Principles of Photovoltaics (PV)

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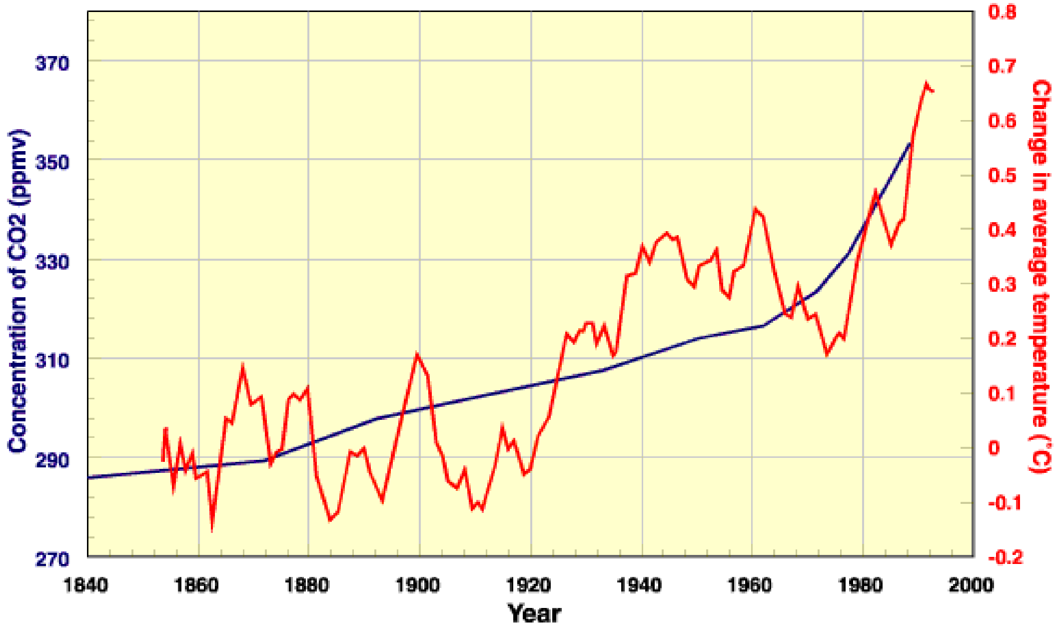
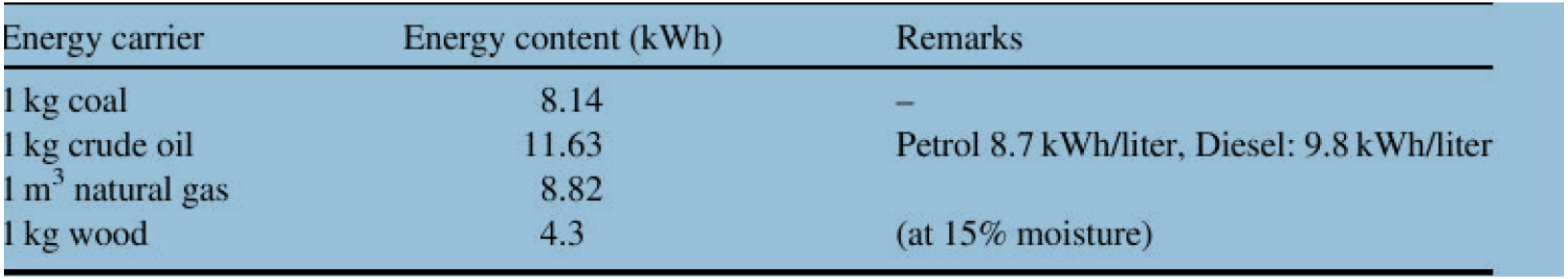
The Greenhouse Effect

- 270 ppm carbon dioxide (CO_2) in the atmosphere absorbs outgoing radiation, thereby keeping this energy in the atmosphere and warming the Earth





Energy carrier	Energy content (kWh)	Remarks
1 kg coal	8.14	–
1 kg crude oil	11.63	Petrol 8.7 kWh/liter, Diesel: 9.8 kWh/liter
1 m^3 natural gas	8.82	
1 kg wood	4.3	(at 15% moisture)

Target Renewable Capacity by 2032

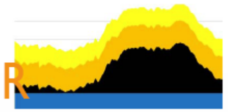
Maximizing Renewable Deployment Return

54 GW

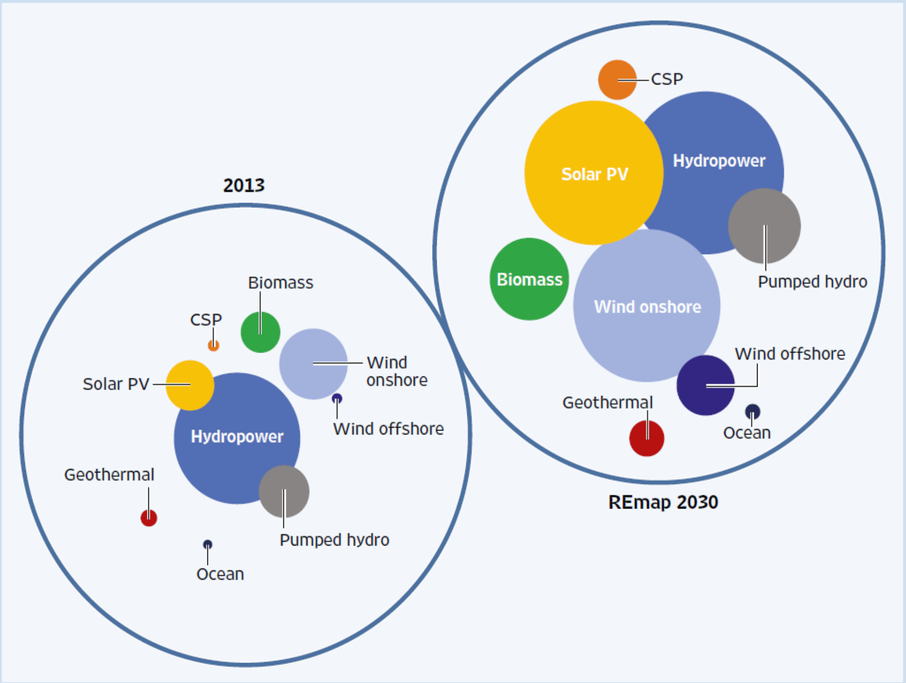
Target Renewable Capacity by 2032

Solar PV	16 GW
Solar CSP	25 GW
Wind الرياح	9 GW
Waste-to-energy	3 GW
Geothermal	1 GW

Load-Specific Technology Component of the Proposed Energy Mix by 2032



- PV will meet total day time demand year round
- GEOTHERMAL + WASTE-TO-ENERGY + OTHER SOURCES will meet base-load demand up to night time demand during winter
- CSP with storage will meet maximum demand difference between PV and base-load technologies
- HYDROCARBONS will meet the rest of the demand
- WIND will be dedicated for desalination



Source: IRENA statistics and IRENA, 2014

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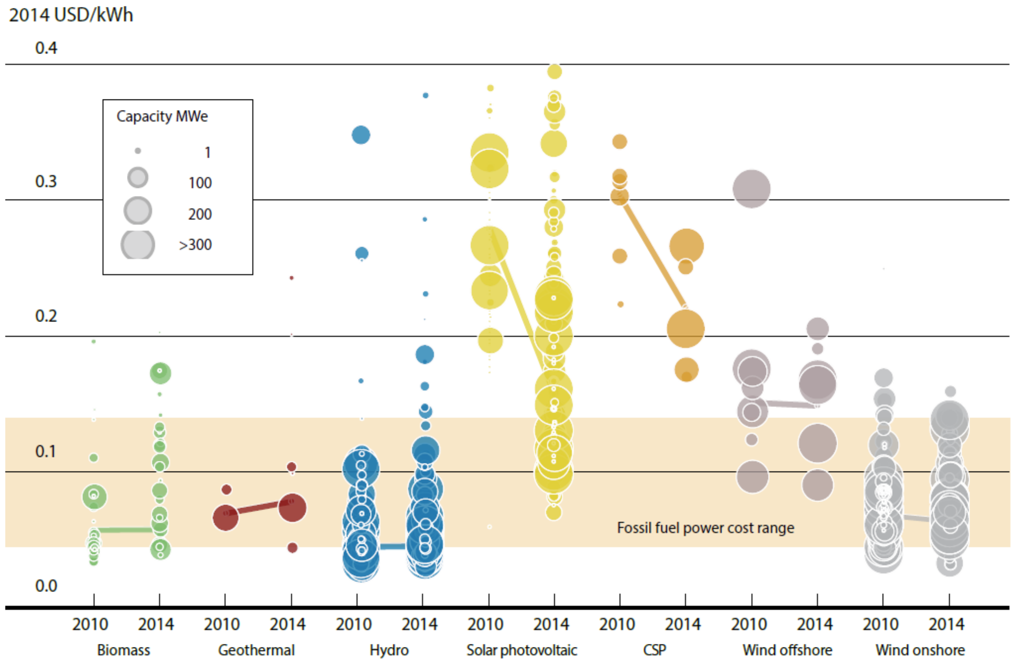
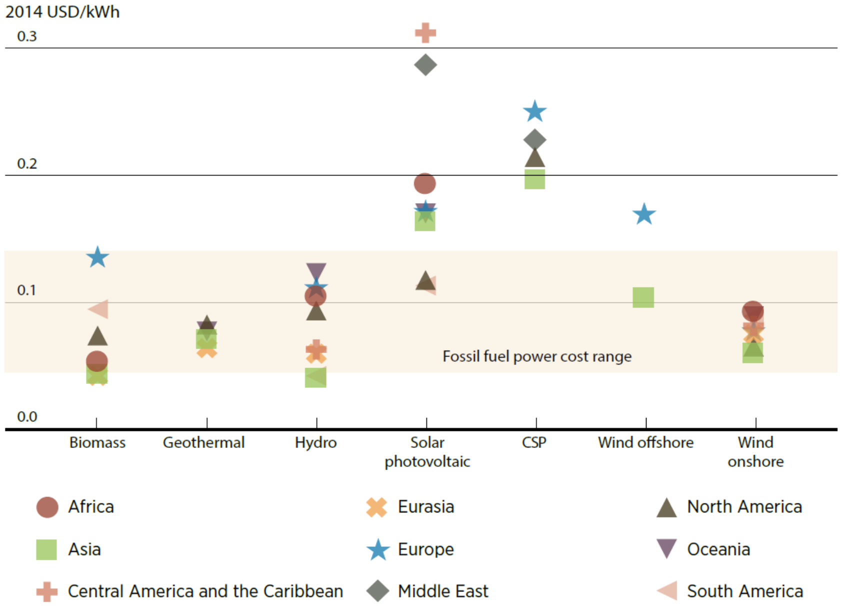


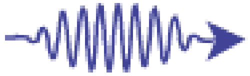


PV Module	Inverter	BOS/Installation
Semiconductor • Raw materials (Si feedstock, saw slurry, saw wire) • Utilities, maintainence, labour • Equipment, tooling, building, cost of capital • Manufacturer's margin **Cell** • Raw materials (eg. metallization, SiNX, dopants, chemicals) • Utilities, maintainence, labour • Equipment, tooling, building, cost of capital • Manufacturer's margin **Module** • Raw materials (eg. glass, EVA, metal frame, j-box) • Utilities, maintainence, labour • Equipment, tooling, building, cost of capital • Shipping • Manufacturer's margin • Retail margin	• Magnetics • Manufacture • Board and electronics (capacitors) • Enclosure • Power electronics	• Mounting and racking hardware • Wiring • Other • Permits • System design, management, marketing • Installer overhead and other • Installation labour

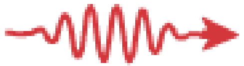
Source: GlobalData, 2014.

Properties of Light

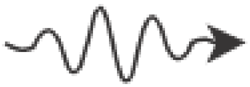
High energy photon for blue light.



Lower energy photon for red light.

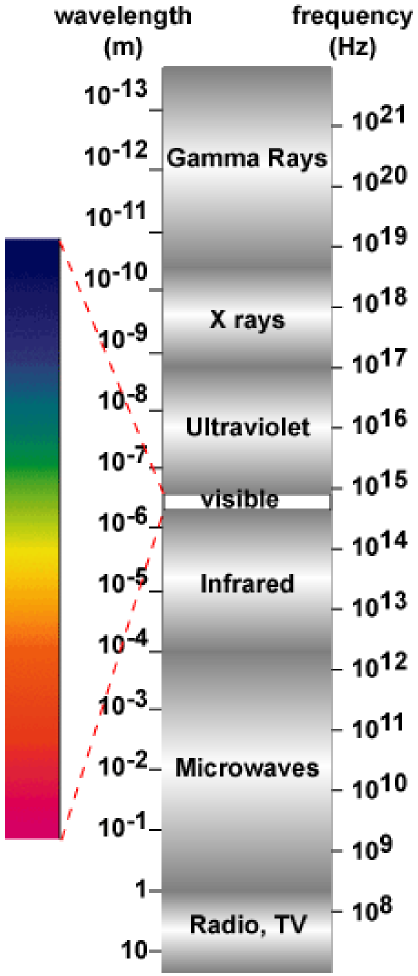


Low energy photon for infrared light.
Should be invisible!



$E = hc/\lambda$

$h = 6.626 \times 10^{-34}$ joule·s
$c = 2.998 \times 10^{8}$ m/s



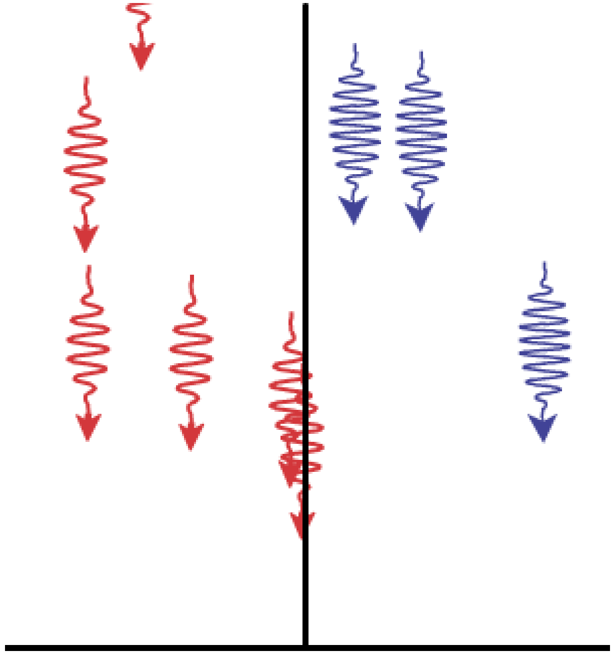
Photon Flux

- the photon flux gives the energy striking a surface per unit time, which is equivalent to a power density.

$$\Phi = \frac{\#\ of\ photons}{\sec m^2}$$

For determining the power density

the energy or wavelength of the photons in the light source must also be specified.



For the same light intensity, blue light requires fewer photons since the energy content of each photon is greater.

Solar Radiation at the Earth's Surface

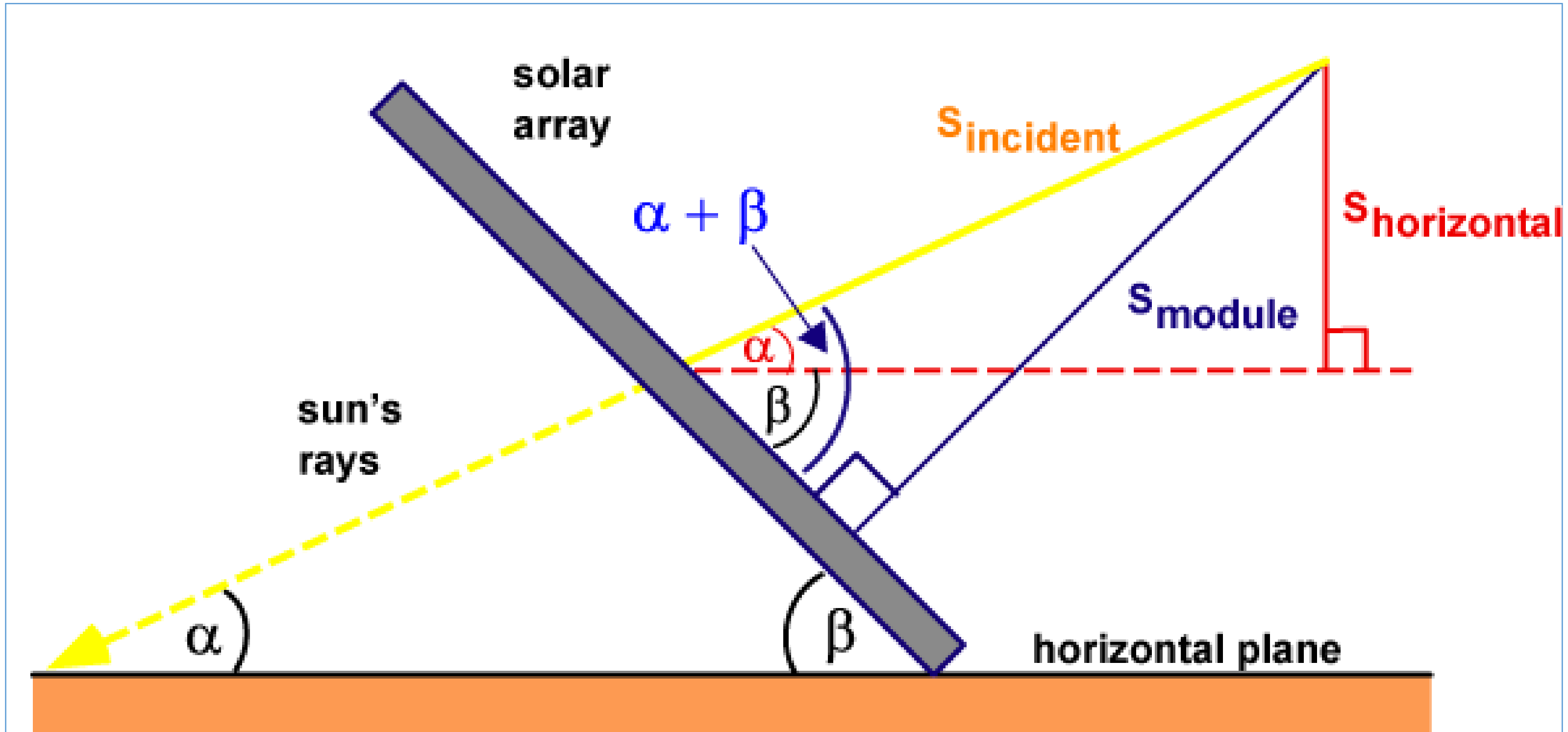
- atmospheric effects, including absorption and scattering
- local variations in the atmosphere, such as water vapour, clouds, and pollution
- latitude of the location
- the season of the year and the time of day.

Solar Radiation on a Tilted Surface

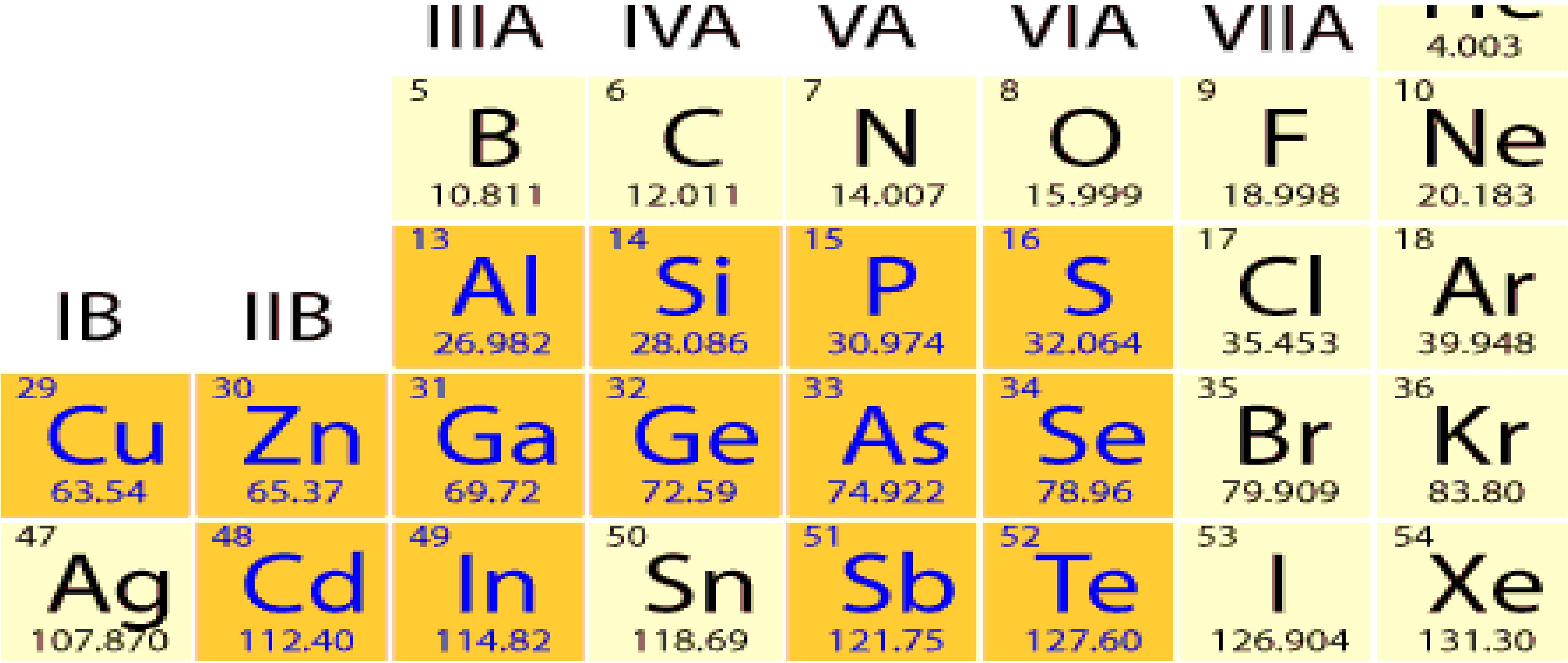
- α is the elevation angle; and β is the tilt angle of the module measured from the horizontal.

$$S_{horizontal} = S_{incident} \sin\alpha$$

$$S_{module} = \frac{S_{horizontal} \sin(\alpha+\beta)}{\sin\alpha}$$



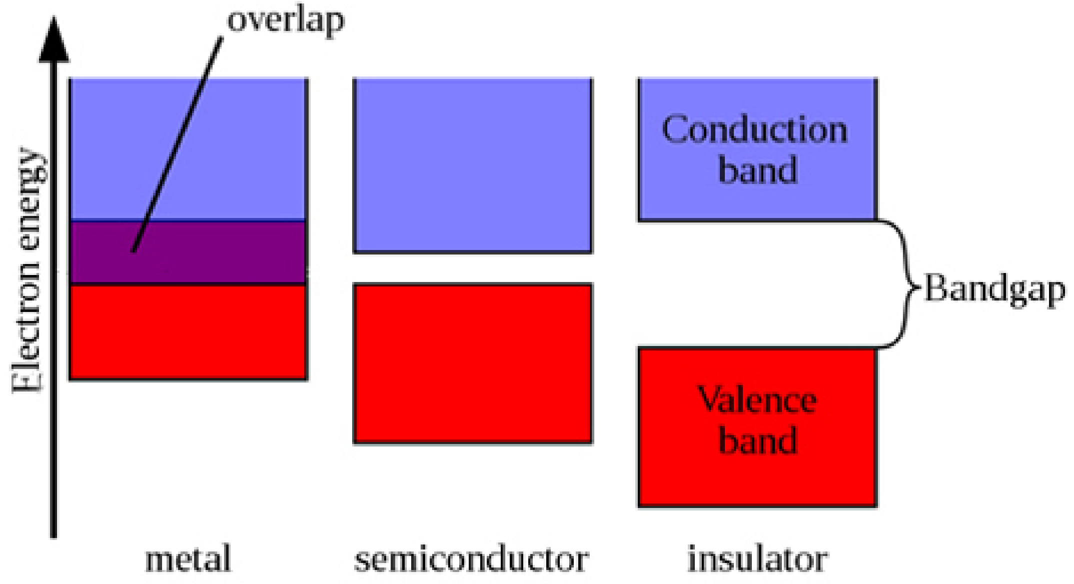
Semiconductor Materials



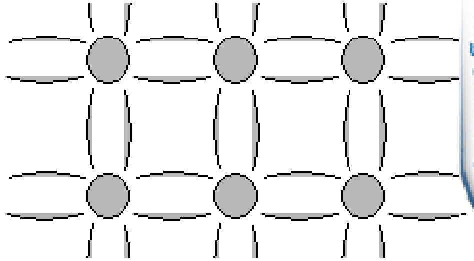
IB	IIB	IIIA	IVA	VA	VIA	VIIA	
							4.003
		5 B 10.811	6 C 12.011	7 N 14.007	8 O 15.999	9 F 18.998	10 Ne 20.183
		13 Al 26.982	14 Si 28.086	15 P 30.974	16 S 32.064	17 Cl 35.453	18 Ar 39.948
29 Cu 63.54	30 Zn 65.37	31 Ga 69.72	32 Ge 72.59	33 As 74.922	34 Se 78.96	35 Br 79.909	36 Kr 83.80
47 Ag 107.870	48 Cd 112.40	49 In 114.82	50 Sn 118.69	51 Sb 121.75	52 Te 127.60	53 I 126.904	54 Xe 131.30

Band Gaps Of Different Materials

Material	Symbol	Band Gap (eV)
Silicon	Si	1.11
Cadmium telluride	CdTe	1.49
Cadmium selenide	CdSe	1.73
Copper oxide	CuO	1.20
Gallium arsenide	GaAs	1.43
Indium phosphide	InP	1.35
Selenium	Se	1.74
Visible light		1.59- 3.26



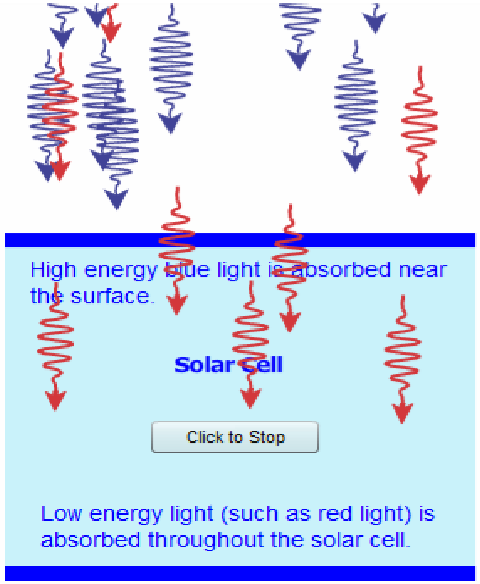
Conduction in Semiconductors



- The electrons in the covalent bond formed between each of the atoms in the lattice structure are held in place by this bond and hence they are localized to the region surrounding the atom. These bonded electrons cannot move or change energy, and thus are not considered "free" and cannot participate in current flow, absorption, or other physical processes of interest in solar cells. **However, only at absolute zero are all electrons in this "stuck," bonded arrangement.** At elevated temperatures, especially at the temperatures where solar cells operate, electrons can gain enough energy to escape from their bonds. When this happens, the electrons are free to move about the crystal lattice and participate in conduction. At room temperature, a semiconductor has enough free electrons to allow it to conduct current. At or close to absolute zero a semiconductor behaves like an insulator.
- The band gap is the minimum amount of energy required for an electron to break free of its bound state.

Absorption of Light

- $E_{ph} < E_G$ Photons with energy E_{ph} less than the band gap energy E_G interact only weakly with the semiconductor, passing through it as if it were transparent.
- $E_{ph} = E_G$ have just enough energy to create an electron hole pair and are efficiently absorbed.
- $E_{ph} > E_G$ Photons with energy much greater than the band gap are strongly absorbed. However, for photovoltaic applications, the photon energy greater than the band gap is wasted as electrons quickly thermalize back down to the conduction band edges.

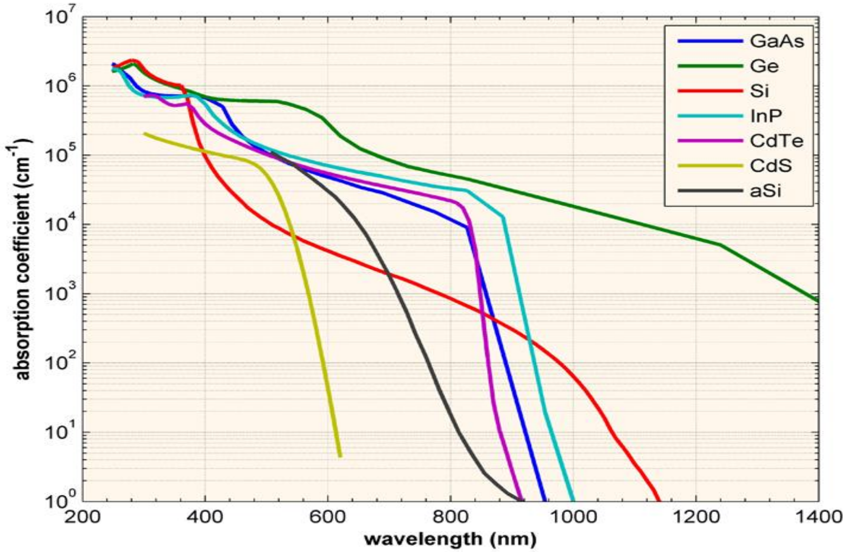


High energy blue light is absorbed near the surface.

Low energy light (such as red light) is absorbed throughout the solar cell.

Absorption Coefficient

- The absorption coefficient determines how far into a material light of a particular wavelength can penetrate before it is absorbed. In a material with a low absorption coefficient, light is only poorly absorbed, and if the material is thin enough, it will appear transparent to that wavelength. The absorption coefficient depends on the material and also on the wavelength of light which is being absorbed. Semiconductor materials have a sharp edge in their absorption coefficient, since light which has energy below the band gap does not have sufficient energy to excite an electron into the conduction band from the valence band. Consequently this light is not absorbed.
- Materials with higher absorption coefficients more readily absorb photons, which excite electrons into the conduction band.

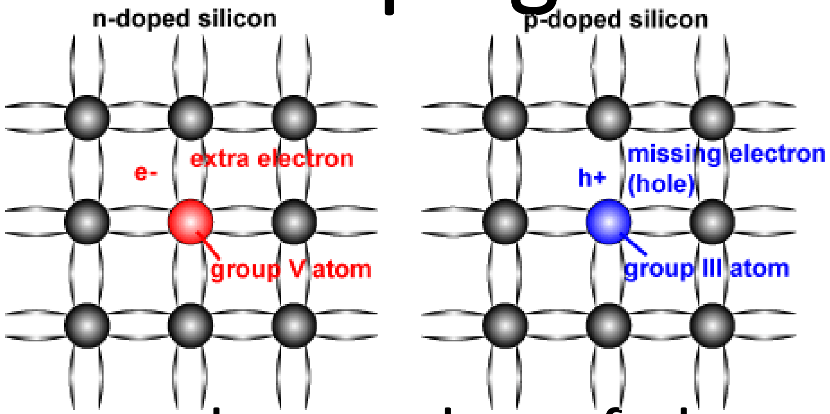


The absorption coefficient for several semiconductor materials is shown.

Absorption Depth

- The absorption depth is given by the inverse of the absorption coefficient, and describes how deeply light penetrates into a semiconductor before being absorbed.
- Higher energy light is of a shorter wavelength and has a shorter absorption depth than lower energy light, which is not as readily absorbed, and has a greater absorption depth.
- Absorption depth affects aspects of solar cell design, such as the thickness of the semiconductor material.

Doping



- Doping is a technique used to vary the number of electrons and holes in semiconductors.
- Doping creates N-type material when semiconductor materials from group IV are doped with group V atoms. P-type materials are created when semiconductor materials from group IV are doped with group III atoms.
- N-type materials increase the conductivity of a semiconductor by increasing the number of available electrons; P-type materials increase conductivity by increasing the number of holes present.

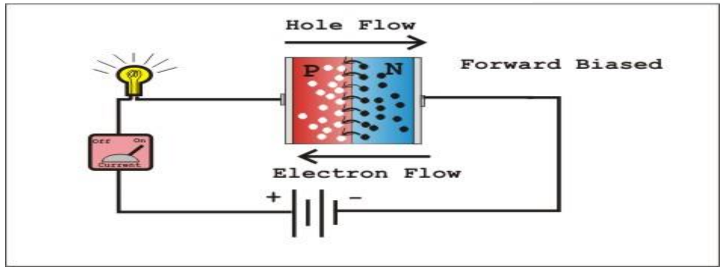
Generation Rate

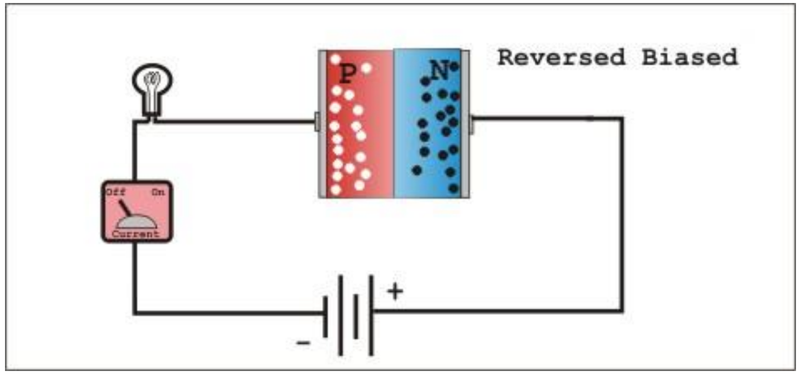
- The generation of an electron-hole pair can be calculated at any location within the solar cell, at any wavelength of light, or for the entire standard solar spectrum.
- Generation is the greatest at the surface of the material, where the majority of the light is absorbed.
- Because the light used in PV applications contains many different wavelengths, many different generation rates must be taken into account when designing a solar cell.

Types of Recombination&Lifetime

- The lifetime of a semiconductor is contingent upon the recombination rate, which is dependent upon the concentration of minority carriers.
- The lifetime of the material takes into account the different types of recombination.
- Lifetime is an indicator of the efficiency of a solar cell, and thus is a key consideration in choosing materials for solar cells.
- Eventually, electrons lose energy and stabilize back to the valence band, recombining with a hole.
- There are three types of recombination; Radiative, Shockley-Read-Hall, and Auger.
- Auger and Shockley-Read-Hall recombination dominate in silicon-based solar cells.
- Among other factors, recombination is associated with the lifetime of the material, and thus of the solar cell.

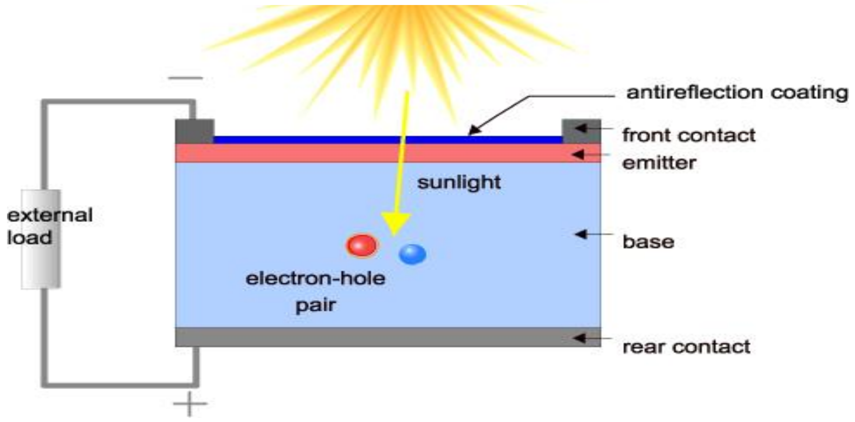
P-N Junction Diodes





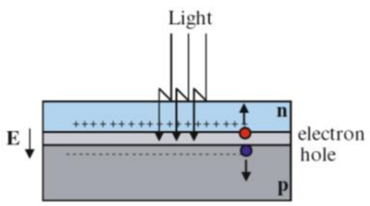
- *P-n* junction diodes form the basis not only of solar cells, but of many other electronic devices such as LEDs, lasers, photodiodes and bipolar junction transistors (BJTs). A p-n junction aggregates the recombination, generation, diffusion and drift effects described in the previous pages into a single device.
- Majority carriers can diffuse across the P-N junction depletion region, even though the electric field impedes their crossing. Minority carriers that reach the junction are swept across the depletion region due to drift.
- At equilibrium, the net current (diffusion and drift current) is zero for both electrons and holes because the diffusion current is equal and opposite to the drift current for both carriers.
- Forward bias occurs when a voltage is applied across the the solar cell such that the electric field formed by the P-N junction is decreased. It eases carrier diffusion across the depletion region, and leads to increased diffusion current.
- In the presence of an external circuit that continually provides majority carriers, recombination increases which constantly depletes the influx of carriers into the solar cell. This increases diffusion and ultimately increases current across the depletion region.
- Reverse bias occurs when a voltage is applied across the solar cell such that the electric field formed by the P-N junction is increased. Diffusion current decreases.

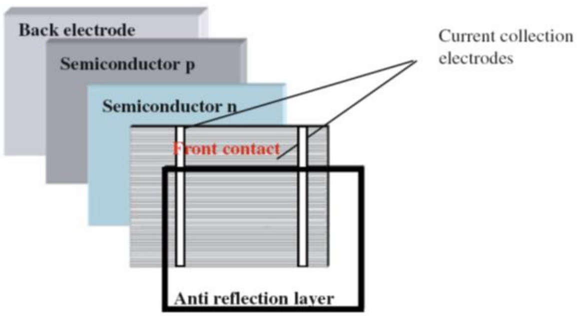
Solar Cell Structure

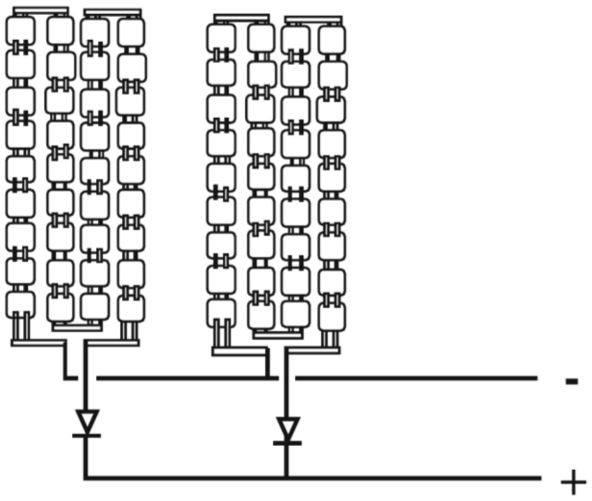


- A solar cell is an electronic device which directly converts sunlight into electricity. Light shining on the solar cell produces both a current and a voltage to generate electric power. This process requires firstly, a material in which the absorption of light raises an electron to a higher energy state, and secondly, the movement of this higher energy electron from the solar cell into an external circuit. The electron then dissipates its energy in the external circuit and returns to the solar cell. A variety of materials and processes can potentially satisfy the requirements for photovoltaic energy conversion, but in practice nearly all photovoltaic energy conversion uses semiconductor materials in the form of a *p-n* junction.

- the collection of these carriers by the *p-n* junction, prevents this recombination by using a *p-n* junction to spatially separate the electron and the hole. The carriers are separated by the action of the electric field existing at the *p-n* junction. If the light-generated minority carrier reaches the *p-n* junction, it is swept across the junction by the electric field at the junction, where it is now a majority carrier. If the emitter and base of the solar cell are connected together (i.e., if the solar cell is short-circuited), the the light-generated carriers flow through the external circuit. The ideal flow at short circuit is shown in the animation below.







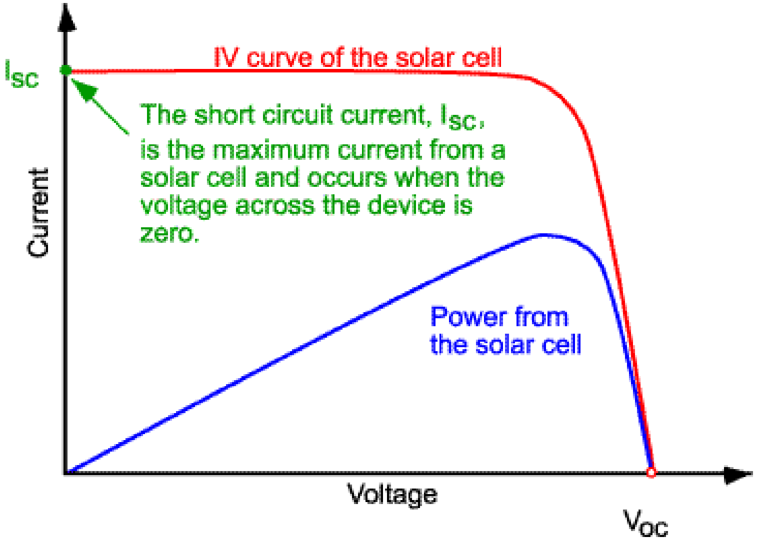
A photovoltaic (PV) cell, also known as “solar cell,”
is a semiconductor device that generates electricity when light falls on it with
(0.5–0.55 V) for the individual cells.

To increase power output, many PV cells are connected together to
form modules. A photovoltaic solar panel or module is made of similar cells
assembled in series or parallel in
order to achieve a given voltage or current output.

current depends on the size of the cells as the individual cells
and a voltage equal to the sum of their individual voltages.

Factors affecting PV performance

Many factors affect solar PV performance such as orientation of the PV module, tracking the sun, temperature of PV module, incidence/tilt angle of the PV panel, shading of the panel, mounting rooftop material, mounting height, solar irradiance, type of PV module, and dust on module. The output power can be shown in the I-V Characteristics curve (relation between current and voltage)



The short circuit current, I_{SC}, is the maximum current from a solar cell and occurs when the voltage across the device is zero.

I-V Characteristics curve for solar cell

The Fill Factor (FF) is a measure of the quality of the solar cell.

$$FF = P_{max} / P_{theoretical}$$

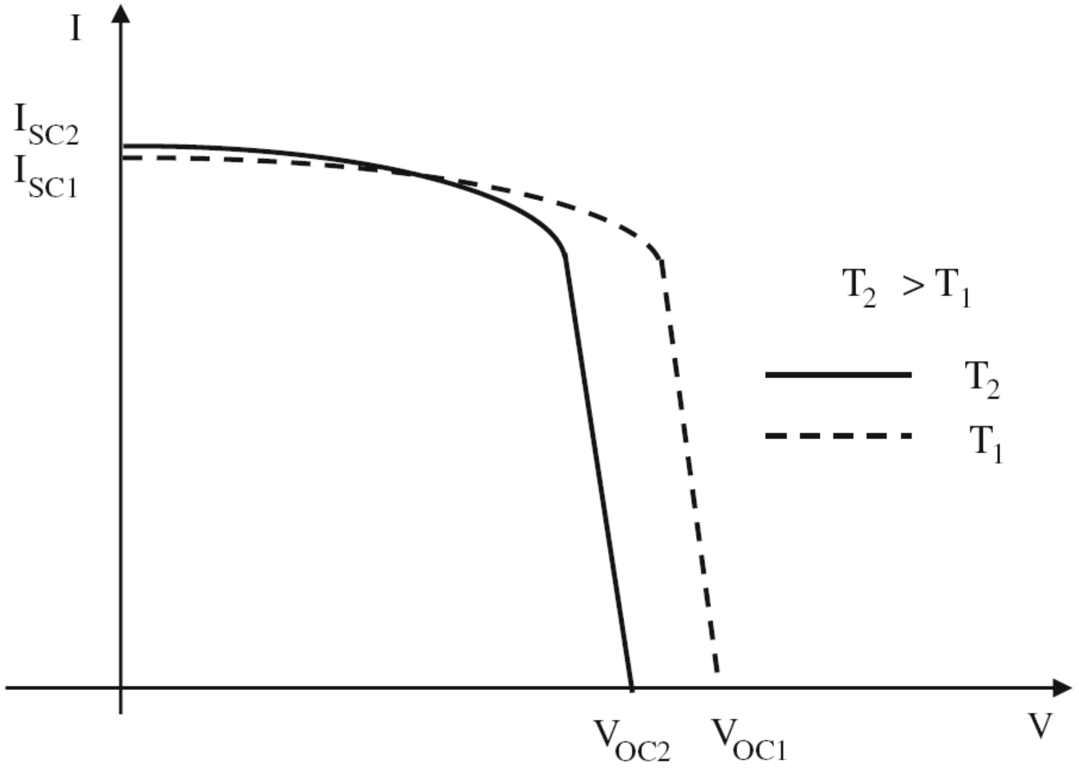
The efficiency of a photovoltaic solar cell is the ratio of the electrical power output P_{out}, compared to the solar optical power input P_{in}

$$Efficiency = P_{out} / P_{in} = P_{max} / P_{in} = (FF * V_{oc} * I_{sc}) / P_{in}$$

So, For most purposes, FF, V_{oc}, and I_{sc} are enough information to give a useful approximate model of the electrical behavior of a photovoltaic cell under typical conditions.

Temperature

As the temperature increases the rate of photon generation increases, Hence this leads to marginal changes in current but major changes in voltage



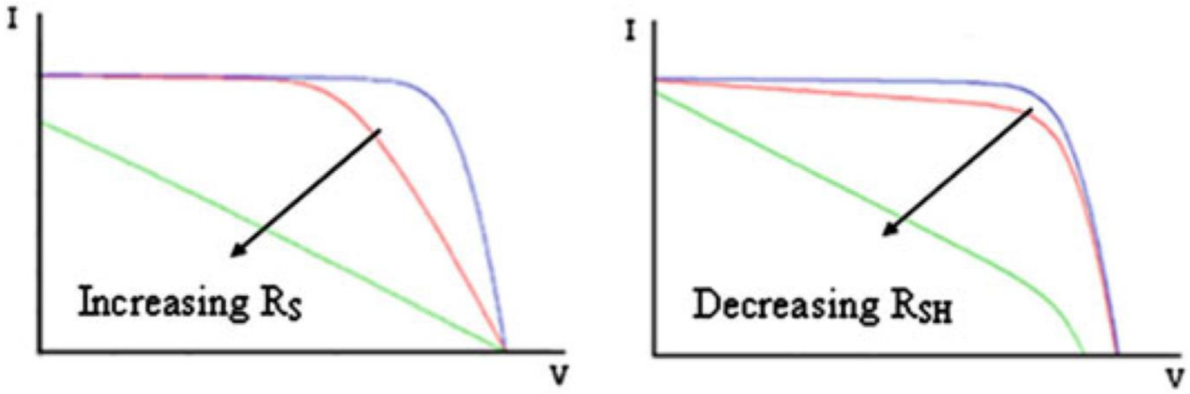
Temperature effect On I-V

Shading

Shading mainly affects the series connected PV module. Since the current produced by shaded portion is less as compared to the illuminated portion. But current in series must be same illuminated cells current forced the shaded portion current to increase result in hotspot and may cause damage to the entire module. For this problem to overcome parallel configuration is used for arranging the PV module. In parallel the output is not so affected as in case of series configuration. Since the current in parallel is not same in the entire panel but voltage should be same. It is experimentally proved that parallel configuration is better than series.

Dusts

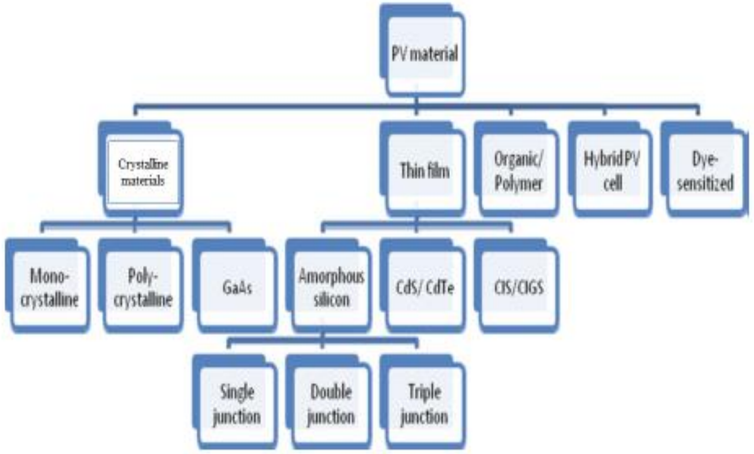
Dusts impact solar photovoltaic (PV) performance because they block the transmission of sunlight and affect the temperature of the module in addition to surface corrosion.



Shunt Resistance (R_{SH}) and Series Resistance (R_S)

The efficiency of solar cells is reduced by the dissipation of power through internal resistances. These parasitic resistances can be modeled as a shunt resistance (R_{SH}) and a series resistance (R_S),

The shunt resistance is due to fabrication defects, the photogenerated current will find alternative paths rather than flowing through the cell’s junction. An estimated value of R_{SH} can be determined from the I–V curve as detailed below. The shunt resistance will lower the open circuit voltage without changing the short circuit current. The series resistance of a solar cell originates mostly from the contact between the metal connections, especially the front contact, and the semiconductor or the current in the emitter. The high-series resistance will reduce the short circuit current without affecting the open circuit voltage.



- PV material
  - Crystalline materials
    - Mono-crystalline
    - Poly-crystalline
    - GaAs
  - Thin film
    - Amorphous silicon
      - Single junction
      - Double junction
      - Triple junction
    - CdS/ CdTe
    - CIS/CIGS
  - Organic/ Polymer
  - Hybrid PV cell
  - Dye-sensitized

Photovoltaic Cell Types

Crystalline silicon is the traditional cell material for solar modules,
and has maintained at least 80% market share of worldwide production for nearly all of the past 30 years

thin film technology are because it uses less material and the layers are much thinner
compared to mono- and polycrystalline solar cell
thus lowering the manufacturing cost. However, the efficiency of these technology-based solar cells is still low.
Three materials that have been given much attention under thin film technology are amorphous silicon,
CdS/CdTe and copper indium selenide CIS) copper indium diselenide (CIS), and copper indium gallium diselenide (CIGS).
Also, polymer and organic materials were used as solar cell material.
Polymer materials have many advantages like low cost, lightweight and environmental friendly.
The only problem is it has very low efficiency compared to other materials.

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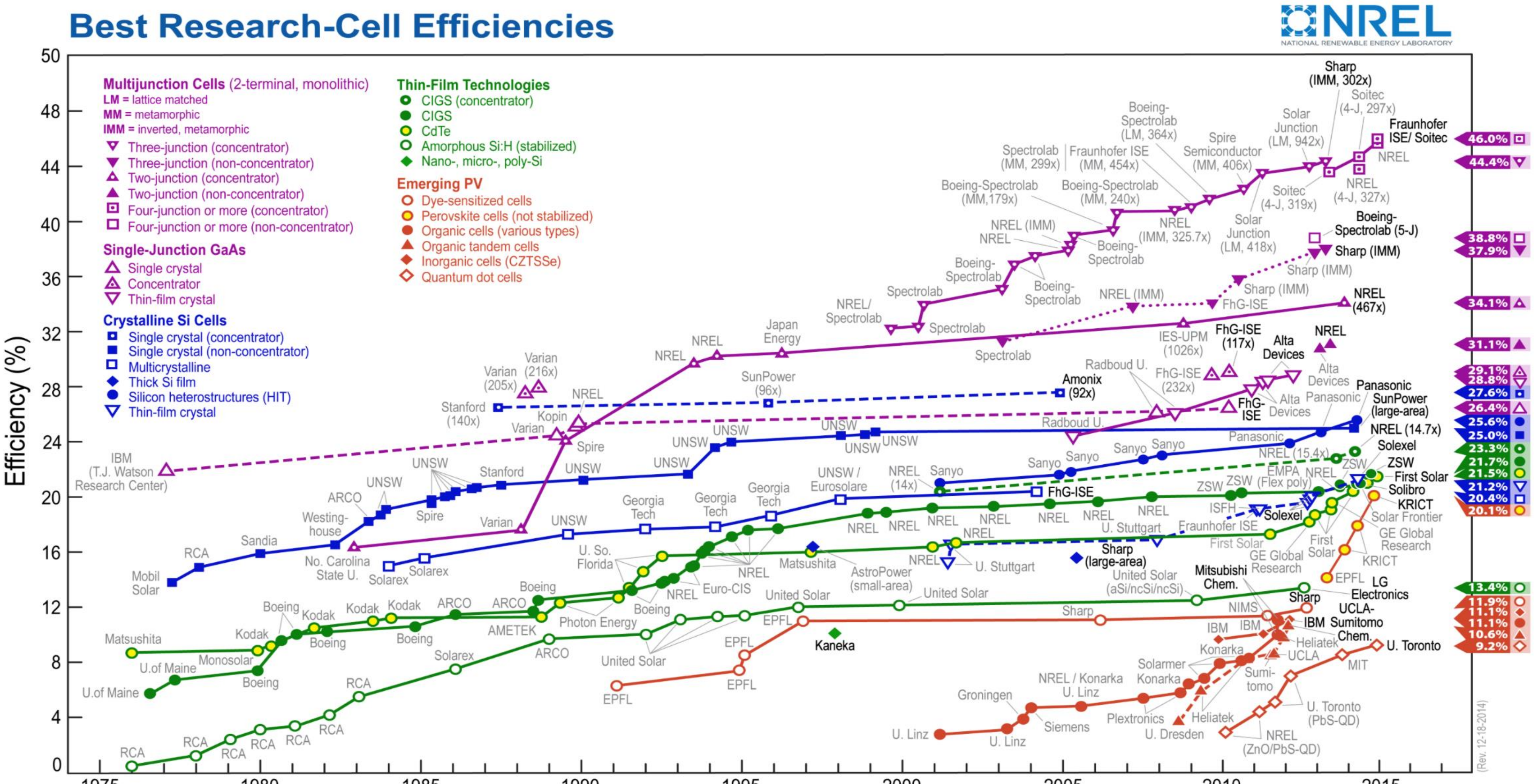
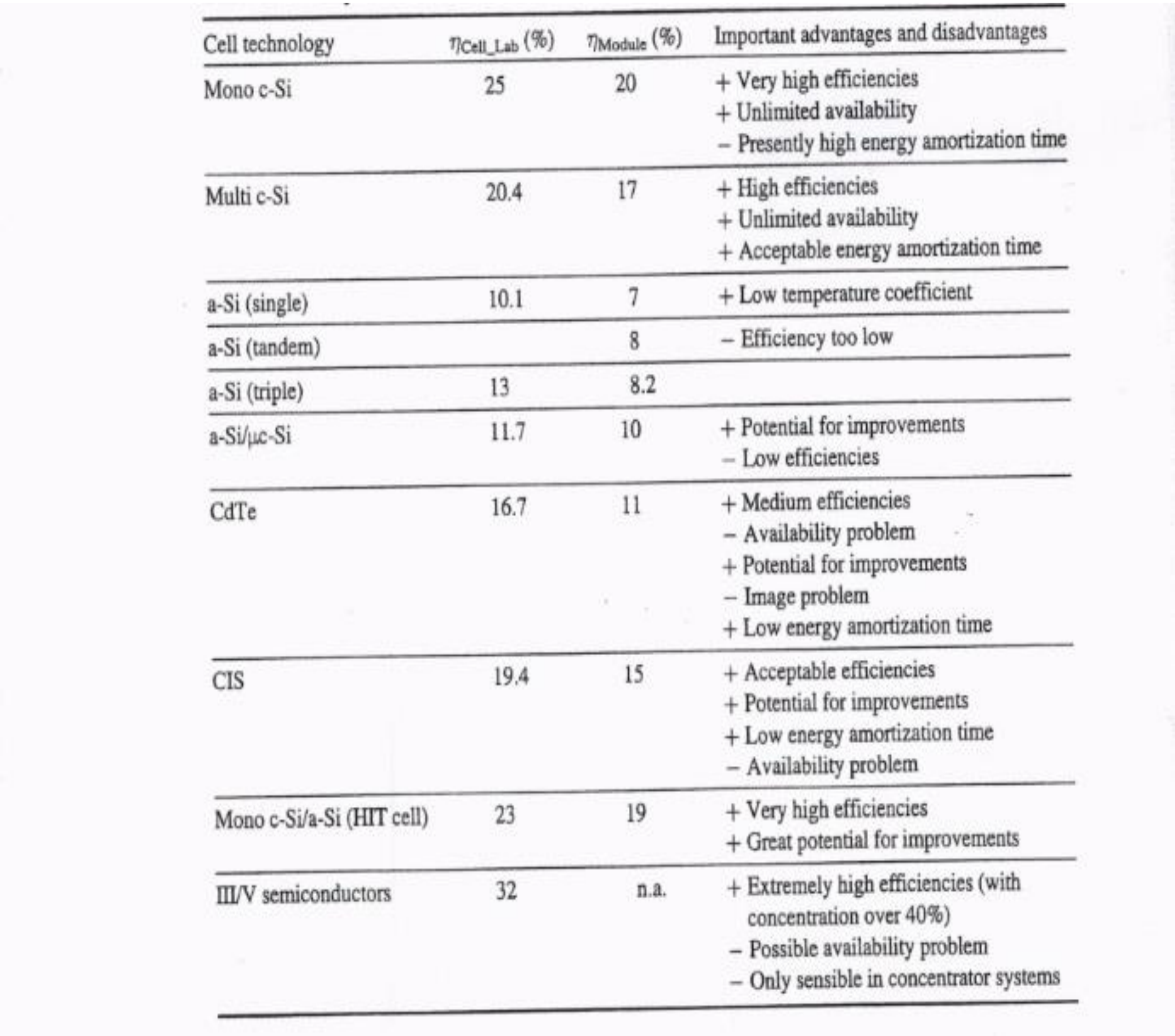
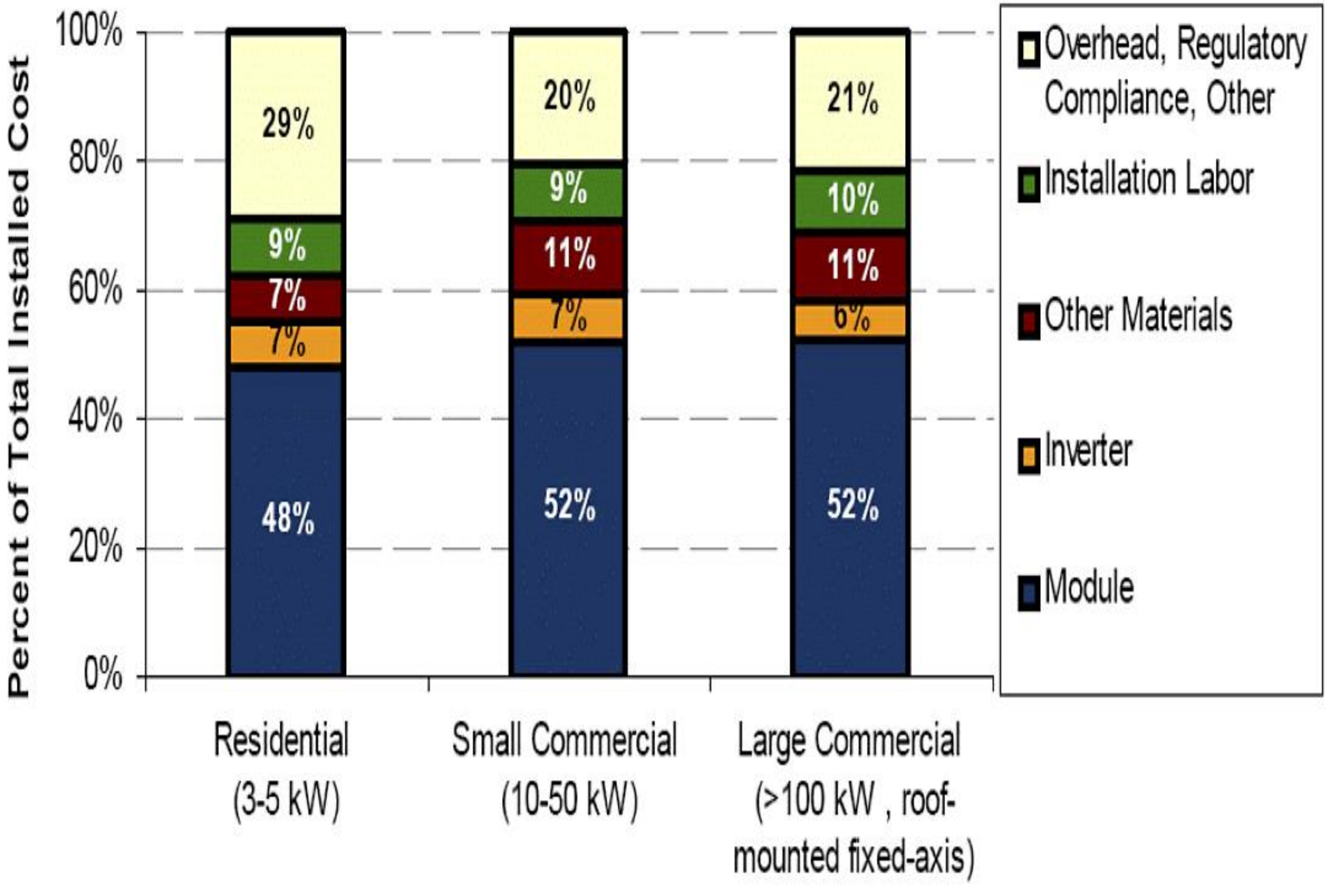




Cell technology	η_{Cell_Lab} (%)	η_{Module} (%)	Important advantages and disadvantages
Mono c-Si	25	20	+ Very high efficiencies + Unlimited availability − Presently high energy amortization time
Multi c-Si	20.4	17	+ High efficiencies + Unlimited availability + Acceptable energy amortization time
a-Si (single)	10.1	7	+ Low temperature coefficient
a-Si (tandem)		8	− Efficiency too low
a-Si (triple)	13	8.2	
a-Si/μc-Si	11.7	10	+ Potential for improvements − Low efficiencies
CdTe	16.7	11	+ Medium efficiencies − Availability problem + Potential for improvements − Image problem + Low energy amortization time
CIS	19.4	15	+ Acceptable efficiencies + Potential for improvements + Low energy amortization time − Availability problem
Mono c-Si/a-Si (HIT cell)	23	19	+ Very high efficiencies + Great potential for improvements
III/V semiconductors	32	n.a.	+ Extremely high efficiencies (with concentration over 40%) − Possible availability problem − Only sensible in concentrator systems


Percent of Total Installed Cost
100%
80%
60%
40%
20%
0%
29%
9%
7%
7%
48%
20%
9%
11%
7%
52%
21%
10%
11%
6%
52%
Residential (3-5 kW)
Small Commercial (10-50 kW)
Large Commercial (>100 kW , roof-mounted fixed-axis)
Overhead, Regulatory Compliance, Other
Installation Labor
Other Materials
Inverter
Module

System Sizing

Sizing Process

System sizing is the process used for determining the minimum panel and battery size needed
to deliver the required electrical energy under the solar conditions that exist at the system site.
It balances the output from the system with the solar input while taking into consideration losses in the system

- ❑ **Determine the load to be served in Wh/day**
- ❑ **Determine the available solar energy on at least a month by month basis**
- ❑ **Determine the types of equipment that will be used in the system so losses can be estimated**
- ❑ **Calculate the size of panel that will be needed to meet the required load under the worst month conditions.**
- ❑ **Calculate the size and type of battery that will be needed to provide needed reliability of power**

Estimating the load

- Determine the Watts required by each of the appliances
- Estimate the hours per day that each appliance will be used.
- For each appliance multiply the Watts times hours to get Wh/day, total the Wh/day for all appliances

Wh/day that needs to come from the panel for systems with batteries including (LOSSES)

- Wiring and connection losses about 10%

- Losses in the battery about 20%

- Total losses around 30% so the panel will need to produce enough Wh/day for the load plus enough to cover the losses.
  So it will have to produce about 130% of the energy required by the load

- To calculate the Wh/d needed from the panel, multiply the load Wh/d times 1.3

The Solar Resource

Actual measurements at the site are best but at least one full year is needed
and several years is preferred. Measurements taken with instruments tilted
at the same angle as the solar panels are best but horizontal “meteorological” measurements are ok.
NASA satellite measurements are better than “sunshine hours” recorded for the site
Choose the average value of solar for the lowest month as the design basis

The lowest month ***kWh/m²/day*** value is the starting point.

The sun shining at 1000 W/m² each day for the number of hours equal to the kWh/m²/day.

(Typically between about 5 and 6 kWh/m²/day) That is equivalent to to 5-6 hrs. of 1000 W/m² sunlight every day.

This is the ideal power from the panel system

Calculating the panel generation factor

To get the panel generation factor (Wh/day per Wp capacity) multiply the daily sun hours times 0.62.
that would be 5.2x0.62 = 3.22 Wh/Wp/day.
That is, for every Wp capacity in the panel we can expect to get an average of 3.22 Wh/day during the lowest solar month

Corrections include:

- 15% for temperature above 25 C
- 5% for losses due to sunlight not striking the panel straight on
  (caused by glass having increasing reflectance at lower angles of incidence)
- 10% for losses due to not receiving energy at the maximum power point (not present if there is a MPPT controller)
- 5% allowance for dirt
- 10% allowance for the panel being below specification and for ageing

Total power = .85 X .95 X .90 X .95X .90 = .62 of the original Wp rating.

Calculating the panel size needed

Divide the Wh/day needed from the panel (1.3 times the load Wh/day) by the Generation Factor in Wh/Wp/day.
The result is the minimum Wp of panel needed to meet the design load for the lowest solar month after
all losses and corrections have been applied.

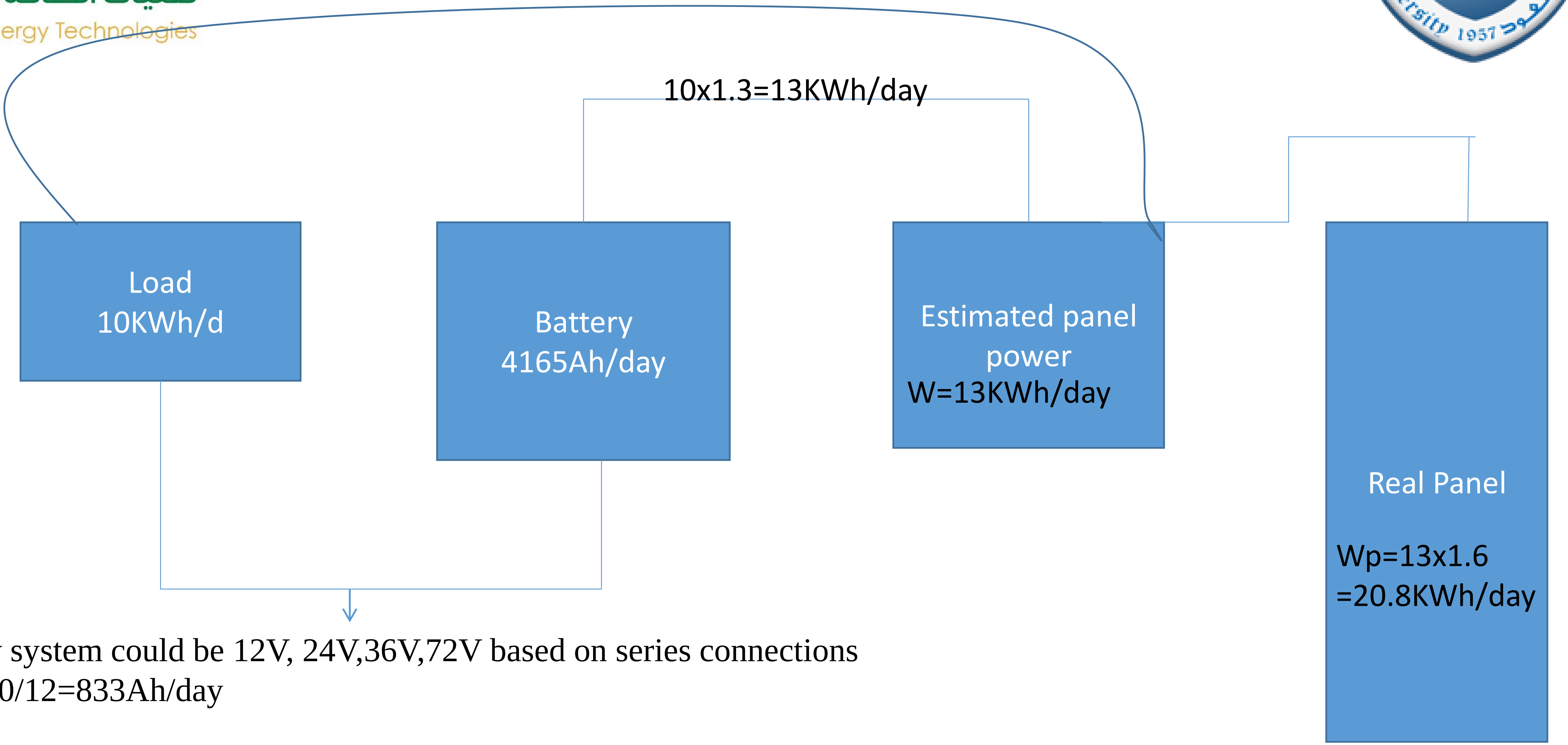
Calculating the battery size The load electricity is provided by the battery.
Determining the Ah/day needed by the load will determine the battery capacity that has to be available each day to operate the appliances.

For a 12V system, $\boldsymbol{Ah/day = Wh/day/12V}$

Solar design methods usually choose a 20% daily depth of discharge (DOD) for deep discharge batteries.
For the modified automotive battery longer life will be seen if that percentage is reduced to 15% DOD.
So the total battery capacity needs to be the daily Ah at C_{20} divided by 0.15 if 15% is to be the daily depth of discharge.

Summary of Sizing calculation

1. Estimate the Wh/day of the load
2. Multiply the load Wh/day times 1.3
3. Determine the kWh/m^2/day of sunlight for the lowest solar month
4. Multiply the kWh/m^2/day times .62 to get the generation factor Wh/d/Wp
5. Divide the result of (2) by the result of (4) to get minimum panel Wp.
6. Divide (1) by the battery voltage (12V) to get Ah/day
7. Divide (6) by .2(DOD) to get the minimum Ah of the battery at C_{20}.



10x1.3=13KWh/day

Load
10KWh/d

Battery
4165Ah/day

Estimated panel power
W=13KWh/day

Real Panel

Wp=13x1.6
=20.8KWh/day

Your Battery system could be 12V, 24V,36V,72V based on series connections
Ah/day=1000/12=833Ah/day
DOD=20%
The needed current=833/.2=4165Ah/day

Thank you