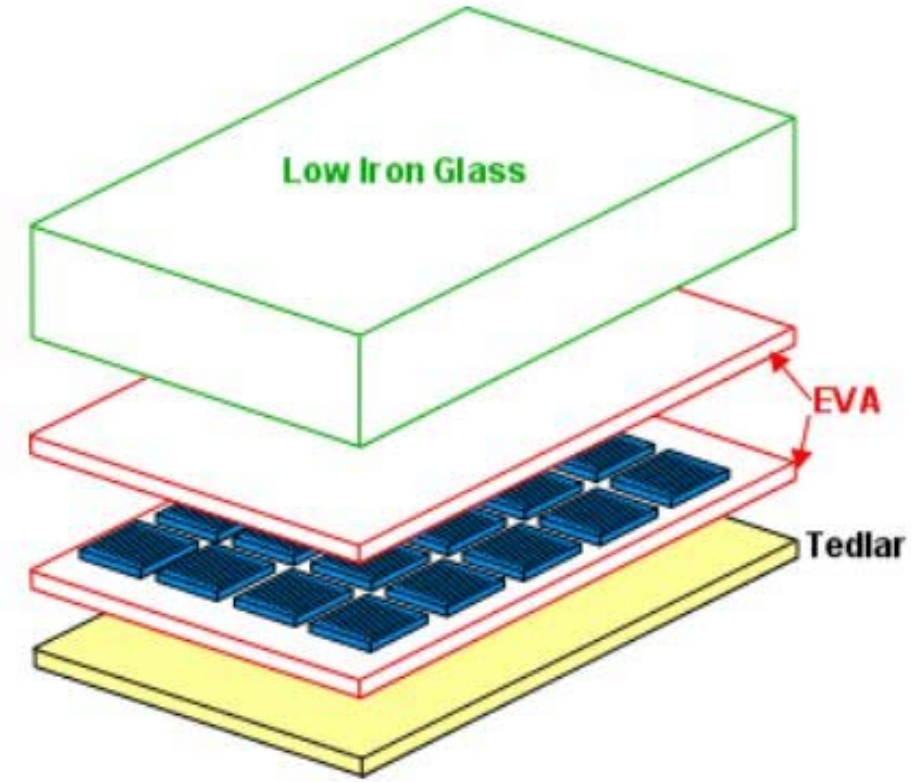
  Panel-mounting hardware and structures, electrical connection hardware, overcurrent protection, disconnect switchgear, grounding hardware

Photovoltaic Cells

- Each *individual cell* in a PV array is essentially a 'large area' diode that *produces current in the reverse-bias direction due to incident light*
- Single-crystal Silicon PV cells, 156 mm diameter:
  - open circuit voltage ~ 0.6 volts
  - 3-7 Watts per cell
- A panel typically has between 60 and 96 cells in series, to provide 36-57 volts at 3-7 amps
- PV arrays use several panels in series to produce up to 600 volts at 3-7 amps

Solar Modules

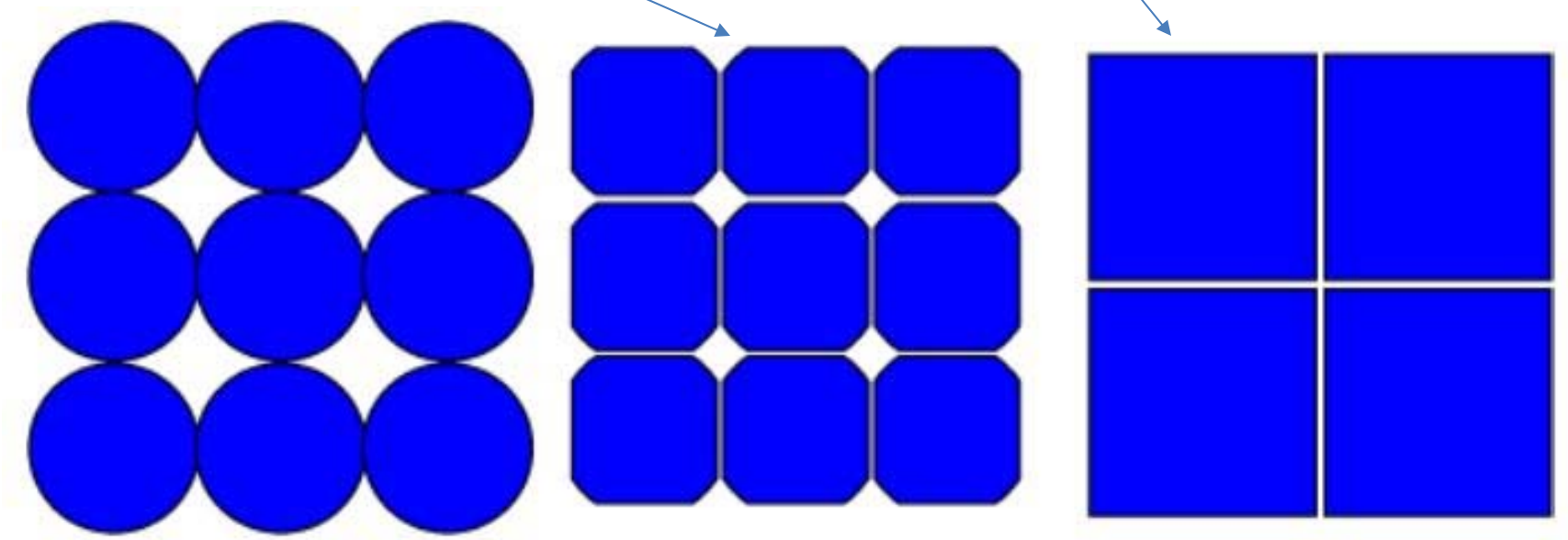
- A simplified silicon PV module sandwich:
  - Transparent top surface (glass)
  - Encapsulant (EVA - ethyl vinyl acetate)
  - Rear layer (Tedlar or similar UV-durable protective cover)
  - Frame



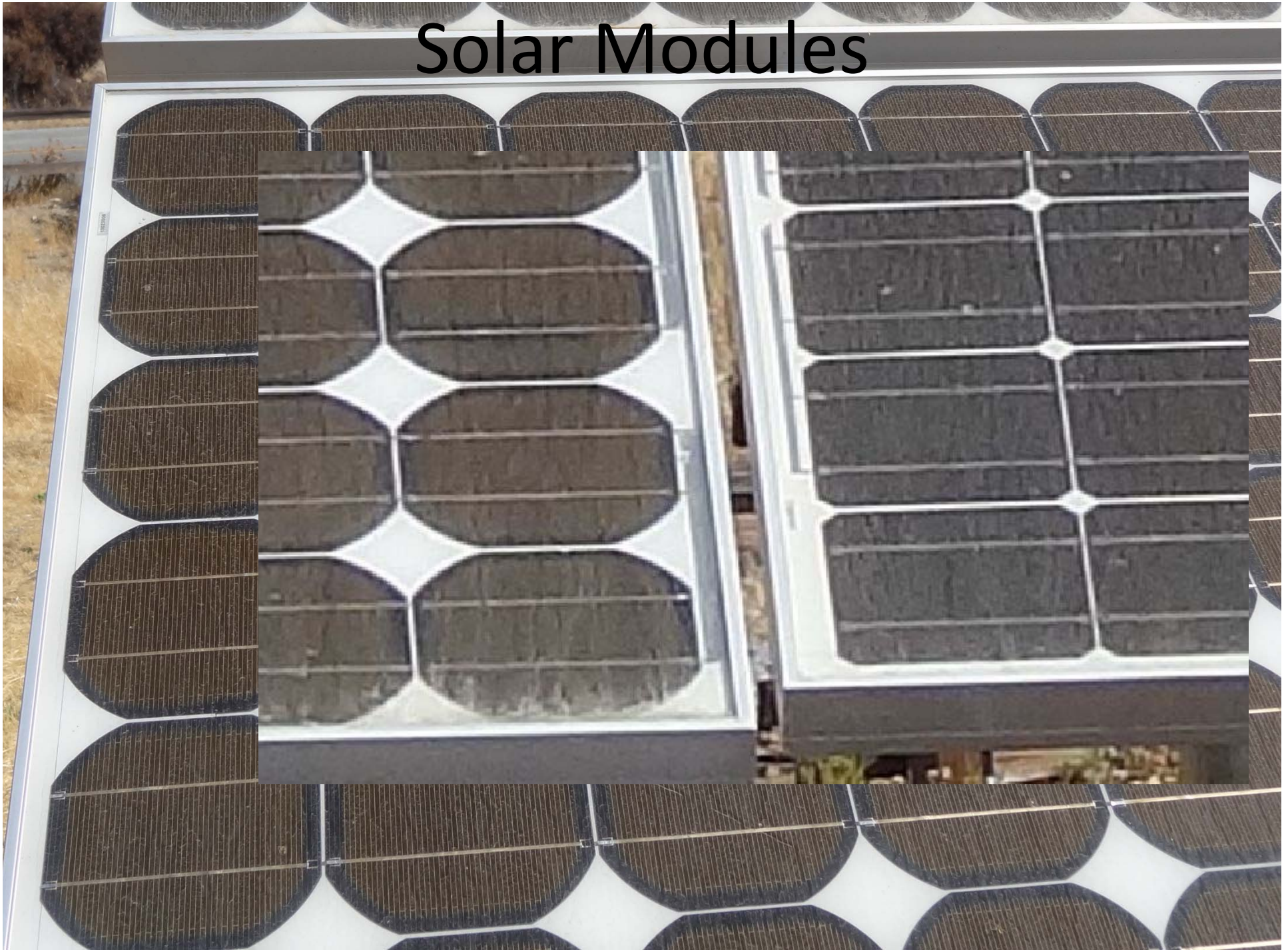
Solar Modules

Some Solar Cell Shapes

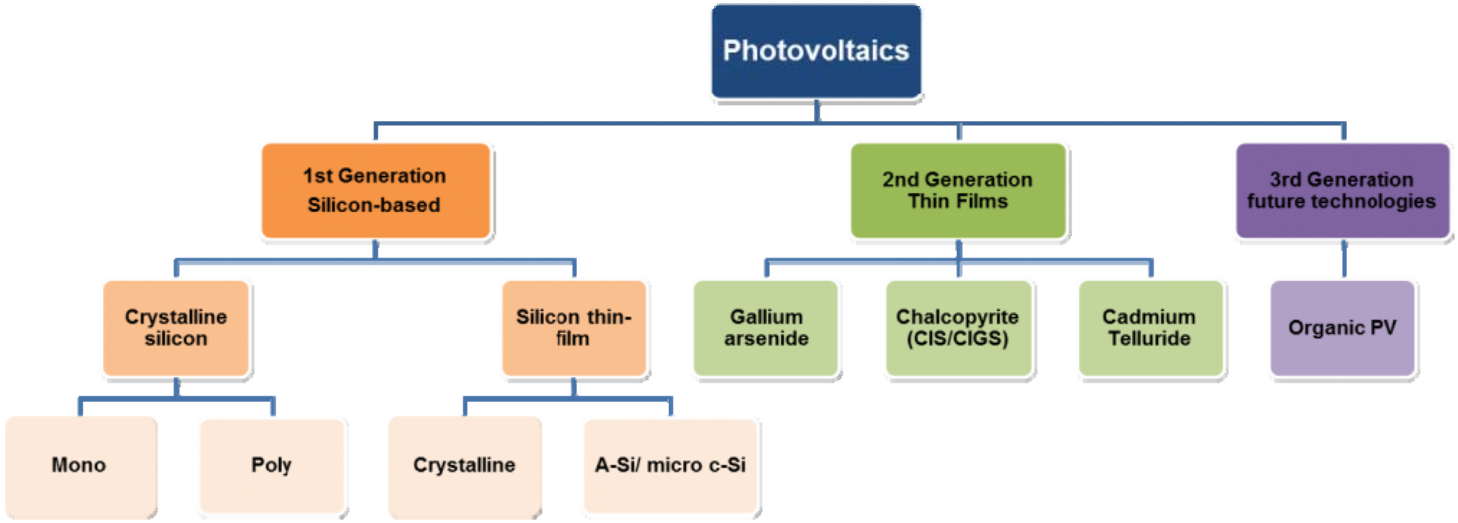
- Monocrystalline from round ingots (to achieve higher packing density edges are cut off)
- Polycrystalline material cast in square blocks



Solar Modules



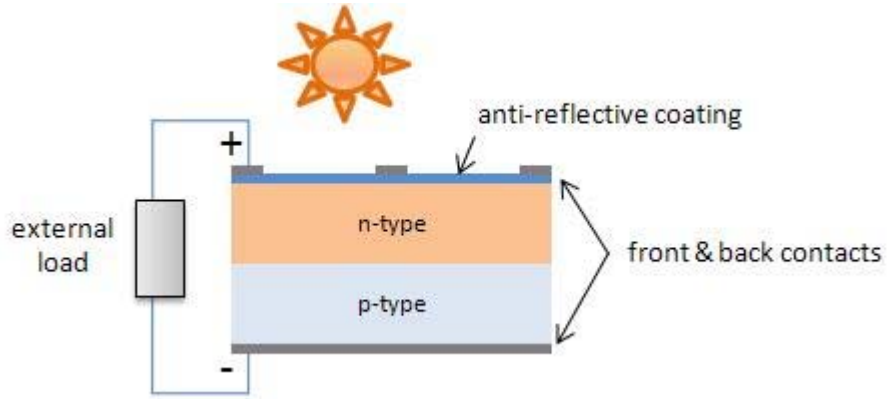
Photovoltaic (PV) Technologies



- Silicon Monocrystalline
- Silicon Polycrystalline
- Amorphous Silicon (aSi)
- Cadmium telluride (CdTe)
- Copper Indium Gallium Selenide (CIGS)
- Gallium Arsenide
- Organic PV

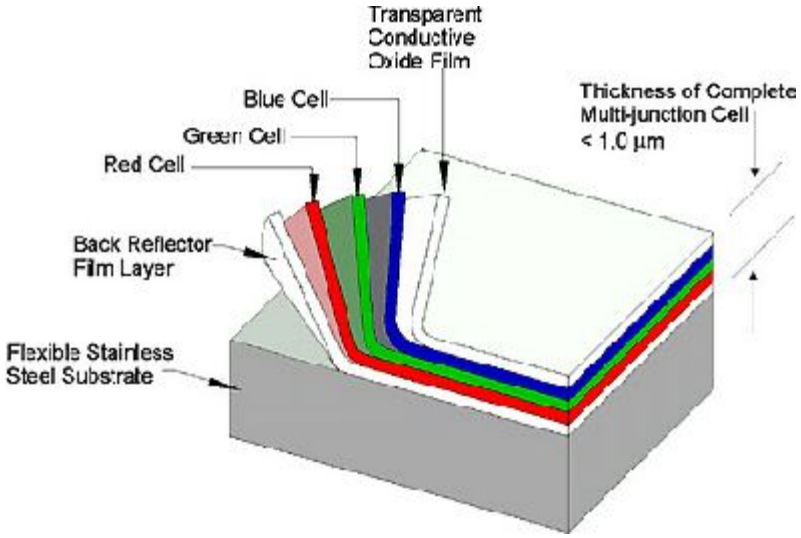
Silicon - Monocrystaline or single-crystal

- Made from the same pure-silicon crystal growth process used for production of wafers for integrated circuits →

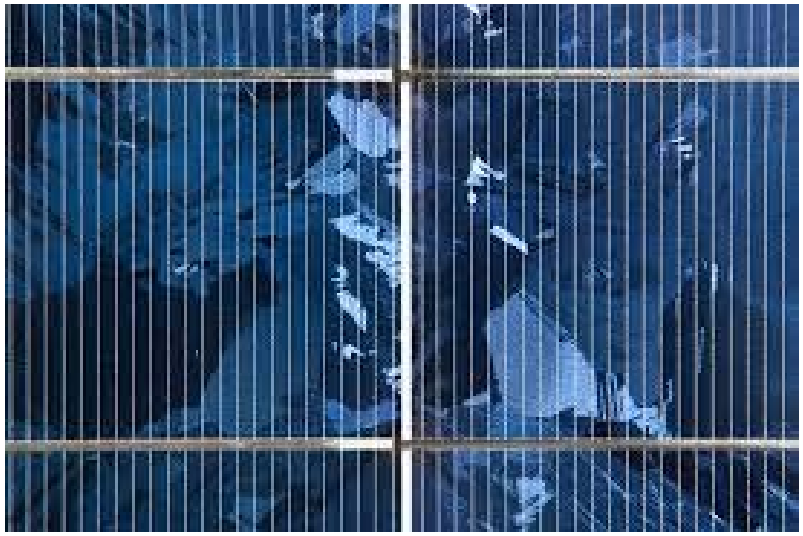


- Highest power and efficiency
- Most expensive per cell
- About 25% of the world-wide PV market

Silicon Polycrystalline (multicrystalline)

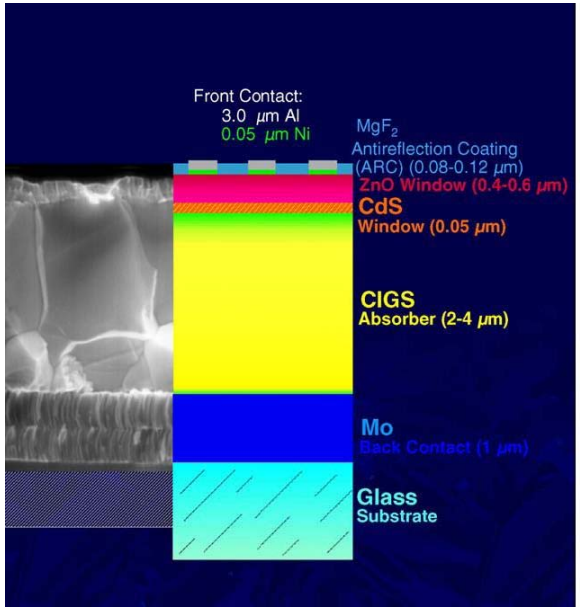


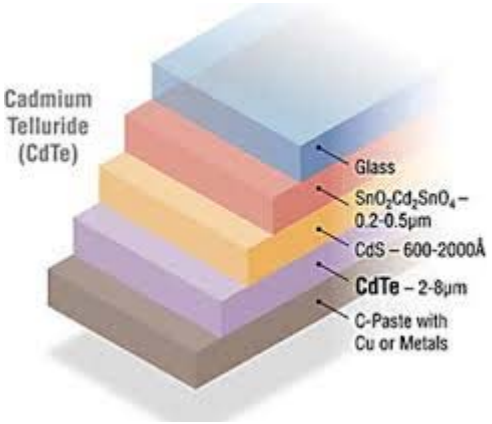
- Uses cast silicon instead of single crystal
- Can be recognized by a visible grain (cell usually square)
- Low cost, durable
- Easy to manufacture
- Efficiencies 12-18% (70%-80% of mono)
- Minimal hazardous materials – good end-of-life
- Greater efficiency reduction with temperature
- About 65% of the worldwide PV market, strong market competition



CIGS (Copper Indium Gallium Selenide)

- Solyndra, Nanosolar, Miasole
- Most common thin-film and flexible panel technology
- Manufacturing process is more difficult
- Medium efficiency, < 20%
- Less sensitive to temperature effects than Silicon
- Lower environmental concerns than CdTe
- Current cost is high



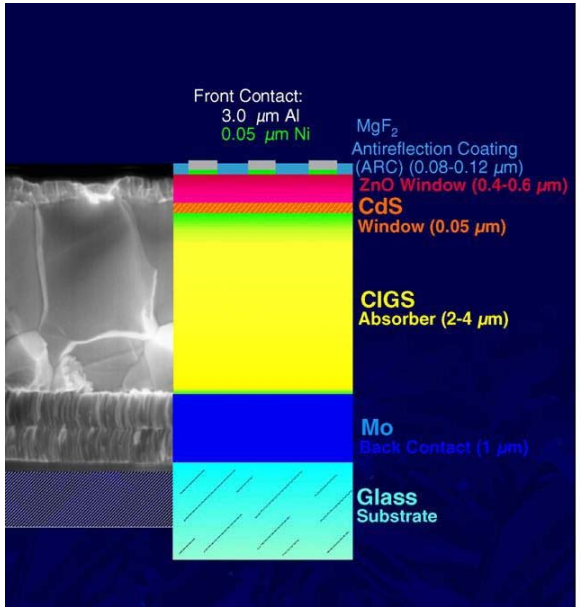


Cadmium Telluride

- First Solar, Advanced Solar Power, GE Solar
- Most often used for *thin-film* PV cells
- Moderate cost materials
- Medium conversion efficiency, typically 16%
- Can easily be made into flexible panels
- Manufacturing process is relatively easy and low-cost
- Cadmium is abundant, but not so sure about Tellurdide
- Cadmium and CdTe are extremely toxic: end-of-life issues

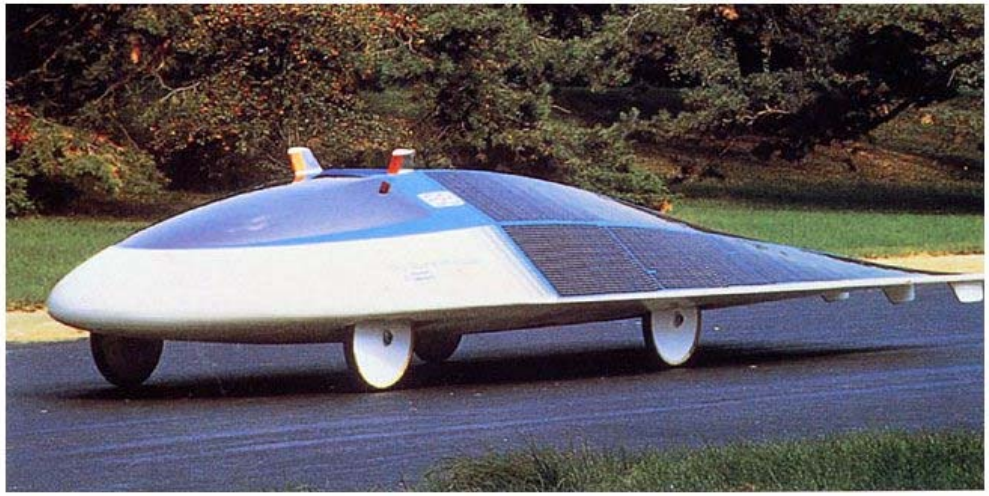
CIGS (Copper Indium Gallium Selenide)

- Solyndra, Nanosolar, Miasole
- Most common thin-film and flexible panel technology
- Manufacturing process is more difficult
- Medium efficiency, 15 - 18%
- Less sensitive to temperature effects than Silicon
- Lower environmental concerns than CdTe
- Current cost is high

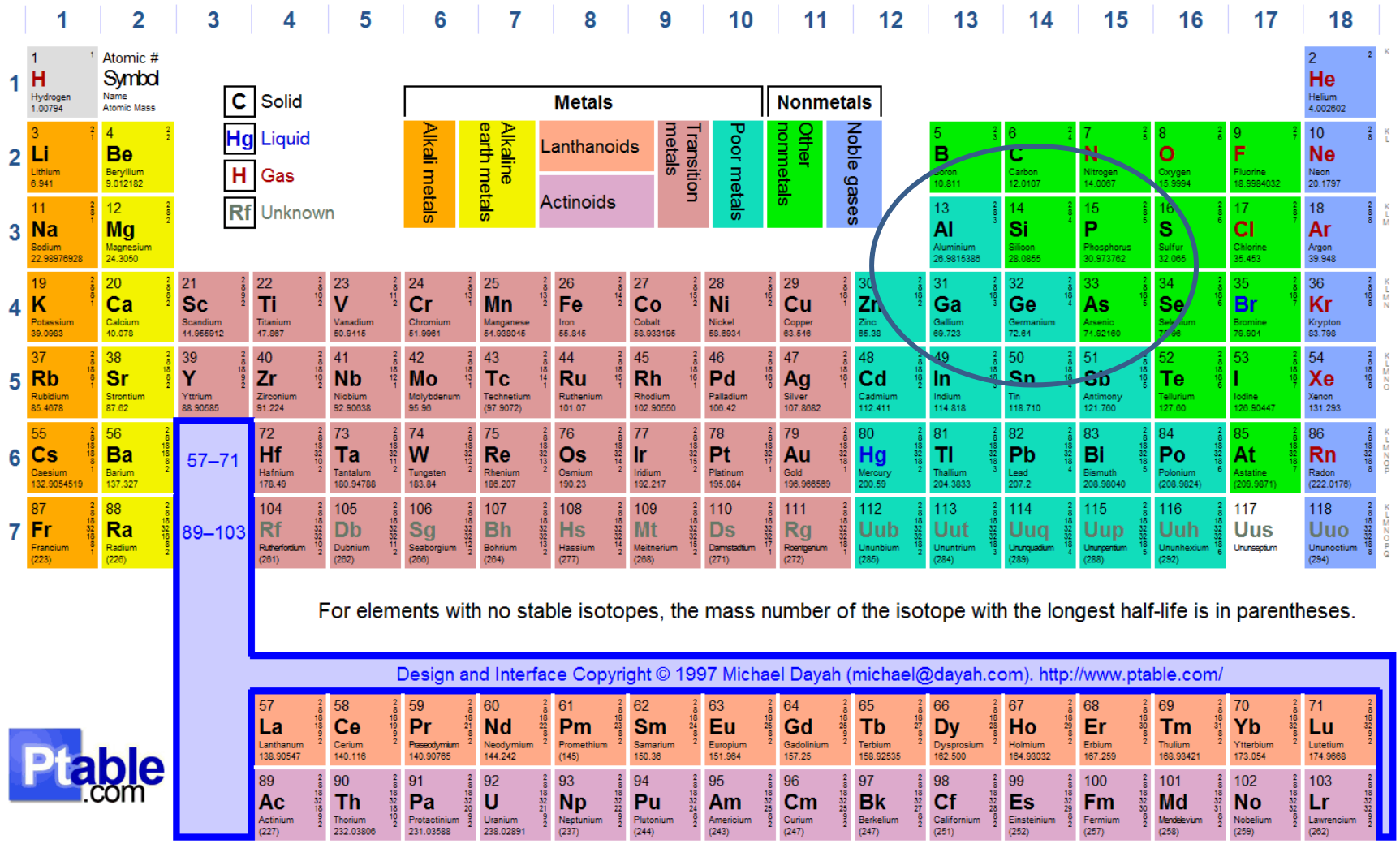


Gallium Arsenide

- A compound semiconductor – see periodic table next slide
- Most efficient – holds world record for single-layer cell efficiency: 28.8%
- Most expensive PV technology
- Used in applications where cost is not a factor, e.g., spacecraft, 1987 GM SunRaycer
- Not in use for residential or utility solar PV

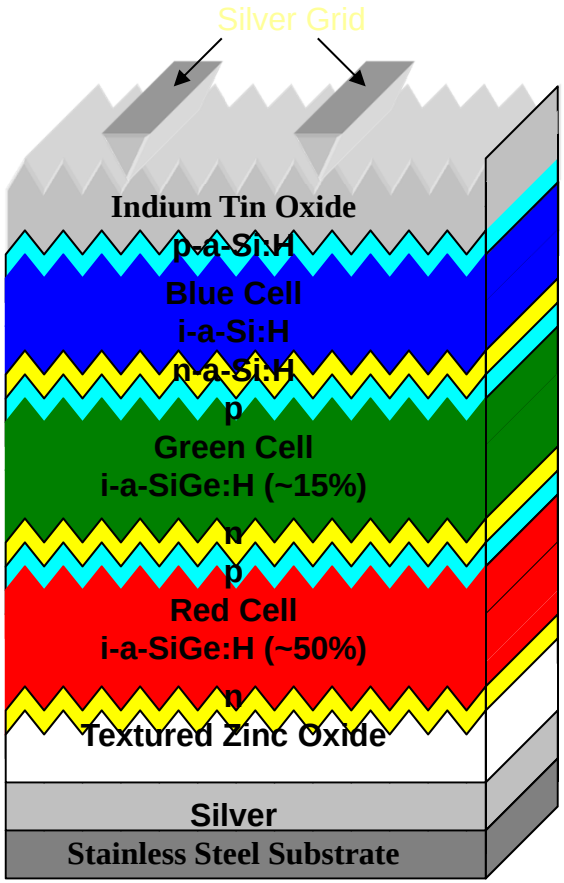


Periodic Table of Elements



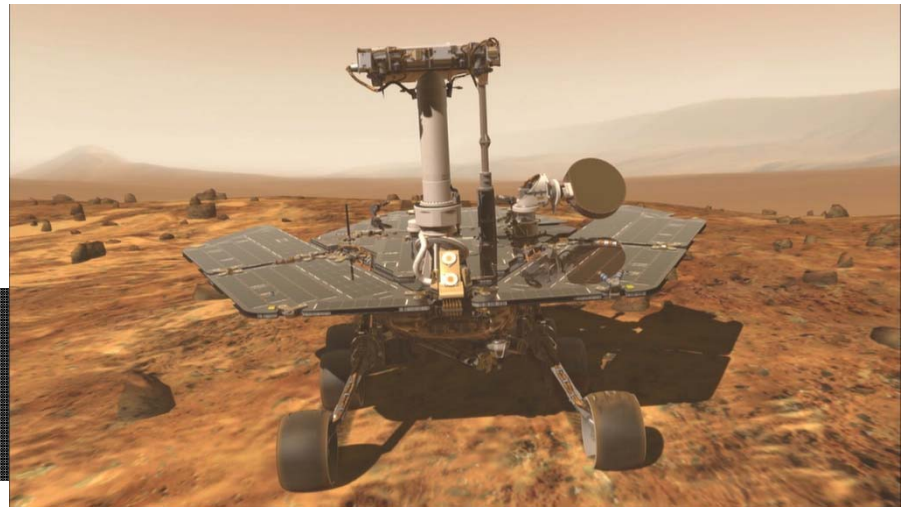
Ptable.com

Tandem, multi-layer or multi-junction cells

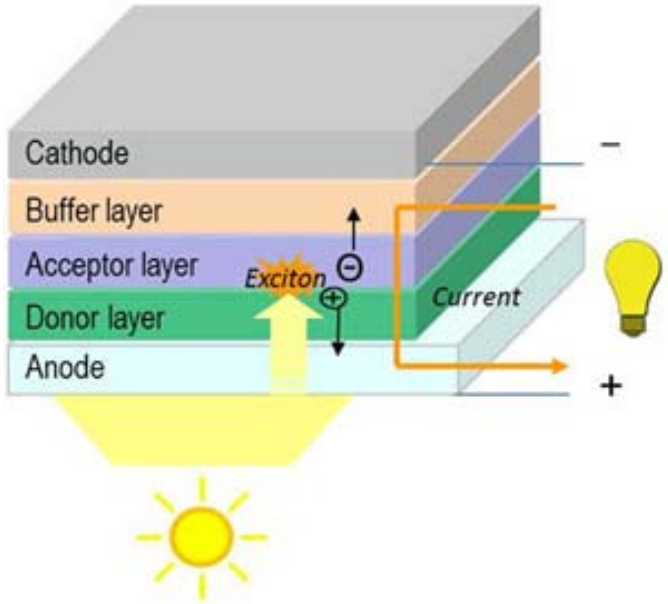


Schematic diagram of state-of-the-art a-Si:H based substrate n-i-p triple junction cell structure.

- Several cells on top of each other, each with optimal sensitivity to particular light wavelengths
- GaAs multilayer cells have efficiencies as high as 32%
- Used for the Mars Rovers

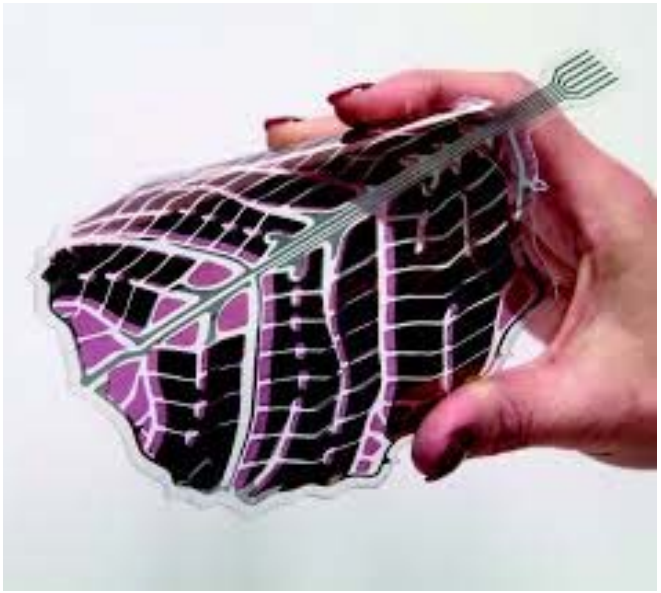


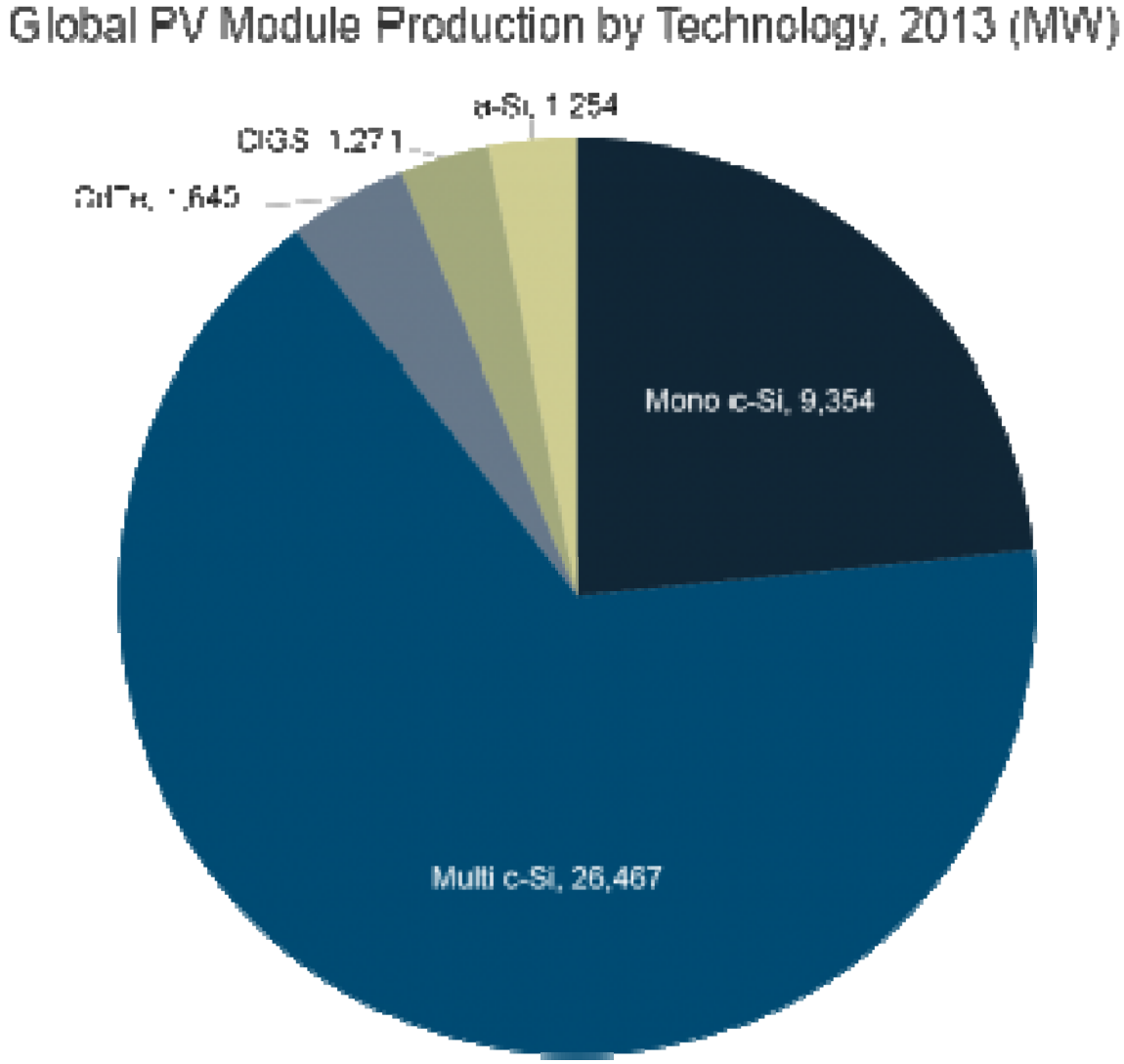
Organic or Polymer Solar PV (OPV)



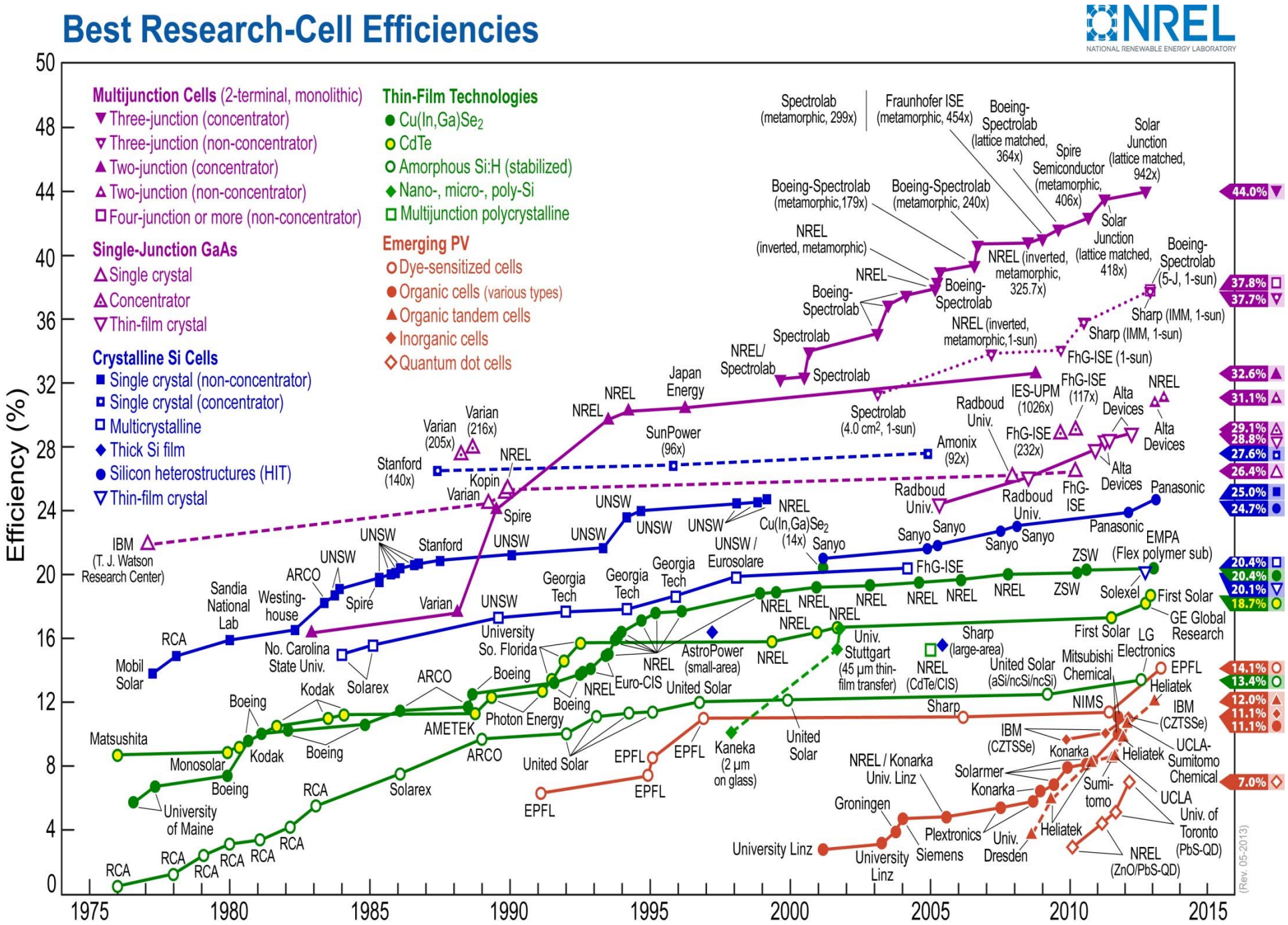
- Organic Photovoltaic (OPV) devices consists of one or several photoactive materials sandwiched between two electrodes
- Low manufacturing cost – possibly even printed by photolithography
- Flexible cells
- Low efficiency
- Can be any color or transparent
- Low efficiency, typically 1-2% for single layer, 4-5% with layers, but as high as 12% has been claimed:

  http://www.laserfocusworld.com/articles/2013/01/heliatek-opv-12-percent.html




Global PV Module Production by Technology, 2013 (MW)
a-Si, 1,254
CIGS, 1,271
CdTe, 1,645
Mono c-Si, 9,354
Multi c-Si, 26,467

Best Research-Cell Efficiencies



Lots of competition to make the most efficient residential or utility PV modules

http://www.solarcity.com/newsroom/press/solarcity-unveils-world%E2%80%99s-most-efficient-rooftop-solar-panel-be-made-america

http://us.sunpower.com/solar-panels-technology/facts/

http://cleantechnica.com/2015/05/01/3-solar-cell-efficiency-records-just-4-days/

http://solarlove.org/sharp-solar-cell-efficiency-record-another-one-44-4/

And the current highest efficiency claim using multilayer concentrator cells

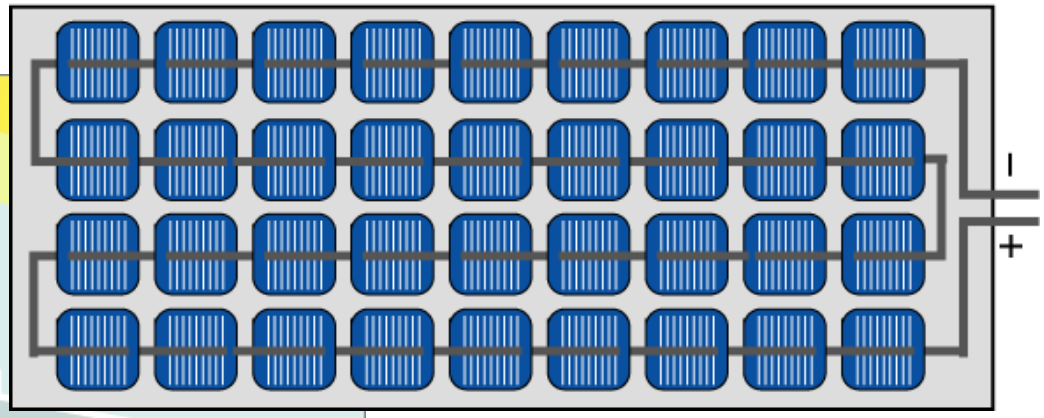
http://cleantechnica.com/2014/12/03/new-solar-cell-efficiency-record-set-46/

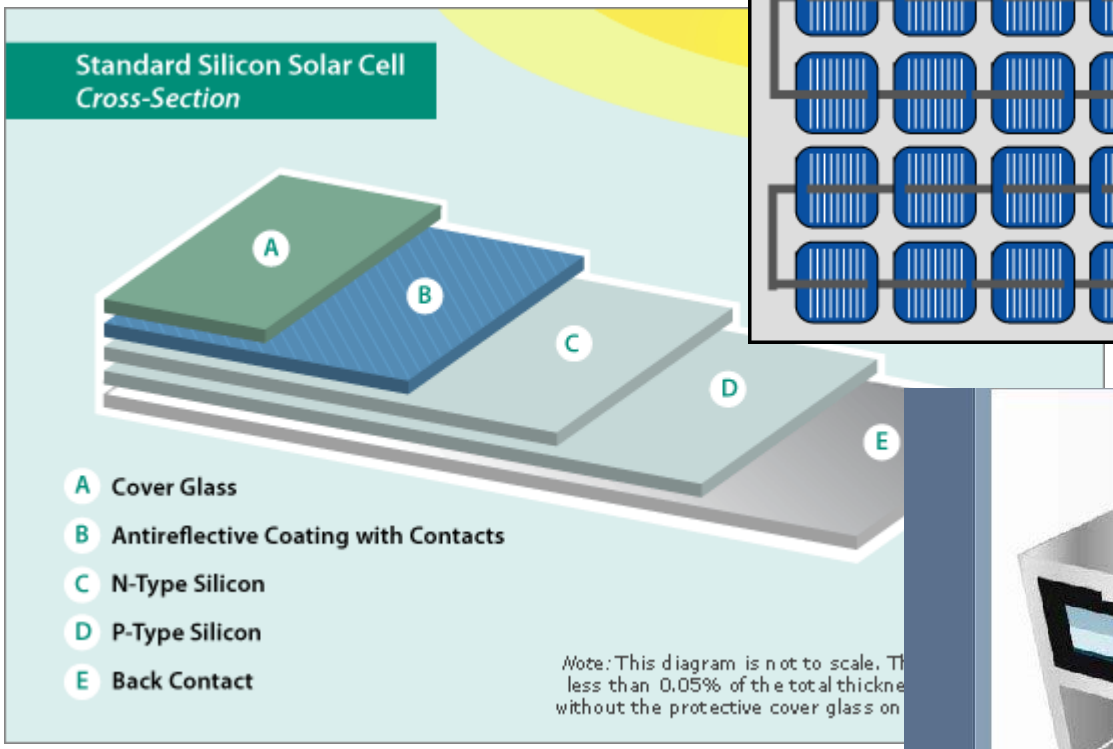
Solar Panel or Module

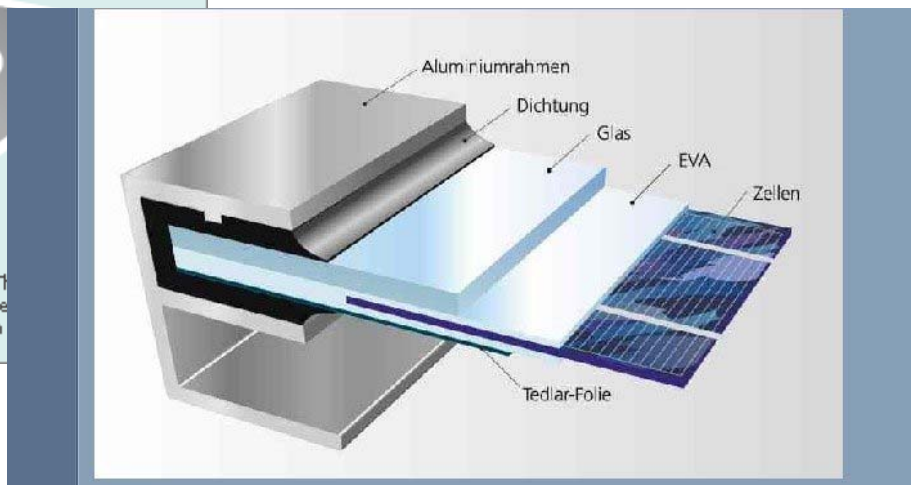
Many solar cells connected together to form a PV panel or module

Usually in series, to achieve higher voltages rather than in parallel to achieve higher current

A typical module has 36 cells connected in series

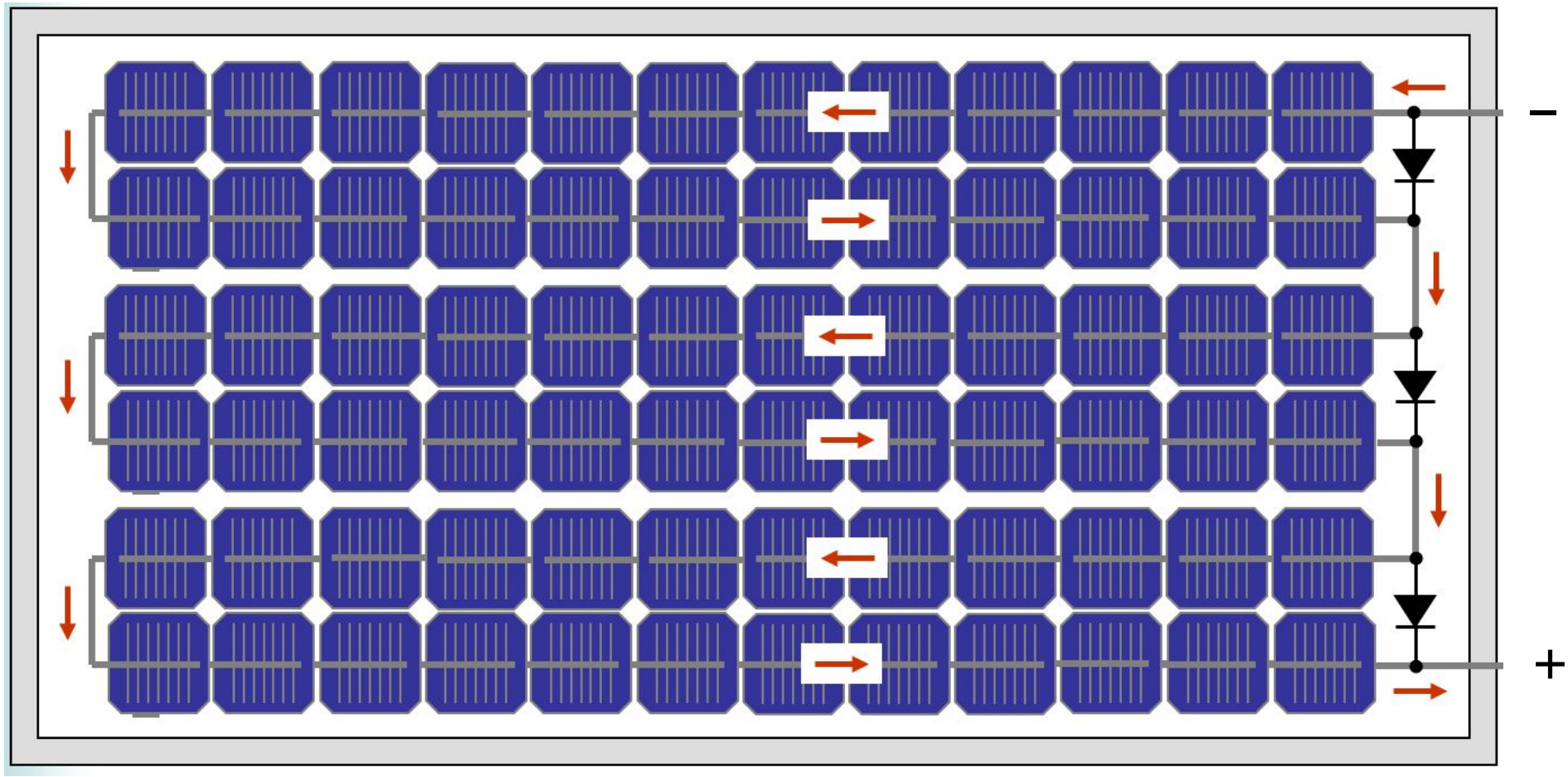




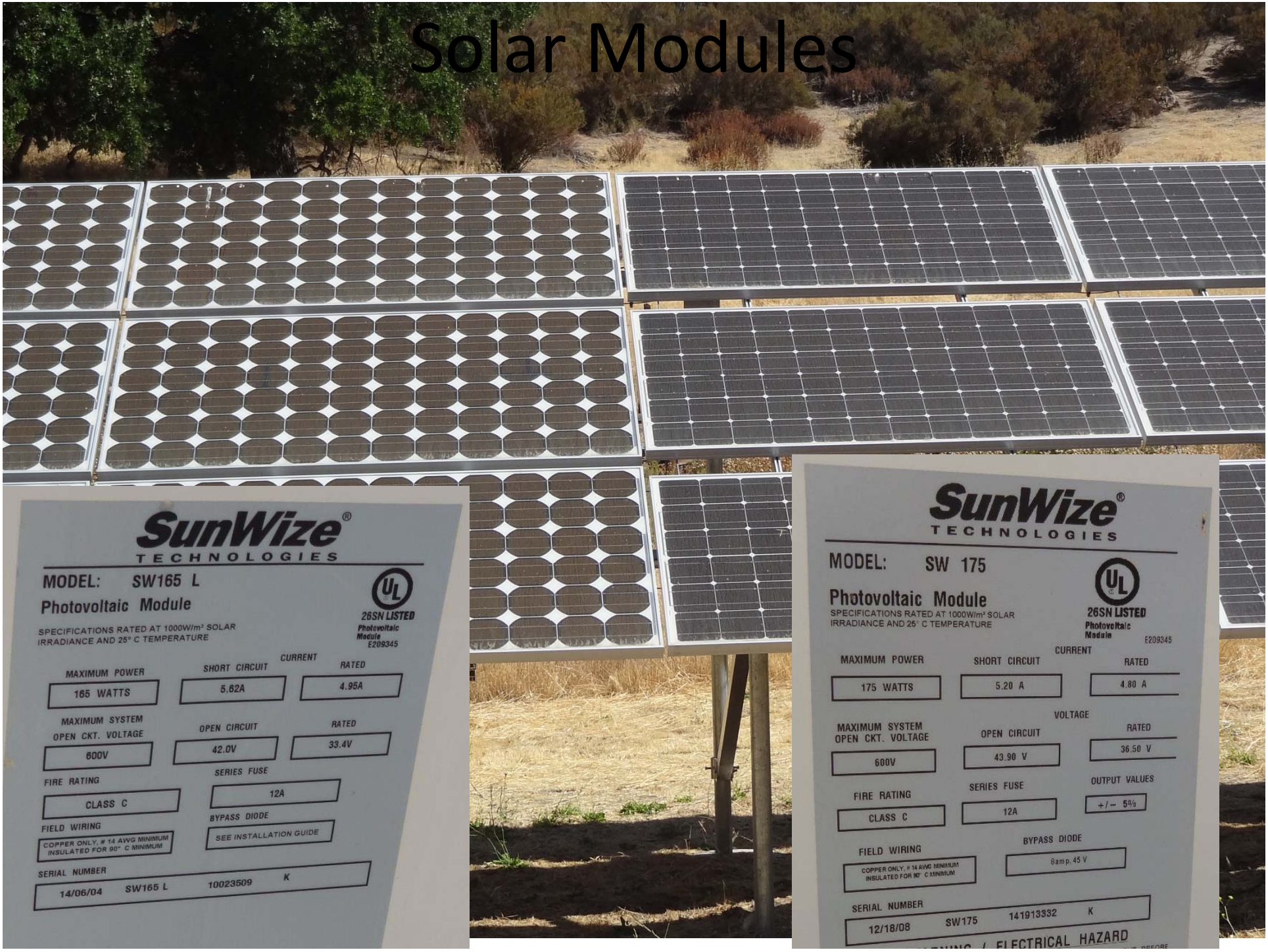


Connection of Cells in PV

72-cell PV Module with bypass diodes shown

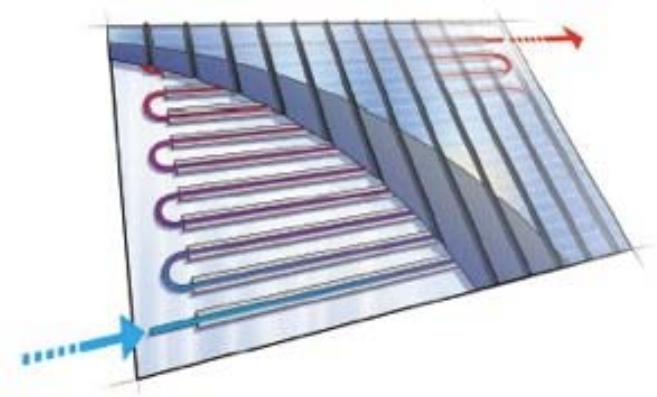


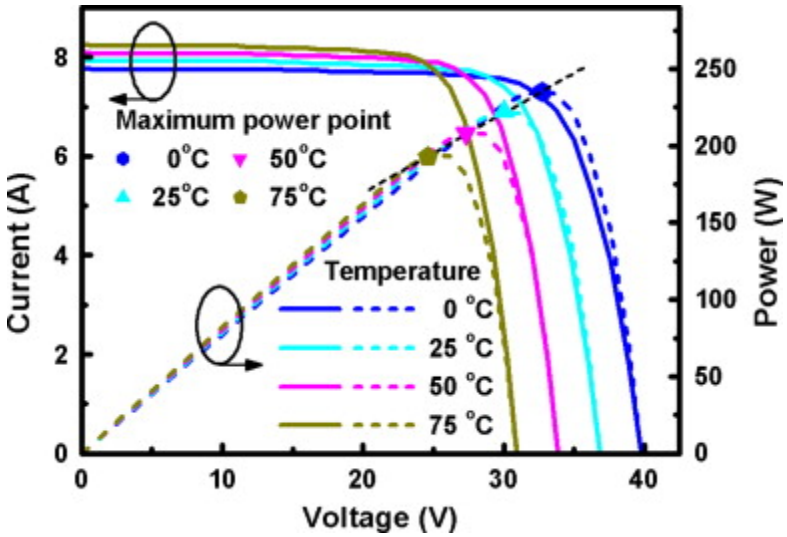
Solar Modules



Combined PV and Thermal Solar

- Aka ‘hybrid panels’
- Converts sunlight to electric power AND to heat for water heating or HVAC
- Cooling of water or coolant reduces temperature, improving PV efficiency





Solar Shingles (BIPVs)

Aka Building-Integrated Photovoltaics.

Replace shingles on a composition, composite or or ceramic tile roof.

Each is a solar panel producing about 12 W / ft^2 but 13-63 W / shingle have been reported https://pureenergies.com/us/how-solar-works/solar-shingles/

Usually wired to adjacent shingles in series.

Silicon-based solar shingles
Usually multicrystaline or amorphous, but some mono-crystalline, e.g., shakes made by SunPower advertised up to 22% efficiency, but were discontinued.

Thin-film solar shingles
Use thin-film technologies such as CIGS of CdTe, laminated in thin films over conventional the shingles. Less efficient than Si, but less expensive.

Organic Solar PV shingles
An obvious application of solar OPVs, but not yet commercial.

Solar PV Skylights and Windows (another BIPV)

Since thin-film and organic solar technologies can be made nearly transparent, why not make windows or skylights or shade structures out of them?

Solar shade panels are being used in the Solar Cal Poly project

One variation is a *Transparent Luminescent Solar Concentrator* (TLSC)

Solar PV Floors (YAPV*)

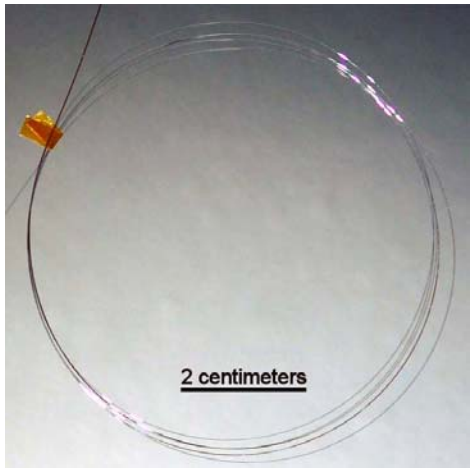
http://www.onyxsolar.com/walkable-photovoltaic-roof.html

Same attributes as other evolving applications of solar PV technologies.

Usually amorphous SI or CIGS, but OPVs may soon be available and could dominate the market due to super-low cost.

(*Yet Another PV. Not really.)

Solar PV Clothing (AYAPV)



Solar PV fiber (above) has been developed. http://www.treehugger.com/solar-technology/silicon-based-fibers-could-make-fabric-solar-cells.html

http://wearablesolar.nl/

Not just small PC cells attached to clothing

You know where this is headed…

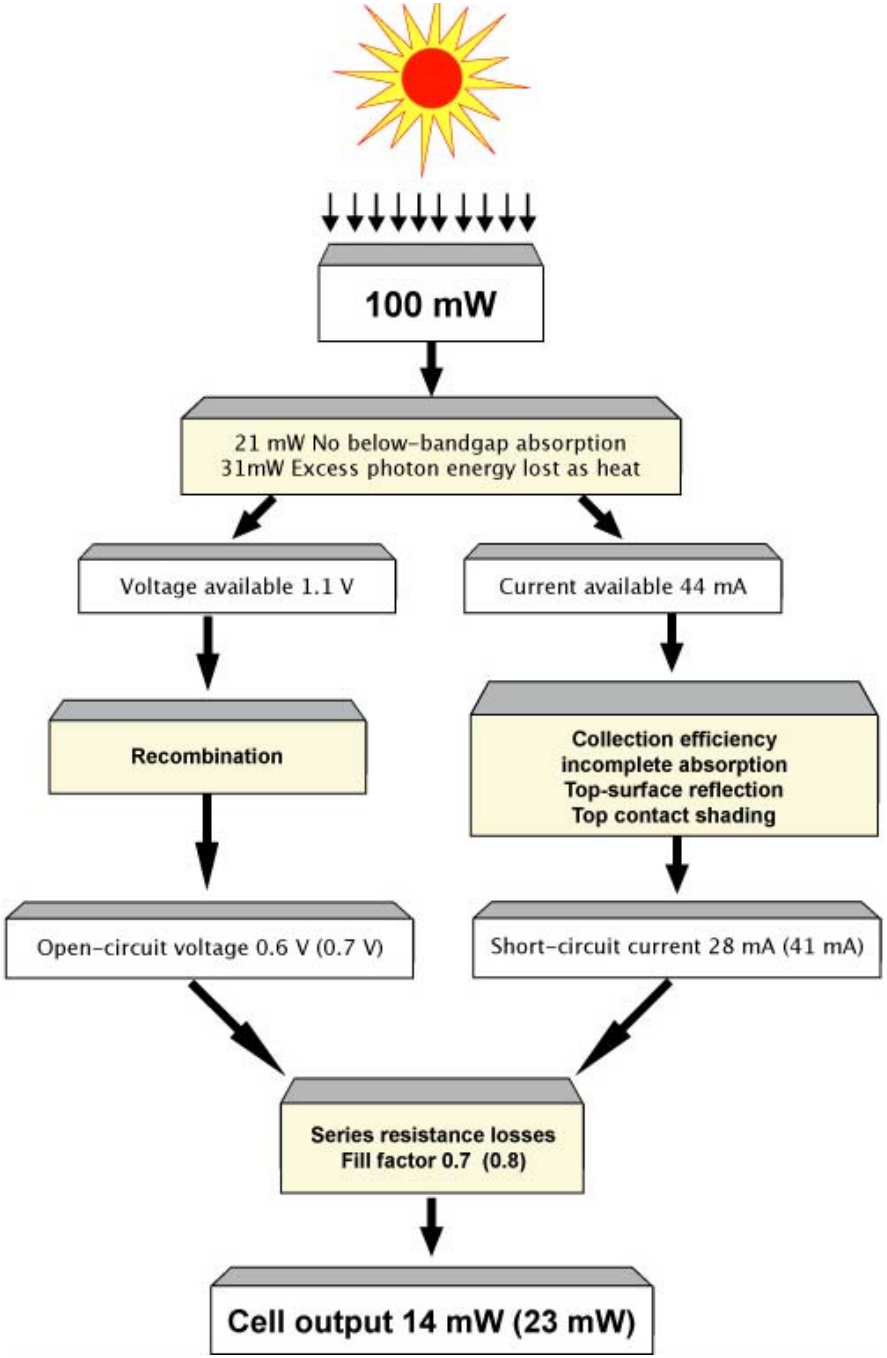
http://solarenergy.net/News/2010042101-organic-photovoltaics-are-making-wearable-solar-possible/

Other Parts of Solar Modules

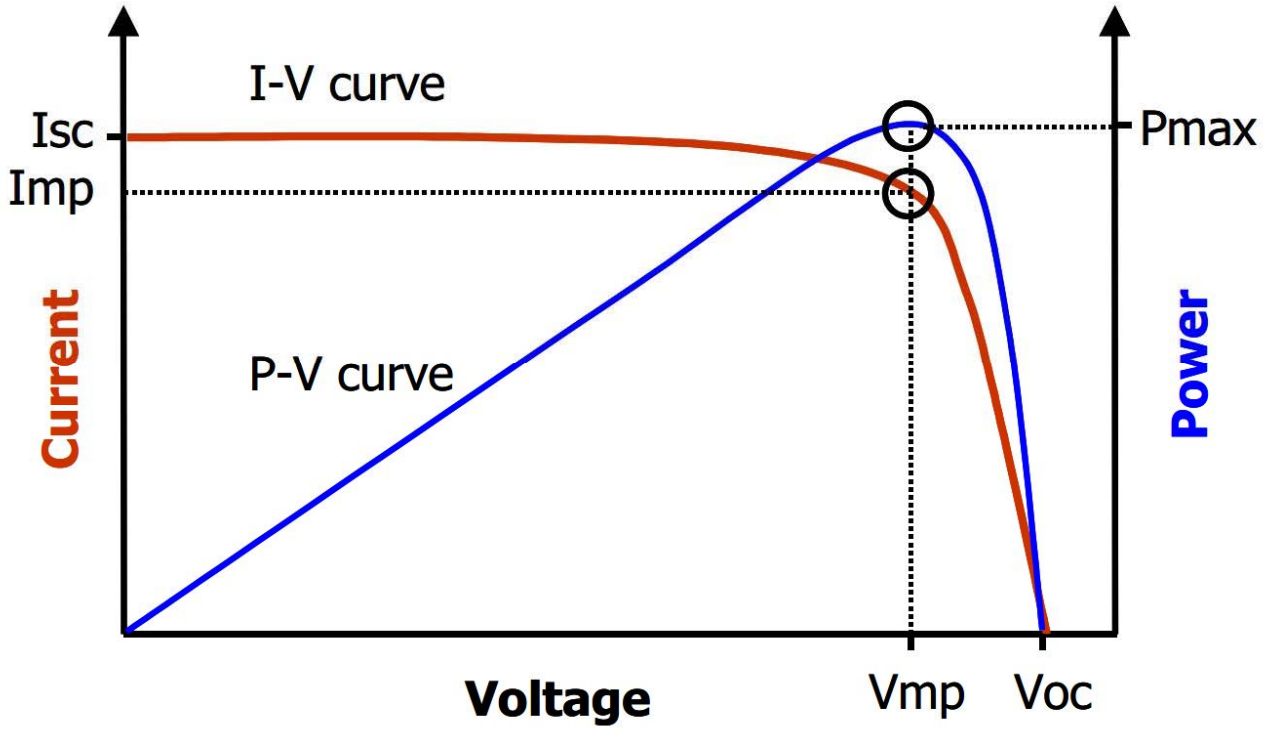
- Encapsulant
  - Provides good adhesion between PV cell, top and rear surfaces
  - Stable at high temperature and UV exposure
  - Usually EVA (ethyl vinyl acetate), many EVA formulations possible
  - Must be transparent at all usable wavelengths
  - Should have low thermal resistance (increase cell efficiency)
  - The ARCO Solar ‘disaster’ due to bad choice of encapsulant
- Rear Surface
  - Low Thermal resistance
  - Prevents water penetration from back
  - Tedlar common (UV-resistant polymer)
  - Bifacial modules
- Frame
  - Aluminum common
  - Provides support

Power Losses in Solar Cells

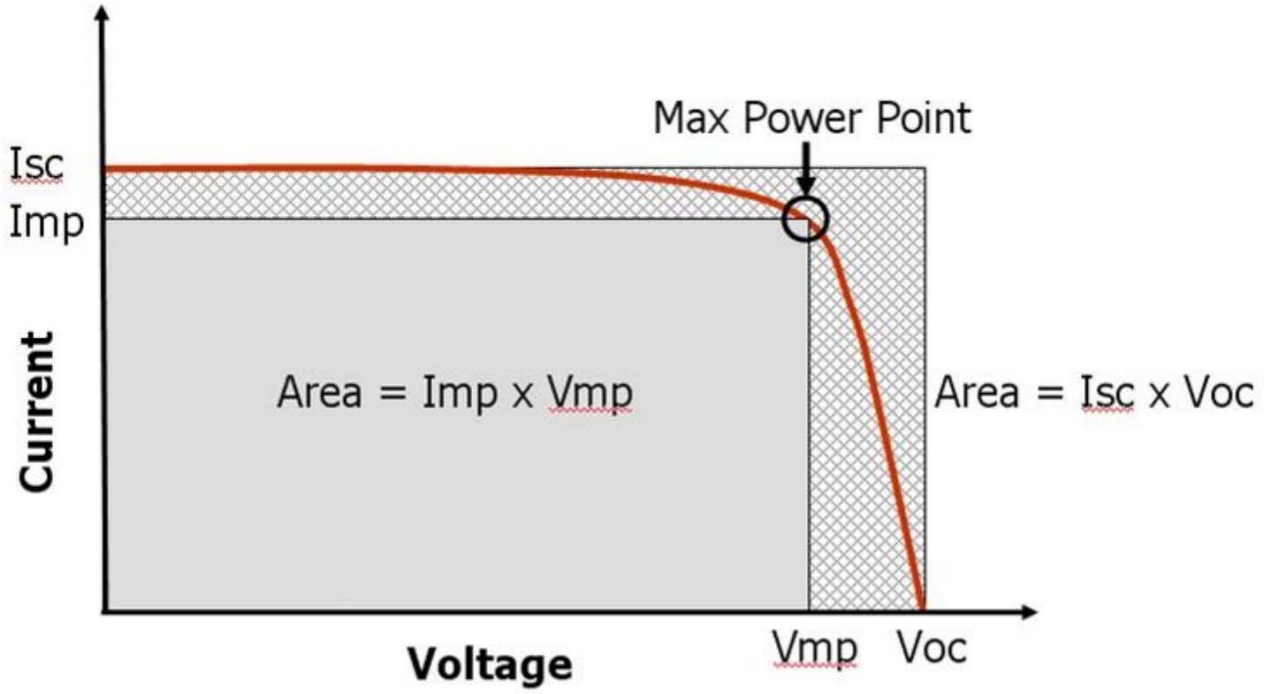
If a solar panel is 20% efficient, then where does the other 80% of the sunlight energy go?



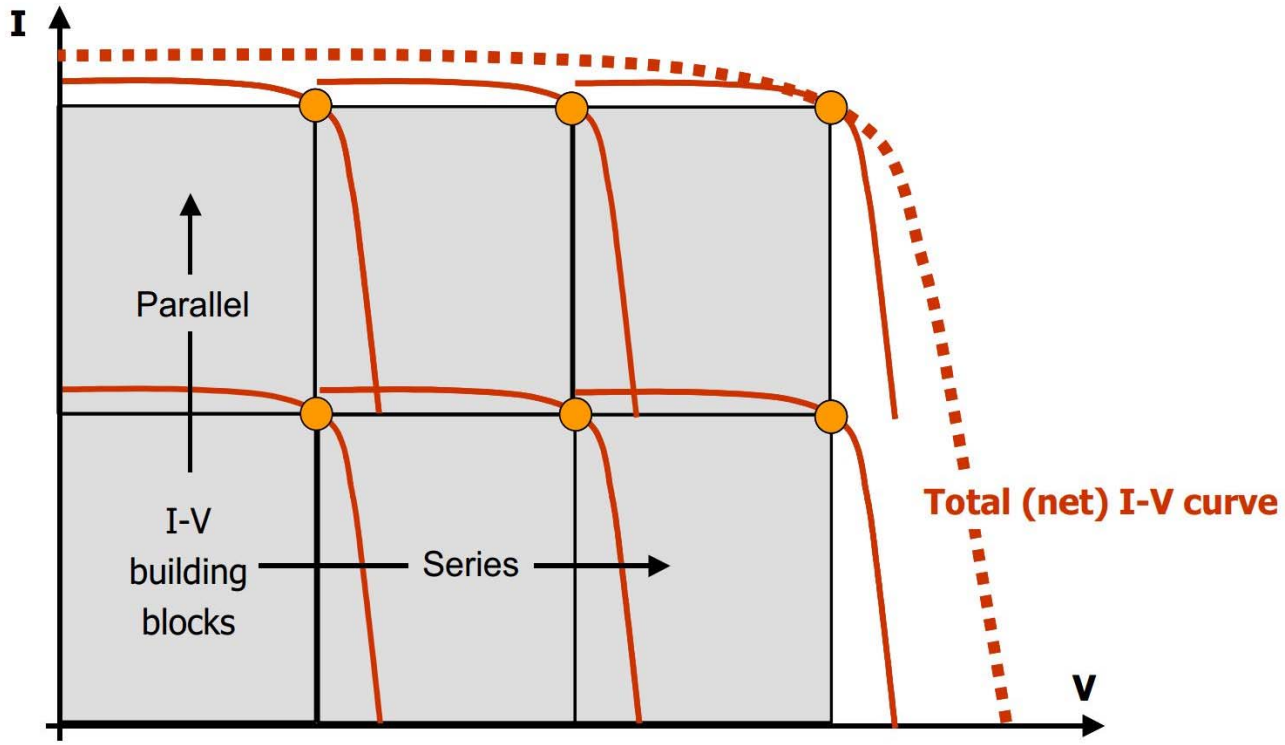
IV Curve



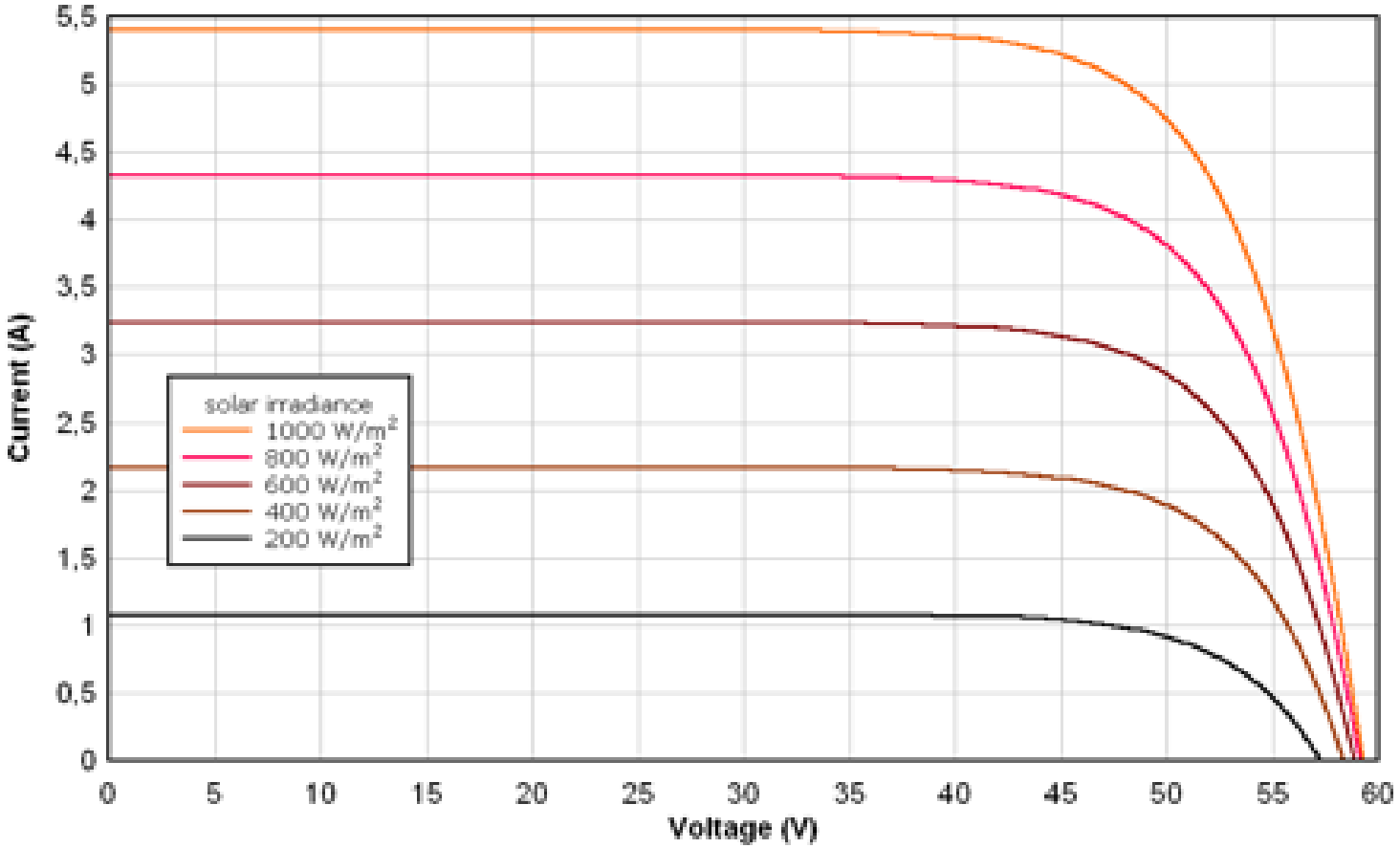
IV Curve - Fill Factor



IV Curve - Scaling



IV Curve - Irradiance



IV Curve - Temperature