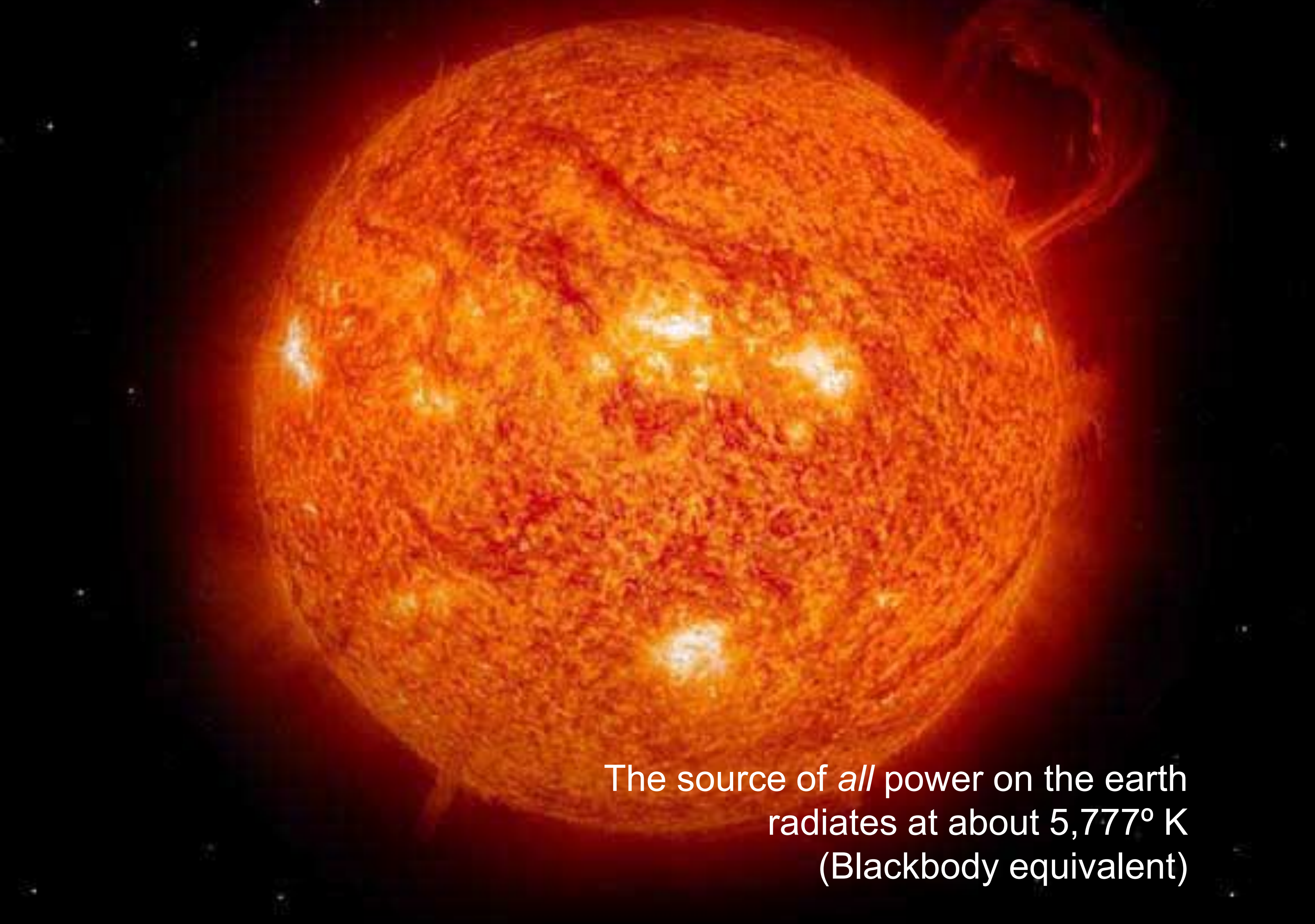
Energy Environment and Climate Change

CE 1201N
Module-4_Solar Energy

Solar Energy

Sun and its Source of Energy

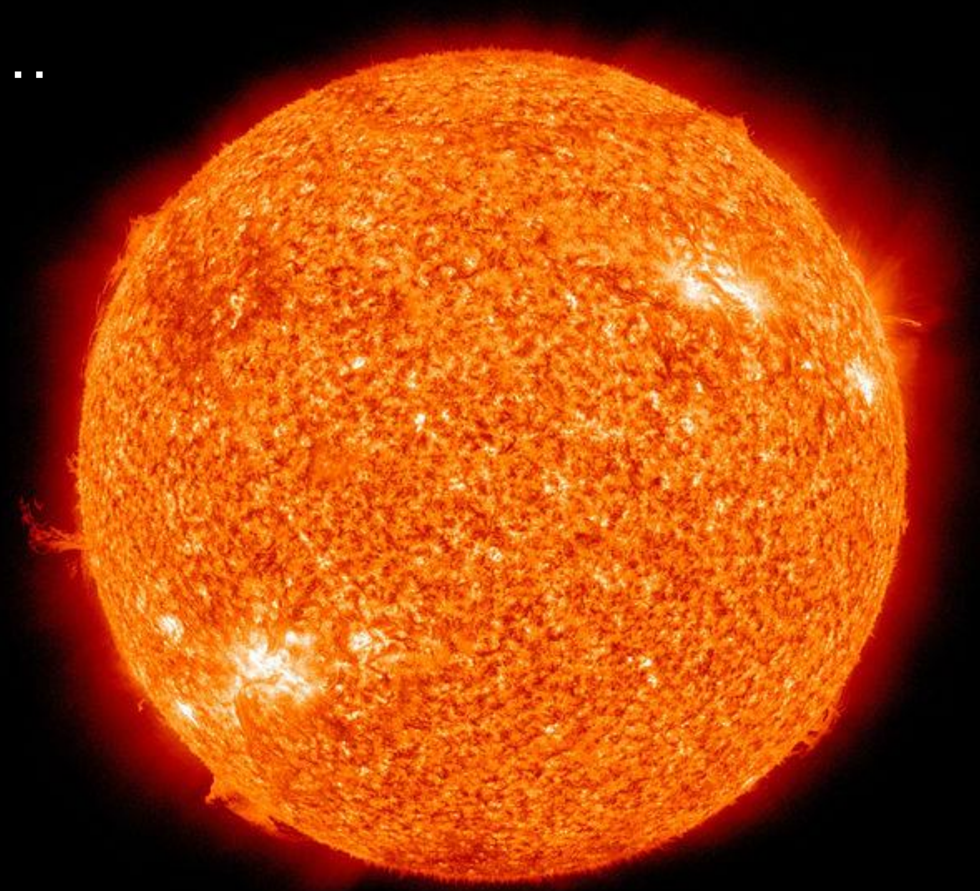
Nature of the solar resource : The sun



The source of *all* power on the earth
radiates at about 5,777º K
(Blackbody equivalent)

The Sun

- A sphere of intensely hot gaseous matter
- Consist of H, He, O, C, Ne, Fe…
- Surface temperature: 5,800K
- Core temperature:13,600,000K



- **The Sun generates a large amount of energy due to a continuous thermonuclear fusion reaction occurring in its interior.**

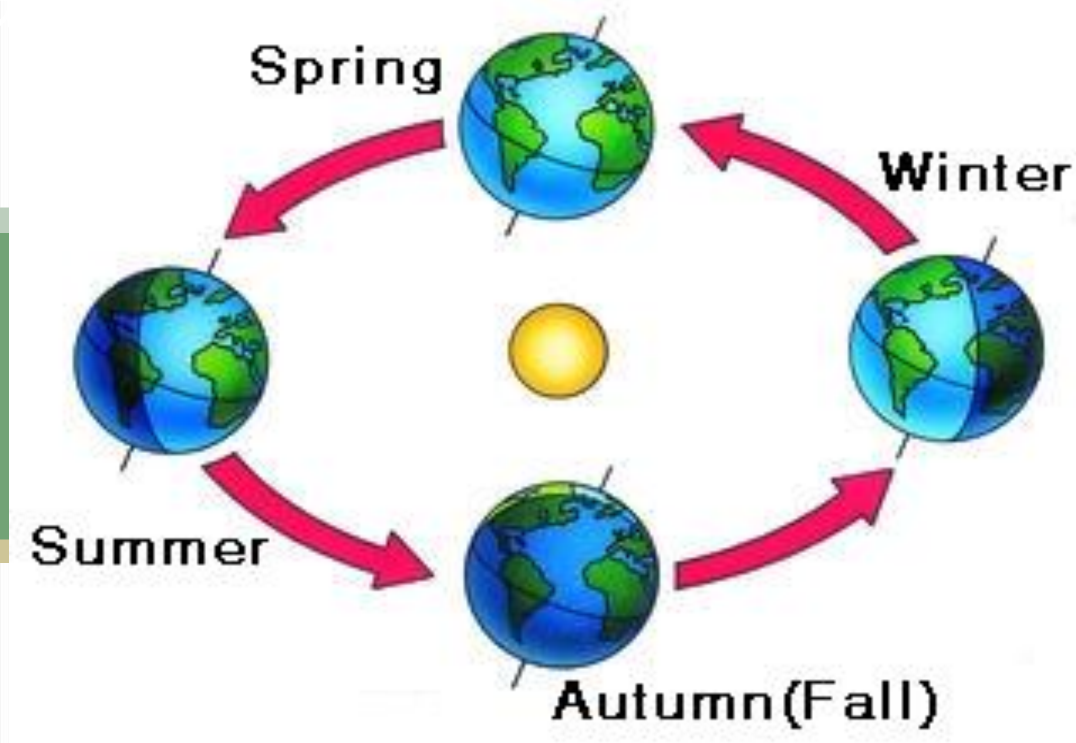
- **In this interaction Hydrogen combine to form Helium and the excess energy is released in the form of electromagnetic radiation.**

Two nuclei combine into one nucleus plus a nucleon is called **nuclear fusion**, a nuclear reaction.

Stars are giant fusion reactors.

Nuclear fusion reactions provide energy in the Sun and other stars. Solar energy drives the weather and makes plants grow.

Energy stored in plants sustains animal lives, ours included.

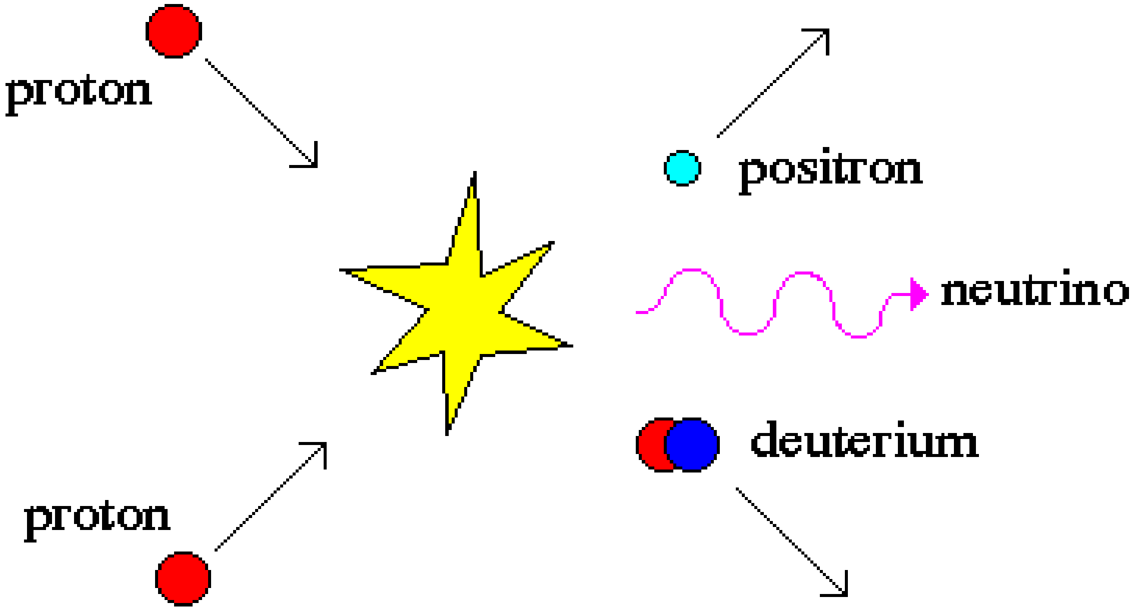


The amount of insolation that reaches the earth is consistently the same amount. However, any given location on the earth's surface will receive varying amounts due to the tilt, rotation and revolution of the earth, as well as cloud cover and particulate matter in the atmosphere. The time of day, season, latitude, and daily weather patterns all affect the amount of available solar energy in a particular location.

Fusion in Sun : Source of Energy

proton–proton chain: stage 1

$$ {}^{1}H_{1} + {}^{1}H_{1} \longrightarrow {}^{2}H_{1} + e^{+} + \nu $$

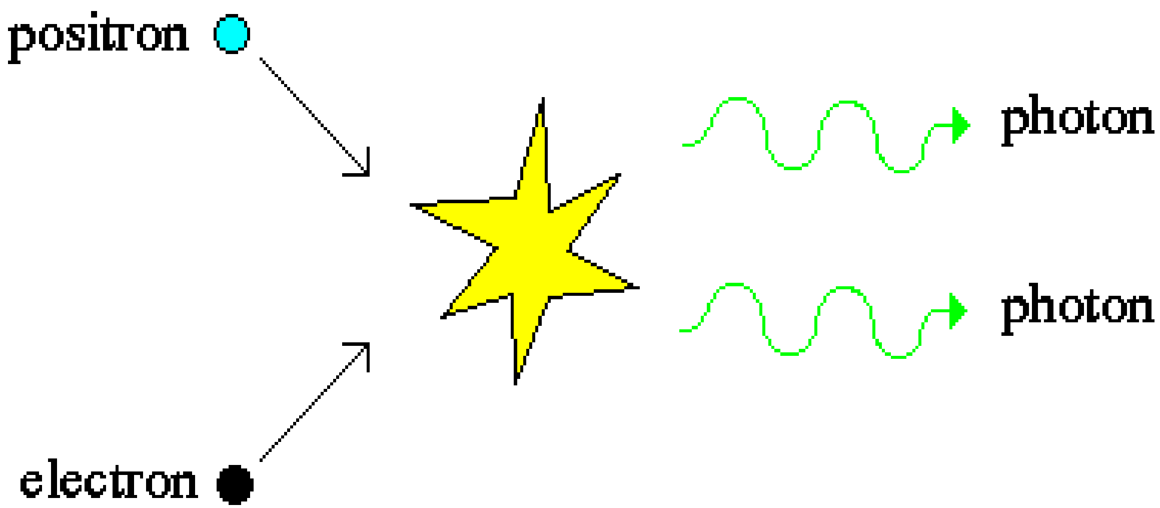


the 1st stage of the proton–proton chain is the fusion of two protons to produce deuterium, a positron and a neutrino – neutrino's travel close to the speed of light and interact very weakly with other forms of matter, so they escape from the Sun's core instantly

Fusion in Sun : Source of Energy

proton–proton chain: stage 2

$$e^{+} + e^{-} \longrightarrow \gamma + \gamma$$

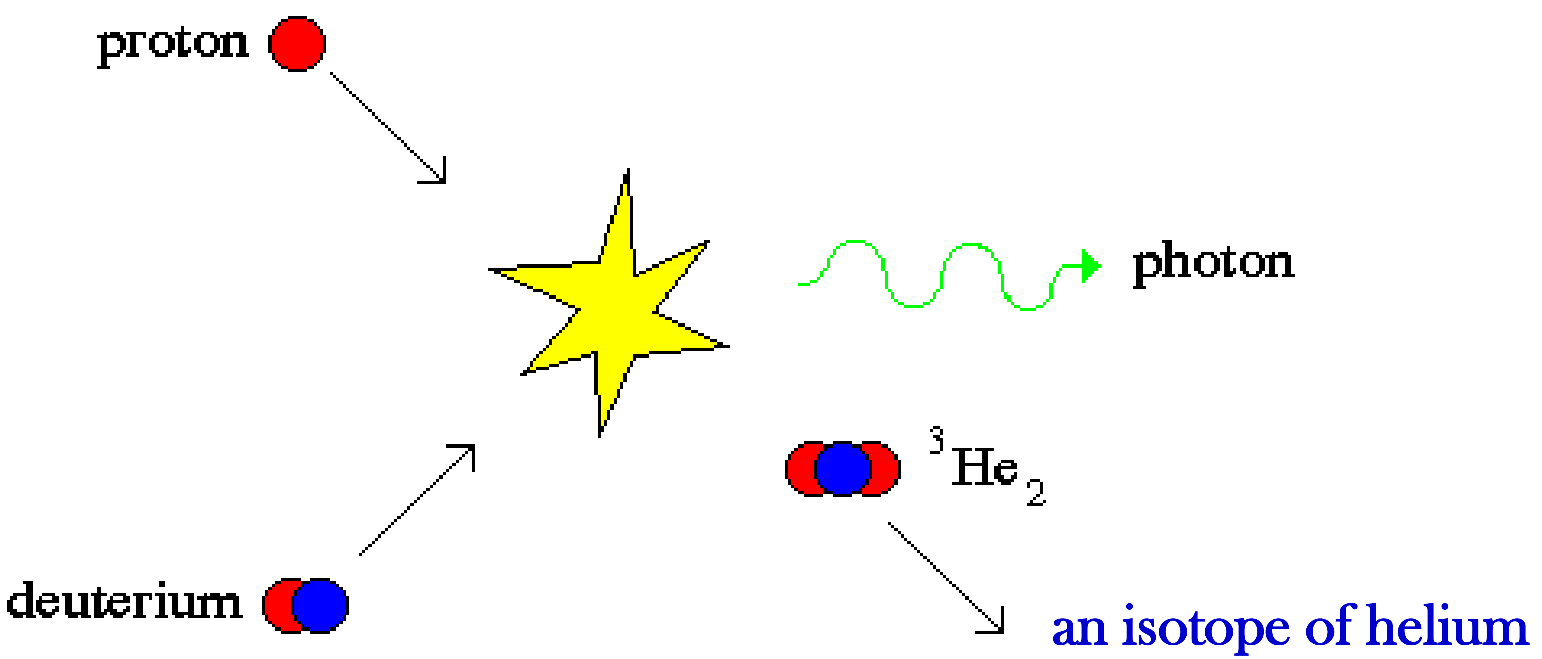


the 2nd second stage of the proton–proton chain is the destruction of the positron from the 1st stage by a collision with an electron – when matter and anti–matter collide they annihilate each other to produce two photons (gamma–rays) – the gamma–rays are the 1st amounts of energy produced by the proton–proton chain

Fusion in Sun : Source of Energy

proton–proton chain: stage 3

$$^{2}H_{1} + {}^{1}H_{1} \longrightarrow {}^{3}He_{2} + \gamma$$

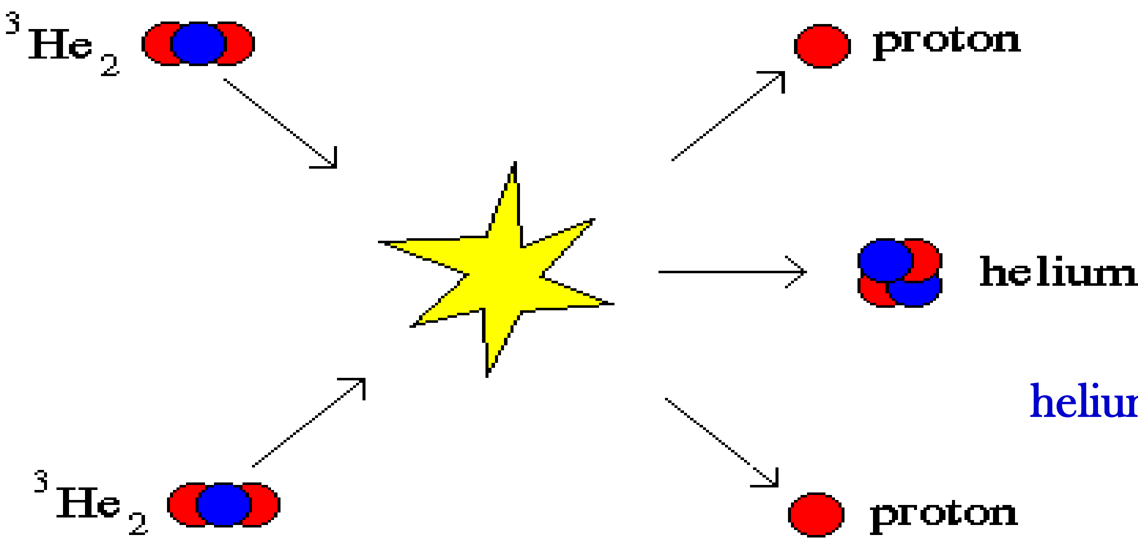


the 3rd stage to the proton chain used the deuterium from stage 1 and another proton to produce tritium (an isotope of helium) and energy in the form of another gamma-ray – isotopes are protons and neutrons combined to produce a nucleus, but usually missing a proton or neutron needed to make a complete element – isotopes tend to decay in short times

Fusion in Sun : Source of Energy

proton–proton chain: stage 4

$$^{3}He_{2} + {}^{3}He_{2} \longrightarrow {}^{4}He_{2} + {}^{1}H_{1} + {}^{1}H_{1}$$



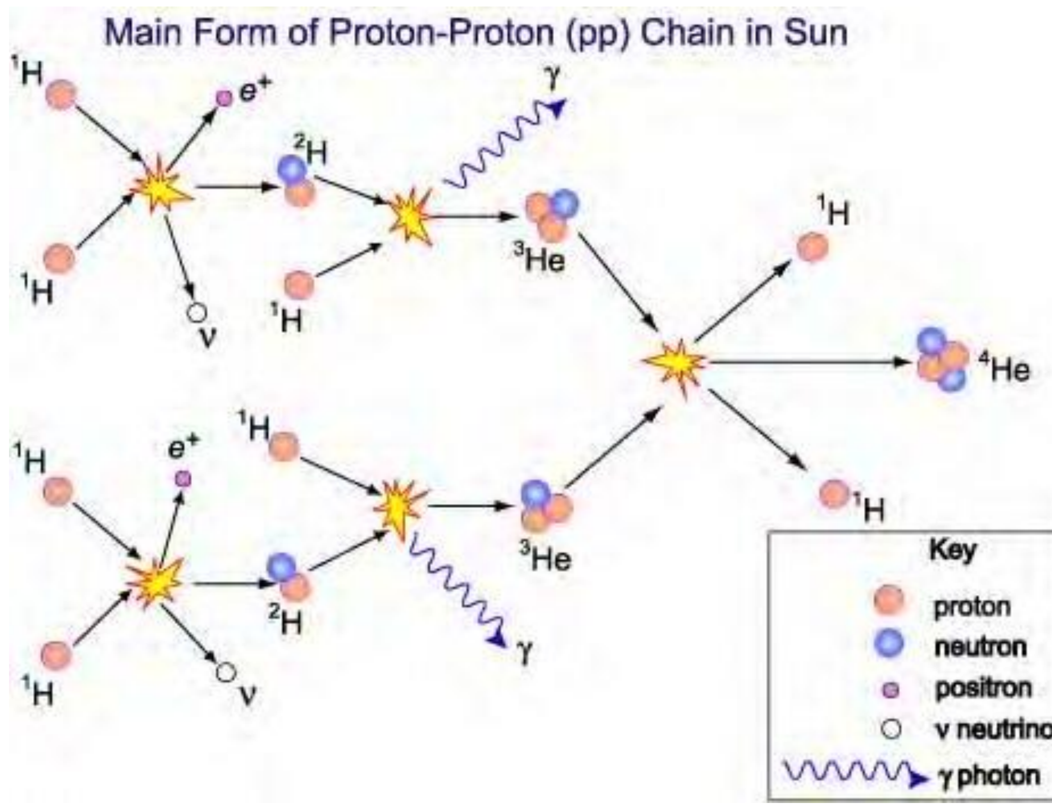
helium isotope nuclei

the last stage in the proton–proton chain is to convert two tritium nuclei into a full helium nuclei and release two protons – note that the protons can now go off and start two more stage 1 chains (thus the origin of the words ''chain reaction'') – the endresult of the proton–proton chain is to convert 4 hydrogen nuclei (protons) into 1 helium nuclei with the release of several photons in the form of high–energy gamma–rays

Note also the the mass of $^{4}He_{2}$ is 99.29% the mass of 4 protons, so 0.71% of the mass is ''missing'' – this is the mass used in $E=mc^2$, the famous formula to relate mass and energy for nuclear reactions

Sun : a powerful fusion reactor

The temperature inside the Sun is so high that electrons have all been stripped from their atomic nuclei.



The principal nuclear reactions inside the Sun convert hydrogen into helium in three stages. Because this chain of reactions starts with two hydrogen nuclei -- that is, two single protons -- it is called the proton-proton chain.

Solar Energy Production

The net result is

$6\ ^{1}H + 2\ e \rightarrow\ ^{4}He + 2\ ^{1}H + 2$ neutrinos $+ 6$ photons

or

$4\ ^{1}H + 2\ e \rightarrow\ ^{4}He + 2$ neutrinos $+ 6$ photons

The net energy release is 26 MeV! How?

Energy of fusing hydrogen to helium

$$4(^1H) \Rightarrow {}^4He + 2\,e^+ + 2 \text{ neutrinos} + \text{energy}$$

Energy per fusion reaction

The energy comes from the difference in the mass of the 4 hydrogen atom and the resulting helium atom through Einstein's famous equation: $E=mc^2$.

[Note that the masses of the 2 e^+ and the 2 neutrinos are so small compared to the masses of hydrogen and helium that we can neglect them from this simple calculation.]

To make this calculation, you'll need the following:

Mass of a hydrogen atom, $m_H = 1.673 \times 10^{-27}$ kg

Mass of a helium atom, $m_{He} = 6.645 \times 10^{-27}$ kg

Speed of light, $c = 2.998 \times 10^8$ m/s

Energy released in each fusion reaction

Solution :

Mass difference: Energy released in each fusion reaction:

$m_H = 1.673 \times 10^{-27}$ kg

$m_{He} = 6.645 \times 10^{-27}$ kg

$\Delta m = (4 \times m_H) - m_{He}$

$= 4.7 \times 10^{-29}$ kg

$$\boxed{1 \text{ MeV} = 1.6 \times 10^{-13} \text{ J}}$$

$E = mc^2$

$= (\Delta m) \times c^2$

$= 4.7 \times 10^{-29} \text{ kg} \times (3 \times 10^8 \text{ m/s})^2$

$= 4.224 \times 10^{-12} \text{ kg m}^2/\text{s}^2$

$= 4.224 \times 10^{-12}$ J

~ 26 MeV

$4(^1H) \Rightarrow {}^4He + 2\,e^+ + 2$ neutrinos + energy

Sun’s Structure

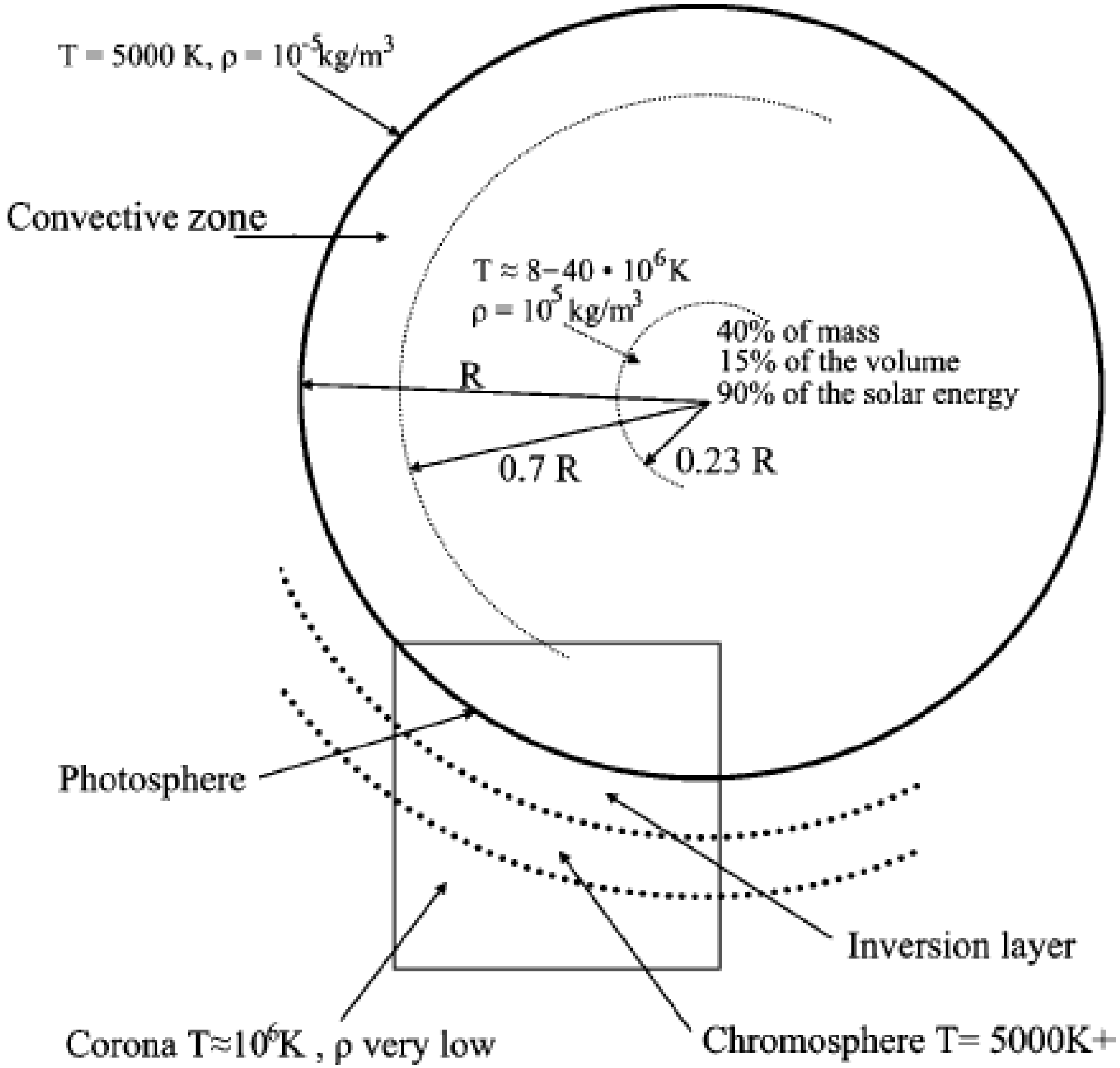
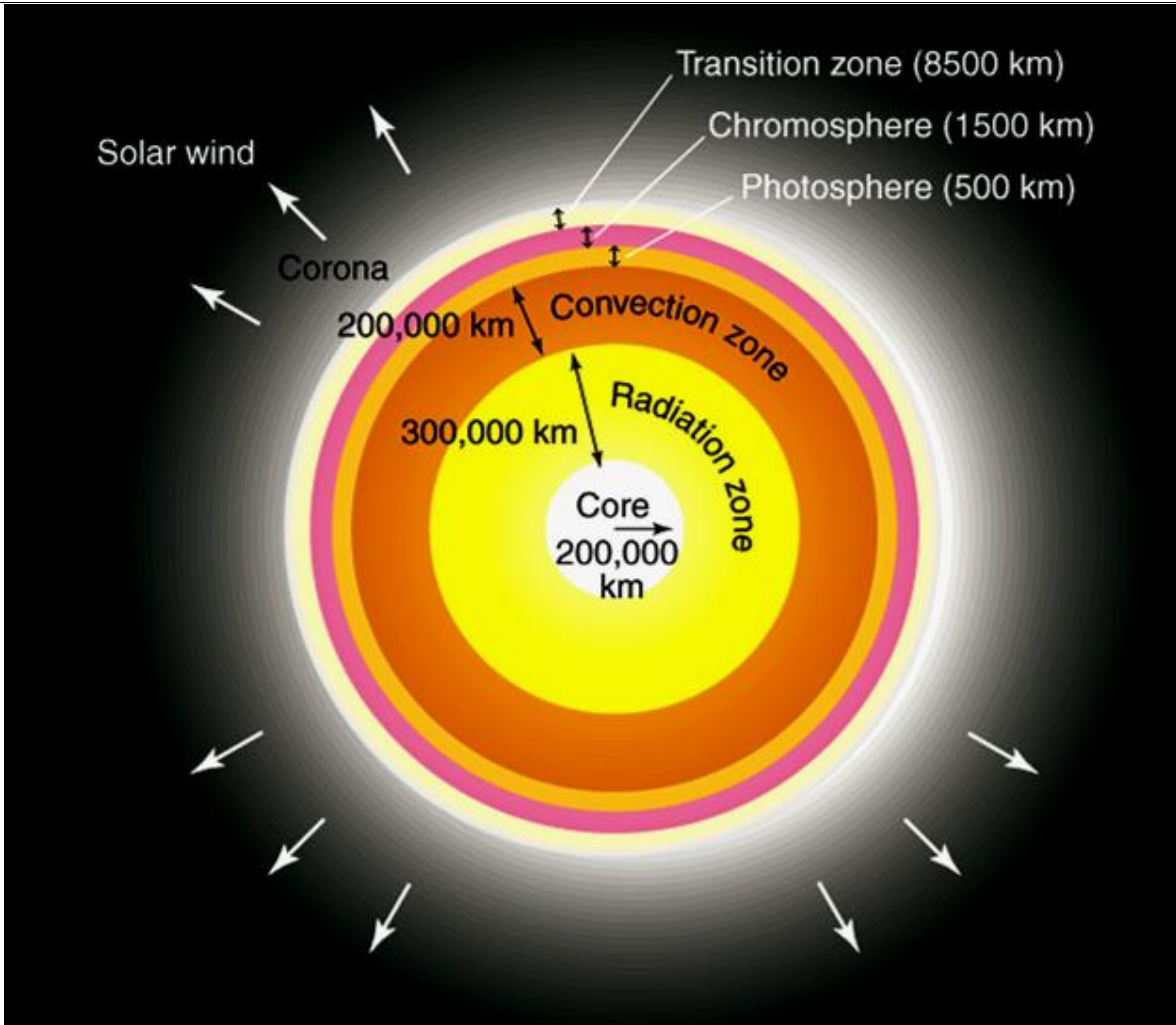
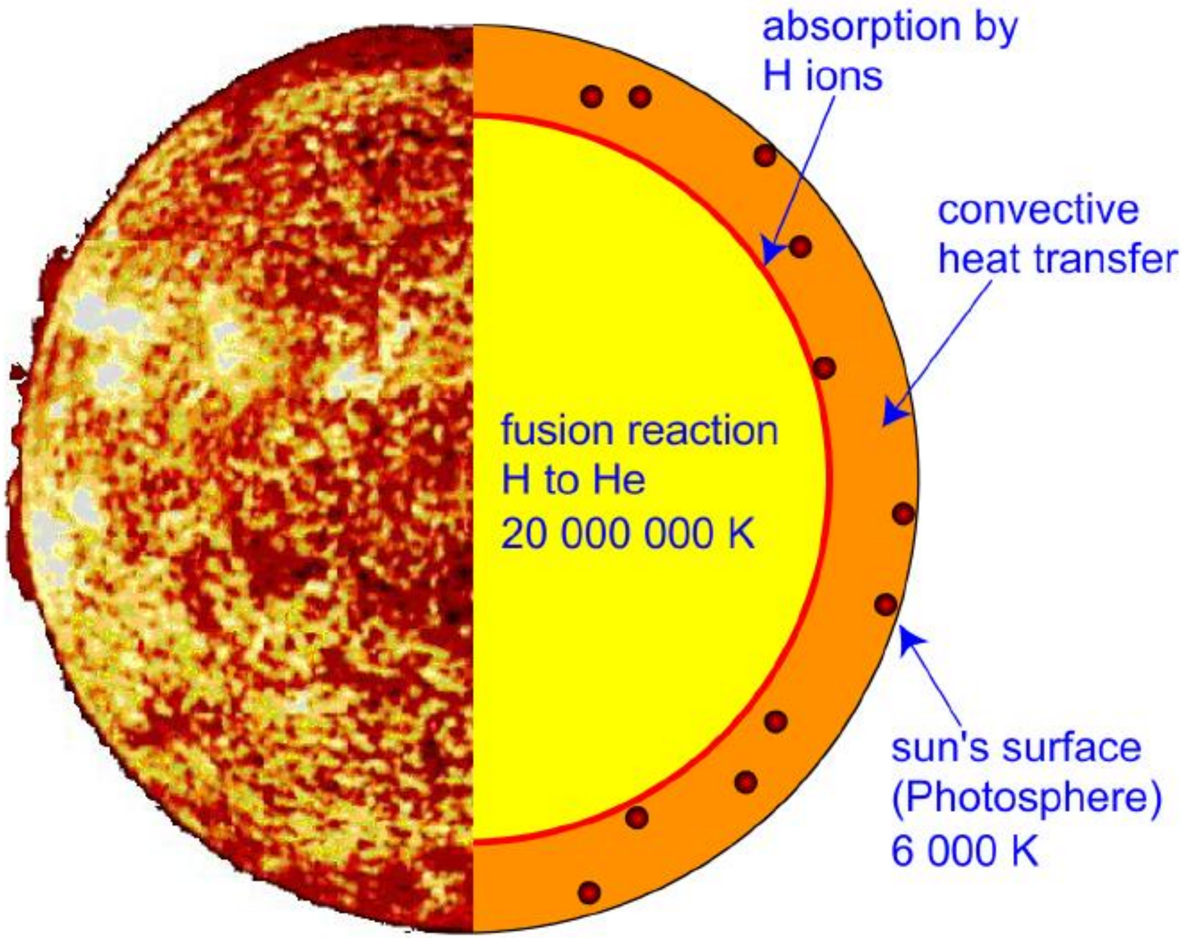


Figure 1: The Sun’s structure.


Transition zone (8500 km)
Chromosphere (1500 km)
Photosphere (500 km)
Solar wind
Corona
200,000 km
Convection zone
Radiation zone
300,000 km
Core
200,000
km

The sun is a hot sphere of gas whose internal temperatures reach over 20 million degrees kelvin due to nuclear fusion reactions at the sun's core which convert hydrogen to helium.

The surface of the sun, called the photosphere, is at a temperature of about 6000K



Core of the Sun

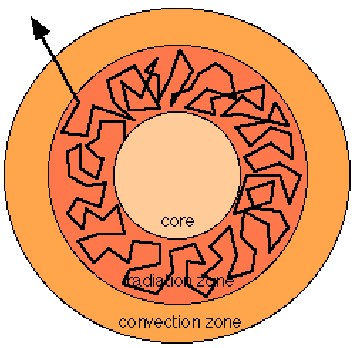
The core of the Sun is considered to extend from the center to about 0.2 to 0.25 solar radius.

It is the hottest part of the Sun and of the Solar System. It has a density of 150 g/cm³ (150 times the density of liquid water) at the center, and a temperature of close to 15,700,000 kelvin,

The core is made of hot, dense gas in the plasmic state,

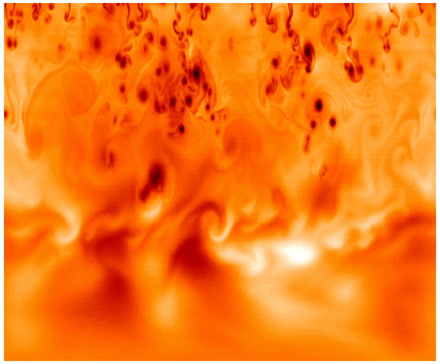
Sun’s radiative zone

The Sun's radiative zone is the section of the solar interior between the innermost core and the outer convective zone. In the radiative zone, energy generated by nuclear fusion in the core moves outward as electromagnetic radiation. In other words, the energy is conveyed by photons.



Sun’s convective zone

When the energy reaches the top of the radiative zone, it begins to move in a different fashion in the convective zone. In the convective zone, heat and energy are carried outward along with matter in swirling flows called convection cells. This motion is similar to the roiling flows seen in a pot of boiling water.



Sun’s photosphere

The lowest layer of the sun's atmosphere is the photosphere. It is about 300 miles (500 kilometers) thick. This layer is where the sun's energy is released as light. Because of the distance from the sun to Earth, light reaches our planet in about eight minutes.

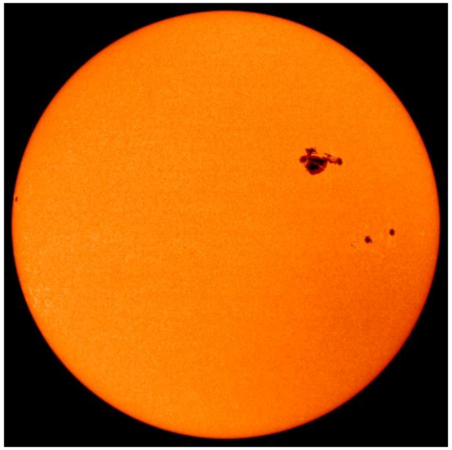
Sun’s chromosphere

The next layer is the chromosphere. The chromosphere emits a reddish glow as super-heated hydrogen burns off. But the red rim can only be seen during a total solar eclipse. At other times, light from the chromosphere is usually too weak to be seen against the brighter photosphere.

Sunspots: (Photo of the Sun taken on Jan. 17, 2005)

Sunspots are regions with high magnetic fields (1000 x higher magnetic field than average!)

Typical size of spots is similar to the size of the Earth. These regions are cooler than average, so they look darker than the surrounding hotter region.



Photosphere: Temperature decreases outwards.

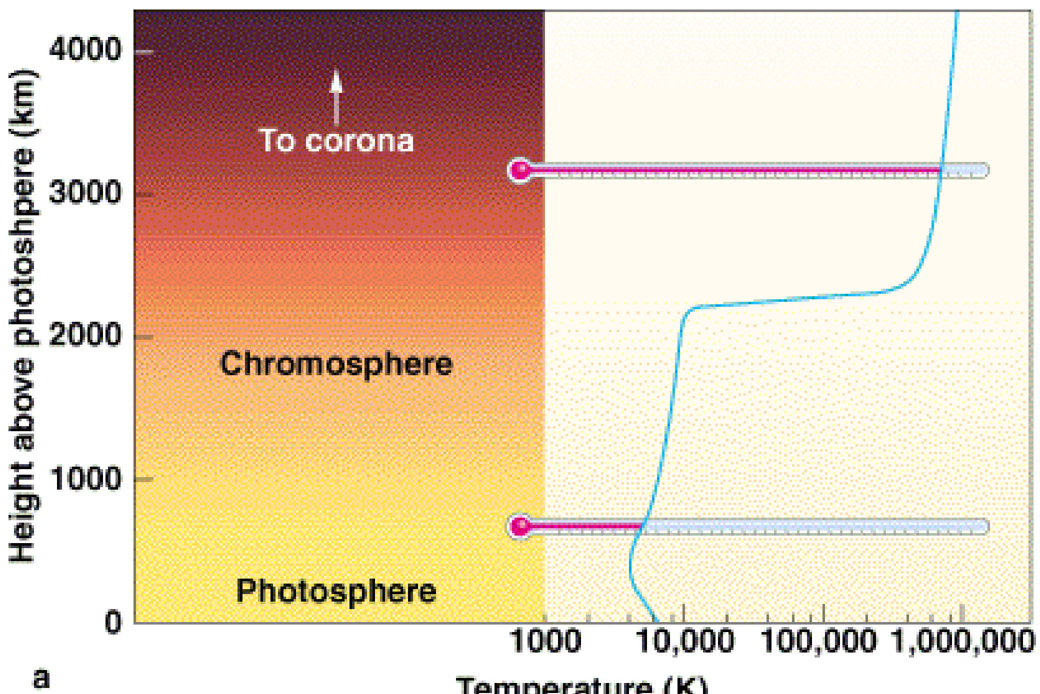
At bottom: T = 6400 K , At top: T = 4000 K

Chromosphere: Temperature increases outwards. At top: T = 10,000 K

Transition Zone: Temperature shoots up to near 1 million K

Corona: Temperatures increase to about 2 million K

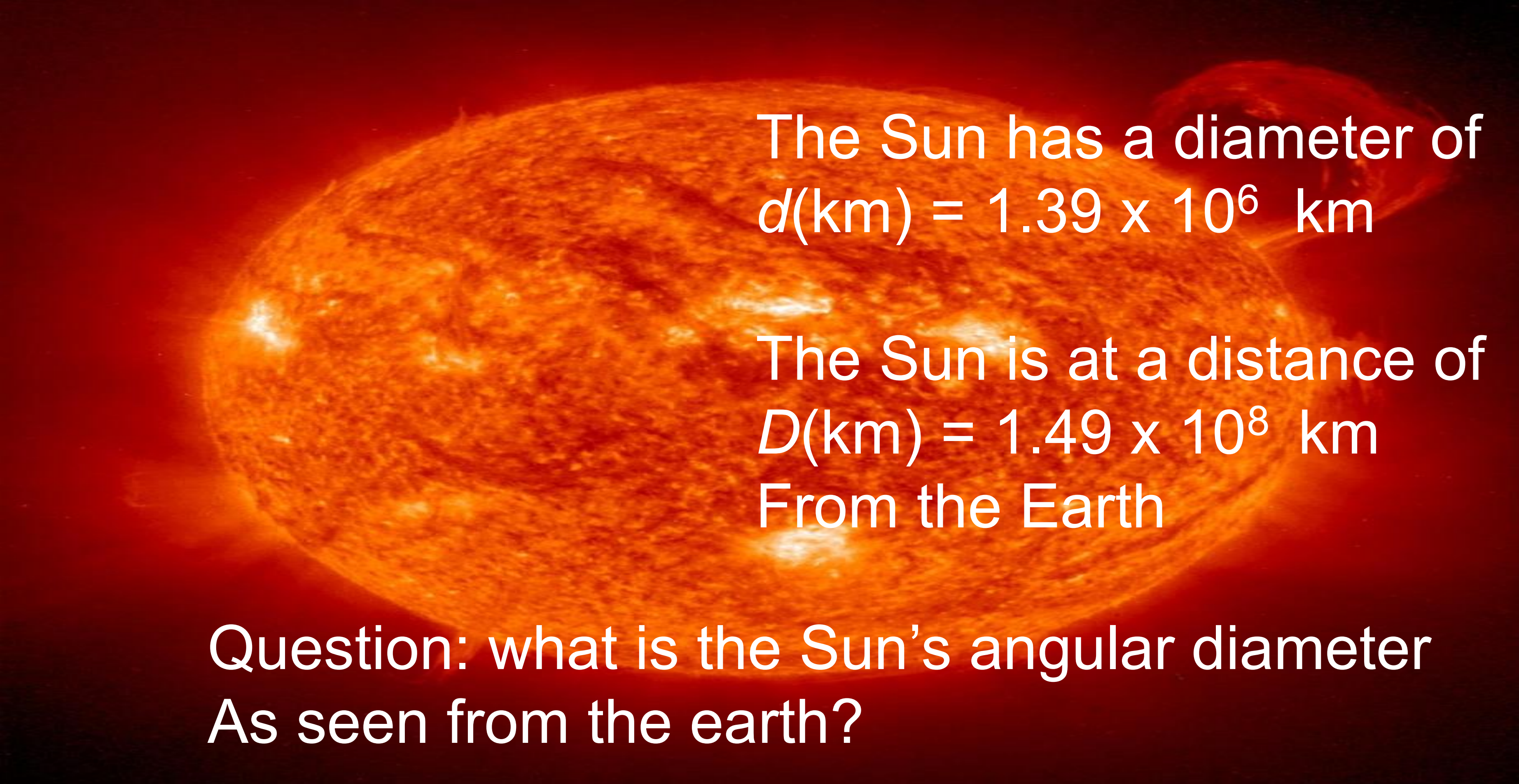
The source of this heat is not well understood. Current theories suggest that magnetic waves might transport energy from the convective zone to the corona.



solar wind.

The constant flow of ionized gas away from the corona is called the solar wind. Every second, a million tons of gas flows away from the Sun

During the Sun's lifetime, so great is the mass of the Sun, the mass loss from the solar wind has been negligibly small. (It takes about 200 million years to lose the equivalent of the Earth's mass -- and it takes 330,000 Earths to equal the Sun.)



The Sun has a diameter of
d(km) = 1.39×10^{6} km

The Sun is at a distance of
D(km) = 1.49×10^{8} km
From the Earth

Question: what is the Sun's angular diameter
As seen from the earth?

$$\alpha(in\ \mathrm{radian}) = \frac{d}{D}$$

Sun Fact Sheet

The Sun is a normal star, one of more than 100 billion stars in our galaxy.

Diameter: 1,390,000 km (Earth 12,742 km or nearly 100 times smaller)
Mass: 1.1989 x 10^{30} kg (333,000 times Earth's mass)

Temperature: 5800 K (surface) 15,600,000 K (core)

The Sun contains more than 99.8% of the total mass of the Solar System (Jupiter contains most of the rest).

Chemical composition:

Hydrogen 92.1% , Helium 7.8%
Rest of the other 90 naturally occurring elements: 0.1%

The Light Year

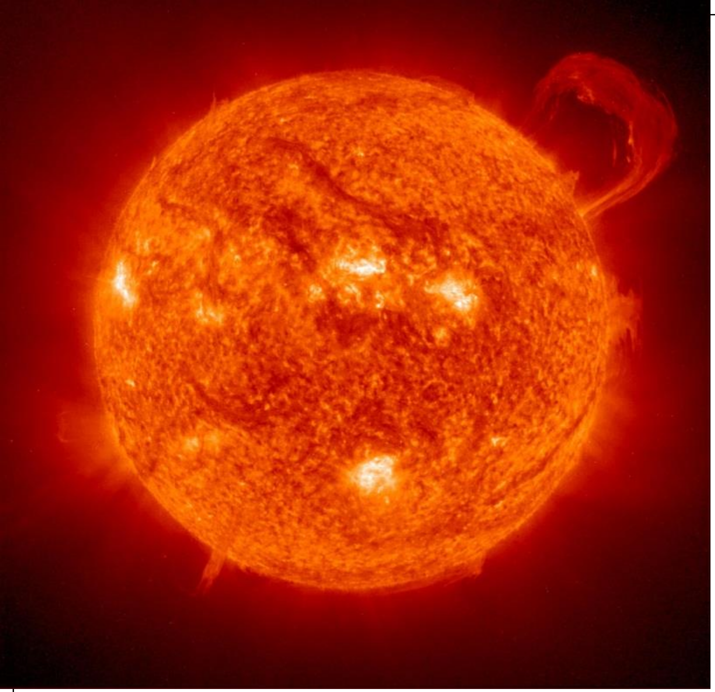
Definition:

The distance traveled by a light ray in one year

1 light year = speed of light x number of seconds in a year

$$= 3 \times 10^8 \times 365.25 \times 24 \times 60 \times 60 \text{ (meters)}$$

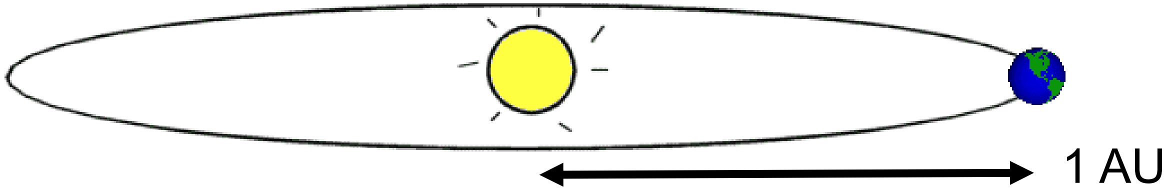
$$= 9.46 \times 10^{15} \text{ meters}$$



- The Sun again….
- Distance to the Sun from Earth is about 150 million kilometers (150 billion meters)

Hence:
Light travel time from Sun to Earth
$= 150 \times 10^9 / 3 \times 10^8$ - seconds
$= 500$ seconds $= 8.3$ - minutes
The Sun is 8.3 light minutes away from Earth

The nearest star to the Sun (Proxima Centauri) is 4.243 light years away
Implication: space is very big and mostly empty

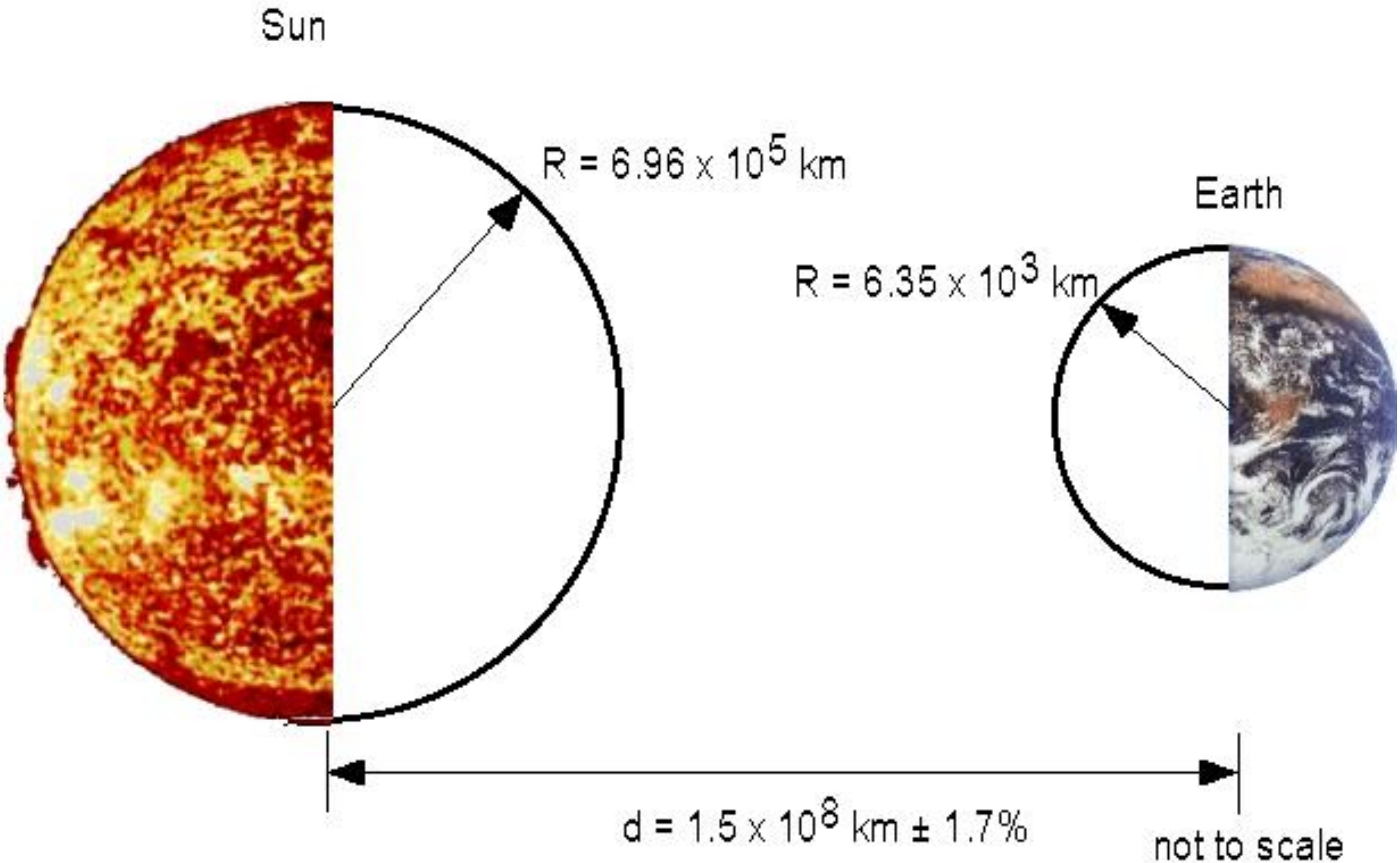


- Definition:

The Astronomical Unit (AU) is the average distance between the Earth and the Sun

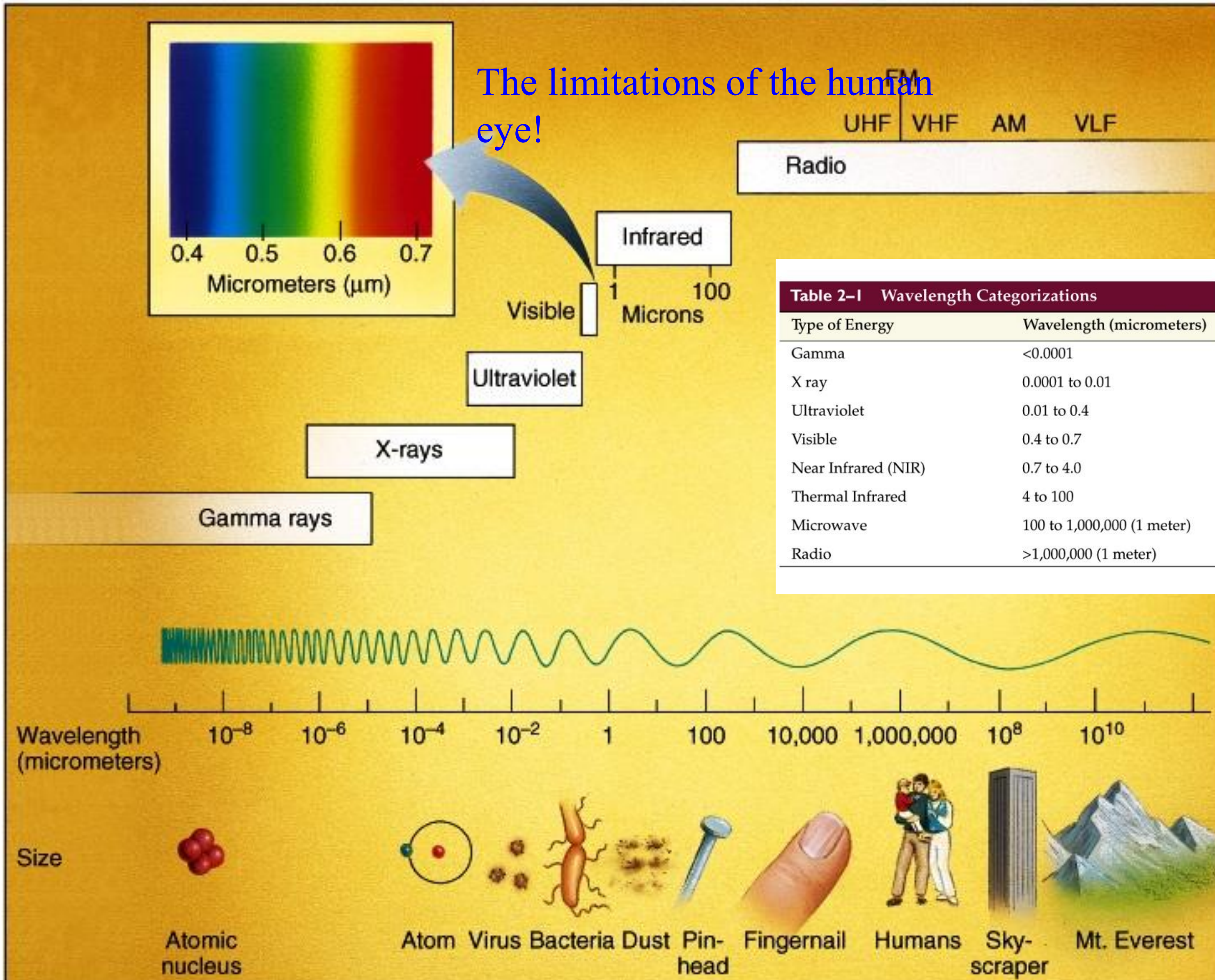
1 AU = 1.496×10^8 km

Sun - Earth relative size and distance of separation



Characteristics of solar radiation

The Electromagnetic Spectrum

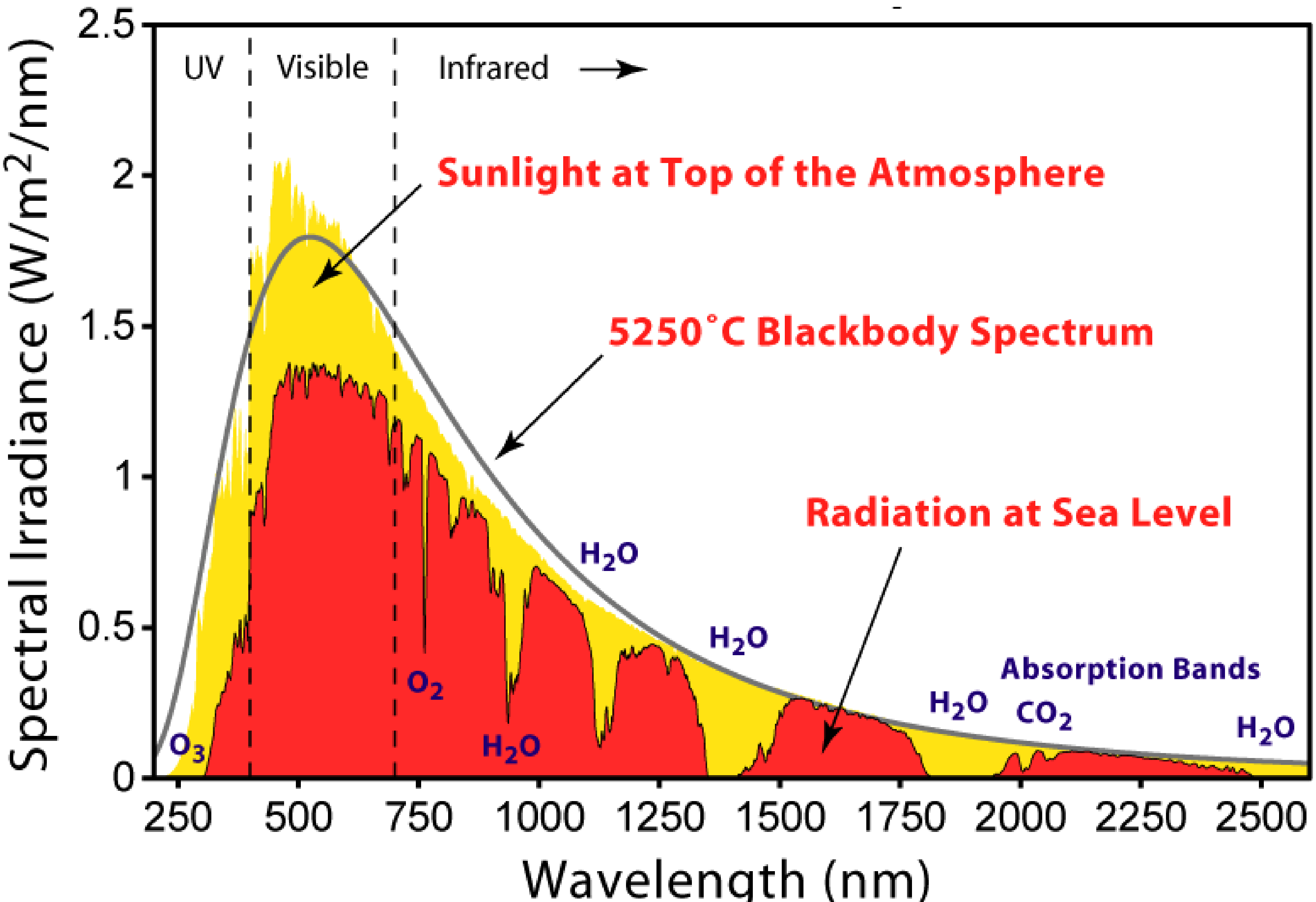


The limitations of the human eye!

Table 2–1 Wavelength Categorizations

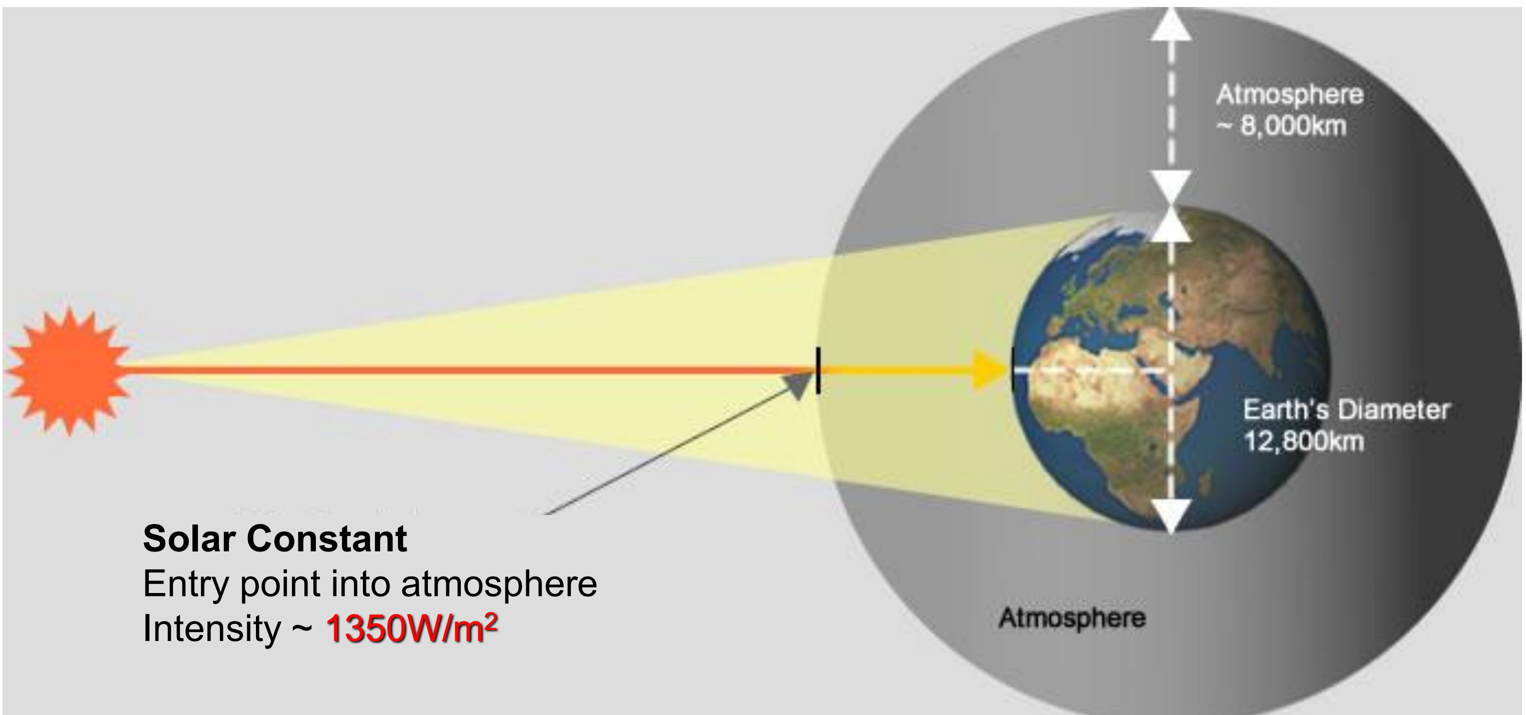
Type of Energy	Wavelength (micrometers)
Gamma	<0.0001
X ray	0.0001 to 0.01
Ultraviolet	0.01 to 0.4
Visible	0.4 to 0.7
Near Infrared (NIR)	0.7 to 4.0
Thermal Infrared	4 to 100
Microwave	100 to 1,000,000 (1 meter)
Radio	>1,000,000 (1 meter)

Solar Radiation Spectrum

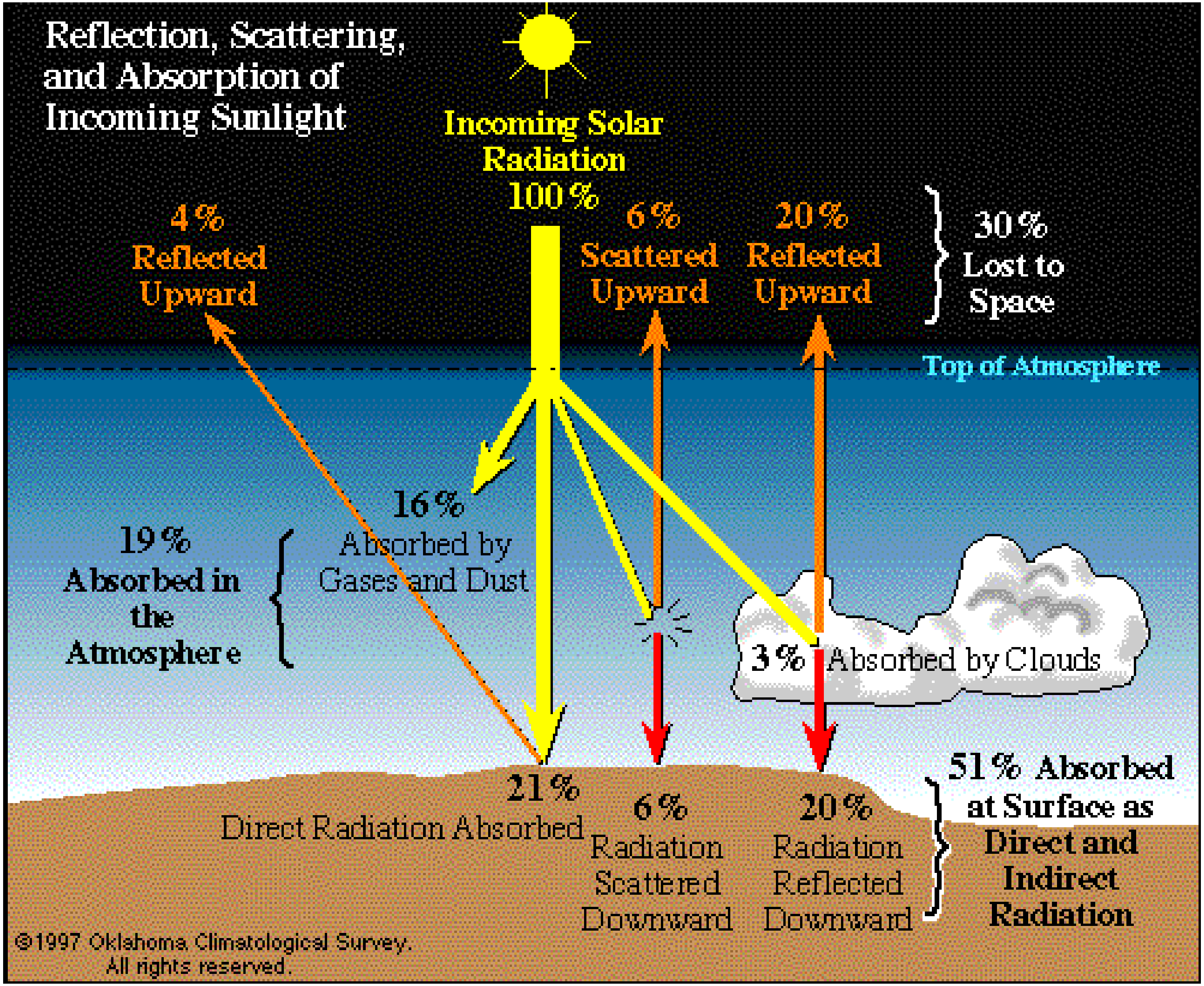


Solar Constant

- **Amount of incoming solar radiation per unit area incident on a plane perpendicular to the rays.**
- **At a distance of one 1AU from the sun (roughly the mean distance from the Sun to the Earth).**
- **Includes a range of wavelength (not just the visible light).**



Solar Radiation Budget (to Earth)



Advantages of solar Energy

All chemical and radioactive polluting byproducts of the thermonuclear reactions remain behind on the sun, while only pure radiant energy reaches the Earth. Energy reaching the earth is incredible. It has been calculated that 30 days of sunshine striking the Earth have the energy equivalent of the total of all the fossil fuels, both used and unused!

Economic

- After the initial investment has been recovered, the energy from the sun is practically FREE.
- Financial incentives are available form the government that will reduce the cost.

Environment friendly

- It is not affected by the supply and demand of fuel and is therefore not subjected to the ever-increasing price of gasoline.
- Solar Energy is clean, renewable (unlike gas, oil and coal), **sustainable** and helping to protect our environment.
- It does no pollute air. Therefore Solar Energy **does not contribute** to **global warming, acid rain or smog**. It actively contributes to the **decrease of harmful green house gas emissions**.
- By not using any fuel, Solar Energy does not contribute to the cost and problems of the recovery and transportation of fuel or the storage of radioactive waste.

Low/ no maintenance

- Solar Energy systems are virtually maintenance free and will last for decades.
- Once installed, there are no recurring costs. They operate silently, have no moving parts, do not release offensive smells.
- More solar panels can easily be added in the future if needed.

Disadvantages of solar Energy

- The initial cost is the main disadvantage of installing a solar energy system, largely because of the **high cost of the semi-conducting materials** used in building one.
- The cost of solar energy is also high compared to non-renewable utility-supplied electricity.
- Solar panels require quite a large area for installation to achieve a good level of efficiency.
- Sun does not shine consistently. The efficiency of the system also relies on the location of the sun. Solar energy is a diffuse source. To harness it, we must concentrate it into an amount and form that we can use, such as heat and electricity. **The production of solar energy is influenced by the presence of clouds or pollution in the air**. Similarly, no solar energy will be produced during nighttime although a battery backup system will solve this problem. All these problems can be overcome by taking care of the following:

1) collection, 2) conversion, 3) storage. .

- As far **as solar powered cars** go - their **slower speed** might not **appeal to everyone** caught up in today's rat race.

- Daylight
- Drying Agricultural Products
- Space Heating
- Heating Water
- Generating Electrical Power
- Concentrating Solar Power
- Photovoltaics

There are two types of solar energy: ***Thermal Energy & Electric Energy***

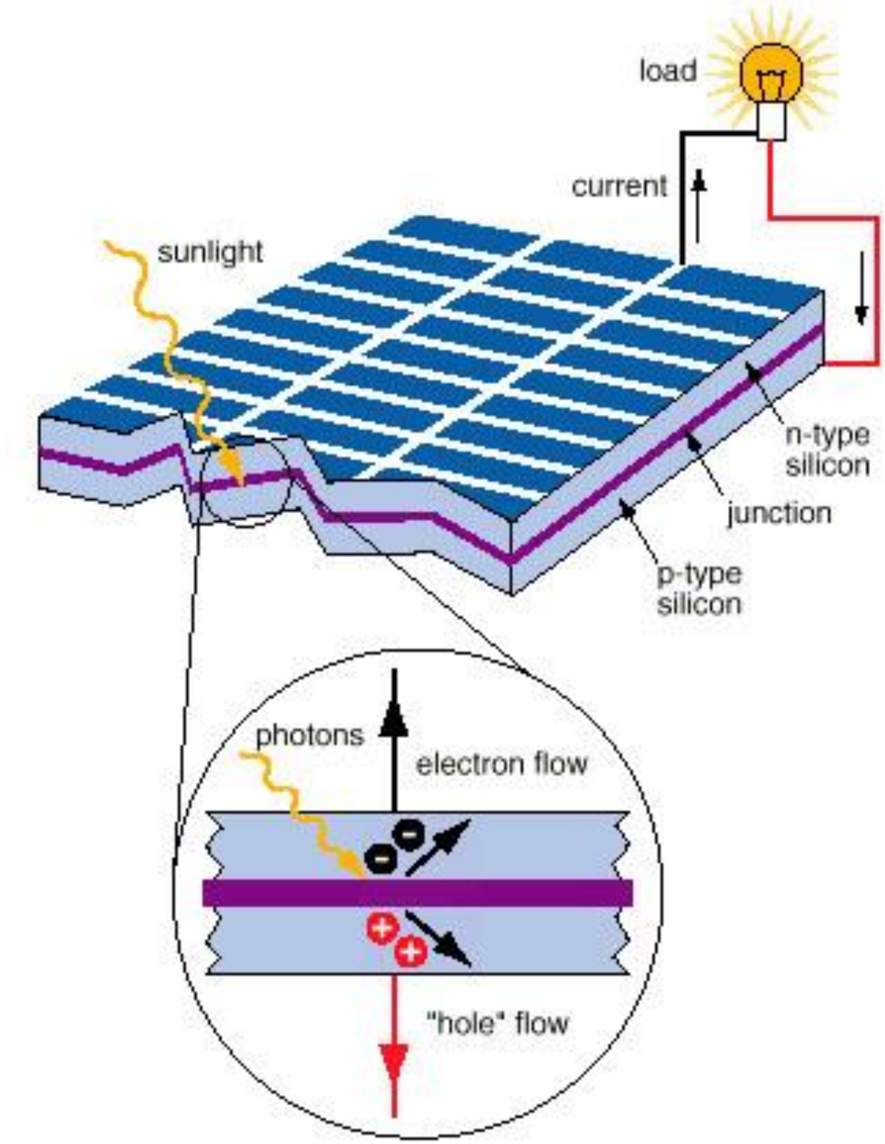
Thermal Energy: Thermal Energy is everywhere. It's lights up our days. It heats the earth, our bodies and our homes. It dries our clothes . All for free!

Electric Energy: Electric Energy uses the power of the sun to produce electricity through solar cells, which is known as ***Photovoltaics*** (PV).

Solar Thermal

- Swimming Pool Heating
- Solar Cooking
- Space Heating
- Solar Hot Water
- Solar Cooling
- Ocean Thermal
- Solar Thermal

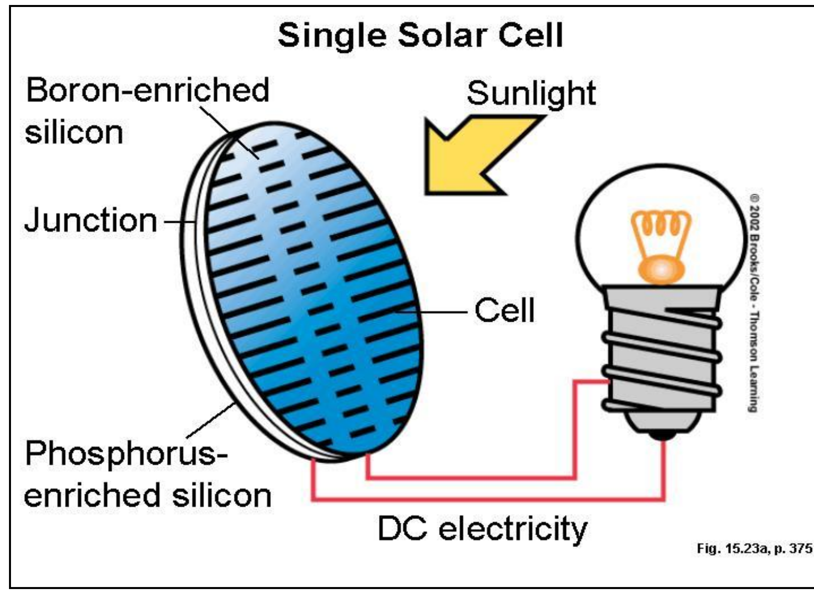
Photovoltaics (PV)



How PV cells work?

Photovoltaics

- **<u>Photo</u>+<u>voltaic</u> = convert <u>light</u> to <u>electricity</u>**

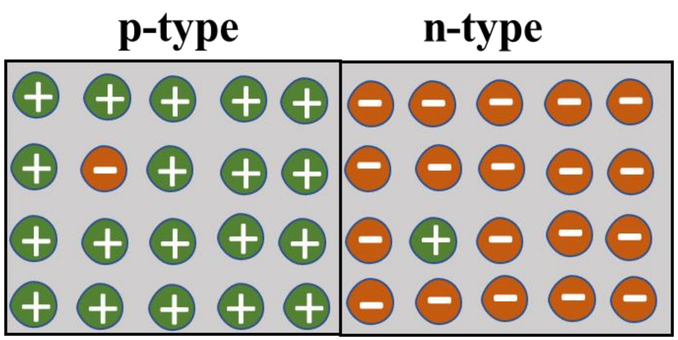


p-n Junction (p-n diode)

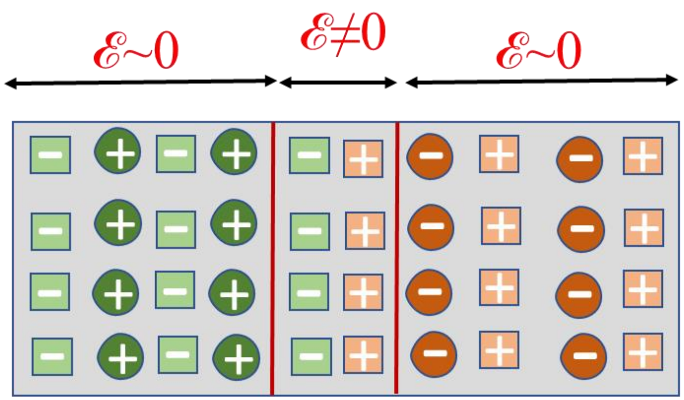
- **Solar Cells**
- Light-emitting Diodes
- Diode Lasers
- Photodetectors
- Transistors

- A p-n junction is the basic device component for many functional electronic devices listed above.

p-n junction



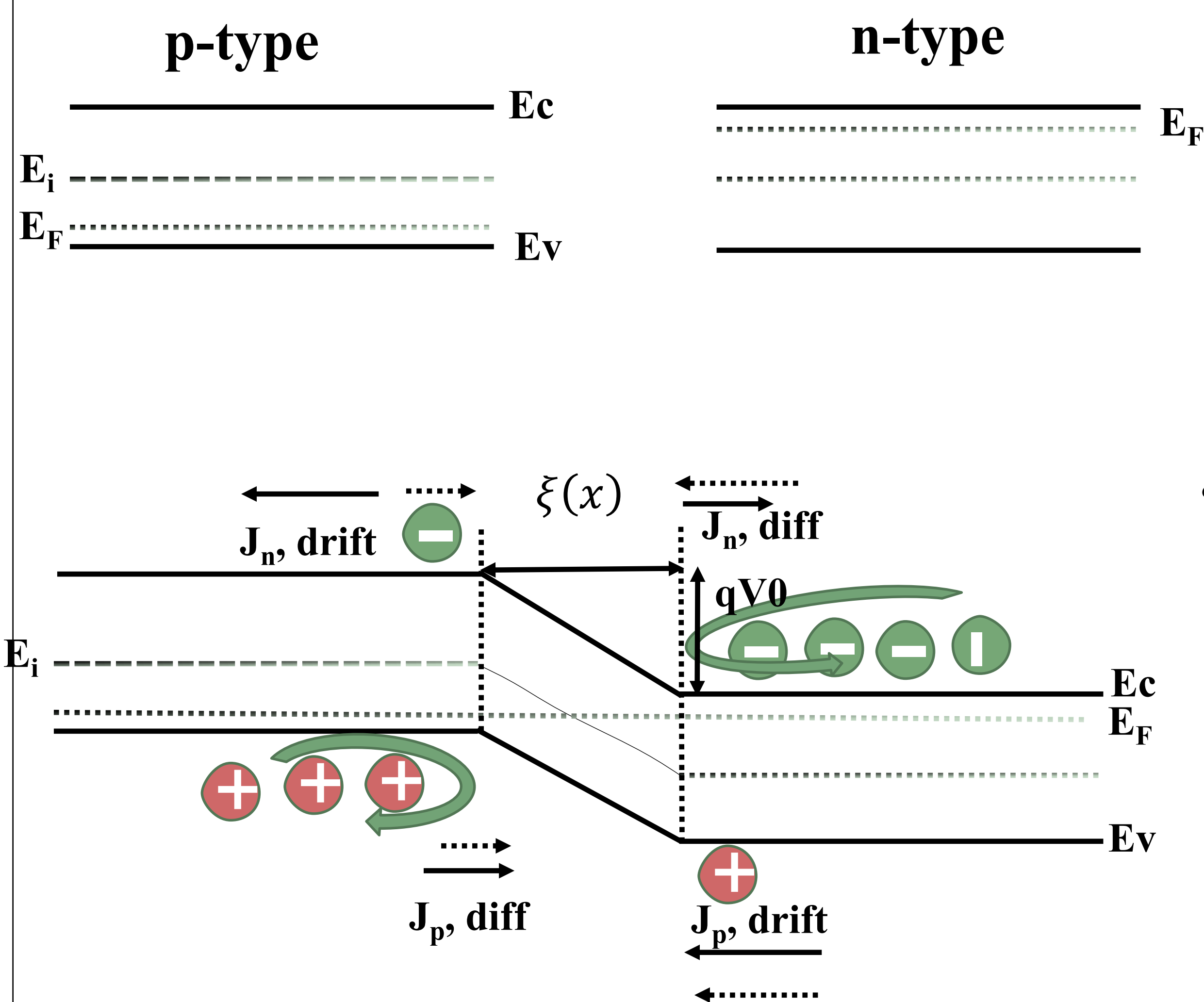
- Mobile –ve charge
- Mobile +ve charge
- Fixed +ve charge in the form of ionised donor impurity
- Fixed –ve charge in the form of ionised acceptor impurity



Separation of a sea of charge, leaving behind a charge depleted region

$\mathcal{E}$≠0, space charge region or depletion region

p-n junction potential



The presence of electric field in the space charge region indicates the presence of voltage drop across it as per the following equation. This potential is known as built in potential or junction potential

$$\xi(x) = -\frac{dV(x)}{dx} \;,\; \text{P.E.= E=} \pm qV$$

$$V_0 = \frac{kT}{q} ln\left(\frac{N_A N_D}{n_i^2}\right)$$

$$I = I_0(e^{qV/nkT}\text{-}1)$$

Fundamentals of Solar Cell:

Absorption of light:

Photons incident on the surface of a semiconductor will

1. either **reflected** from the top surface
2. will be **absorbed** in the material

failing either of the above two processes, will be transmitted through the material.

In photovoltaic devices, **reflection and transmission** are typically considered **loss mechanisms** as photons which are not absorbed **do not generate power**.

If the photon is absorbed it has the possibility of exciting an electron from the valence band to the conduction band.

A key factor in determining if a photon is **absorbed or transmitted is the energy of the photon**.

Photons falling onto a semiconductor material can be divided into three groups based on their energy compared to that of the semiconductor band gap:

- $E_{ph} < E_G$ Photons with energy E_{ph} less than the band gap energy E_G interact 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.

Absorption Coefficient:

- The absorption coefficient determines how far into a material light of a particular wavelength can penetrate before it is absorbed.
- Low absorption coefficient means light is poorly absorbed in the material.
- Absorption coefficient depends on the

  (i) material

  (ii) the wavelength of light which gets absorbed.

Absorption Depth

- This gives the distance into the material at which the light drops to about 36% of its original intensity i.e dropped by a factor of $1/e$.
- High energy light (short wavelength), such as blue light, has a large absorption coefficient that means it is absorbed in a short distance.
- Low energy light i.e long wavelength e.g red light is absorbed less strongly.
- So in the design of solar cell, the thickness of the semiconductor is important.

$$I = I_0 e^{-\alpha x}$$

- Neglecting reflection, the amount of light which is absorbed by a material depends on the absorption coefficient (α in cm^{-1}) and the thickness of the absorbing material.

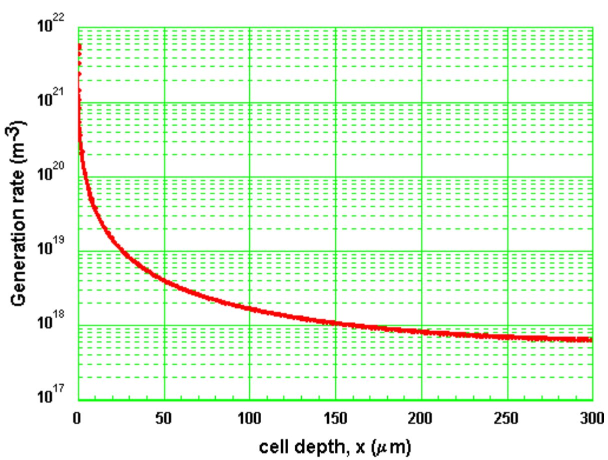
Generation Rate

- The generation rate gives the number of electrons generated at each point in the device due to the absorption of photons.

$$G = \alpha N_0 e^{-\alpha x}$$

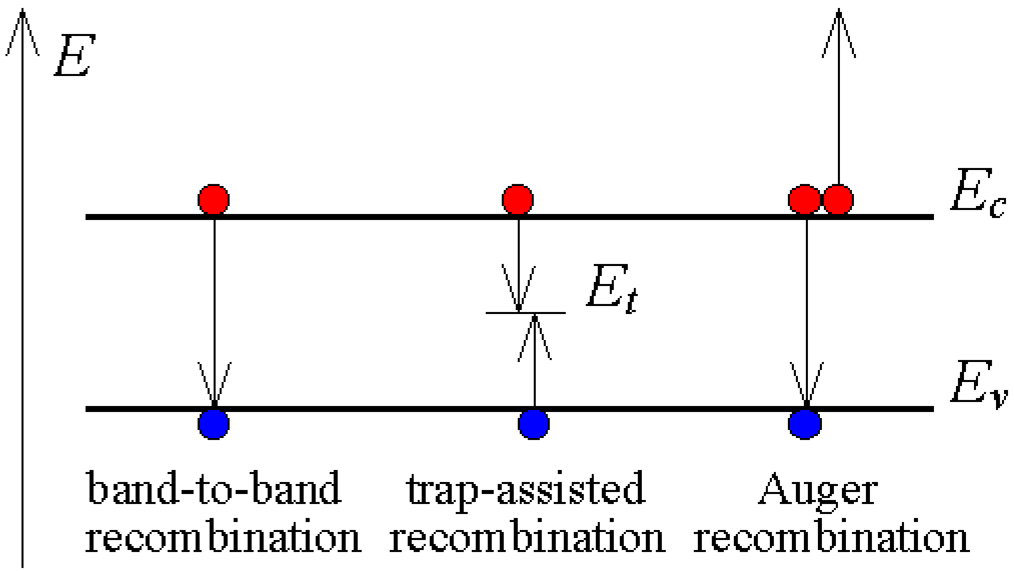
where N_0 = photon flux at the surface (photons/unit-area/sec.)
α = absorption coefficient; and
x = distance into the material

• This equation shows that the light intensity exponentially decreases throughout the material. The generation is highest at the surface of the material.



Recombination

Carrier recombination mechanism in a semiconductor



• **Any electron which is in the conduction band is in metastable state. It stabilizes when it comes to the valence band i.e lower energy position.**

When the electron stabililizes back down into the valence band it efficiently removes a hole .This process is known as recombination.

Lifetime

- Minority carrier lifetime of a material is the average time which a carrier can spend in an excited state after electron-hole generation before it recombines.

- The lifetime is related to the recombination rate by:

$$\tau = \frac{\Delta n}{R}$$

where τ is the minority carrier lifetime,

Δn is the excess minority carriers concentration

R is the recombination rate.

Diffusion Length

- **“Minority carrier diffusion length," is the average distance a carrier moves between generation and recombination.**
- **For a single crystalline silicon solar cell, the diffusion length is typically 100-300 µm.**
- **Lifetime and diffusion length indicates the quality and suitability for solar cell application.**
- **The diffusion length is related to the carrier lifetime by the diffusivity according to the following formula:**

$$L = \sqrt{D\tau}$$

Where L is the diffusion length in meters, D is the diffusivity in m^2/s and τ is the lifetime in seconds.

• Since the semiconducting materials that are heavily doped, so they have greater recombination rates and consequently, have shorter diffusion lengths.

• So a semiconductor with a higher diffusion lengths indicates the materials with longer lifetime.

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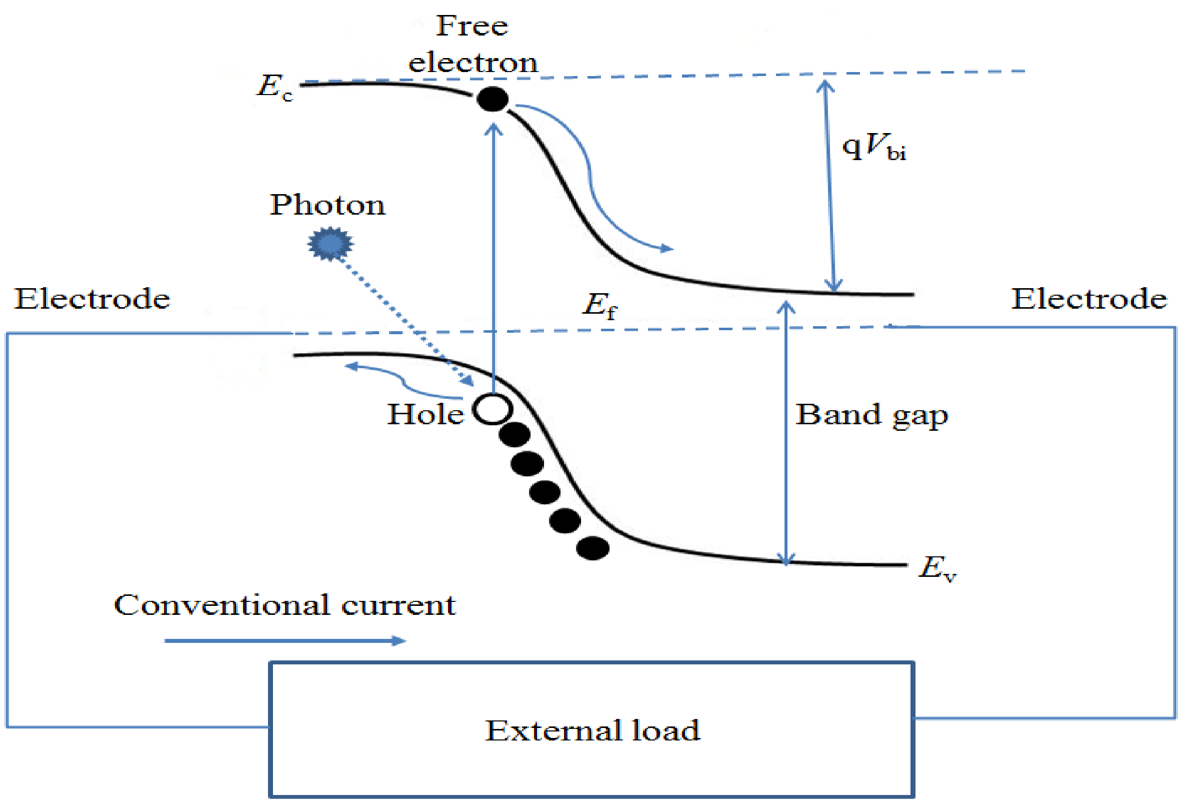
Solar Cell:

A solar cell is an optoelectronic device that converts sunlight into electricity. The photovoltaic effect was first discovered by Becquerel in 1839 . The basic operation of the solar cell can be well understood by the following steps:

- **Generation of electron-hole pairs:** If the energy of the incident photon on the semiconductor or the solar cell is higher than the bandgap energy of the semiconductor then a large number of electron-hole pairs are generated.
- **Separation of generated electron-hole pairs:** Diffusion of photo-generated electron-hole pairs inside the solar cell is random. But to obtain the flow of current in the external circuit, the photo-generated carriers must be separated and this separation is achieved by means of the electric field present at p-n junction. Electric field is directed from n^+emitter to p-substrate. The flow of electrons is directed in the opposite direction of the electric field (p to n^+) and the movement of holes is in the same direction of the electric field ($n^+$to p). But separation of all the photo-generated carriers is practically not possible; some of these are recombined too at the bulk and surface of the semiconductor as well as at the metal-semiconductor interface.
- **Flow of the electric current through an external circuit:** As the electrons and holes are moved in the opposite direction due to the presence of an electric field at the junction, p-substrate becomes enriched with holes and n^+ emitter becomes enriched with electrons. Due to this charge separation phenomenon, a photovoltage is developed and it results in the flow of current in the external circuit.



Light is absorbed by the semiconductor and makes electrons to gain enough energy to jump from the valence band to the conduction band. Charges are circulated through an external circuit by the use of contacts.

When light with energy E=hv where h is the Planck's constant and v the frequency of the radiation, shines on a semiconductor, one of the following situations may occur:

1) If the energy of the photons is smaller than the band gap of the semiconductor, then the material acts transparent to light.

2) If the energy of the photons is equal to or higher than the band gap of the semiconductor, their energy is absorbed by the material, which allows the electrons to jump to the conduction band, leaving a hole in the valence band. Energy from the photons that exceeds the band gap is transformed into heat.

Diode Equation

Ideal Diodes

The diode equation gives an expression for the current through a diode as a function of voltage. The *Ideal Diode Law*, expressed as:

$$I = I_0\left(e^{\frac{qV}{kT}} - 1\right)$$

where:

I = the net current flowing through the diode;

I_0 = "dark saturation current", the diode leakage current density in the absence of light;

V = applied voltage across the terminals of the diode;

q = absolute value of electron charge;

k = Boltzmannn’s constant; and

T = absolute temperature (K).

- The "dark saturation current" (I_0) is an extremely important parameter which differentiates one diode from another. I_0 is a measure of the recombination in a device. A diode with a larger recombination will have a larger I_0.

  It is important to note that

- ✓ I_0 increases as T increases
- ✓ I_0 decreases as material quality increases.

At 300K, $kT/q = 25.85$ mV, the "thermal voltage".

Non-Ideal Diodes

For real diodes, the expression becomes

$$I = I_0\left(e^{\frac{qV}{nkT}} - 1\right)$$

where:

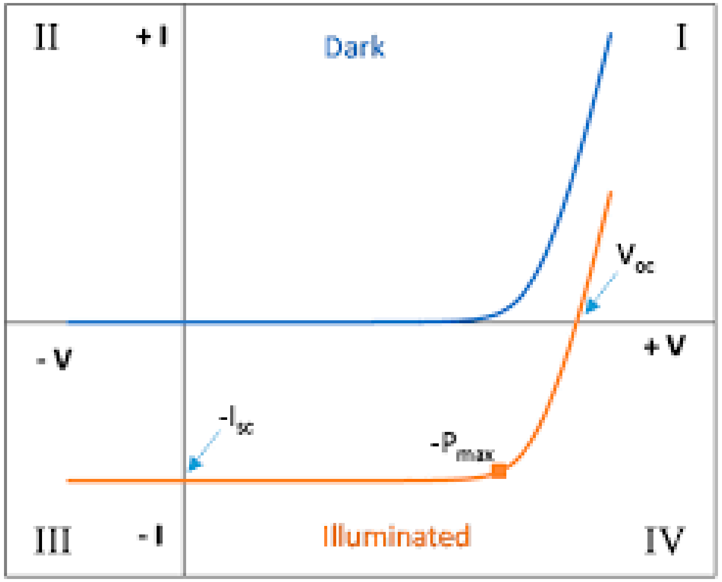
n = ideality factor, n varies between 1 and 2 which increases as the current decreases.

✓For real diodes, the saturation current is strongly dependent on the

(i)diode temperature

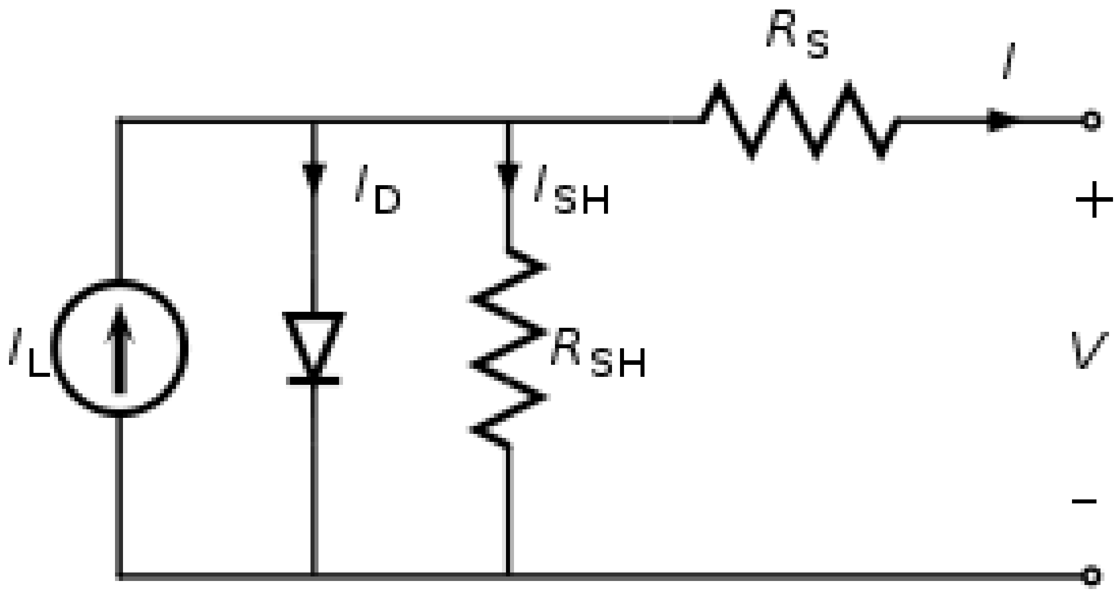
(ii) ideality factor.

Light generated current

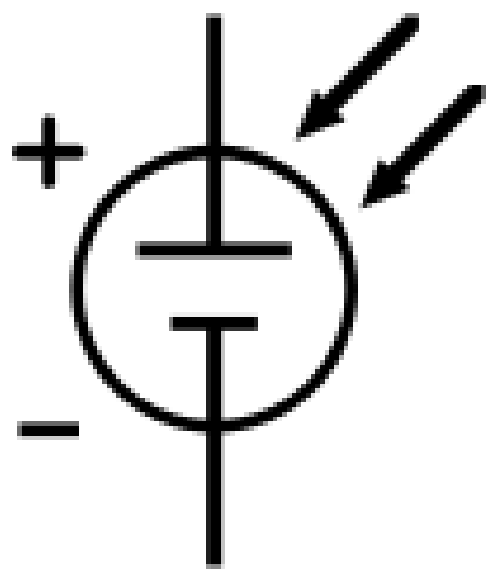


Downward shifting of dark IV curve. When light shines on a pn junction diode i.e curve (b) is illuminated IV curve.

- When light falls on the solar cells two process occurs. In the first step light is being absorbed by the semiconducting material to create e-h pair. Then the e-h pair will be separated out by the electric field that exists in the pn junction.
- In the fourth quadrant of the curve, voltage is positive and current is negative, resulting a –ve power.
- The –ve power implies that the power can be extracted from the device. Therefore, solar cell generates power rather than consuming power like other electronic devices where power is positive.



Equivalent circuit of a solar cell



Schematic symbol of a solar cell

- The series resistance arises due to a) contact resistance at metal semiconductor interface b) ohmic resistance of both metal electrodes, and c) ohmic resistance through the emitter and base of the solar cell.
- The slope of the I-V curve at open circuit voltage is a good estimation of series resistance.
- The shunt resistance presence is due to the leakage current from the solar cell junction which depends on the manufacturing defects.
- These two resistances are the main cause of voltage loss and low fill factor in the solar cell.

- In ideal diodes a current source is there in parallel with a diode.
- But in practice no solar cells are ideal. For real solar cells series resistance and shunt resistance component must be there.
- From the equivalent circuit it is evident that the current produced by the solar cell is equal to that produced by the current source, minus that which flows through the diode, minus that which flows through the shunt resistor.

$$I = I_L - I_D - I_{SH}$$

where

I = output current (ampere)

I_L = photogenerated current (ampere)

I_D = diode current (ampere)

I_{SH} = shunt current (ampere)

- The current through these elements is governed by the voltage across them:

$$V_j = V + IR_S$$

where

V_j = voltage across both diode and resistor R_{SH} (volt)

V = voltage across the output terminals (volt)

I = output current (ampere)

R_S = series resistance (Ω).

By the Shockley diode equation, the current diverted through the diode is:

$$I_D = I_0 \left\{ \exp\left[\frac{qV_j}{nkT}\right] - 1 \right\}$$

where

I_0 = reverse saturation current (ampere)

n = diode ideality factor (1 for an ideal diode)

q = elementary charge

k = Boltzmann's constant

T = absolute temperature

At 25°C, KT/q = 0.025 volt.

- By Ohm's law, the current diverted through the shunt resistor is:

$$I_{SH} = \frac{V_j}{R_{SH}}$$

where

R_{SH} = shunt resistance (Ω).

Substituting these into the first equation produces the characteristic equation of a solar cell, which relates solar cell parameters to the output current and voltage:

$$I = I_L - I_0 \left\{ \exp\left[\frac{q(V + IR_S)}{nkT}\right] - 1 \right\} - \frac{V + IR_S}{R_{SH}}.$$

The parameters I_0, n, R_S, and R_{SH} cannot be measured directly. So open circuit voltage and short circuit current has to be measured.

- The values of I_0, R_S, and R_{SH} are dependent upon the area of the solar cell.
- If we compare two cells, a cell with twice the surface area of another. In principle, the cell which has double surface area has double the the value of I_0 since it has twice the junction area across which current can leak. It will also have half the R_S and R_{SH} because it has twice the cross-sectional area through which current can flow. So it is necessary to write the characteristic equation in terms of current density, or current produced per unit cell area.

$$J = J_L - J_0 \left\{ \exp\left[\frac{q(V + Jr_S)}{nkT}\right] - 1 \right\} - \frac{V + Jr_S}{r_{SH}}$$

where

J = current density (ampere/cm^2)

J_L = photogenerated current density (ampere/cm^2)

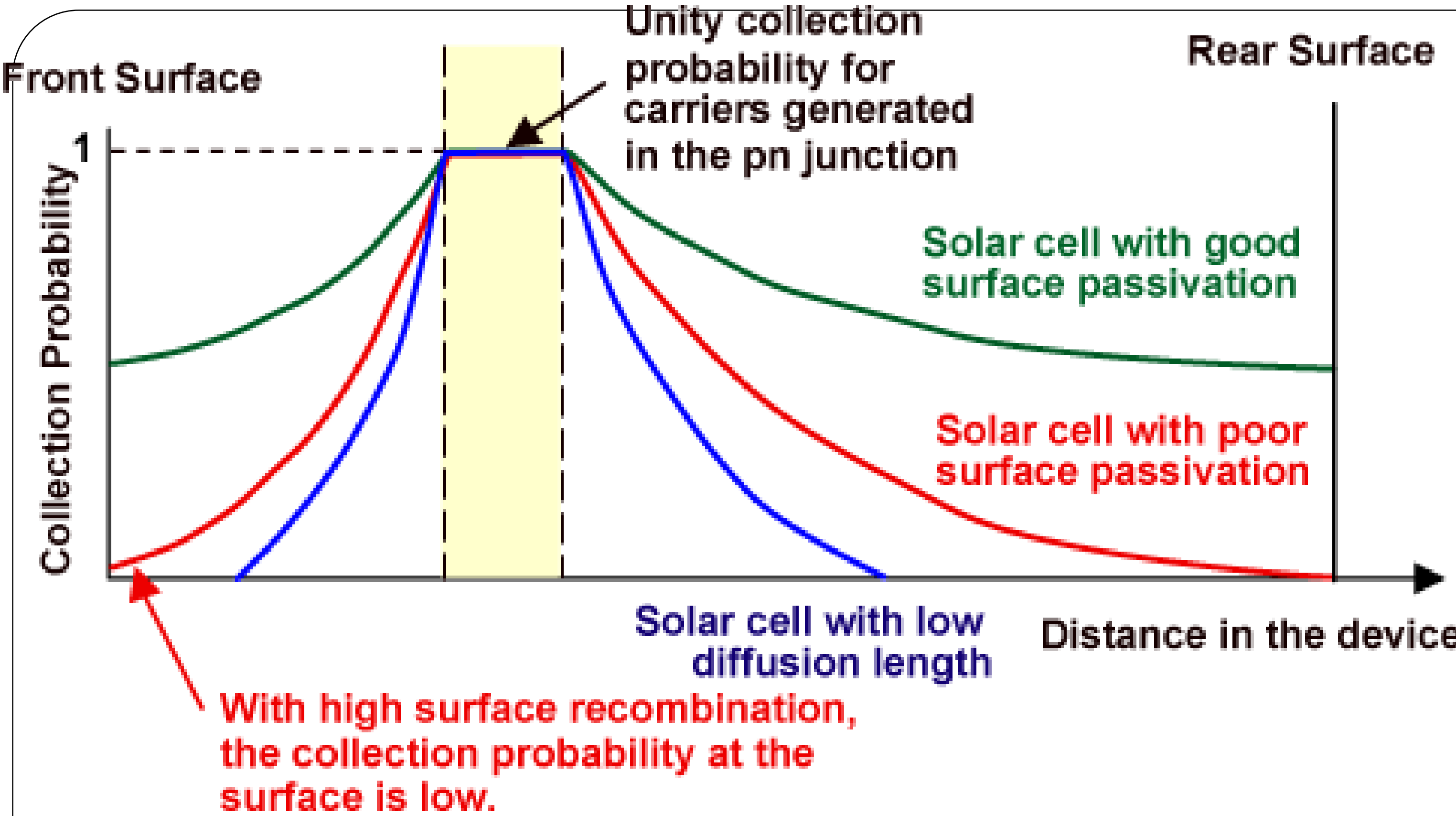
J_0 = reverse saturation current density (ampere/cm^2)

r_S = specific series resistance (Ω-cm^2)

r_{SH} = specific shunt resistance (Ω-cm^2).

Collection Probability

- The "collection probability" describes the probability that a carrier generated by light absorption in a certain region of the device will be collected by the *p-n* junction and therefore contribute to the light-generated current, but probability depends on the distance that a light-generated carrier must travel compared to the diffusion length.
- Collection probability also depends on the surface properties of the device.
- The collection probability of carriers generated in the depletion region is unity as the electron-hole pair are quickly swept apart by the electric field and are collected.
- Away from the junction, the collection probability drops.



The impact of surface passivation and diffusion length on collection probability

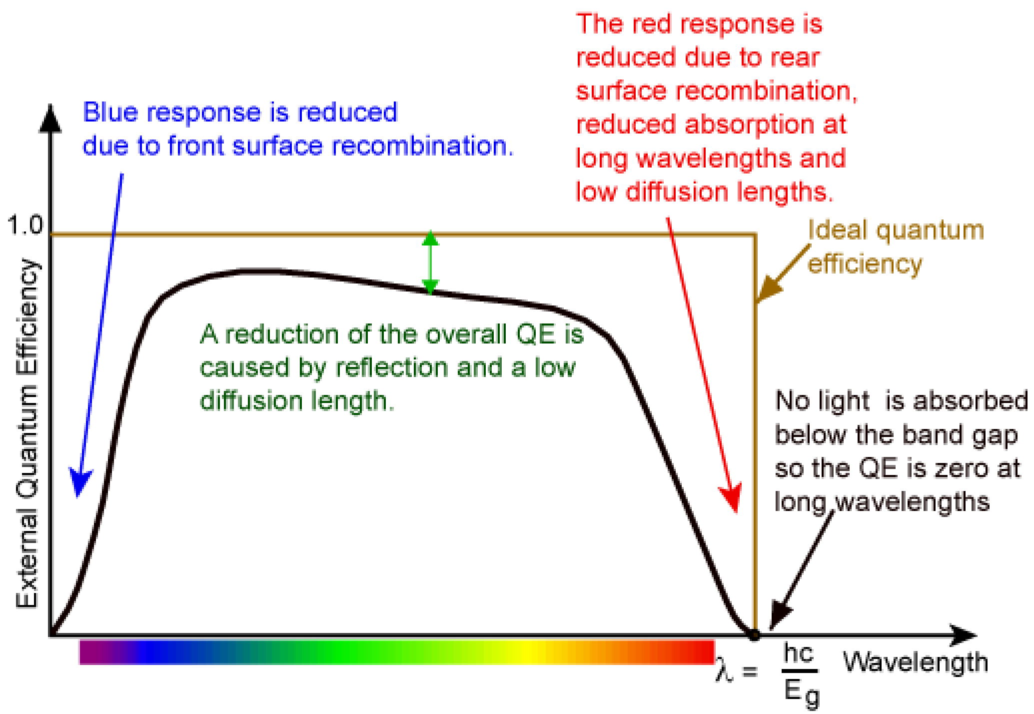
• The collection probability in conjunction with the generation rate in the solar cell determine the light-generated current from the solar cell.

- **At the surfaces, the collection probability is lower than in the bulk. Comparing the generation rates for blue, green and infrared light below, blue light is nearly completely absorbed in the first few tenths of a micron in silicon. Therefore, if the collection probability at the front surface is low, any blue light in the solar spectrum does not contribute to the light-generated current.**

- **Blue light of 0.45 μm has a high absorption coefficient of 10^5 cm^{-1} and is therefore absorbed very close to the front surface. Red light at 0.8 μm and an absorption coefficient of 10^3 cm^{-1} is absorbed deeper into the cell. Infrared light at 1.1 μm with an absorption coefficient of 10^3 cm^{-1} is barely absorbed since it is close to the band gap of silicon.**

Quantum Efficiency

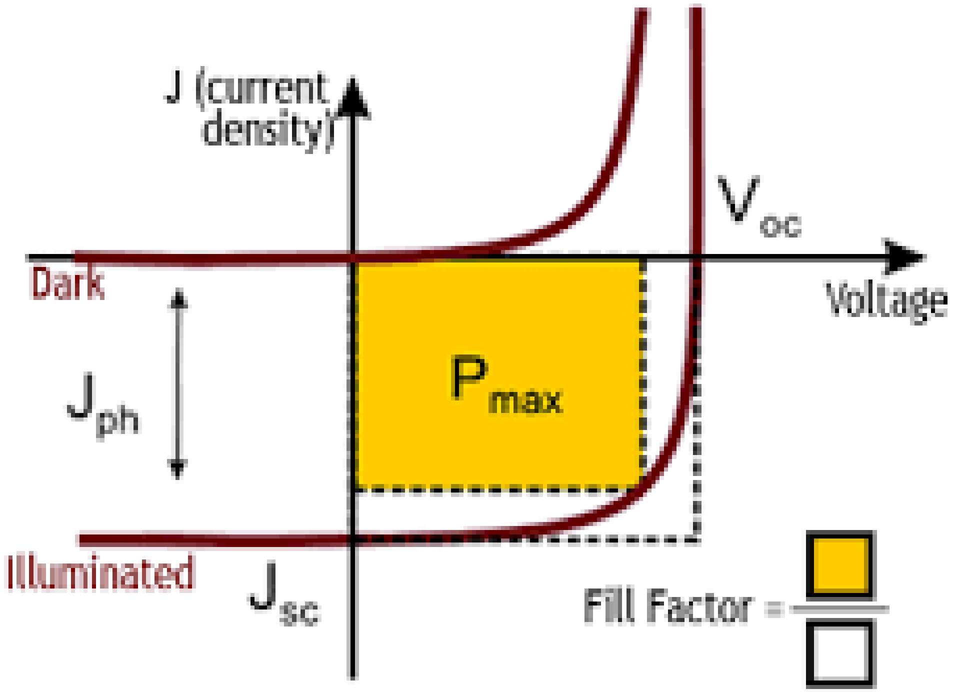
- "Quantum efficiency" (Q.E.) is the ratio of the number of carriers collected by the solar cell to the number of photons of a given energy incident on the solar cell.
- The quantum efficiency can be expressed as a function of wavelength or energy.
- The quantum efficiency for photons with energy below the band gap is zero.



Quantum efficiency curve for an ideal solar cell

Solar cell Characteristics

•Solar cells are characterized and compared with each other with four parameters.: short circuit current I_{sc} , open circuit voltage $V_{oc,}$ fill factor FF and efficiency η.



Short circuit current I_{sc} :

• This is the maximum current that flows in a solar cell when its terminals at p-side and n-side are shorted with each other. i.e V= 0.

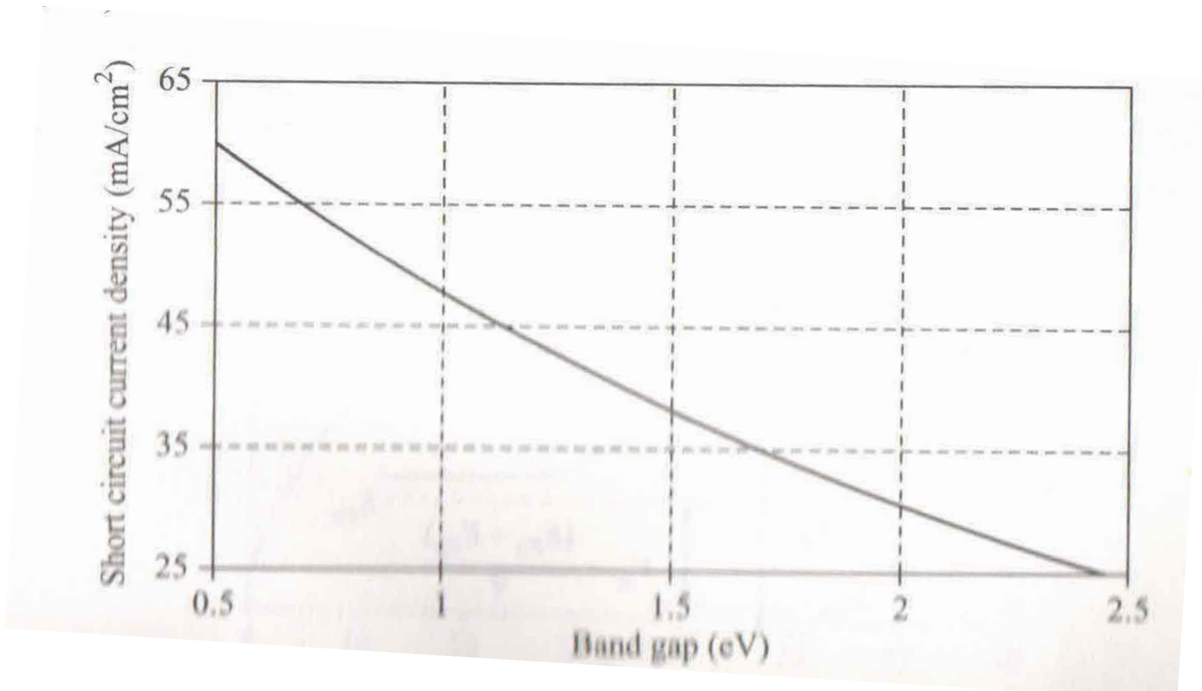
- When we put V=0 in the equation

$$I_{Total} = I_0(e^{qV/kT} - 1) - I_L$$

We will get $I_{sc} = -I_L$

- So short circuit current is nothing but the light generated current. Short circuit current is usually represented in terms of current density i.e current per unit area, in terms of mA/cm^2 .
- When a photon is absorbed in a solar cell it generates an electron-hole pair which is separated by the junction and transported to the external circuit.
- A photon is required to posses energy higher than the band gap energy of the material in ordered to be absorbed. This means short circuit current will depend on the bandgap of the materials.

- A material with a large bandgap will absorb less number of photons as compared to the material with low bandgap.
- So the short circuit current will increase with decrease in bandgap energy.



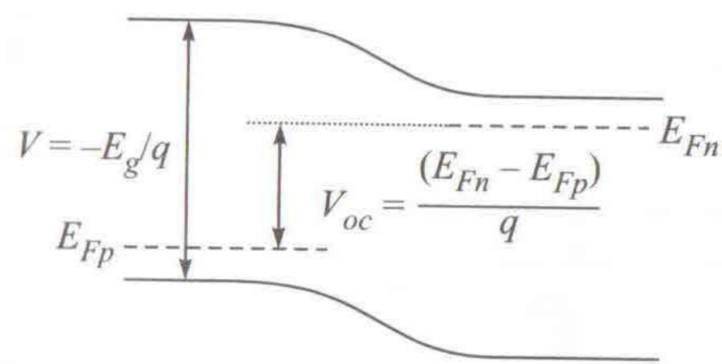
Maximum possible short circuit current as a function of bandgap of semiconductor materials

Open Circuit Voltage V_{oc}

- It is the maximum voltage generated across the terminals of a solar cell when they are kept open i.e I = 0. Putting this in the following equation

$$I_{Total} = I_0(e^{qV/kT} - 1) - I_L$$

$$V_{oc} = \frac{kT}{q} \ln\left(\frac{I_L}{I_0} + 1\right)$$



- So the open circuit voltage depends on the light generated current and reverse saturated current. The V_{oc} is given in terms of mV or V.

- If a photon of energy higher than the bandgap energy is absorbed, it excites an electron from the valence to the conduction band, raising its potential energy by an amount equal to $E_g = qV$.
- If there are no potential drop in solar cell then the electrostatic potential $V = -E_g / q$ should be the maximum possible voltage that can be obtained from a solar cell. Thus the upper limit to V_{oc} is decided by the bandgap energy of the material.
- The larger is the bandgap of the material, the higher is the V_{oc} of the solar cell. The bandgap of Si is 1.1 eV, so maximum possible V_{oc} is 1.1 V.

Fill Factor (FF):

- It is ratio of maximum power $P_m = V_m \times I_m$ that can be extracted from a solar cell to the ideal power $P_o = V_{oc} \times I_{sc}$

  $FF = (V_m \times I_m)/(V_{oc} \times I_{sc})$
- The FF represents the squareness of the solar cell I-V curve. It is represented in terms of percentage.
- FF is mainly related to the resistive losses in a solar cell. In ideal case, its value can be 100% corresponding to square I-V curve.
- Solar cell with higher V_{oc} has higher FF.
- Good solar cell typically will have FF values more than 0.80V or close to this.

Efficiency (η):

- It is defined as the ratio of the power output to power input. The power output is the maximum power point p_m of a solar cell, and input power is the power of solar radiation p_{rad} .
- $\mathbf{P_{rad} = 100\ mW/cm^2}$ **or** $\mathbf{1000\ W/m^2}$

$$\eta = p_m / p_{rad}$$

using $\mathbf{P_m = V_m \times I_m}$

So $\eta = (V_m \times I_m)/ p_{rad} = V_{oc} I_{sc} FF/ p_{rad}$

- **The short circuit current of a solar cell decreases with increase in bandgap. Open circuit voltage of a solar cell increases with increase in bandgap. So there is an optimum bandgap for which efficiency of a solar cell would be maximum.**

A solar cell having an area of 25 cm^2 gives a current of 0.85 A and voltage 0.55 V at maximum power point. The short circuit current is 0.9 A and open circuit voltage is 0.65 V. What is the Fill Factor, maximum power point and efficiency of the solar cell? Consider STC.

Given, Short circuit current (I_{sc}) = 0.9 A

Open circuit voltage (V_{oc}) = 0.65 V

Current at max power point (I_m) = 0.85 A

Voltage at maximum power point (V_m) = 0.55 V

Light input power (W/m^2) = 1000 W/m^2

$$\text{Area} = A = 25 \text{ cm}^2 = 25 \times 10^{-4} \text{ m}^2 = 0.0025 \text{ m}^2$$

Now,

Maximum power point, P_m or $P_{max} = I_m \times V_m = 0.85 \times 0.55 = 0.4675$ W

$$\text{Fill Factor, } FF = \frac{I_m \times V_m}{I_{sc} \times V_{oc}}$$

or

$$FF = \frac{P_m}{I_{sc} \times V_{oc}} = \frac{0.4675}{0.9 \times 0.65} \times 100 = 79.91\%$$

$$\text{Efficiency } (\eta) = \frac{P_{max}}{P_{in} \times A} = \frac{0.4675}{1000 \times 0.0025} \times 100 = 18.7\%$$

Different Loss Mechanisms in Solar Cells

In Solar Cells, various loss mechanisms exist that reduces the efficiency significantly.

- **Loss of low energy photons (18-23%):** The photon having energy <band gap energy (E_g) don't get absorbed in the material, therefore don't contribute to the generation of e-h pair. This is refereed as transmission loss.
- **Loss due to Excess energy of photons (25-30%):** When the high-energy photons i.e. photons with energy much greater than the E_g of the material, incidents on a solar cell, the remaining energy ($h\upsilon$-E_g) is released to the crystal lattice in the form of heat energy. Therefore a large amount of solar energy in lost as heat energy.
- **Voltage loss:** The voltage corresponding to the Eg of a metrial is obtained by dividing the Eg (P.E.) by charge i.e. Eg/q.
- **Fill Factor Losses (1-3%)**: ideal fill factor should be 1, but in reality FF id less than 1.

•**Reflection loss (3-5%):** A considerable amount of the incident light may be lost by the reflection from the shiny surface of the solar cell before entering the cell material.

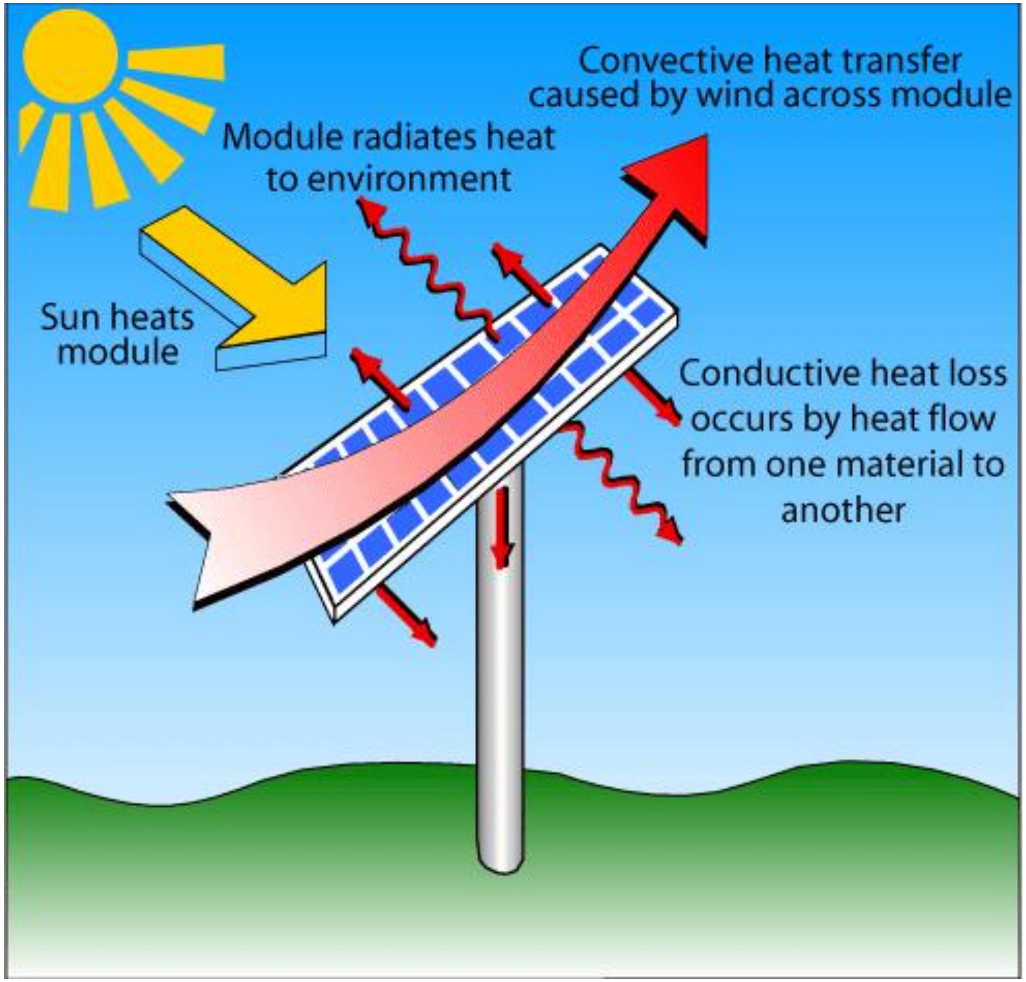
•**Recombination losses (10-15%):** In the doped areas due to recombination the electron-hole pairs are also destroyed and as a result photocurrent decreases.

•**Loss due to incomplete absorption (1-3%)**

•**Loss due to metal coverage (2-4%)**

Heat Loss in PV Modules

The operating temperature of a PV module is an equilibrium between the heat generated by the PV module and the heat loss to the surrounding environment. There are three main mechanisms of heat loss: conduction, convection and radiation.



Nominal Operating Cell Temperature (NOCT)

A PV module will be typically rated at 25 °C under 1 kW/m^2. However, when operating in the field, they typically operate at higher temperatures and at somewhat lower insolation conditions. In order to determine the power output of the solar cell, it is important to determine the expected operating temperature of the PV module. The Nominal Operating Cell Temperature (NOCT) is defined as the temperature reached by open circuited cells in a module under the conditions as listed below:

1. Irradiance on cell surface = 800 W/m^2
2. Air Temperature = 20°C
3. Wind Velocity = 1 m/s
4. Mounting = open back side.

The equations for solar radiation and temperature difference between the module and air show that both conduction and convective losses are linear with incident solar insolation for a given wind speed, provided that the thermal resistance and heat transfer coefficient do not vary strongly with temperature.

An approximate expression for calculating the cell temperature is given by :

$$T_{Cell} = T_{Air} + \frac{NOCT - 20}{80} S$$

where: S = insolation in mW/cm^2. Module temperature will be lower than this when wind velocity is high, but higher under still conditions.

Methods which are used to reduce such losses in crystalline silicon solar cells

•**A**nti-reflection coating reduces the loss due to reflection from the surface of a solar cell.

•Surface Texturing is an efficient strategy to enhance the light trapping in the cell materials. In this process the effective thickness of the cell becomes large as surface texturing creates an angle in the path of the normally incident light.

•Surface Passivation is required to prevents the recombination at the surfaces and interfaces of a solar cell. Currently two complementary approaches are used for surface passivation. They are chemical and field effect surface passivation.

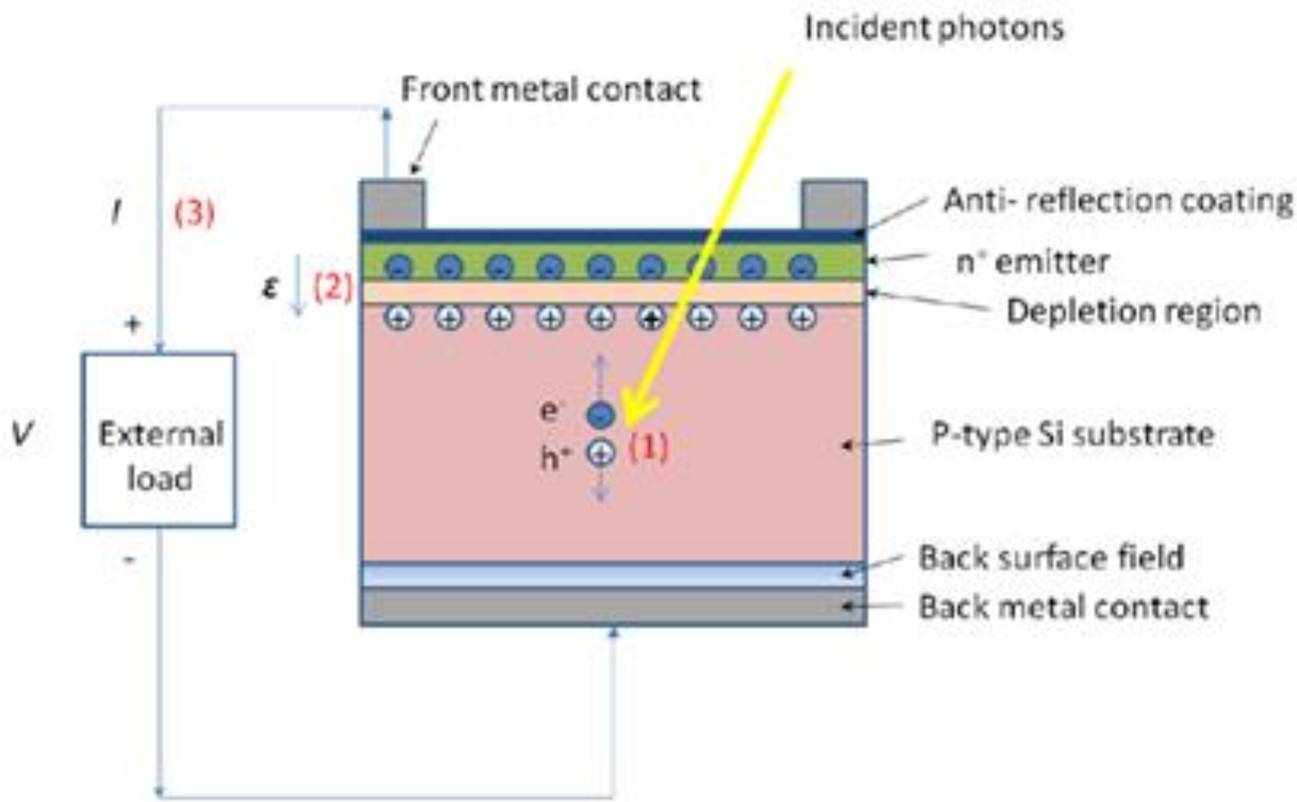
•Back Surface Field (BSF) is generated by introducing a heavily doped layer (n^+ or p^+) close to the back contact of a solar cell. Therefore a high-low junction in created close to the back surface of a solar cell and this results in a effective surface passivation .

• Generally, the efficiency of the solar cells may be improved by three ways:

(a) maximizing the photon absorption in the absorbing layer of the solar cells i.e. enhancing the optical confinement inside the solar cells

(b) increasing the number of photo-generated electron-hole pairs

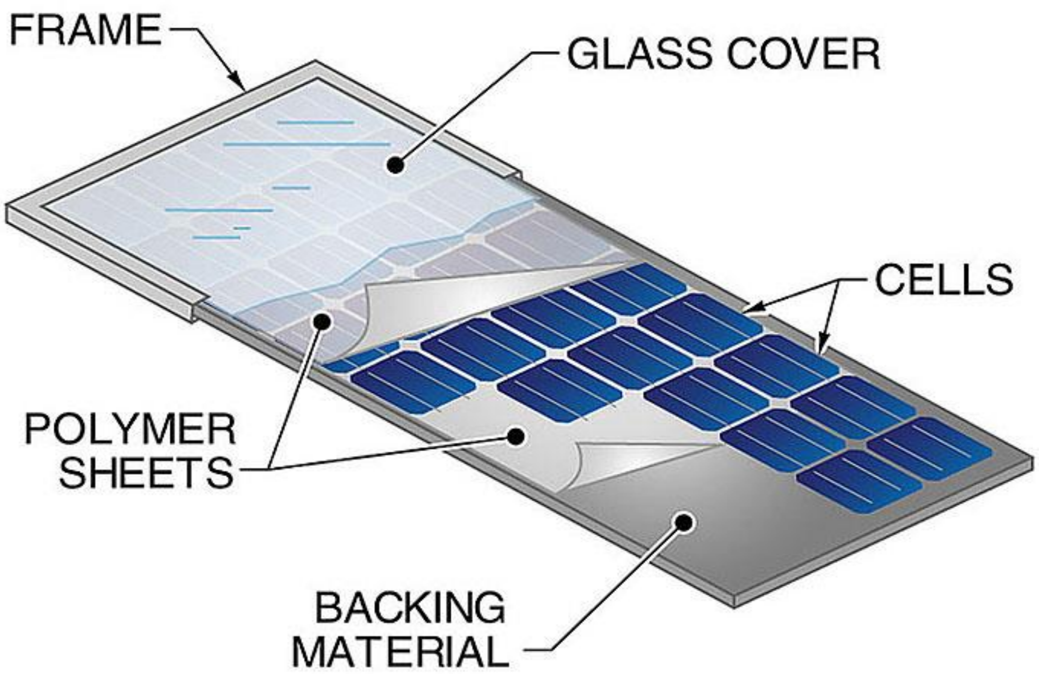
(c) collecting and transferring the photo-generated carriers in the external circuit efficiently.



Schematic of a simple standard solar cell structure showing (1) the generation of electron-hole pairs, (2) the separation of photo-generated electron-hole pairs by the internal electrical field across the p-n junction and (3) the electrical current flowing through an external circuit

- Solar cells are composed of layers of semiconductors such as silicon.
- A solar cell is a multi-layered unit consisting of a:
- **Cover** - glass or plastic layer provides outer protection.
- **Transparent Adhesive** - holds the glass to the rest of the solar cell. Ethyl vinyl acetate (EVA).
- **Anti-reflective Coating** - this layer is required to minimize the reflection, so that absorbed energy becomes maximum.
- **Front Contact** - transmits the electric current.
- **n-layer** - this is a thin layer of silicon which has been mixed with phosphorous to make it a better conductor. Phosphorus gives the layer excess electron making it n-type.
- **p-layer** - This is a thin layer of silicon which has been doped with boron to make it a better conductor. This layer has a tendency to attract electron.
- **P-N Junction** - The contact point and barrier is called the p-n junction.
- A wire can be attached from the p-layer to the n-layer to form a circuit. The wire provides a path for the electrons to flow away from each other. This flow of electrons is an electric current that we can observe.
- **Back Contact** - transmits the electric current.

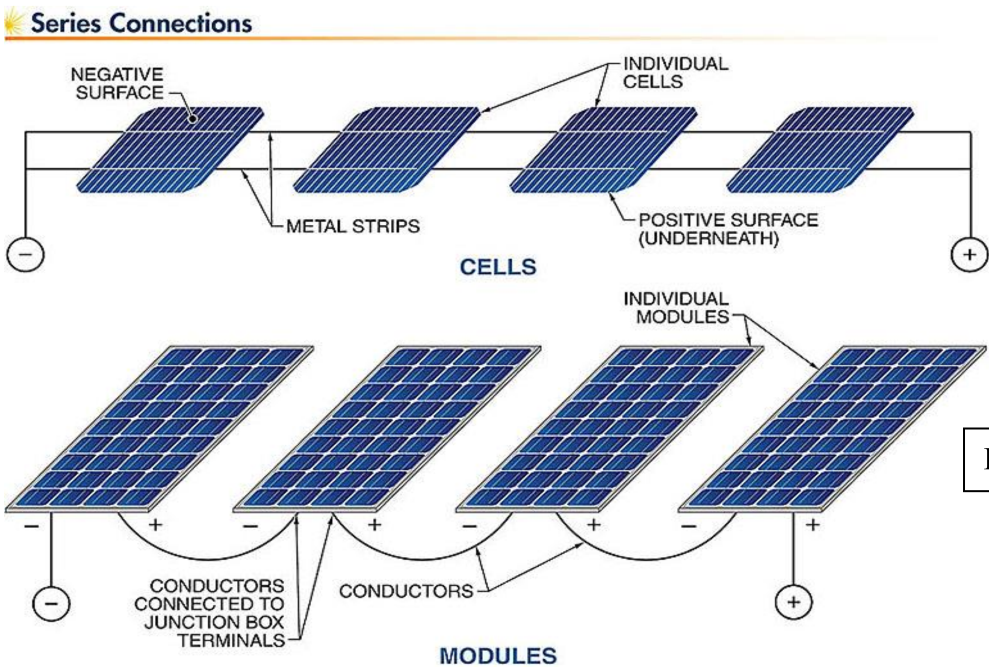
Module Construction



The PV cells are laminated within a polymer (plastic) substrate to hold them in place and to protect the electrical connections between cells. The cell laminates are then encapsulated (sealed) between a rigid backing material and a glass cover. Some thin-film laminates use flexible materials such as aluminum or stainless steel substrate and polymer encapsulation instead of a glass cover.

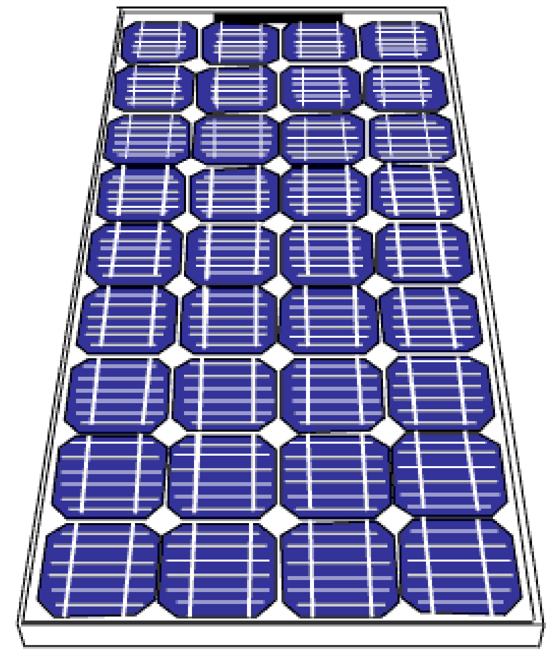
Module Structure

A PV module consists of a number of interconnected solar cells (typically 36 connected in series) encapsulated into a single, long-lasting, stable unit.



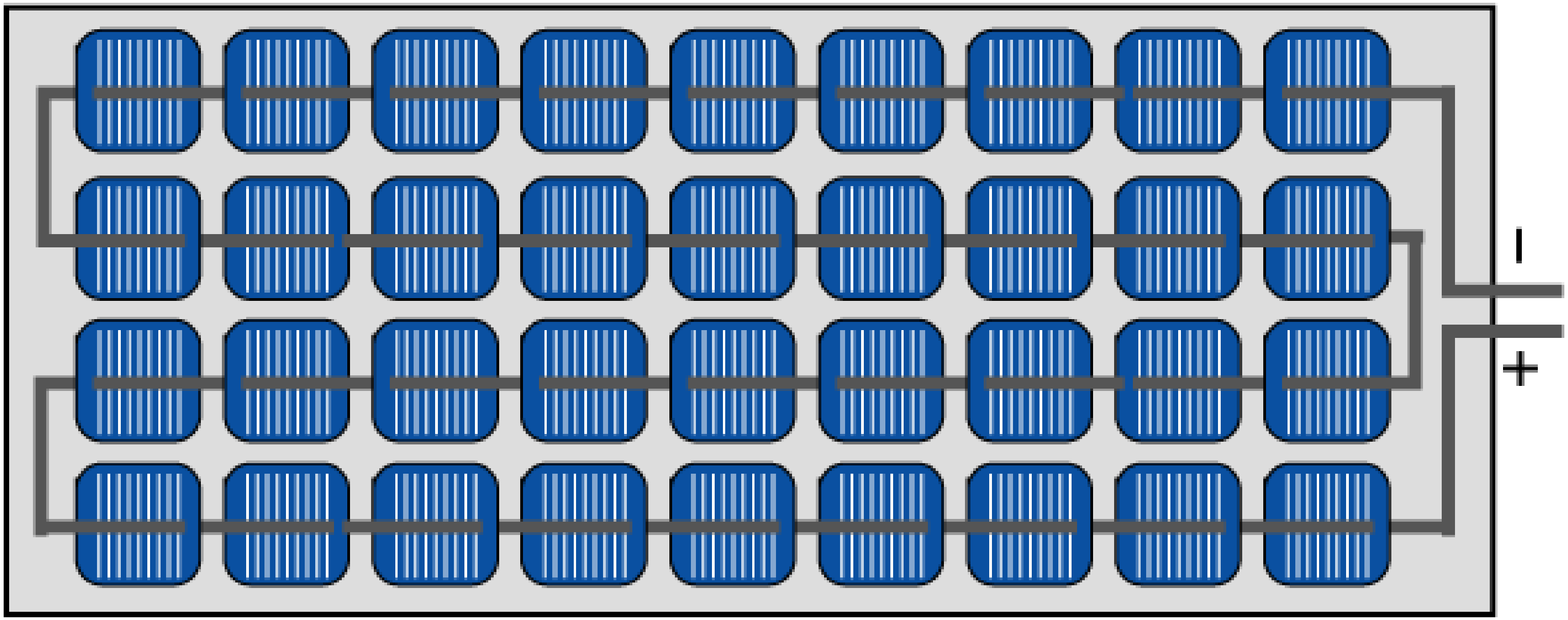
PV Module

PV Arrays

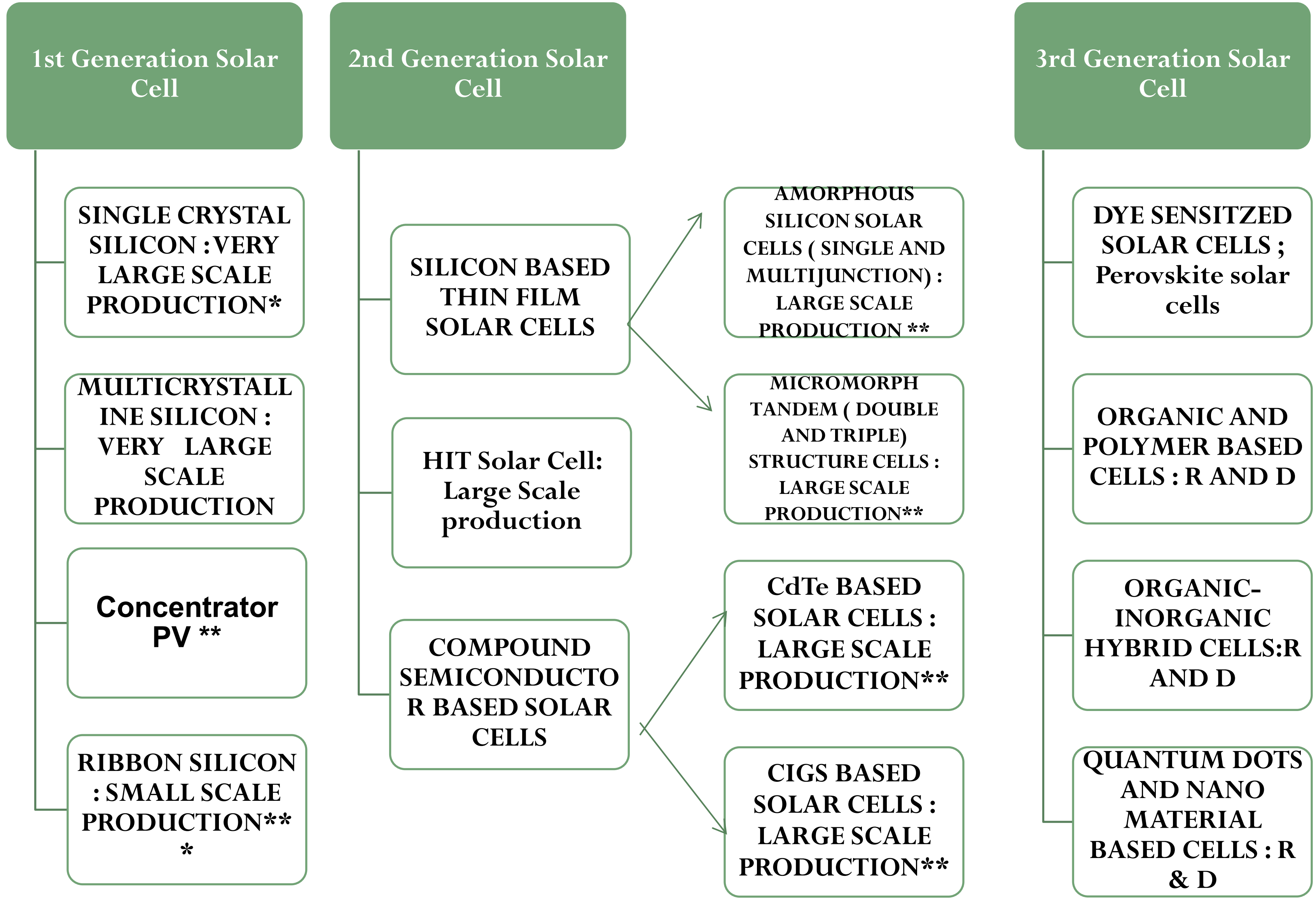


Individual cells are connected in series by soldering thin metal strips from the top surface (negative terminal) of one cell to the back surface (positive terminal) of the next. Modules are connected in series with other modules by connecting conductors between the negative terminal of one module to the positive terminal of another module. When individual devices are electrically connected in series, the positive connection of the whole circuit is made at the device on one end of the string and the negative connection is made at the device on the opposite end

A typical module has 36 cells connected in series



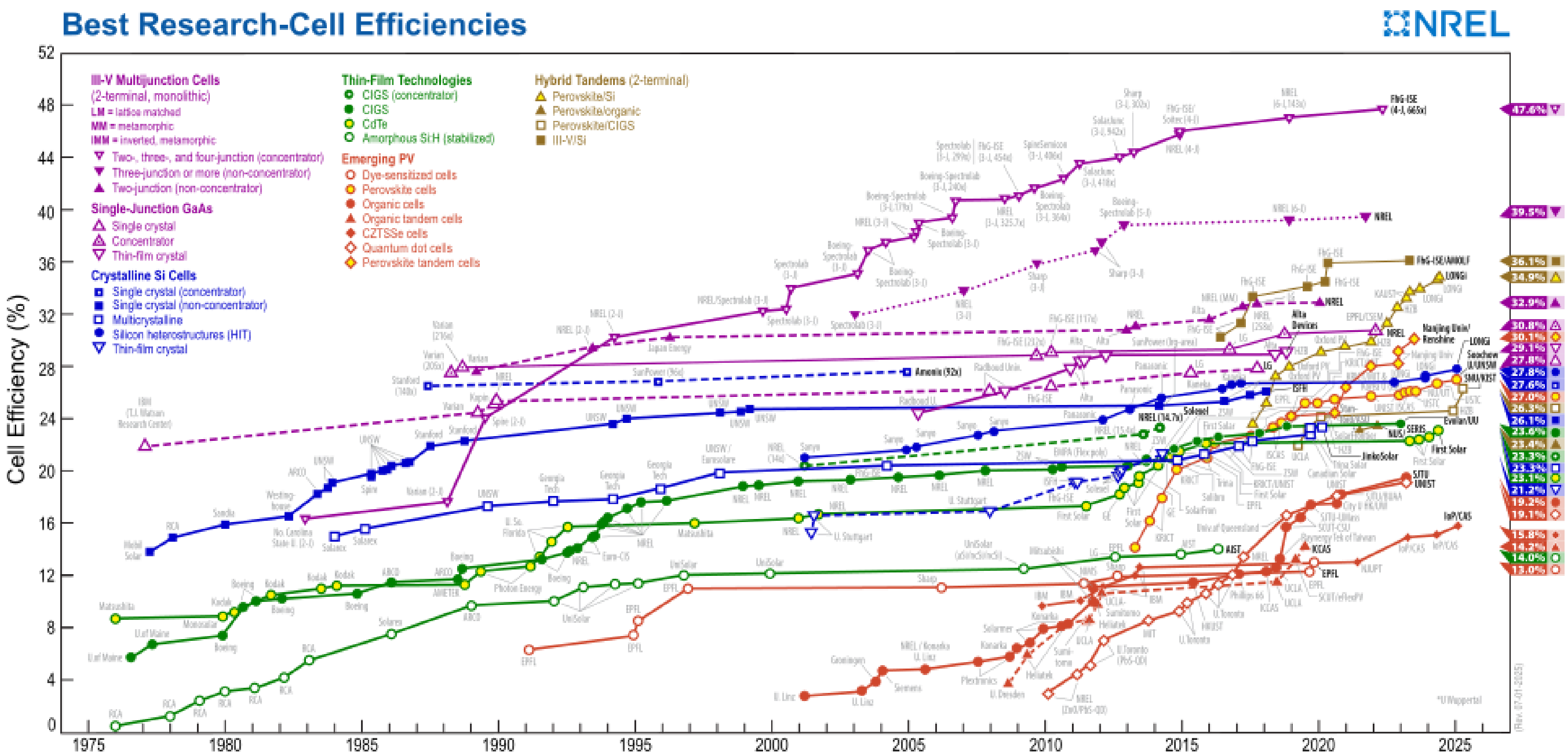
An individual silicon solar cell has a voltage of just under 0.6V under 25 °C and AM1.5 illumination. At AM1.5 and under optimum tilt conditions, the current density from a commercial solar cell is approximately between 30 mA/cm^2 to 36 mA/cm^2. Single crystal solar cells are often $100cm^2$, giving a total current of about 3.5 A from a module. An open-circuit voltage of about 21V may be obtained.



* Very Large Scale Production: Multi GW

** Large Scale Production: 1 GW

*** Small Scale Production: ~ MW


Best Research-Cell Efficiencies
NREL
Cell Efficiency (%)
III-V Multijunction Cells
(2-terminal, monolithic)
LM = lattice matched
MM = metamorphic
IMM = inverted, metamorphic
Two-, three-, and four-junction (concentrator)
Three-junction or more (non-concentrator)
Two-junction (non-concentrator)
Single-Junction GaAs
Single crystal
Concentrator
Thin-film crystal
Crystalline Si Cells
Single crystal (concentrator)
Single crystal (non-concentrator)
Multicrystalline
Silicon heterostructures (HIT)
Thin-film crystal
Thin-Film Technologies
CIGS (concentrator)
CIGS
CdTe
Amorphous Si:H (stabilized)
Emerging PV
Dye-sensitized cells
Perovskite cells
Organic cells
Organic tandem cells
CZTSSe cells
Quantum dot cells
Perovskite tandem cells
Hybrid Tandems (2-terminal)
Perovskite/Si
Perovskite/organic
Perovskite/CIGS
III-V/Si
47.6%
39.5%
36.1%
34.9%
32.9%
30.8%
30.1%
29.1%
27.8%
27.8%
27.6%
27.0%
26.3%
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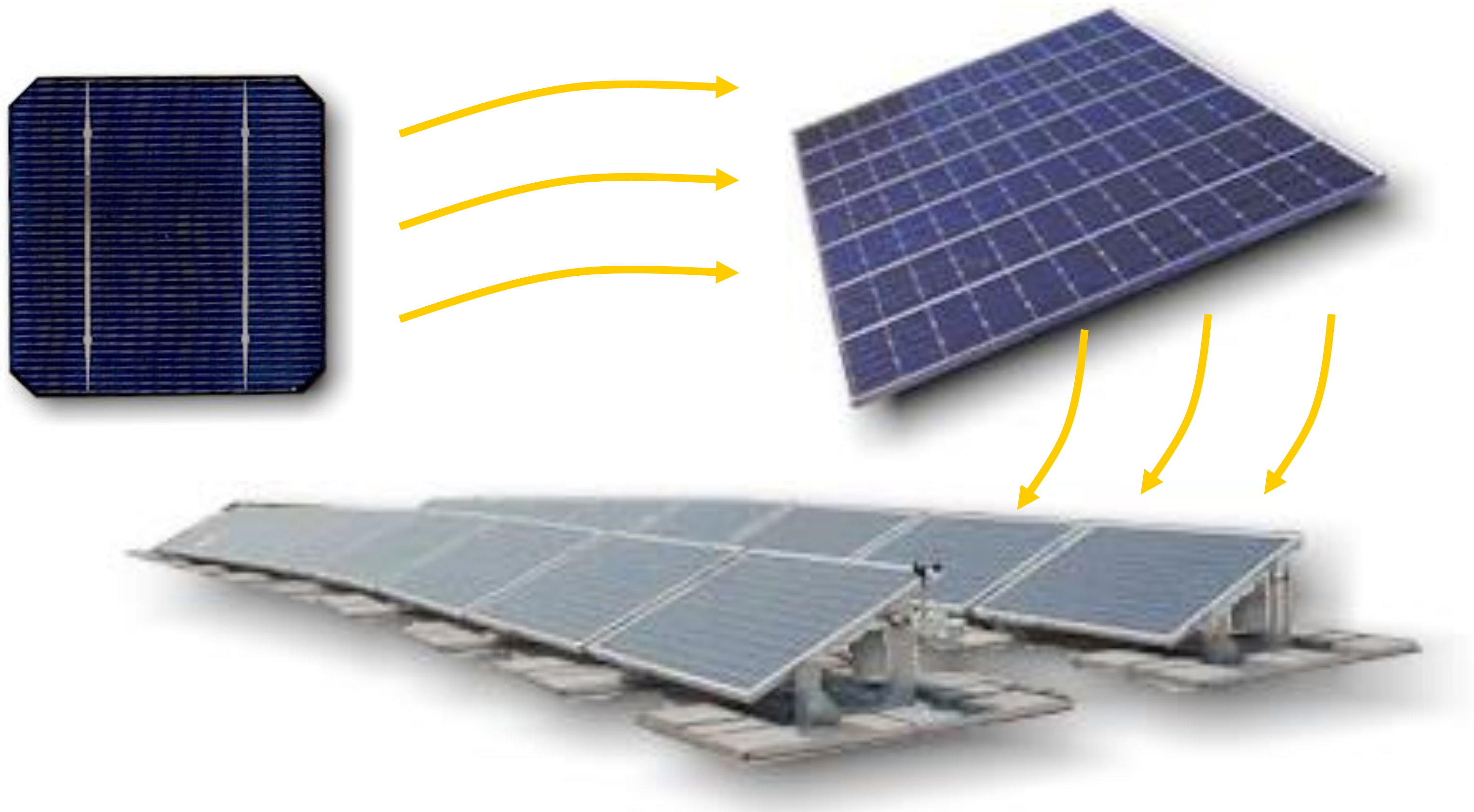
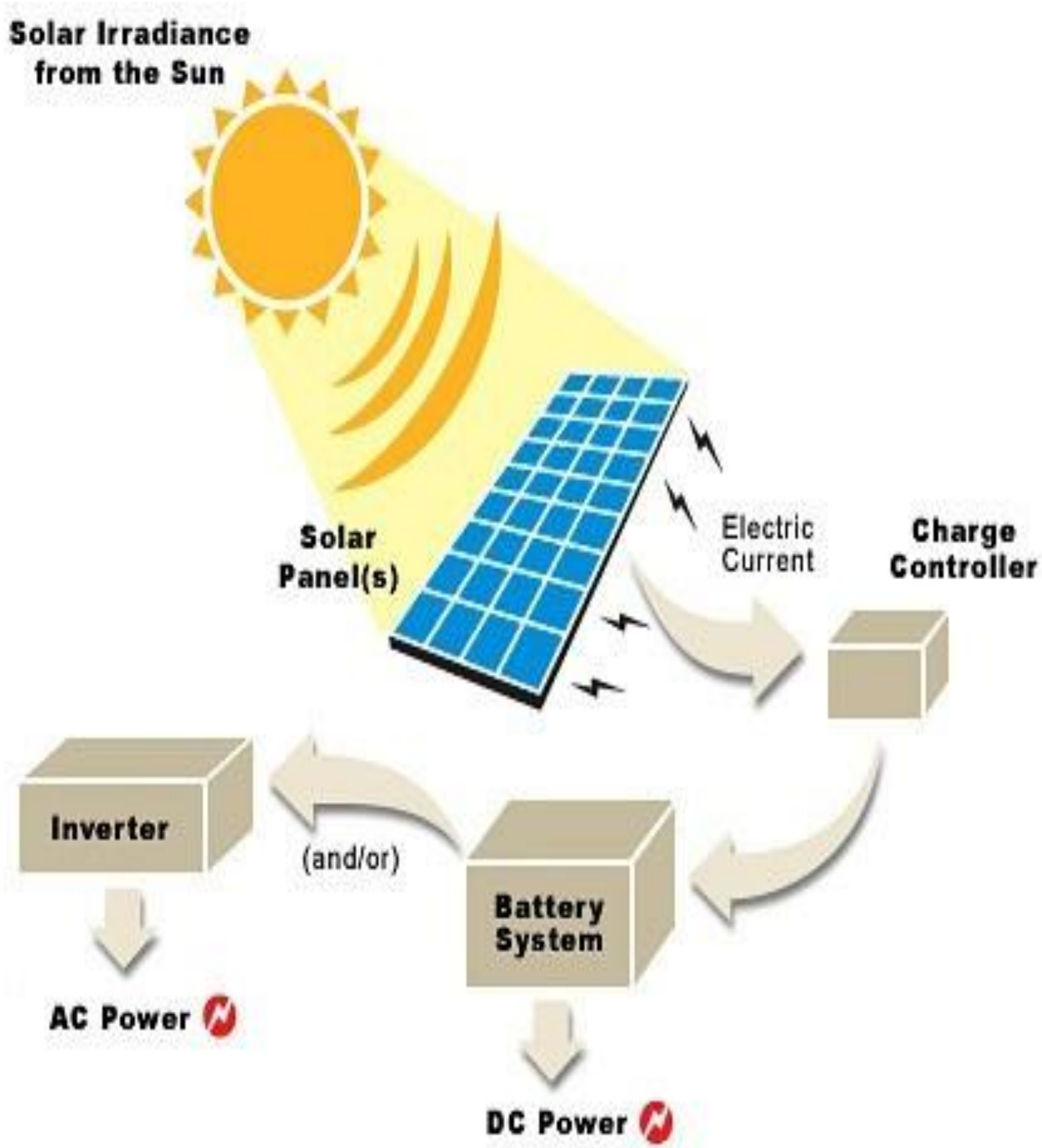
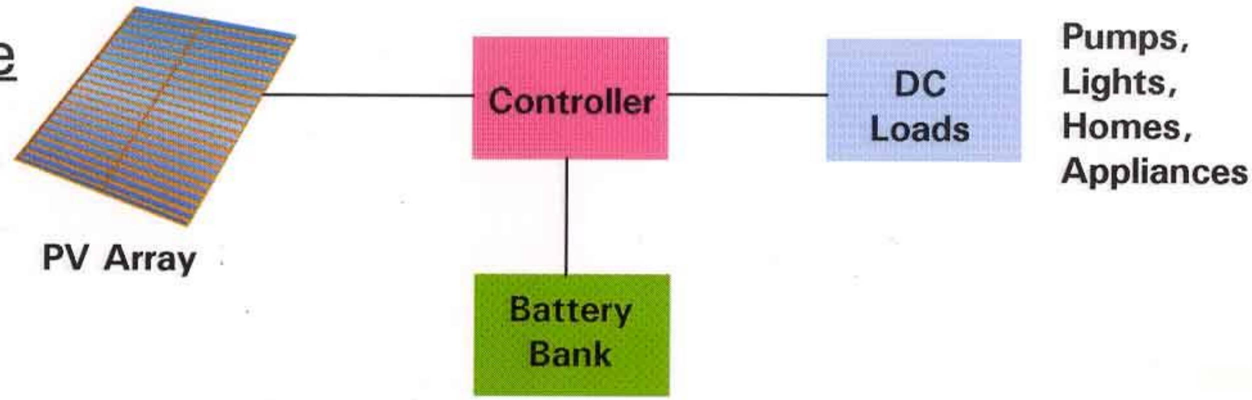
Cells, Modules and Arrays



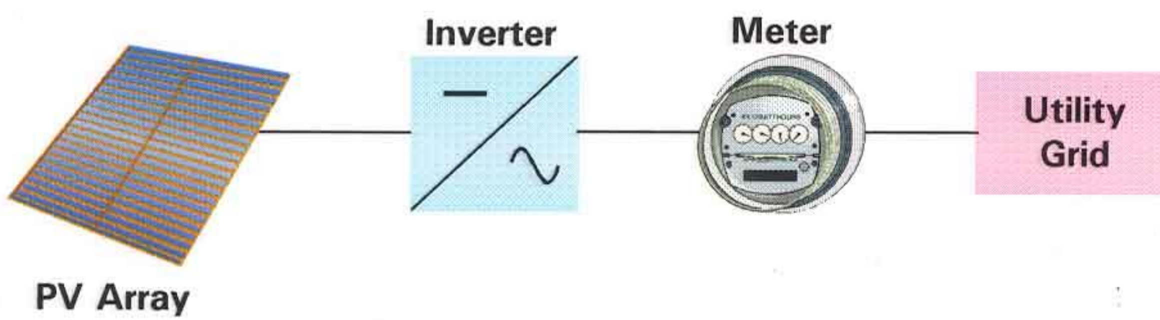

Solar Irradiance
from the Sun
Solar
Panel(s)
Electric
Current
Charge
Controller
Inverter
(and/or)
Battery
System
AC Power
DC Power

Typical PV Systems

Stand-alone

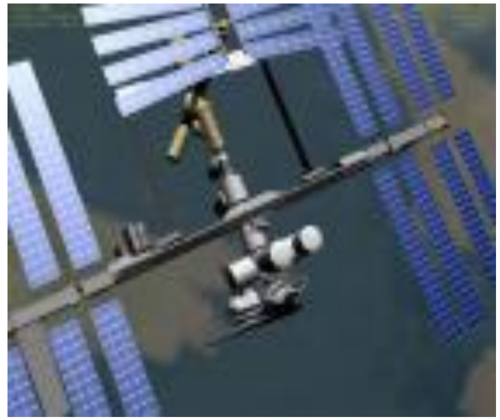


Grid-connected



Main Application Areas – Off-grid

Water Pumping



Space

Telecom

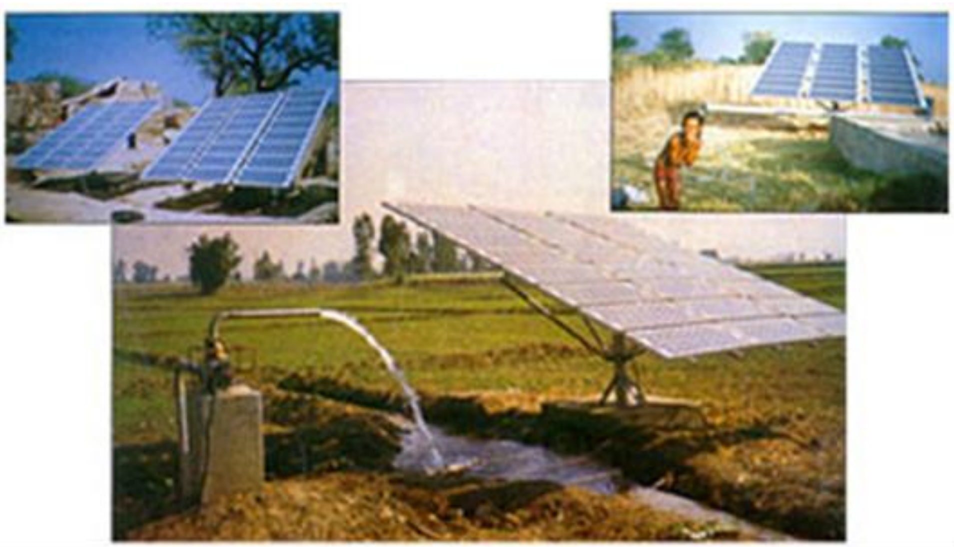
Solar Home Systems

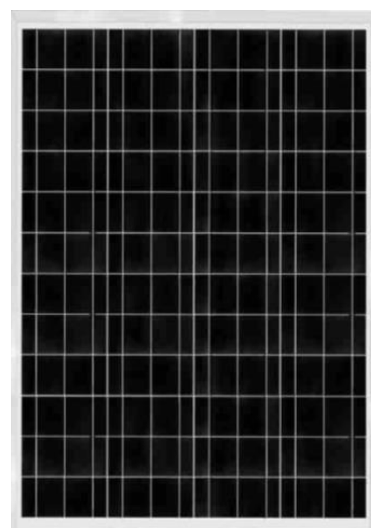
Main Application Areas Grid Connected

Commercial Building
Systems (50 kW)

Residential Home
Systems (2-8 kW)

PV Power Plants
(> 100 kW)





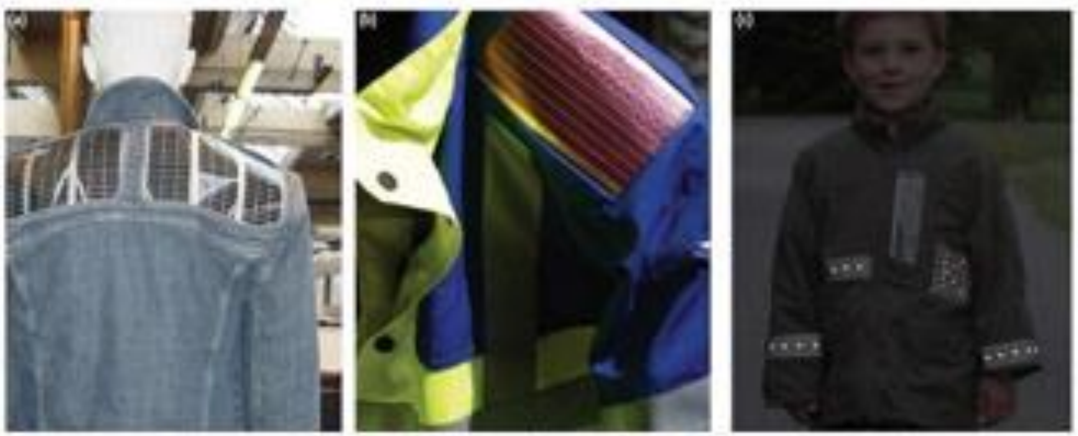

24W

Flexible Solar Cell

www.britisheco.com

www.powerportstore.com

Air Force Research Laboratory



Institut fur Textil- und Verfahrenstechnik