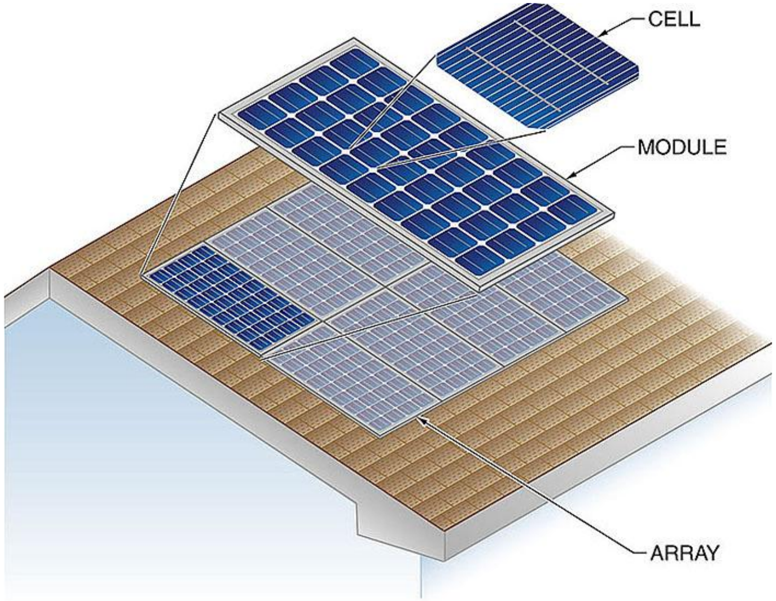
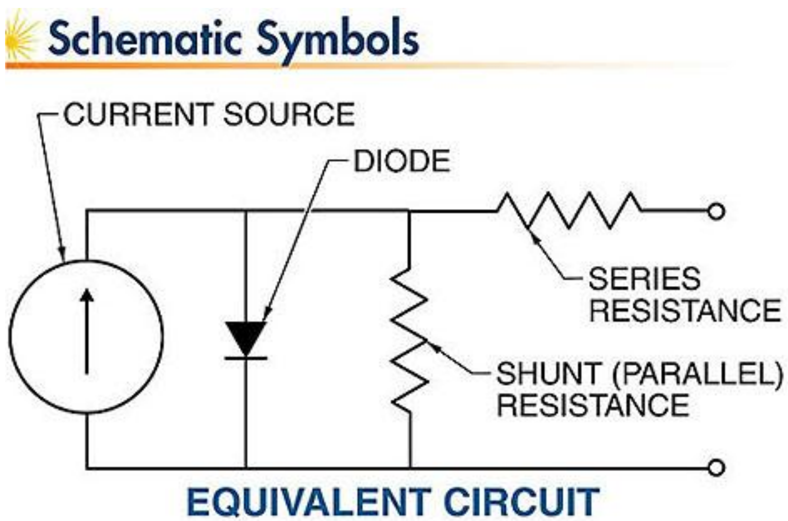
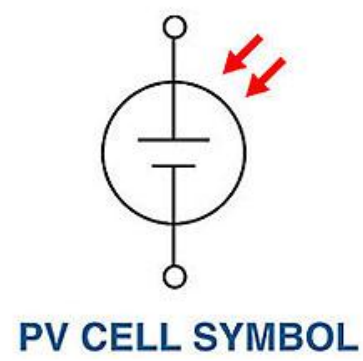
ELG4126: Photovoltaic Materials







Based Partially on Renewable and Efficient Electric Power System, Gilbert M. Masters, Wiely

Introduction

- A material or device that is capable of converting the energy contained in photons of light into an electrical voltage and current is said to be **photovoltaic**.
- A photon with short enough wavelength and high enough energy can cause an electron in a photovoltaic material to break free of the atom that holds it. If a nearby electric field is provided, those electrons can be swept toward a metallic contact where they can emerge as an electric current.
- The force to power photovoltaics comes from the sun. Note that the surface of the earth receives something like 6000 times as much solar energy as our total energy demand.

History

- The history of photovoltaics (PVs) began in 1839 when a 19-year-old French physicist, Edmund Becquerel, was able to cause a voltage to appear when he illuminated a metal electrode in a weak electrolyte solution.
- Almost 40 years later, Adams and Day were the first to study the photovoltaic effect in solids. They were able to build cells made of selenium that were 1% to 2% efficient.
- Selenium cells were quickly adopted by the emerging photography industry for photometric light meters; in fact, they are still used for that purpose today.

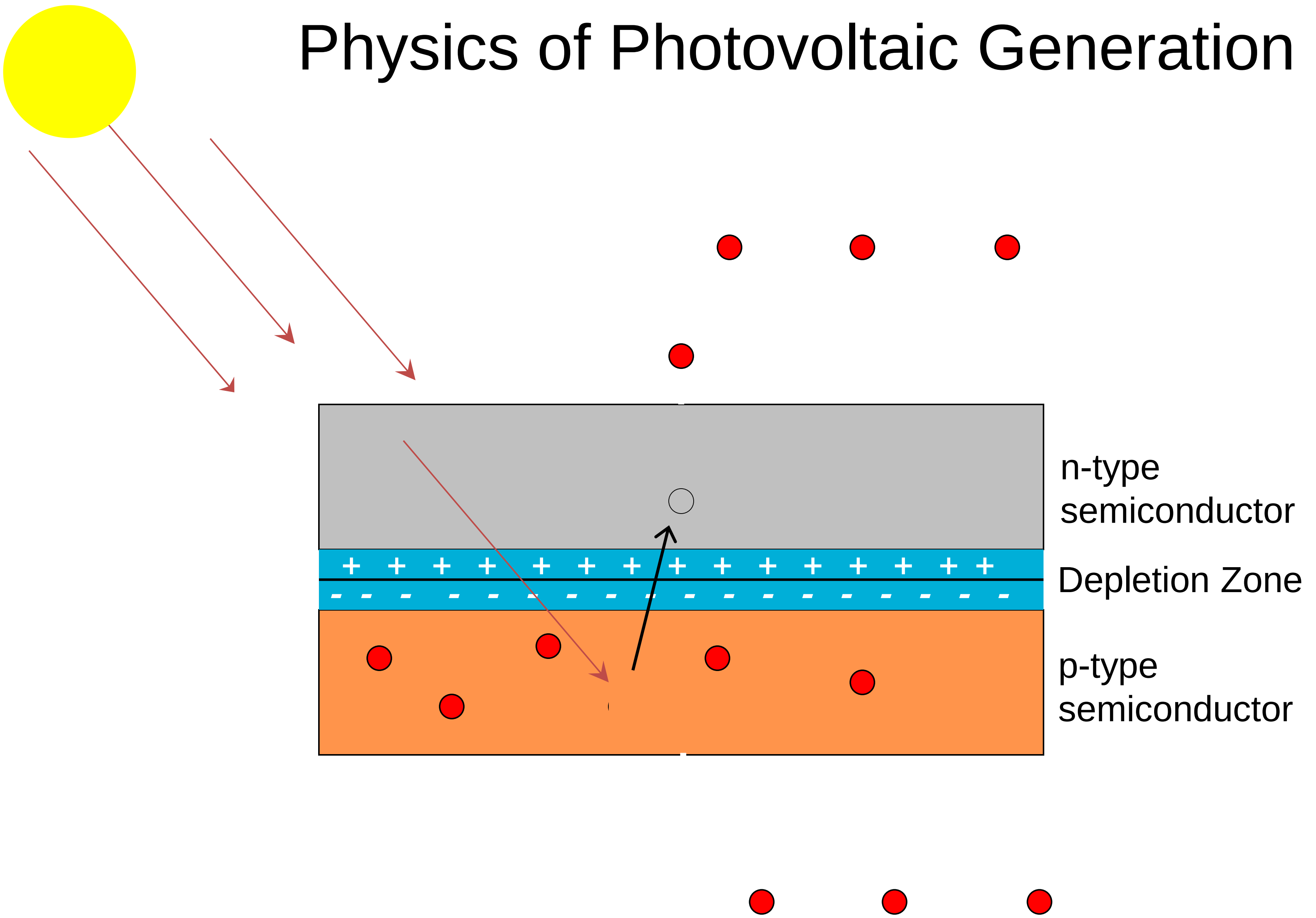
- As part of his development of quantum theory, Albert Einstein published a theoretical explanation of the photovoltaic effect in 1904, which led to a Nobel Prize in 1923.
- About the same time, in what would turn out to be a cornerstone of modern electronics in general, and photovoltaics in particular, a Polish scientist by the name of Czochralski began to develop a method to grow perfect crystals of silicon.
- By the 1940s and 1950s, the Czochralski process began to be used to make the first generation of single-crystal silicon photovoltaics, and that technique continues to dominate the photovoltaic (PV) industry today.

- The real emergence of PVs as a practical energy source came in 1958 when they were first used in space for the Vanguard I satellite. For space vehicles, cost is much less important than weight and reliability, and solar cells have ever since played an important role in providing onboard power for satellites and other space craft.
- Spurred on by the emerging energy crises of the 1970s, the development work supported by the space program began to pay off back on the ground.
- By the late 1980s, higher efficiencies and lower costs brought PVs closer to reality, and they began to find application in many off-grid terrestrial applications such as pocket calculators, off-shore buoys, highway lights, signs and emergency call boxes, rural water pumping, and small home systems.

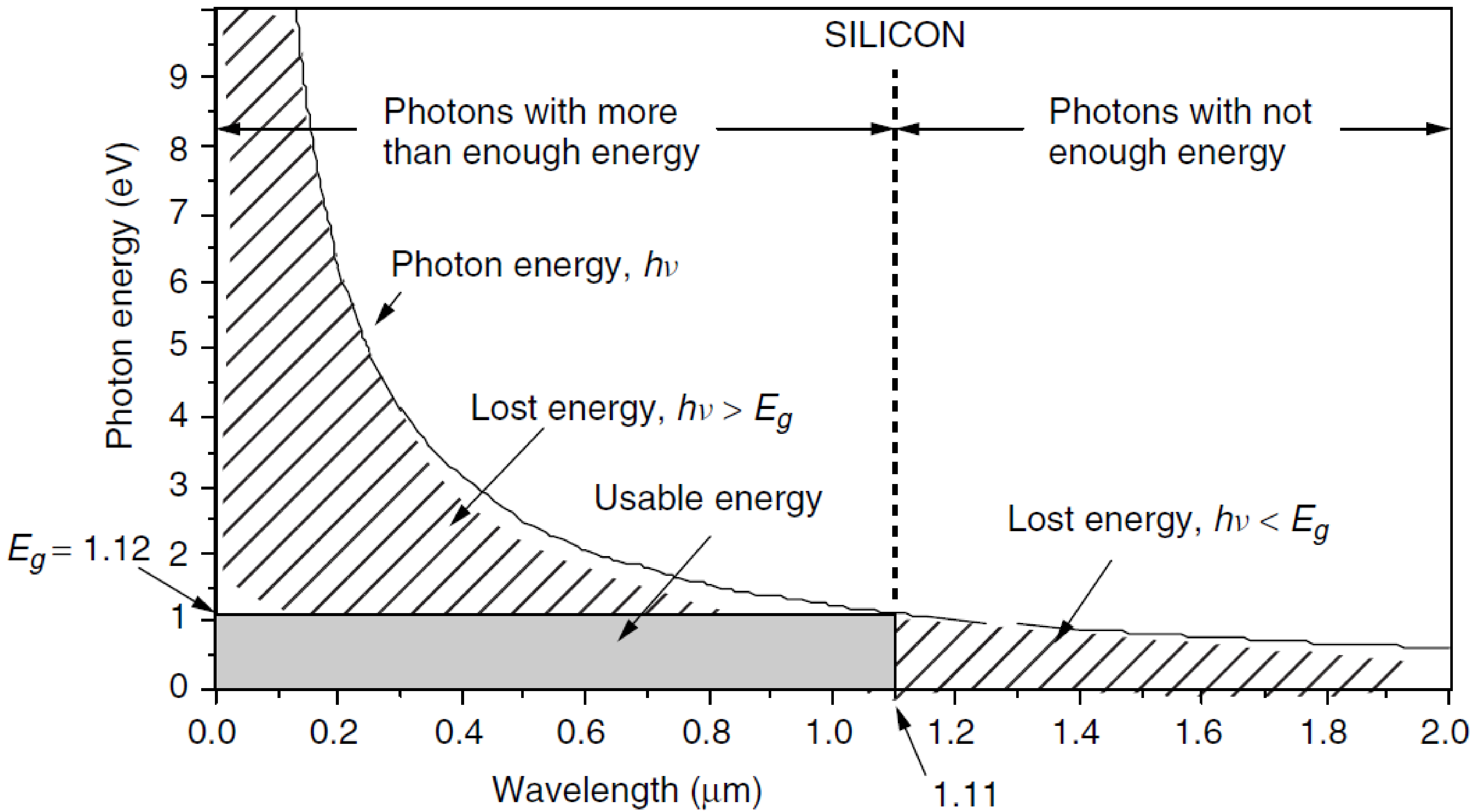
Physics

- The starting point for most of the world's current generation of photovoltaic devices, as well as almost all semiconductors, is pure crystalline silicon. It is in the fourth column of the periodic table, which is referred to as Group IV.
- Germanium is another element, and it too is used as a semiconductor in some electronics. Other elements that play important roles in photovoltaics are boron and phosphorus which are added to silicon to make most PVs.
- Gallium and arsenic are used in GaAs solar cells, while cadmium and tellurium are used in CdTe cells.

Physics of Photovoltaic Generation



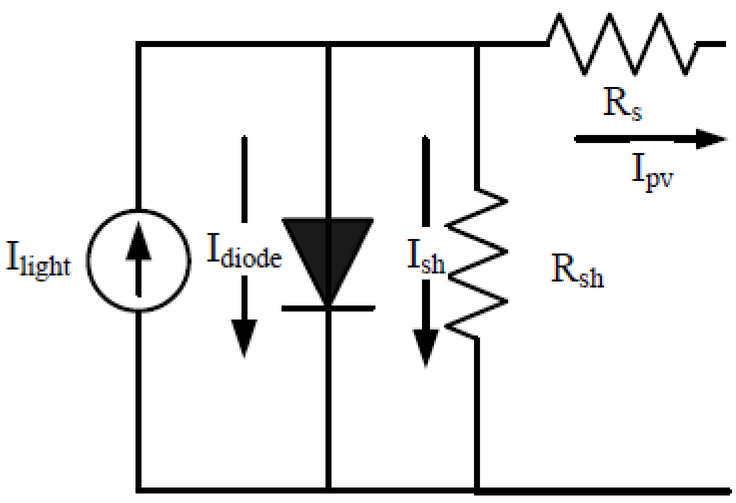
Photons with Wavelengths above 1.11 μm do not have the 1.12 eV Needed to Excite an Electron; and this Energy is Lost.



Equivalent Circuit of the Solar Cell

The current source represents the generated photocurrent when the sunlight hits the solar panel, and the diode represents the P-N transition area of the solar cell. The series and parallel resistances represent the losses due to the body of the semiconductor and the contacts.

$$I_{pv} = I_{light} - I_{diode} - I_{sh}$$



PV Material Technologies

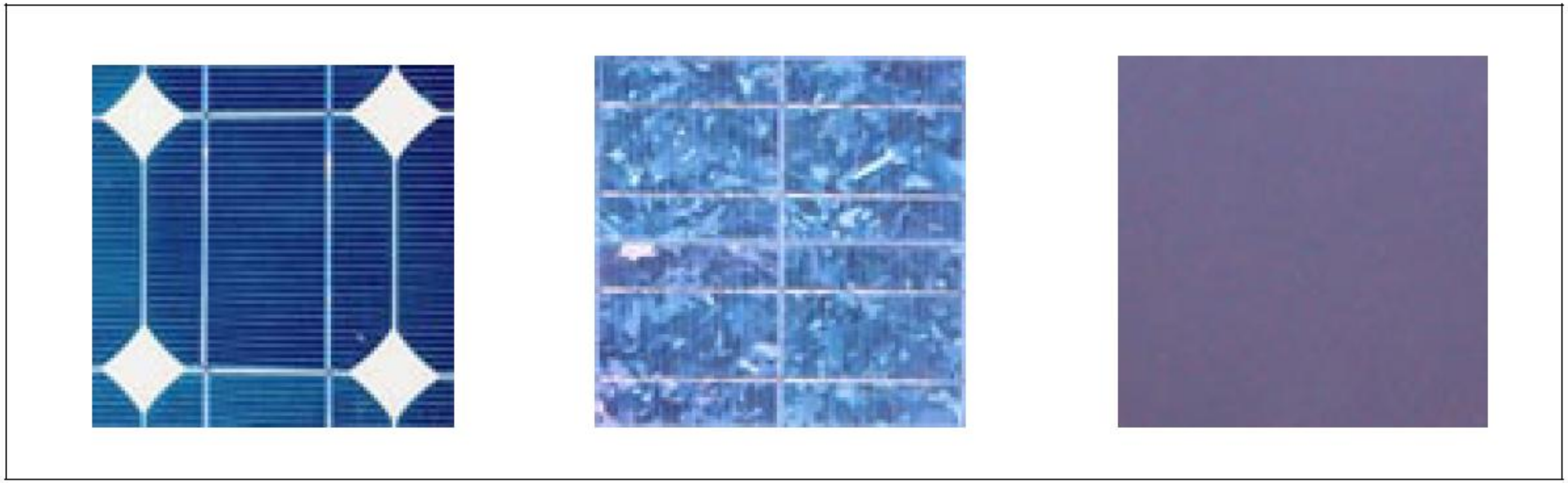
Silicon photovoltaic cell is most popular-not because it is most efficient, but because it is inexpensive as a lot of silicon is produced for making micro-electronics chips.

Many other semiconductor materials such as gallium arsenide, cadmium sulphide, and cadmium telluride are also used in special-purpose high-efficiency cells, but are more expensive than silicon cells.

Multi-junction solar cell is the latest development.

Types of Silicon

- There are two main types of crystalline silicon: mono-crystalline and poly-crystalline. Between them they represent 93% of the solar market). In the former case, silicon wafers are sliced from solid ingots, an expensive process that leads to waste.
- Efficiency is highest in such cells. Thus the story of PV technology development to date is largely one of finding cheaper manufacturing processes while maintaining useful efficiencies.
- The current main options include casting the silicon in a block (polycrystalline cells), and depositing thin layers of silicon on a solid substrate like glass in a vacuum chamber and etching the electrical connections (silicon thin film).



Mono-crystalline, polycrystalline and thin film solar cells

PV Technology Classification

Silicon Crystalline Technology

- Mono Crystalline PV Cells
- Multi Crystalline PV Cells

Thin Film Technology

- Amorphous Silicon PV Cells
- Poly Crystalline PV Cells
  (Non-Silicon based)

Concentrating Solar Cells: Si, GaAs

Silicon Crystalline Technology

- Currently makes up 86% of PV market
- Very stable with module efficiencies 10-16%

Mono crystalline PV Cells

Made using saw-cut from single cylindrical crystal of Si

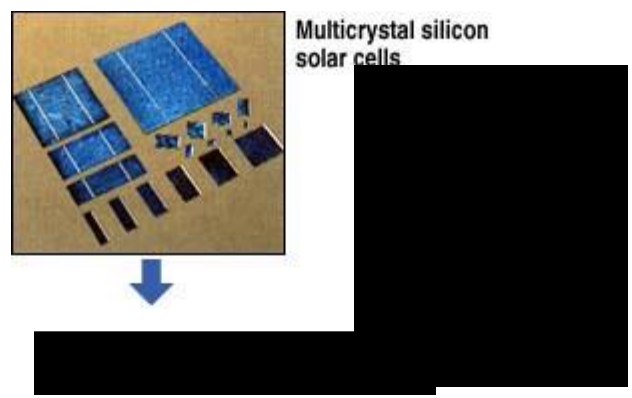
Operating efficiency up to 15%

Multi Crystalline PV Cells

Caste from ingot of melted and recrystallised silicon

Cell efficiency ~12%

Accounts for 90% of crystalline Si market

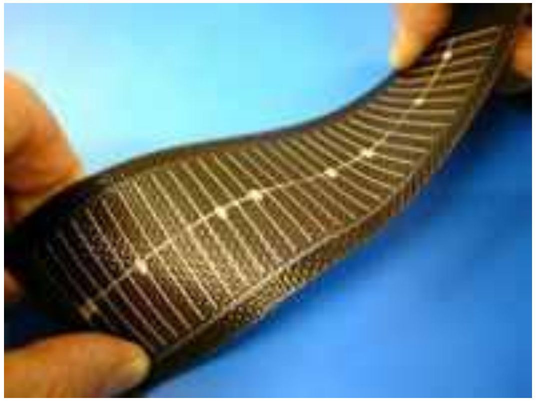


Thin Film Technology

- Silicon deposited in a continuous on a base material such as glass, metal or polymers.
- Thin-film crystalline solar cell consists of layers about 10μm thick compared with 200-300μm layers for crystalline silicon cells.

PROS
Low cost substrate and fabrication process

CONS
Not very stable



Amorphous Silicon PV Cells

The most advanced of thin film technologies

Operating efficiency ~6%

Makes up about 13% of PV market

PROS
Mature manufacturing technologies available

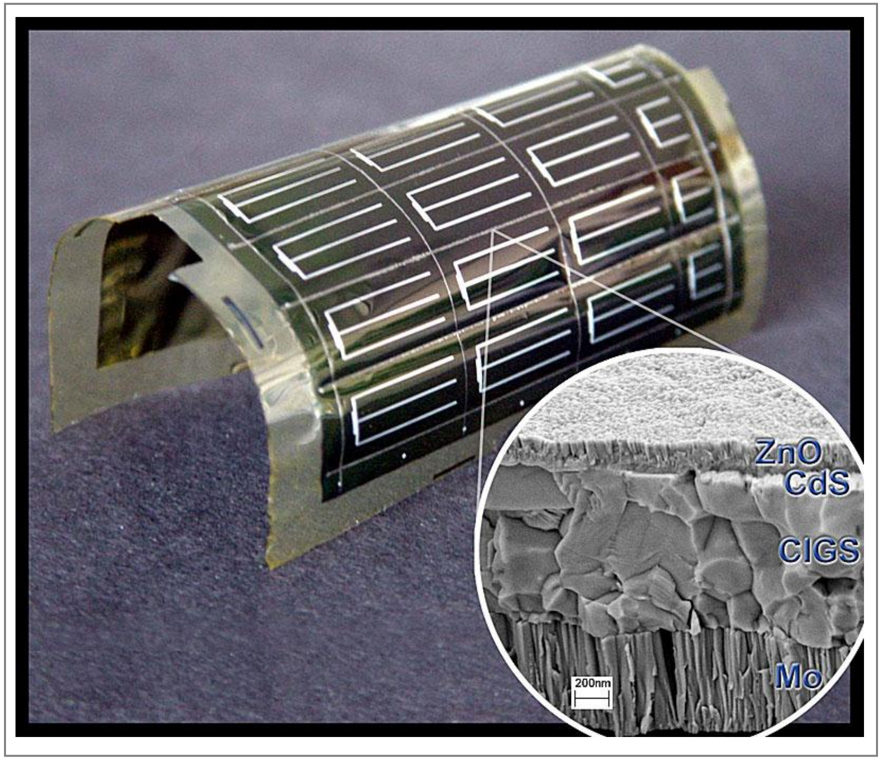
CONS
Initial 20-40% loss in efficiency

Poly Crystalline PV Cells

Non – Silicon Based Technology

With band gap 1eV, high absorption coefficient $10^5 cm^{-1}$

- High efficiency levels



PROS

- 18% laboratory efficiency
- >11% module efficiency

CONS

- Immature manufacturing process
- Slow vacuum process

Poly Crystalline PV Cells

Non – Silicon Based Technology

Unlike most other material, CdTe exhibits direct band gap of 1.4eV and high absorption coefficient

PROS

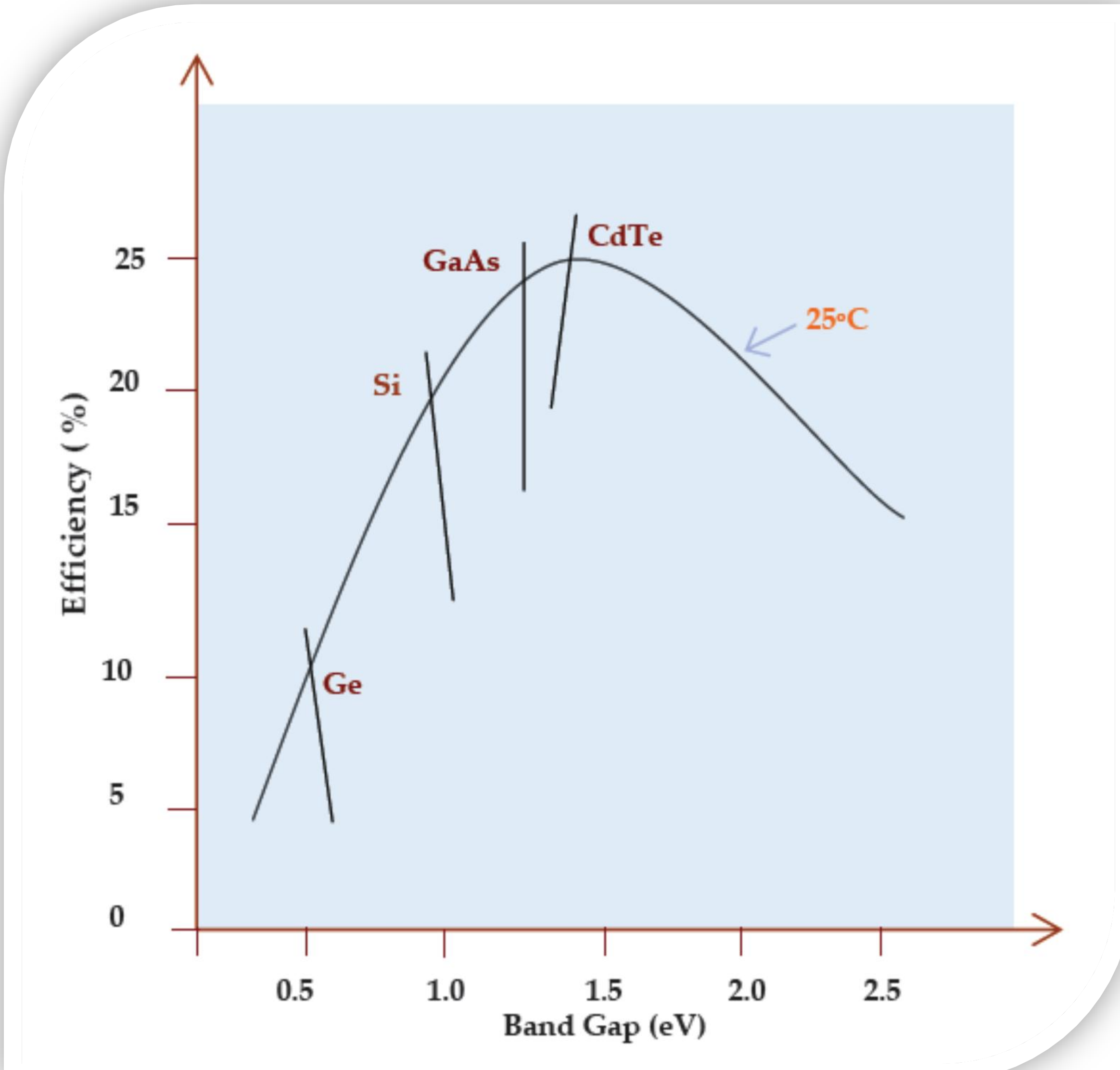
16% laboratory efficiency

6-9% module efficiency

CONS

Immature manufacturing process

Semiconductor Material Efficiencies



Single and Multi-Junction PV Devices

Today most common PV devices use a single junction to create an electric field within a semiconductor such as a PV cell. In a single-junction PV cell, only photons whose energy is equal to or greater than the band cap of the cell material can free an electron for an electric circuit. In other words, the photovoltaic response of single-junction cells is limited to the portion of the solar spectrum whose energy is above the band gap of the absorbing material, and lower-energy photons are not used.

One way to get around this limitation is to use two (or more) different cells, with more than one band gap and more than one junction, to generate a voltage. These are referred to as "multijunction" cells (also called "cascade" or "tandem" cells).

PV Material Efficiencies*

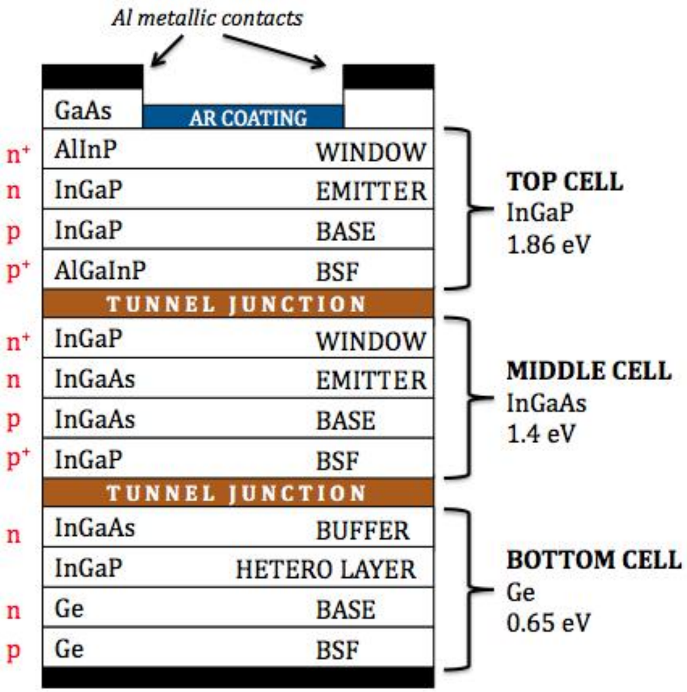
MATERIAL	TYPICAL EFFICIENCIES	BEST LABORATORY EFFICIENCY
Multijunction gallium arsenide (GaAs)	33 to 38†	40.7†
Monocrystalline silicon	14 to 17	24.7
Polycrystalline silicon	11.5 to 14	20.3
Copper indium gallium selenide (CIGS)	9 to 11.5	19.9
Cadmium telluride (CdTe)	8 to 10	16.5
Amorphous silicon (a-Si)	5 to 9.5	12.1
Dye-sensitized (Grätzel)	4 to 5	11.1
Polymer (Organic)	1 to 2.5	5

* in %
† in concentrating applications

Source: NREL

Multi-Junction PV Devices

The **multi-junction** solar cell technology has been used in cells which enables more of the solar spectrum to be captured than is the case with conventional silicon solar cells. Each **multi-junction solar cell** is made of layers with each layer designed to capture one range of wavelengths of sunlight. This increases the number of photons whose band gaps are matched and so more sunlight is absorbed and converted into electric current increasing overall efficiency.



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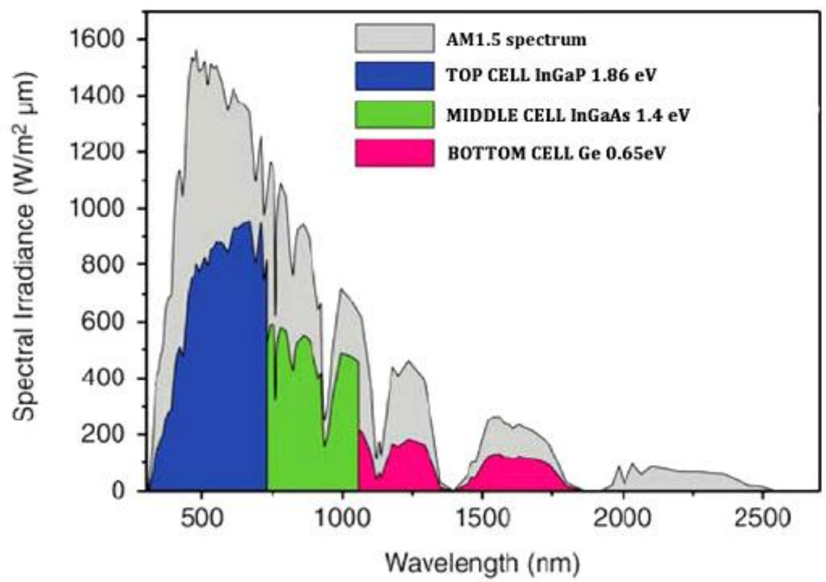
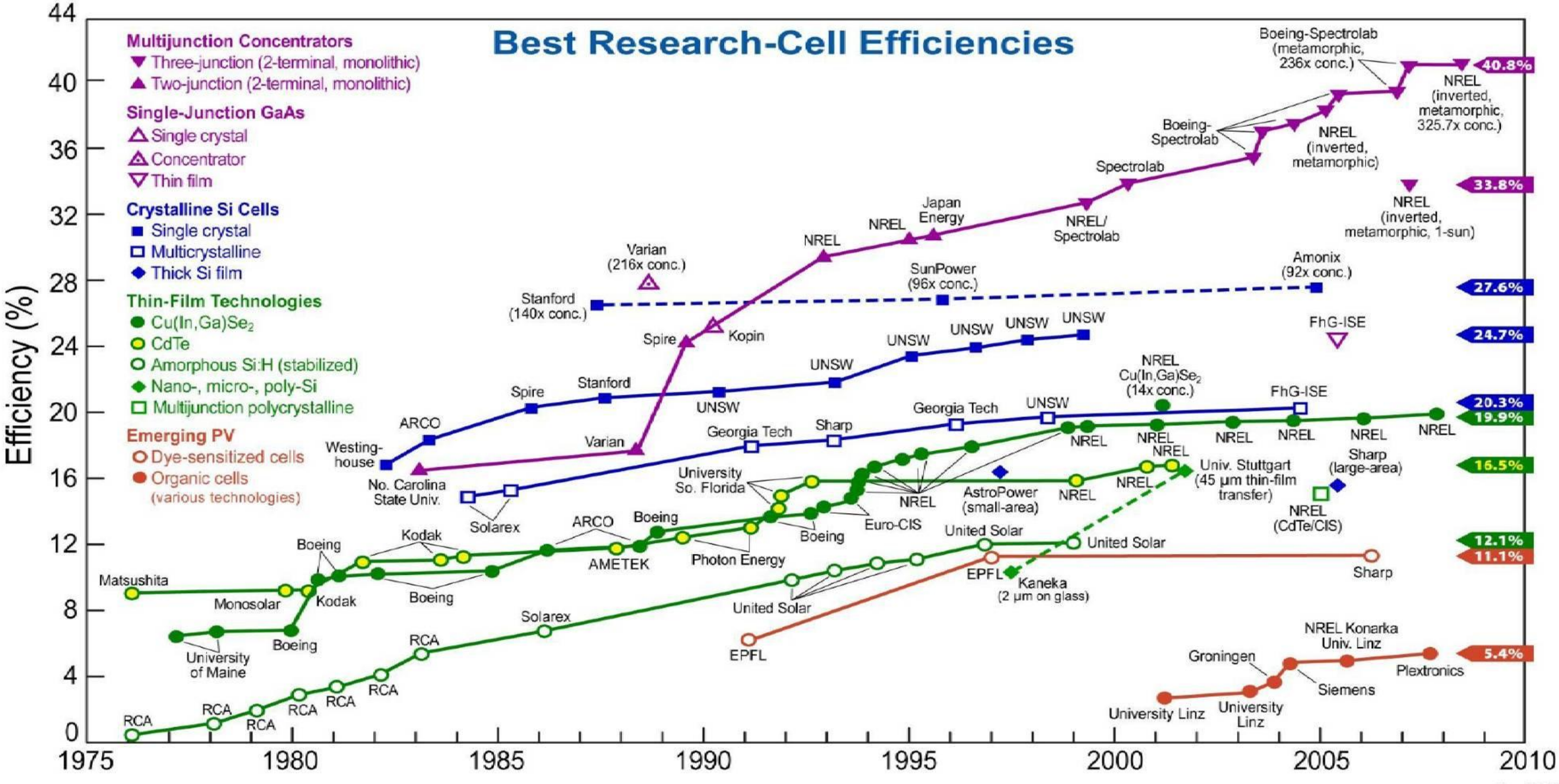


(b)

Best Laboratory PV Cell Efficiencies for Various Technology

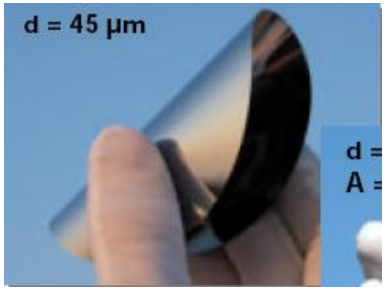


PV Conversion Efficiencies

	Modules	Cells (Lab)
Dye-sensitized solar cells	3 – 5%	8.2%
Amorphous silicon (multijunction)	6 - 8%	13.2%
Cadmium Telluride (CdTe) thin film	8 - 10%	16.5%
Copper-Indium-Gallium-Selenium (CIGS)	9 - 11%	19.9%
Multicrystalline or polycrystalline silicon	12 - 15%	20.3%
Monocrystalline silicon	14 - 16%	23.4%
High performance monocrystalline silicon	17 - 20%	24.7%
Triple-junction (GaInP/GaAs/Ge) cell (~ 250 suns)	-	40.7%
Triple-junction (GaInP/GaInAs/Ge) (454 suns)	-	41.1%

Issues today

- **Silicon Panels**
  - Past: ‘accidental’ technology
  - Present: clear technology of choice, continued cost reduction
  - Future: ‘crossroads’, but not going away



- **Thin Film**
  - Efficiencies finally becoming competitive
  - But there is more to the story than just efficiencies
  - Best on big, commercial roofs with lots of space?
- **Concentration**
  - No longer just thermal-only
  - But installers do not want moving parts
  - Predicated on silicon being expensive

Total Cost

- Aside from the solar cells themselves, costs are also significantly influenced by the **balance of systems** (BoS) – the ancillary equipment such as the components needed for mounting, power storage, power conditioning and site-specific installation.
- As PV is scalable from a single cell to an array as large as desired, and can be either stand-alone (requiring storage) or grid-connected, the proportion of system price due to BoS is highly variable, but can be up to 50% of total costs.
- Technology development tends to be driven by progress in other fields – power conditioning equipment, for example, is not by any means dominated by the solar field

Voltage Terminology

- Nominal Voltage
  - Ex. A PV panel that is sized to charge a 12 V battery, but reads higher than 12 V)
- Maximum Power Voltage (V_{max} / V_{mp})
  - Ex. A PV panel with a 12 V nominal voltage will read 17V-18V under MPPT conditions)
- Open Circuit Voltage (V_{oc})
  - This is seen in the early morning, late evening, and while testing the module)
- Standard Test Conditions (STC)
  - 25 º C (77 º) cell temperature and 1000 W/m^2 insolation

Peak Power Point (Maximum Power)

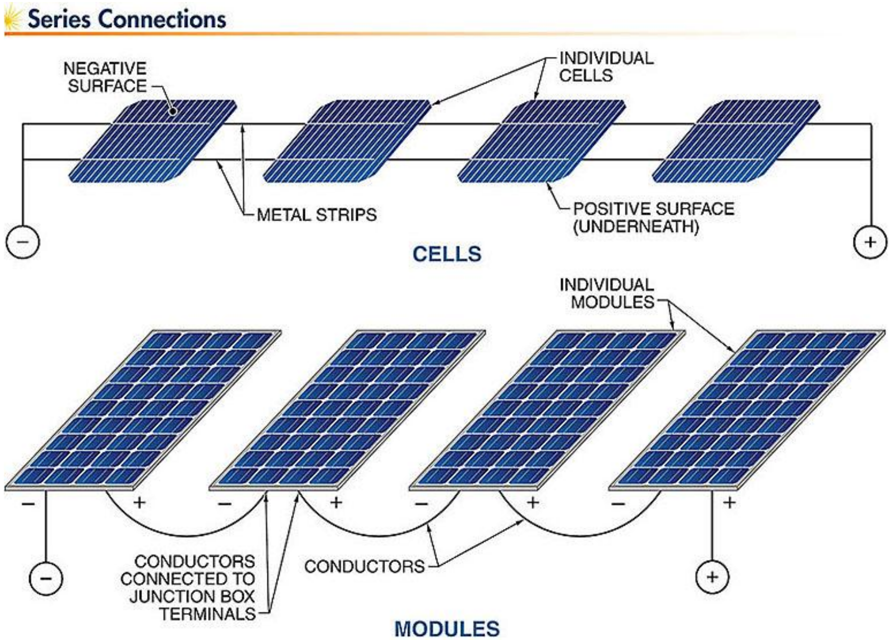
- A solar cell may operate over a wide range of voltages (V) and currents (I). By increasing the resistive load on an irradiated cell continuously from zero (a *short circuit*) to a very high value (an *open circuit*) one can determine the maximum-power point, the point that maximizes V×I, that is, the load for which the cell can deliver maximum electrical power at that level of irradiation.
- Dynamically adjust the load so the maximum power is *always* transferred, regardless of the variation in lighting.

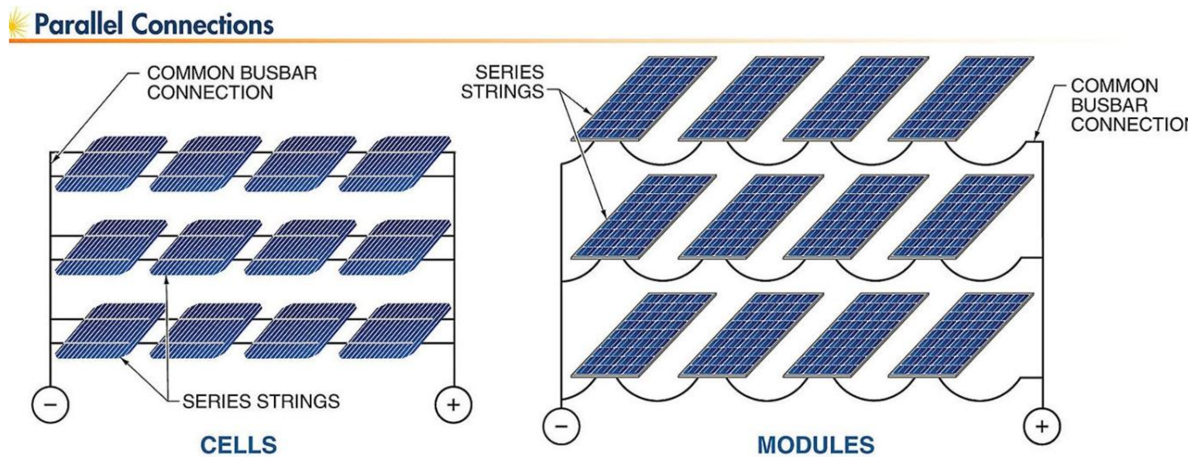
Efficiency

A solar cell's energy conversion efficiency (*η*, "eta"), is the percentage of power converted (from absorbed light to electrical energy) and collected, when a solar cell is connected to an electrical circuit. This term is calculated using the ratio of P_m, divided by the input light irradiance under "standard" test conditions (E, in W/m^2) and the surface area of the solar cell (A_c in m^2).

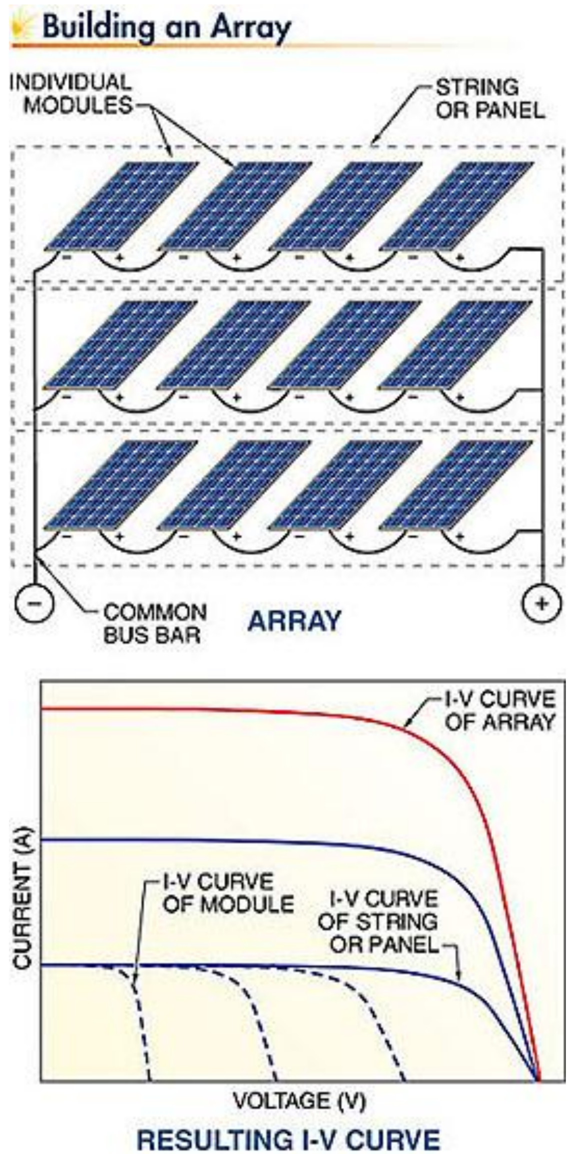
$$\eta = \frac{P_m}{E \times A_c}$$

Connection

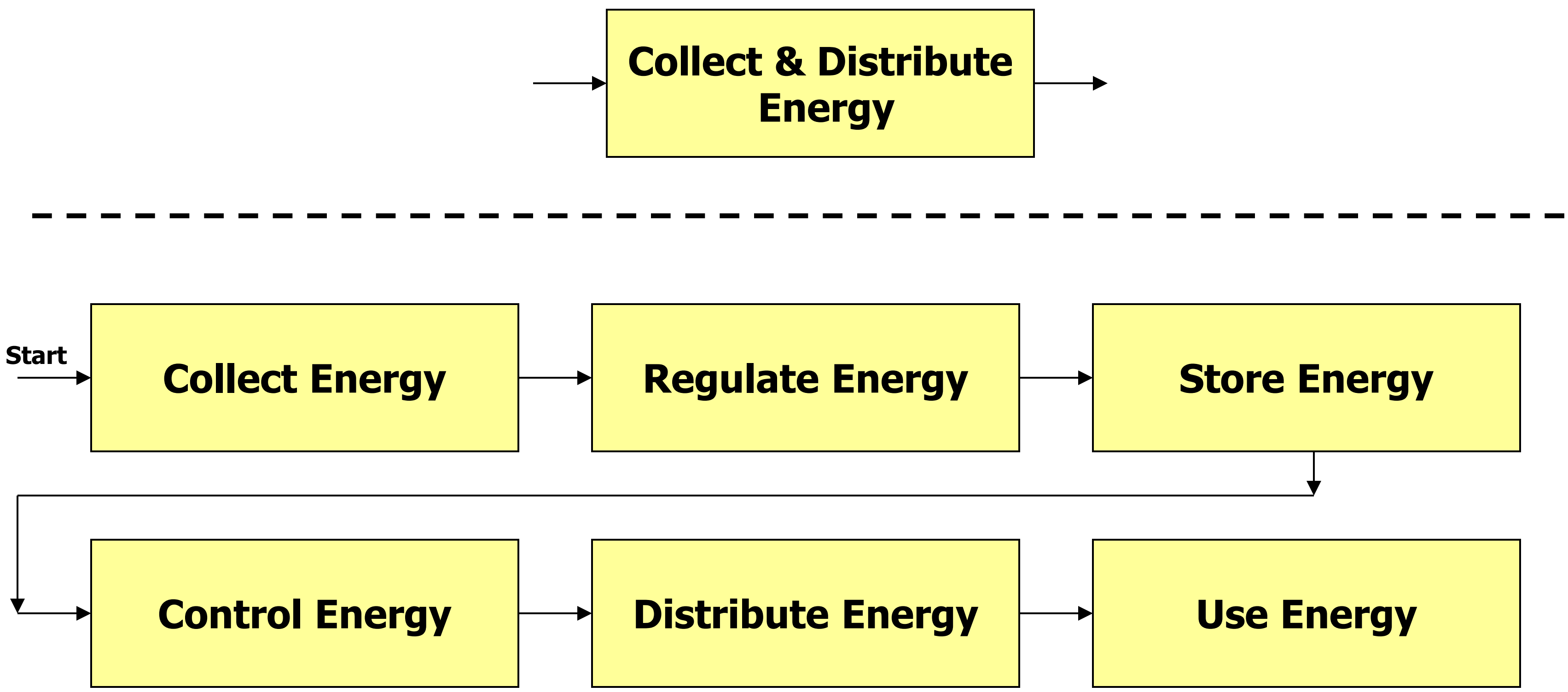

Series Connections
NEGATIVE SURFACE
INDIVIDUAL CELLS
METAL STRIPS
POSITIVE SURFACE (UNDERNEATH)
CELLS
INDIVIDUAL MODULES
CONDUCTORS CONNECTED TO JUNCTION BOX TERMINALS
CONDUCTORS
MODULES


Parallel Connections
COMMON BUSBAR CONNECTION
SERIES STRINGS
CELLS
SERIES STRINGS
COMMON BUSBAR CONNECTION
MODULES

Building an Array

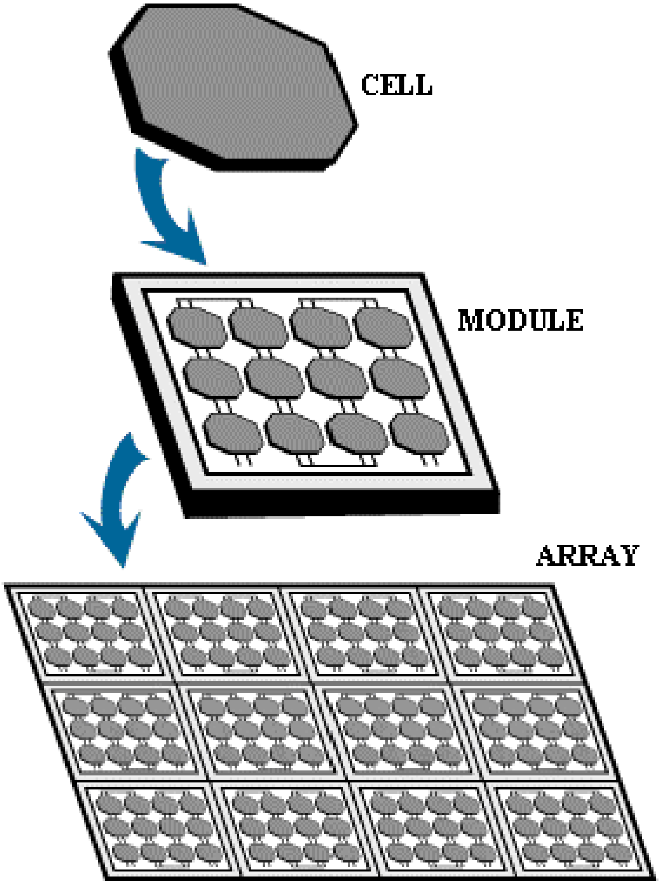


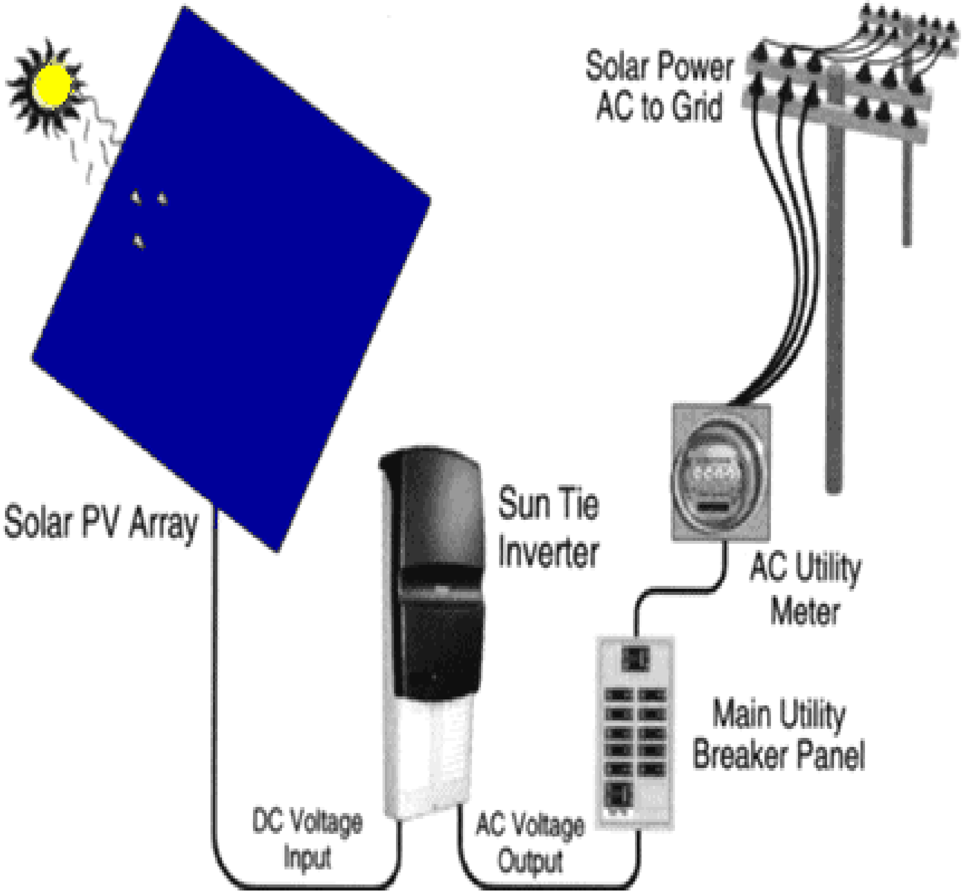
Solar Energy Systems Decomposition



Each function drives a part of the design, while the interfaces between them will be defined and agreed upon to ensure follow-on upgrades

Photovoltaic System





Typical output of a module (~30 cells) is ≈ 15 V, with 1.5 A current

PV Technology Basics

Batteries are often used in PV systems for the purpose of storing energy produced by the PV array during the day, and to supply it to electrical loads as needed (during the night and periods of cloudy weather). Other reasons batteries are used in PV systems are to operate the PV array near its maximum power point, to power electrical loads at stable voltages, and to supply surge currents to electrical loads and inverters. In most cases, a battery charge controller is used in these systems to protect the battery from overcharge and over-discharge.

In many stand-alone PV systems, batteries are used for energy storage. This figure shows a diagram of a typical stand-alone PV system powering DC and AC loads