Physics of Materials

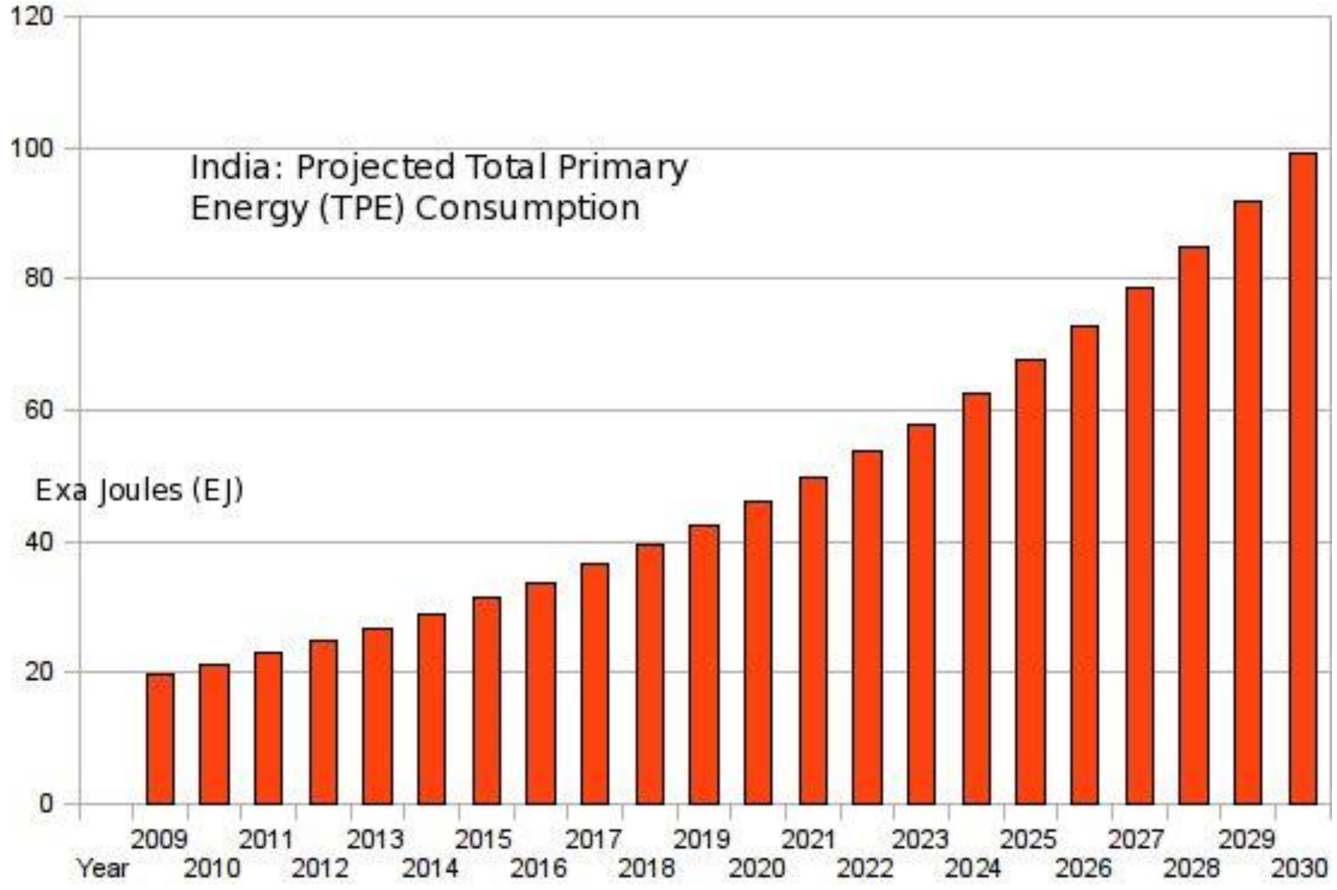
Unit III - Physics of Energy

Energy sources

Energy – ability/capacity to do work.

It is measured the total amount of work that the body can do.

Requirement of energy



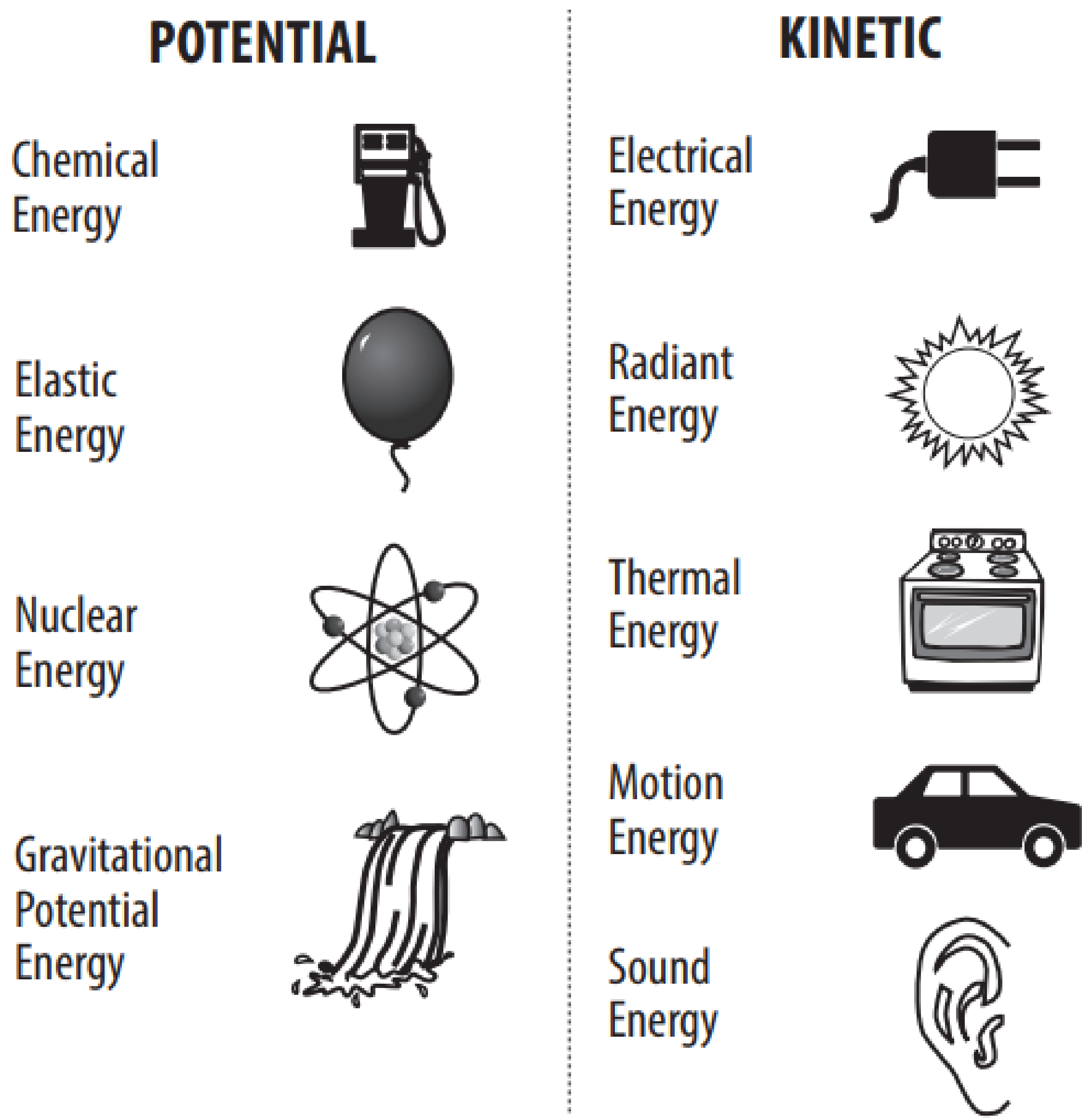
Characteristics of Good Sources Of Energy

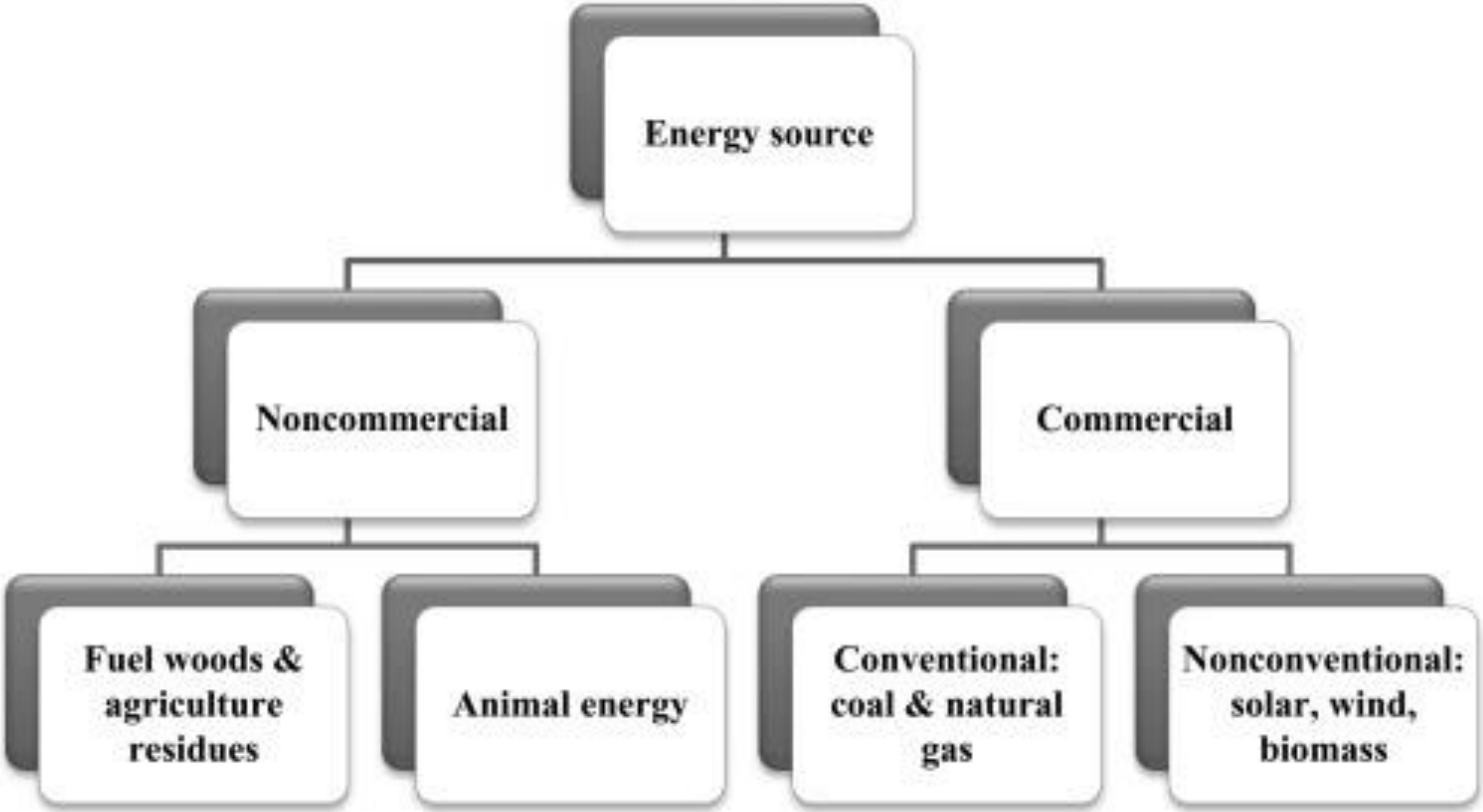
- Capable of providing adequate amount of energy
- Convenient to use & easy to store, handle & transport
- Capable of giving desired quantity at required rate steadily over a long period
- Easily accessible
- Economical
- Should release energy in mostly all forms in which the day-to-day requirement exists

Various form of energy

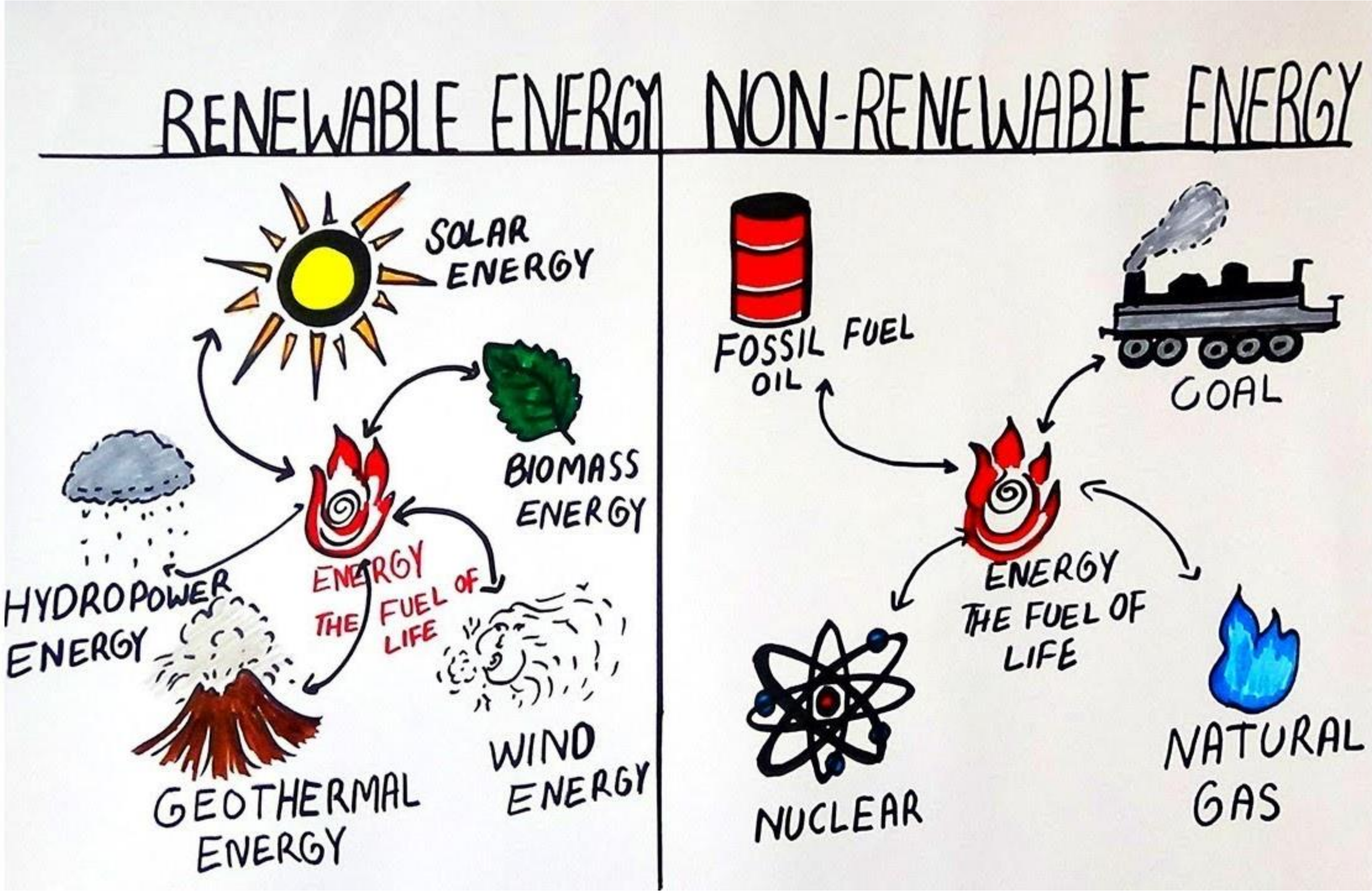
Potential energy is stored energy and the energy of position, or gravitational potential energy,

Kinetic energy is motion—the motion of waves, electrons, atoms, molecules, substances, and objects



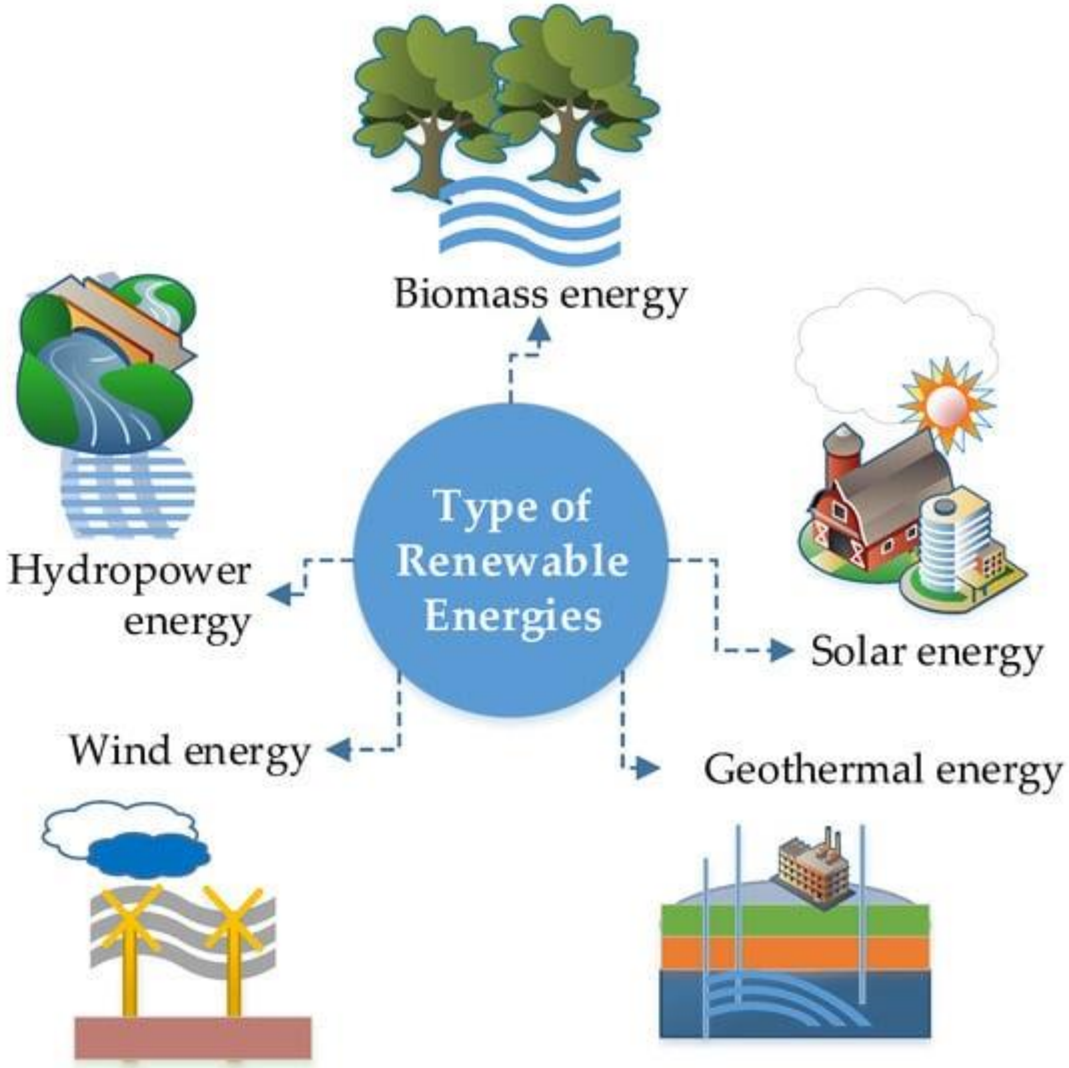

Energy source
Noncommercial
Commercial
Fuel woods & agriculture residues
Animal energy
Conventional: coal & natural gas
Nonconventional: solar, wind, biomass

Classification of energy sources



Non-conventional or renewable sources

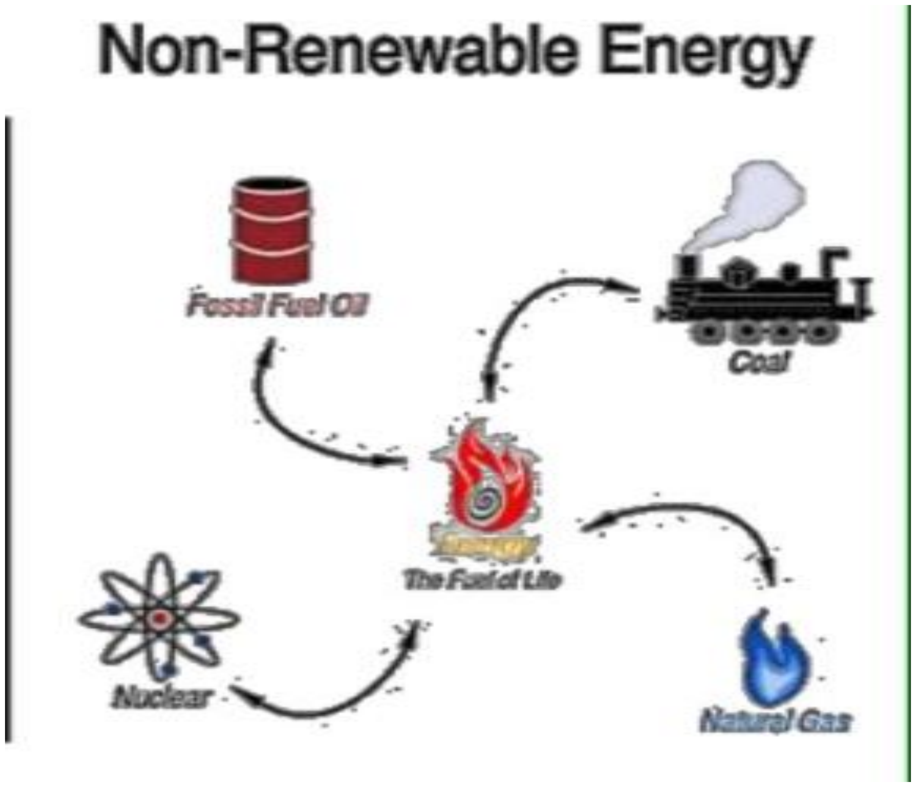
Resources that can be replenished naturally in the course of time are called Renewable resources



Conventional or non- renewable sources

Resources that exist in limited supply and

cannot be replaced if they are used up



Solar energy

- Sun is heaviest body of the solar system.
- The temperature and pressure in the interior of the sun are extremely high, and the temperature on the surface is 6000K.
- The light emitted from the sun reaches the earth in 8.3 minutes, and it is the main source of heat and light energy.
- Solar energy is an important , clean, cheap and abundantly available renewable energy.
- It is received on earth in cyclic, intermittent and dilute form with very low power density 0 to 1 kW/m^2.
- Solar energy received on the ground level is affected by atmospheric clarity, degree of latitude, etc

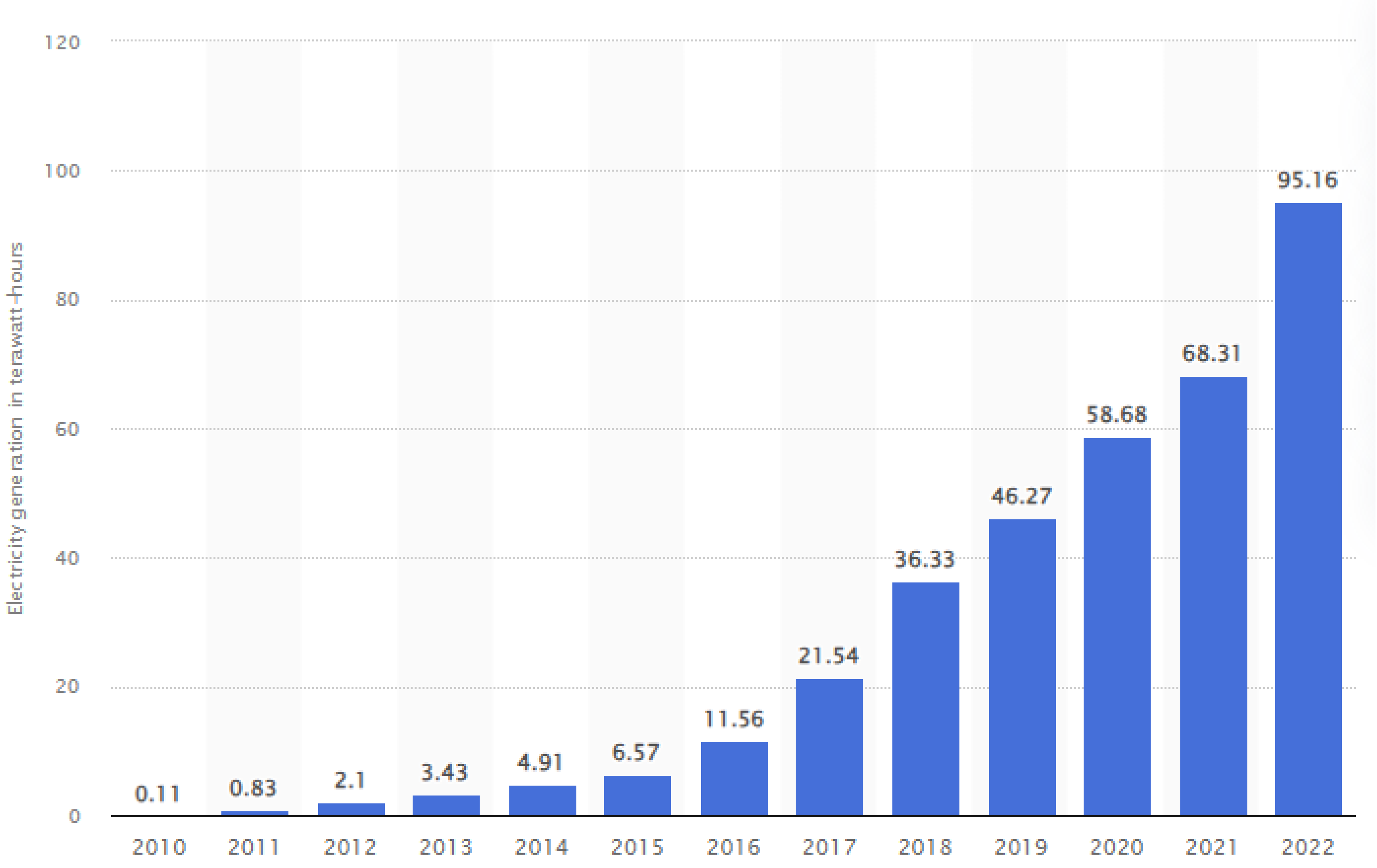
Pros of Solar energy

- Environmentally clean source of energy
- Freely available in adequate quantities
- It is renewable source of energy
- Available widely in any part of world

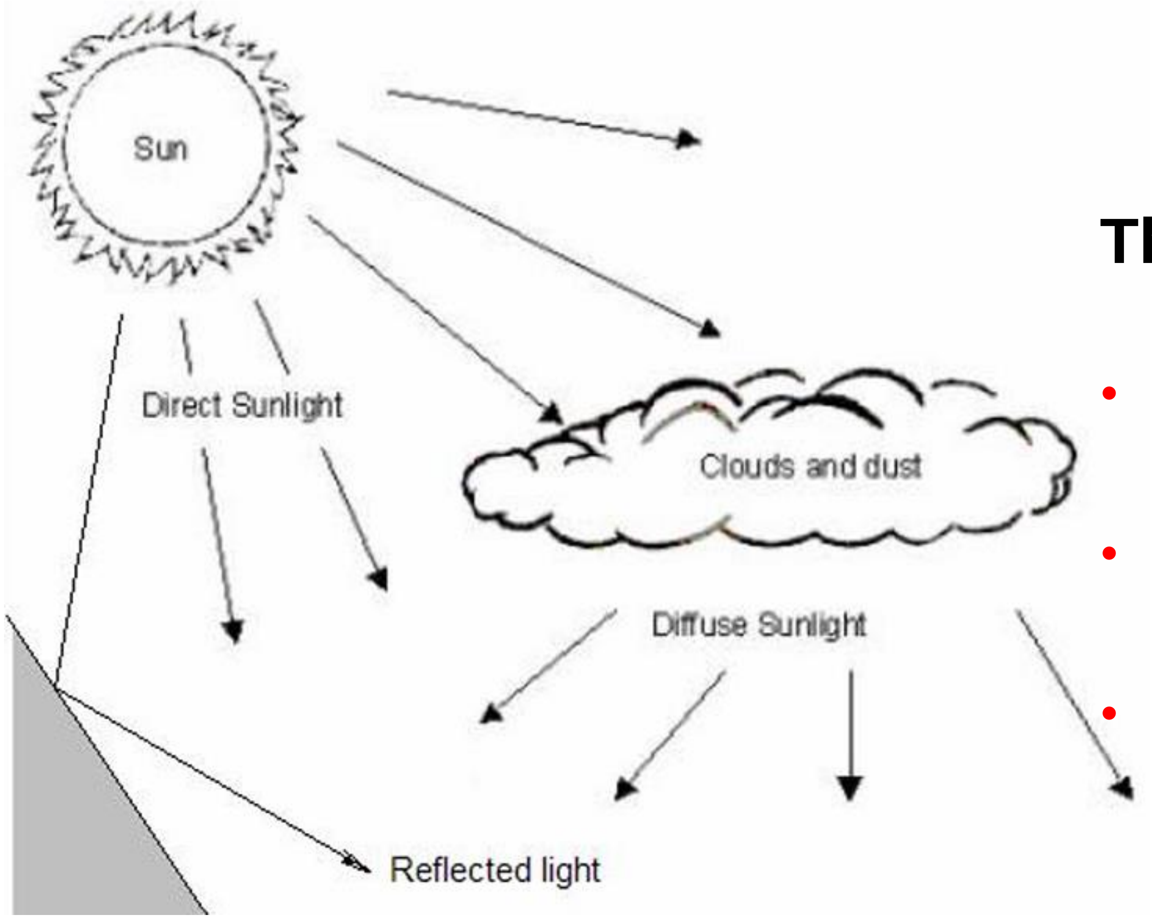
Cons of Solar energy

- Dilute source of energy
- Availability varies widely with time

Solar energy generation in India



Types of solar Radiation



The total radiation (sunlight) is comprised of

- Direct light: Straight from the sun
- Diffuse light: Dispersed by clouds
- Reflected light: From snow, water, etc.

Most Photovoltic panels produce the most power in direct radiation

Energy from the sun is harnessed in two ways**:**

1. **Active** solar involves capturing and redistributing sunlight through the use of solar panels, pumps or solar fans to generate power usually on a large scale.
2. **Passive** solar works to reduce the amount of energy traditionally used to power allocation such as a building or house.

Photovoltaic solar cells

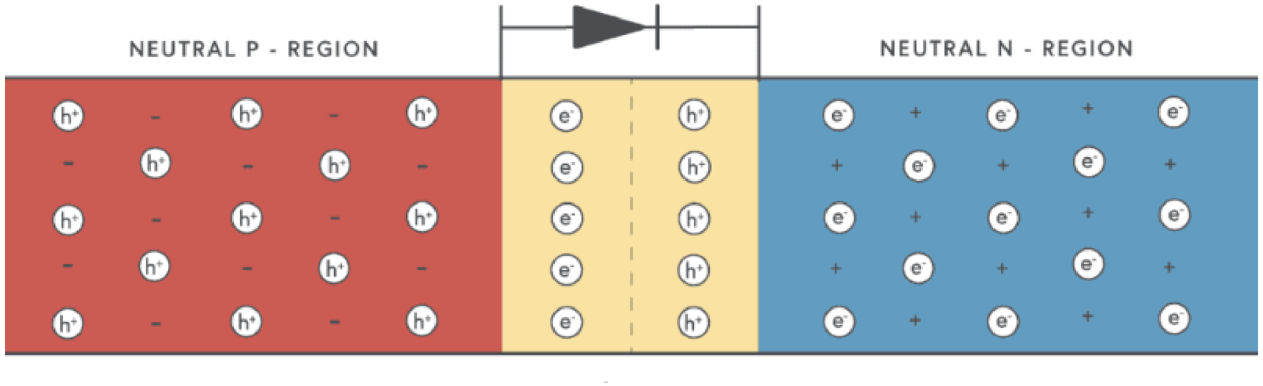
- Photovoltaics (PV) - the process of converting light (photons) to electricity (voltage) - *photovoltaic effect*.

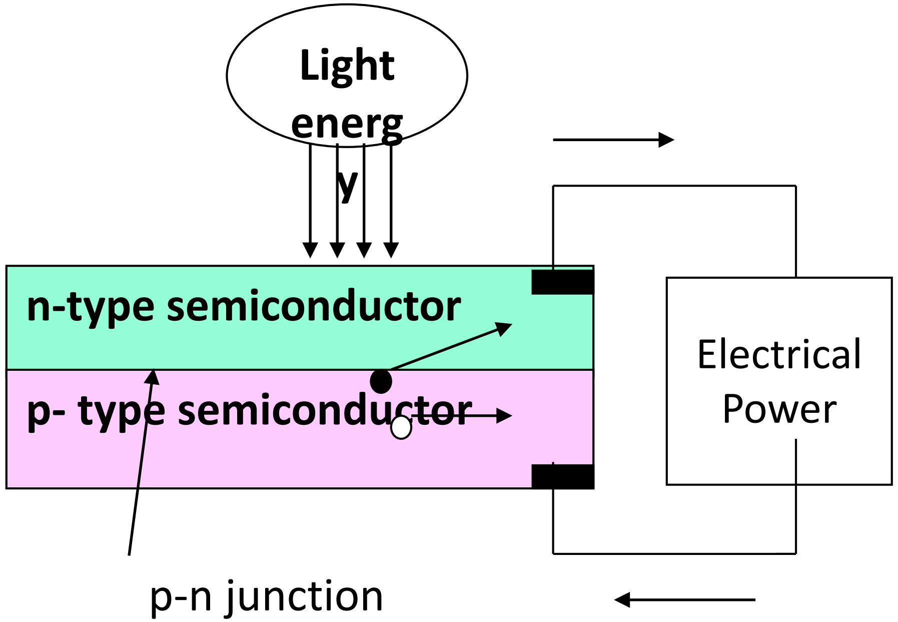
(*Photovoltaics* - Photo means light in Greek and Volt is the name of a pioneer in the study of electricity Alessandro Volta)

- This phenomenon was first exploited in 1954 by scientists at Bell Laboratories who created a working solar cell made from silicon that generated an electric current when exposed to sunlight.
- The solar cells are based on the principles of photovoltaic effect.

Construction of solar cell

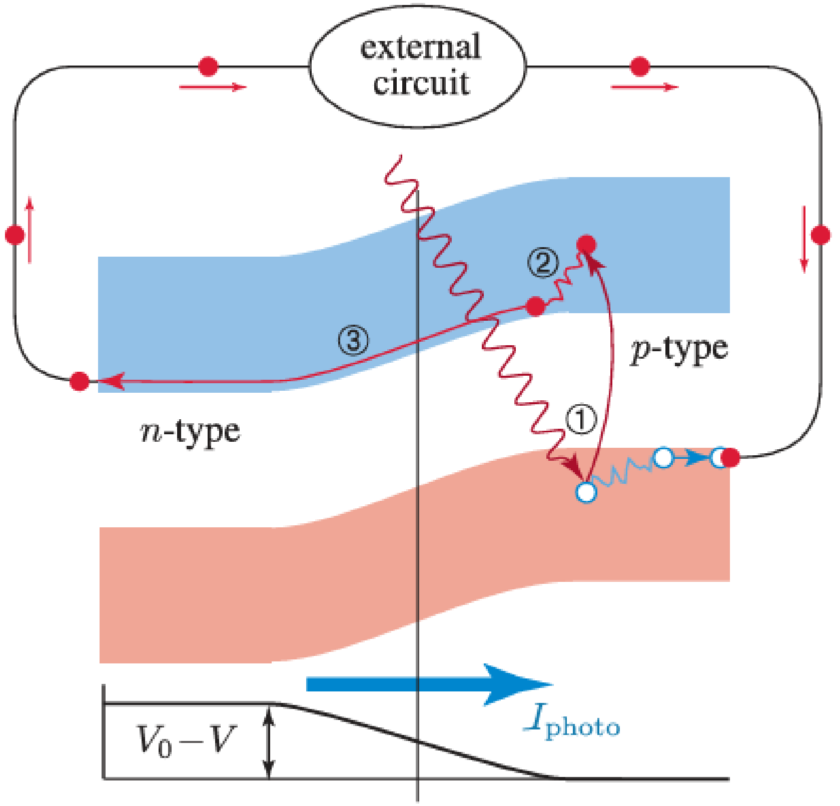
- Solar cell consists of a n-type semiconductor layer and p-type semiconductor layer. The two layers are sandwiched and hence there is formation of p-n junction.





- The surface is coated with anti-refection coating to avoid the loss of incident light energy due to reflection.

Working Principle of Solar cell

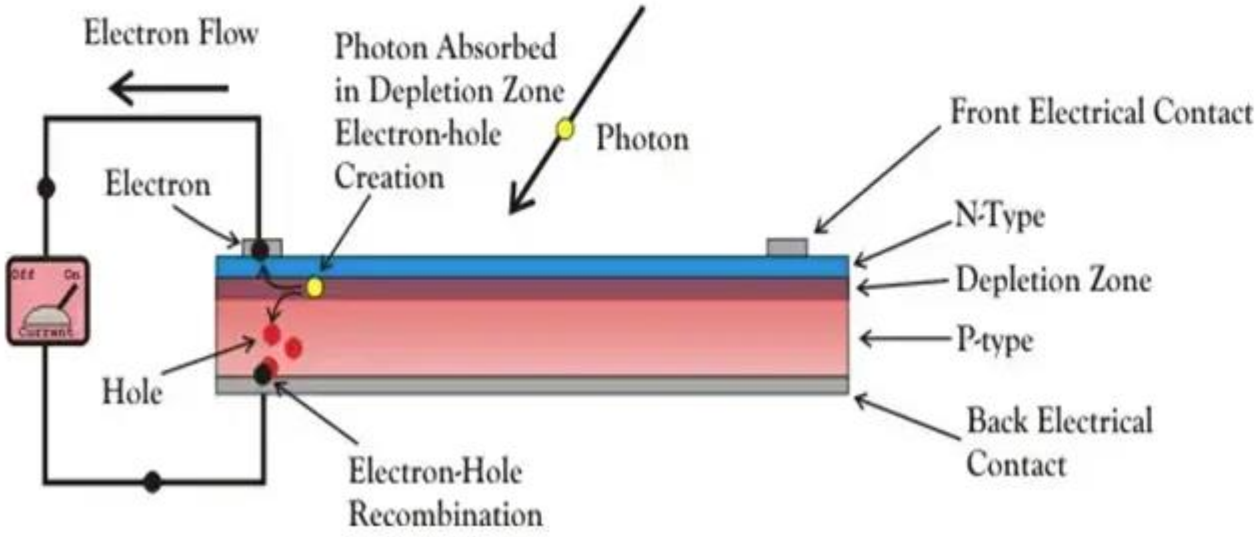


Photovoltaic effect, i.e. the generation of a potential difference at the junction of two different materials in response to electromagnetic radiation.

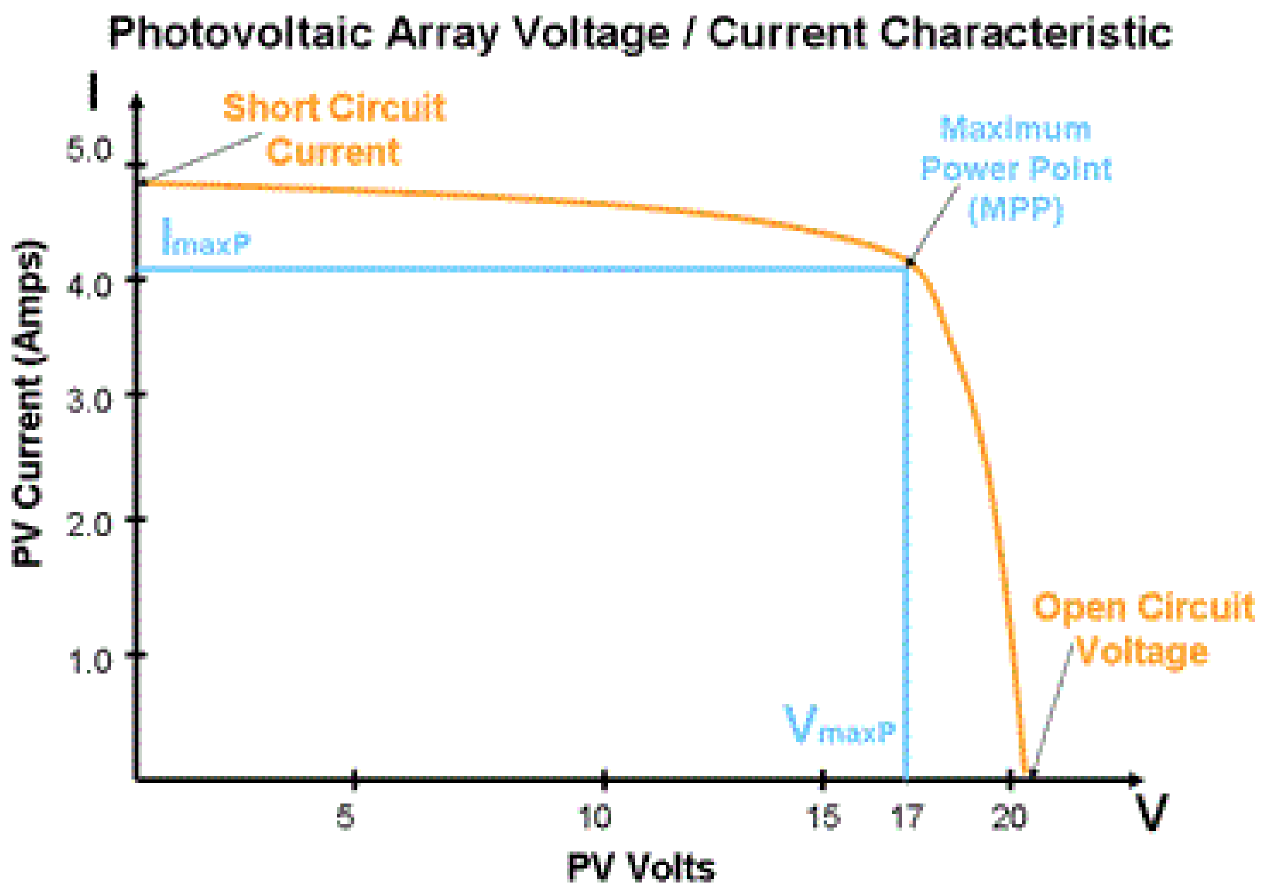
- When light reaches the p-n junction, The photons (light energy) supplies sufficient energy to the junction.
- The incident light breaks the thermal equilibrium condition of the junction.

In a p-n junction photocell, an incoming photon **(1)** excites an electron into the conduction band leaving behind a hole. When this occurs in the p-doped region, after losing excess energy to thermalization **(2),** the electron is pushed across the junction **(3)** by the potential differenceV_0−Vand leaves the junction on the left. The hole produced by the electron's excitation leaves the junction on the right. These charge motions contribute to the current I photodriving an external connected circuit.

- The free electrons in the depletion region can quickly come to the n-type side of the junction.
- The holes in the depletion can quickly come to the p-type side of the junction.
- As the concentration of electrons becomes higher in n-type side of the junction and concentration of holes becomes more in p-type side of the junction, the charge flow will start to take place.
- A voltage is set up which is known as photo voltage.



V-I Characteristics of a Photovoltaic Cell



Criteria for materials to be used in solar cell

- Must have band gap from 1ev to 1.8ev.
- High optical absorption.
- High electrical conductivity.
- The raw material must be available in abundance and the cost of the material must be low.

Pros and Cons

Pros

- No pollution.
- Last for a long time.
- No maintenance cost.

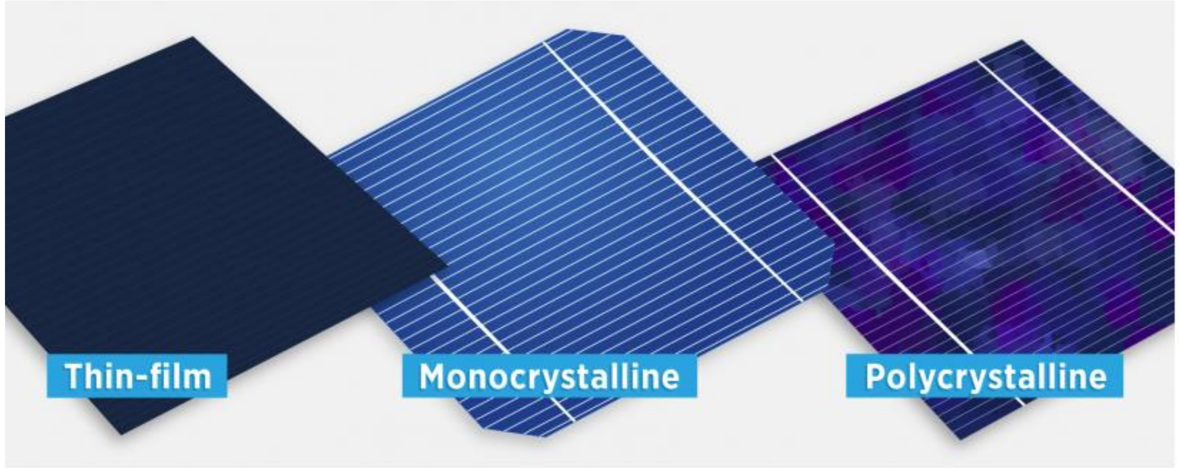
Cons

- High cost of installation.
- Low efficiency.
- During cloudy day, the energy cannot be produced and also at night we will not get solar energy.

Types of Solar cell

Silicon

- Commonly used in Solar cell
- Band gap energy – 1.1 eV
- second most abundant material on Earth.
- Crystalline silicon - organized structure that makes conversion of light into electricity more efficient.
- High efficiency, low cost, and long lifetime.
- Expected to last for 25 years or more



Thin-film Photovoltaics

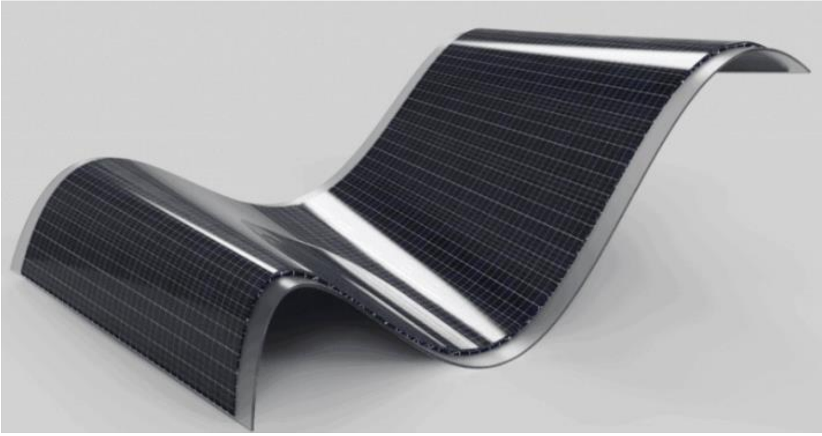
- Two types- cadmium telluride(CdTe) and **copper indium gallium diselenide**(CIGS)
- Made by depositing one or more thin layer of material on the substrate like glass, plastic or metal.

CdTe	CIGS
• Second commonly used material after silicon • Low cost manufacturing process • Efficiency is quite low compare to Si	• Have optimal property for the PV material • High efficiency in lab testing but not in large scale production

Both CdTe and CIGS require more protection than silicon to enable long-lasting operation outdoors.

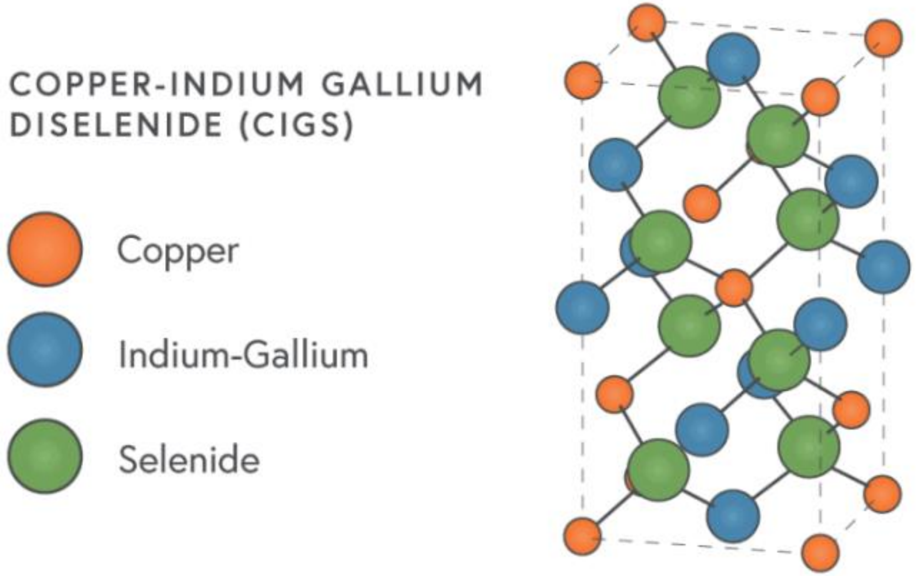
Copper Indium Gallium Diselenide (CIGS)

- Copper-indium diselenide (CIS) has the highest **optical absorption**.
- Band gap of CIS - **1 eV**, introduction of gallium into the lattice to raise the band gap energy closer to the solar ideal
- Crystal structure- **Chalcopyrite**.
- Made either by vapour deposition, or by "selenising" copper-indium films.



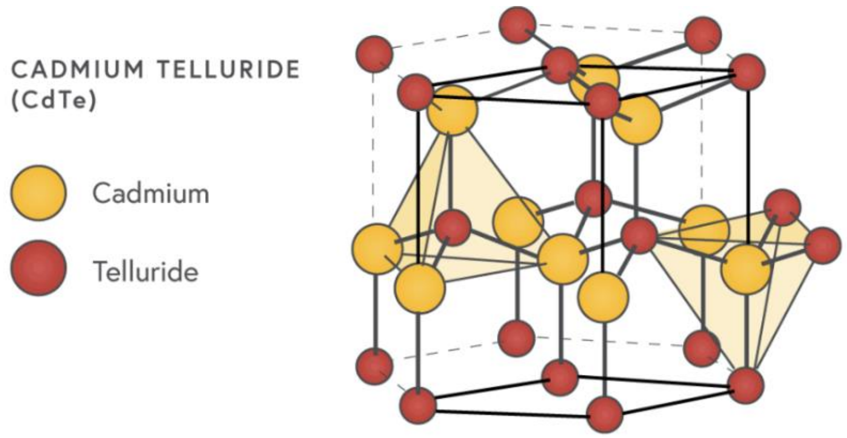
CIGS solar cells - best candidates for flexible solar cells.

- **Homojuction** CIGS next to CIGS - quite low efficiency
- A different material is needed for the front, usually **cadmium sulfide** (CdS) (window layer) to diminish surface recombination.
- Heterojunction introduces **lattice differences and diffusion of particles** between the materials - distort the energy bands throughout the material.
- The grains of CIGS crystals also **limit how far carriers can move** before recombining.



Cadmium Telluride(CdTe)

- Made from the II-VI group elements
- Direct band gap - **1.44 eV**
- Best-suited materials for photovoltaic applications
- Crystal structure - **Wurtzite**
- **Higher defect density** – Hader to dope
- Heating in Cadmium chloride ($CdCl_2$) was discovered to be crucial in improving the material quality of CdTe cells.
- Like CIGS, CdTe also performs better with a CdS heterojunction on the front.
- The heterojunction introduces the same problems here as in CIGS.
- The higher density of defects in CdTe at the boundaries results in a high dark-current and a low maximum voltage achievable.
- Dark Current - the unwanted current that flows when no light is shining on a cell
- However, the ideal band gap energy of CdTe is excellent for solar cell applications



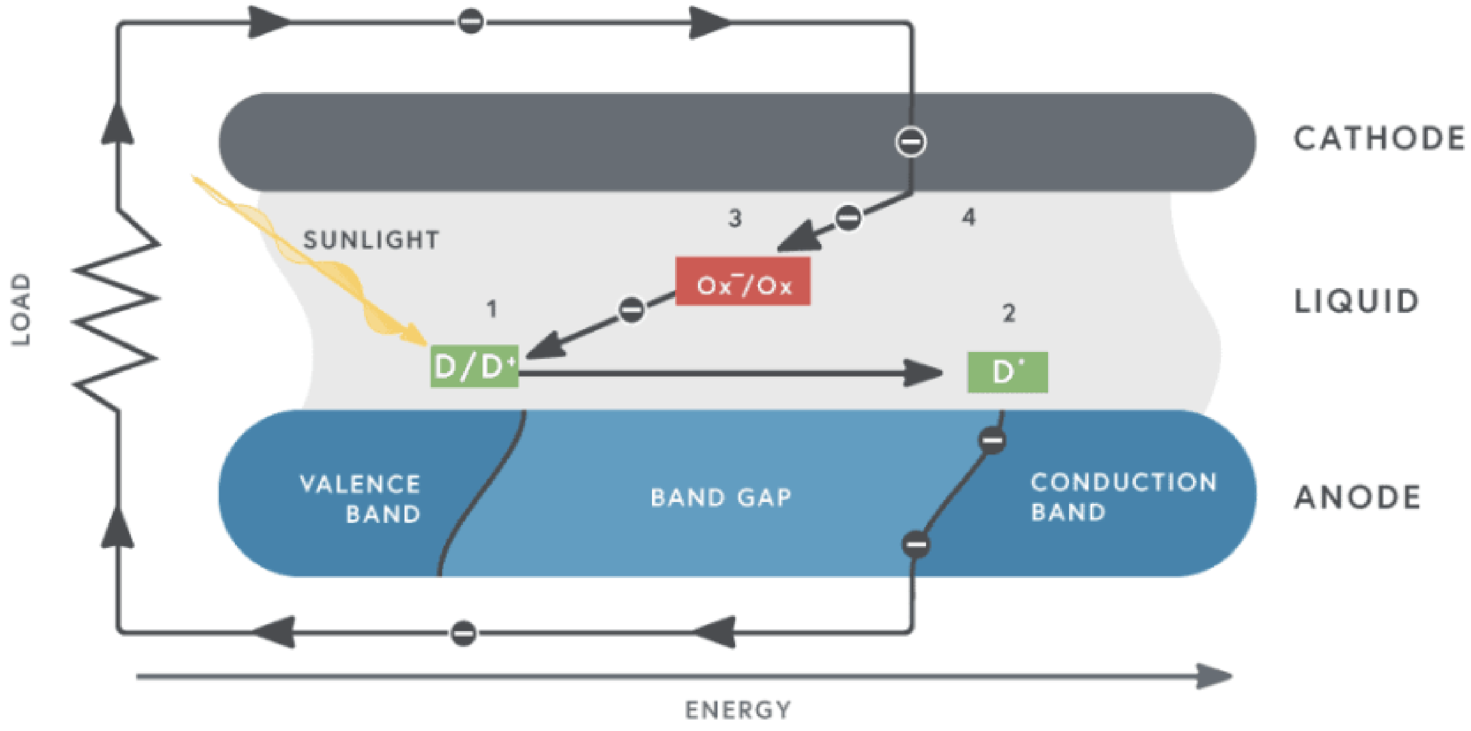
Dye-Sensitized Solar Cells

- It has **liquid dye** – similar to batteries
- Electrodes at the both the side – Anode (oxidation) & Cathode (Reduction)
- Here, the electron loss (into the conduction band) starts with absorption of a photon
- In 1991, Gratzel and Regan realized a low-cost solar cell that used liquid **dye on a titanium (IV) oxide film.**

Mechanism

- A dye molecule (D) absorbs light and becomes (D*)
- One of its electrons move away from the D* and get into conduction band.
- It then moves through the wire from the anode to the cathode.

- On its way there, it travels through a load and does useful work.
- When it gets to the cathode, it’s absorbed by an oxidizer (Ox) (often iodide). The oxidizer, in turn, replaces the electron needed by D+



Drawbacks

- The presence of liquid could freeze.
- Instability.
- Short transport properties of charge carrier.
- Low efficiency (12%).

Application

In sunglasses that could power devices.

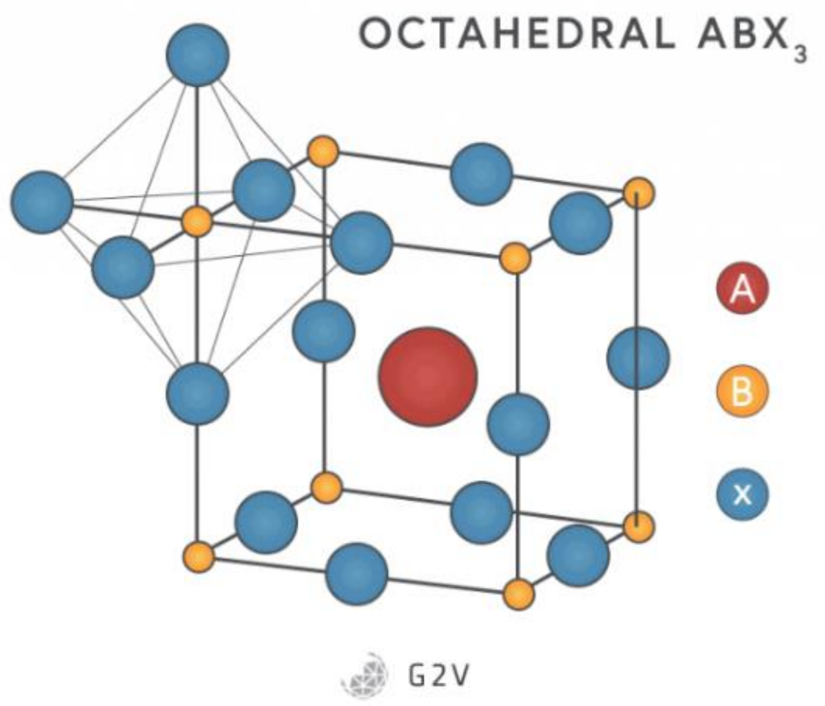
The lenses were the solar cells.

A dye-sensitized solar cell made the lenses of these glasses that could then charge devices.

Perovskite Photovoltaics

- Type of thin-film cell – crystal structure – Perovskite.
- Built with layers of materials that are printed, coated, or vacuum-deposited onto a substrate.
- Easy to assemble
- Efficiencies similar to crystalline Si
- Efficiency improved from 3% in 2009 to over 25% in 2020.
- Stable enough to survive 20 years outdoors.
- Research going on – more durable and developing large-scale, low-cost manufacturing techniques.

- Perovskites – ionic - dissolve easily in **polar solvents**.
- Initially, started as a type of dye-sensitized solar cell, when a **methylammonium lead halide perovskite** was adsorbed onto titanium (IV) oxide.
- Like other dye-based solar cells, it exhibited instability and had a fairly **low efficiency of 3-4%.**
- In 2012, however, a long-term stable perovskite solar cell was developed by replacing the liquid electrolyte with a **solid hole (p-type) conductor**.
- That led to a marked increase in efficiency and interest in the material which pushed the **efficiencies above 20%**.



Organic Solar cell

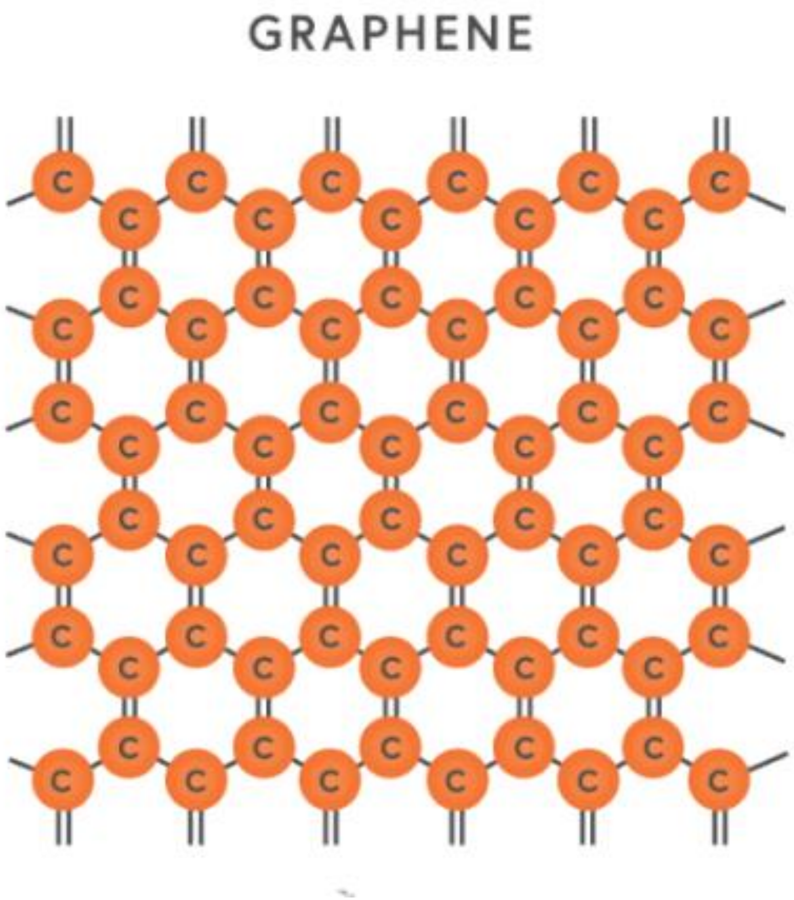
- Composed of **carbon-rich** (organic) compounds and the majority rely on organic molecules with **sp2 hybridization** – that is, carbon double bonds.
- Tailored to enhance a specific function of the such as **bandgap, transparency, or color**.
- **Half as efficient** as crystalline silicon cells (9-11%).
- Shorter operating lifetime.
- **Less expensive** to manufacture in high volumes.
- Applied to a variety of supporting materials, such as **flexible plastic**.

Graphene Solar Cells

Graphene is a form of carbon with alternating double-bonds that form a **two-dimensional honeycomb sheet**

Discovery

- Discovered in 2004 by Andre Geim and Konstantin Novoselov.
- isolated it by peeling a layer off graphite (pencil lead) using scotch tape.
- won the Nobel prize for it in 2010



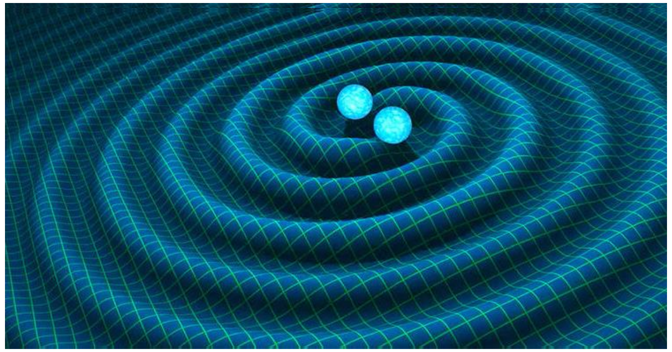
Properties of graphene

- Stronger than steel
- High conductive (due to the array of double bonds)
- Very flexible
- Optically transparent (absorbing 2.3% of incident light from UV to IR).

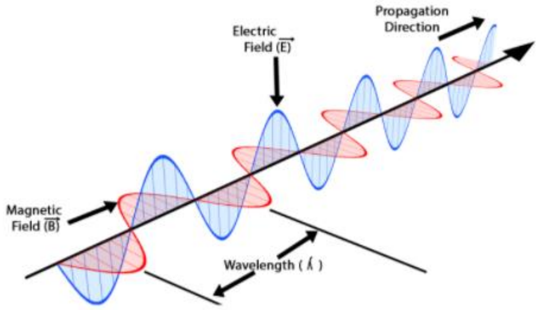
These properties of graphene make it ideal for application of thin film solar cells.

- Graphene has been used to **increase photon collection efficiency** in the perovskite active material itself, with some doped graphene allowing larger perovskite grains to form on the carbon network. In this role, it has been used as a **carrier transport material**.
- It has been used to **protect the unstable perovskite** films, because graphene has better physical, chemical, and thermal stability

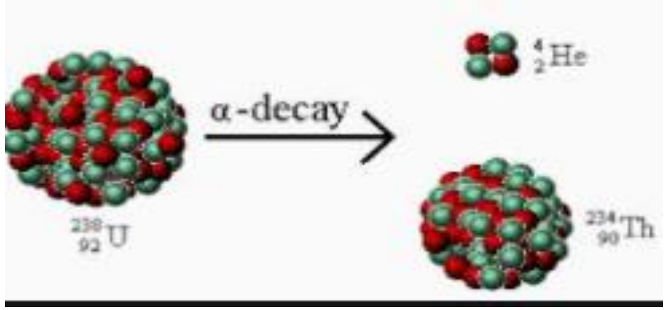
Fundamental forces



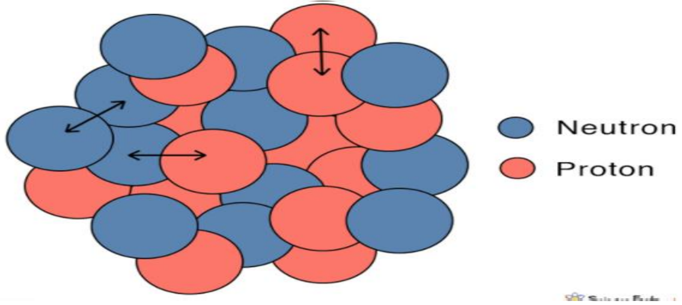
Gravitational force



Electromagnetic force



Weak nuclear force



Strong nuclear force

Nuclear Force

- Strong interactions – that holds nucleons together
- Three attractive forces in the nucleus
  - Neutron-neutron (n-n)
  - Neutron – Proton (n-p)
  - Proton- Proton (p-p)

Nuclear Binding Energy : total mass of the nucleus is less than the sum of the masses of its individual nucleons. Therefore the rest energy of the bound system is less than the combined rest energy of the separated nucleons

Nuclear Model

- **Liquid drop model** : proposed by Bohr, observed similarities between atomic nucleus and liquid drop
- **Shell model** : nucleus assume that the energy structure is similar to that of an electron cell in atom
- **Collective model** : combines the feature of liquid drop model and shell model.

Nuclear Fission Reaction

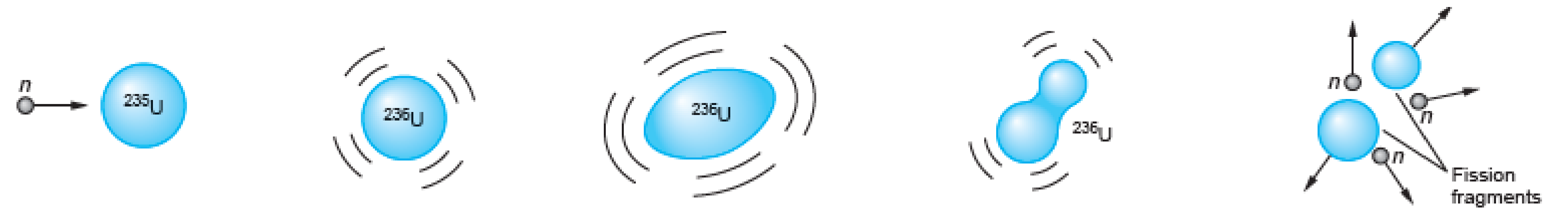
Breaking up of the nucleus of heavy atom split up into two or more equal fragments with release the large amount of energy

$$_{92}U^{235} + {}_{0}n^{1} \rightarrow {}_{92}U^{236*} \rightarrow X + Y + \text{neutrons}$$

Explained by Bohr and Wheeler theory

Nuclear reaction is similar to the liquid drop model when excess of energy added to it ,Bohr and Wheeler successfully explain the phenomenon of liquid drop model

If we bombarded U-235 with neutrons, the rapid oscillation into the spherical compound nucleus, this result shape of the nucleus may change their shape



Otto Hahn

Germany – Nobel laureate

Discovery of Nuclear Fission

Fritz Strassman

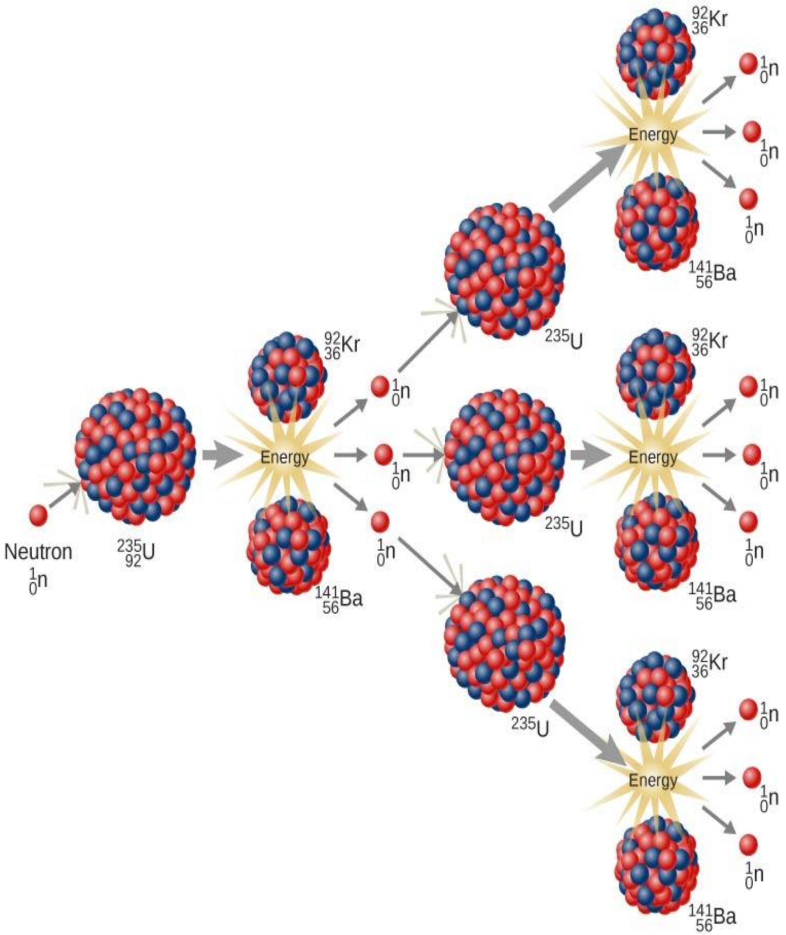
Germany – Nobel laureate
With Otto Hahn, Identifying Ba in the residue after bombarding uranium with neutrons

Enrico Fermi

Italy – Nobel laureate

Creation of world first nuclear chain reaction

Chain Reaction

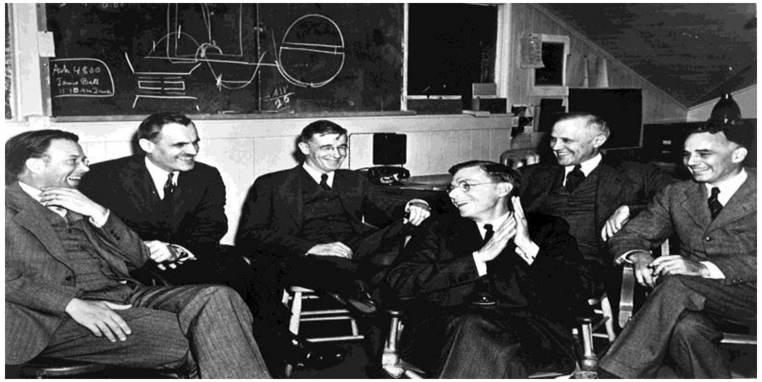


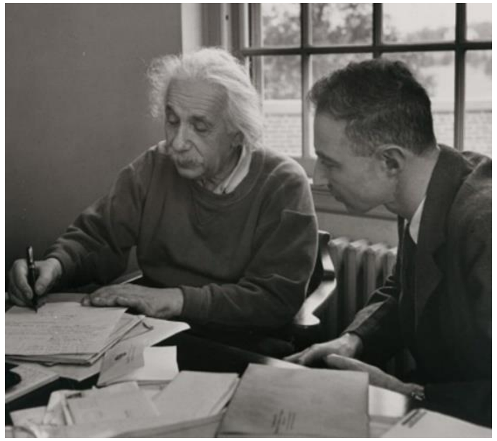
- Self-propagating process in which the number of neutrons goes on multiplying rapidly (3^n)
- ***Multiplication factor (k)*** – the ratio of secondary neutron produced by the original neutron
- Time taken by each fission 10^{-8} s
- Energy releases ≈ 5×10^{26} MeV in 0.6μs
- High temperature in the order of 10^7 K
- K = No. neutrons in one generation / No. neutrons in the preceding generation

- K < 1 *Subcritical (Reaction does not develop)*
- K = 1 *Critical (Limit)*
- K > 1 *Supercritical (chain reaction occurs)*

Atom bomb

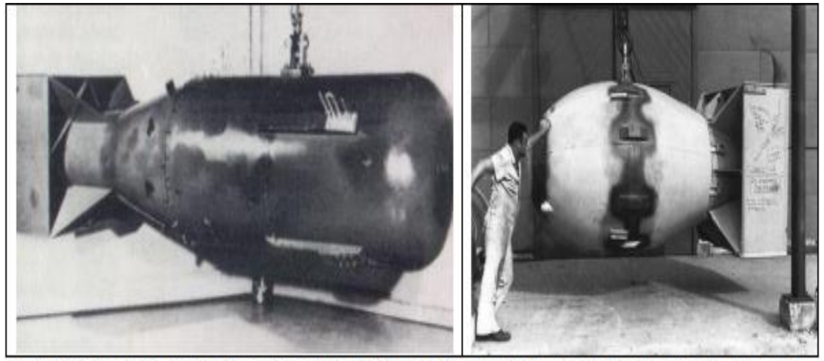
- In chain reaction, the frequency of fission increases the energy released will be so rapid that an explosion will occur (atomic bomb)
- Essentially consists two pieces of U-235 or Pu-239 each smaller than critical size





Manhattan Project

- Research and development of nuclear energy during the world war II
- Little boy (U-235) – Hiroshima (Aug 6 -1945)
- Fat mam (Pu-239) – Nagasaki (Aug 9- 1945)



The U235 atomic bomb Little Boy (left) and the Pu239 bomb Fat Man (right). The imploding Fat Man became the prototype nuclear weapon after the Second World War, with all the plutonium being manufactured at Hanford, WA.

Controlled chain reaction

- Slow neutron bombards U-235 and split up into two equal fragment with 3 fast neutrons (neutron have a large K.E, 2 MeV on the average)

- One neutron may escape

- *Resonance Capture* : One neutron captured by the U-238 and form U-239, then it will decayed into Np-239 and then Plutonium-239 (usually does not go fission because U-238 has small cross section for capture slow neutron)

- One neutron still available for carrying the chain reaction, which is slow down by the moderator

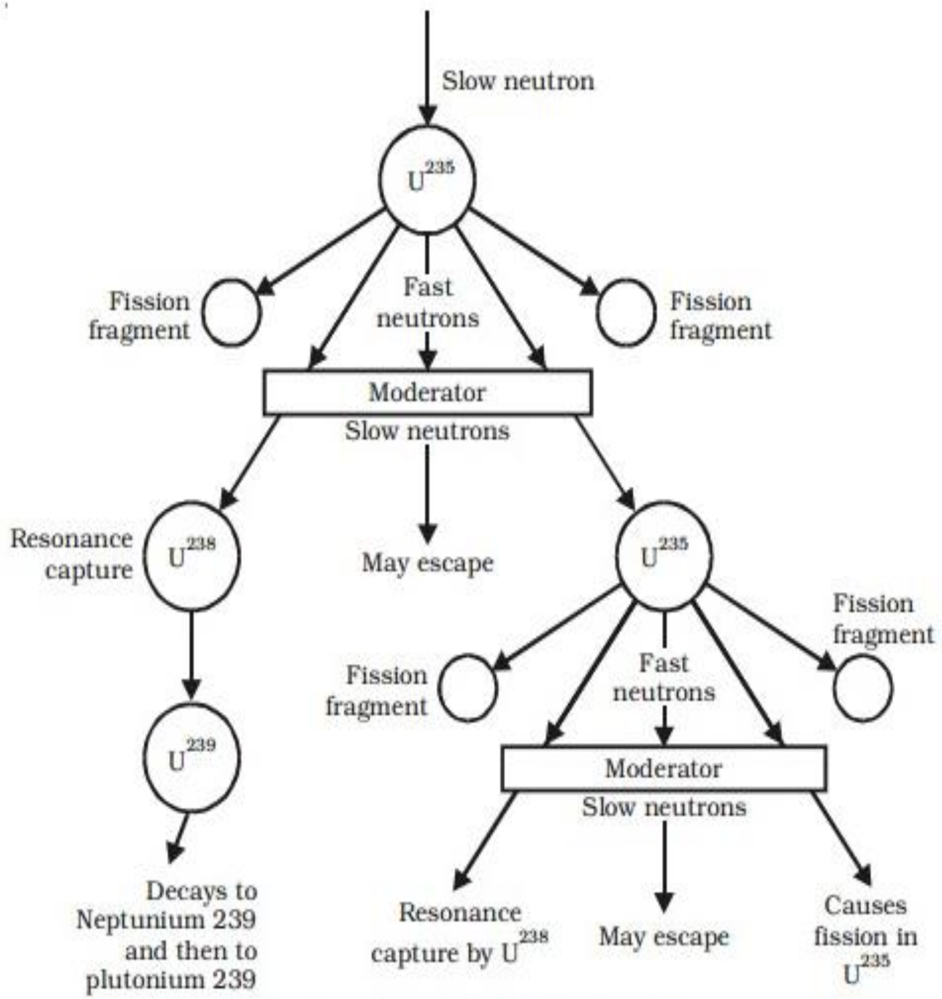
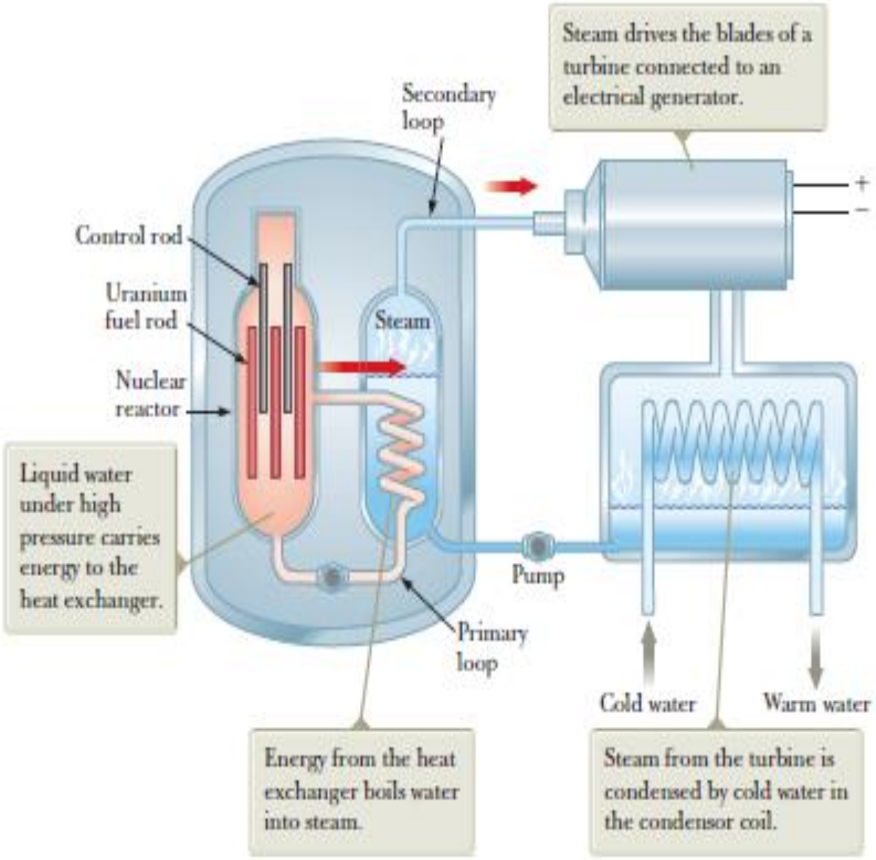


Fig Controlled chain reaction

Nuclear Reactor

- The reaction is brought about under controlled.
- Due to fission reaction, the reactor core rise the temperature of the water contained primary loop, which maintain high pressure to keep boiling
- This water also served as the moderator to slow down the neutrons
- Hot water is pumped through the heat exchanger then hot water in the secondary loop converted into steam
- The main elements of the nuclear reactor
  - Fuel
  - Control rod
  - Moderator
  - Cooling system
  - Safety system



Fissile material :

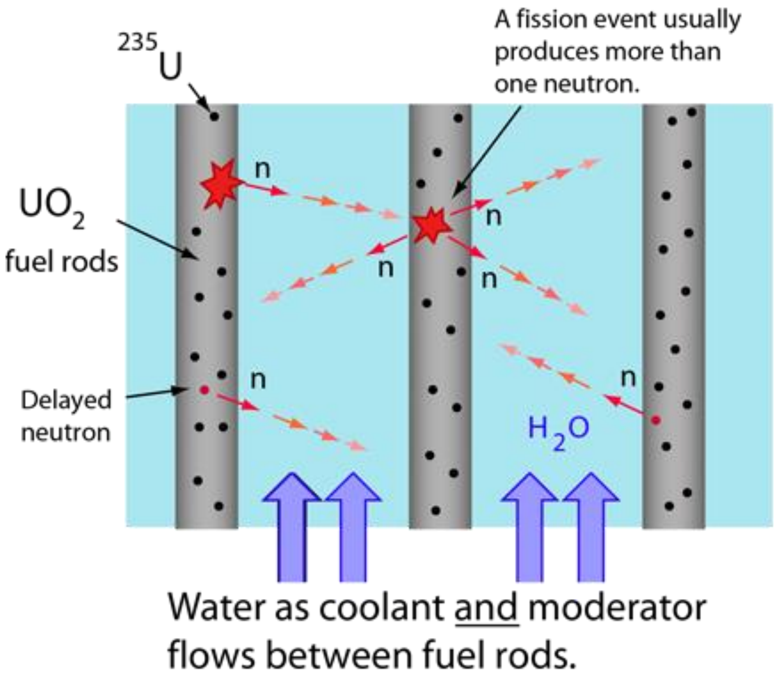
- Natural Uranium (0.72% of U-235),
- Enriched Uranium (> 0.72% of U-235)

Moderator :

- Moderator is slow down the highly energetic neutrons
- Usually should be abundant, chemically stable, absorb maximum amount of energy collision with neutrons and low absorption cross-section of neutrons
- Heavy water (D_2O), Graphite, Beryllium

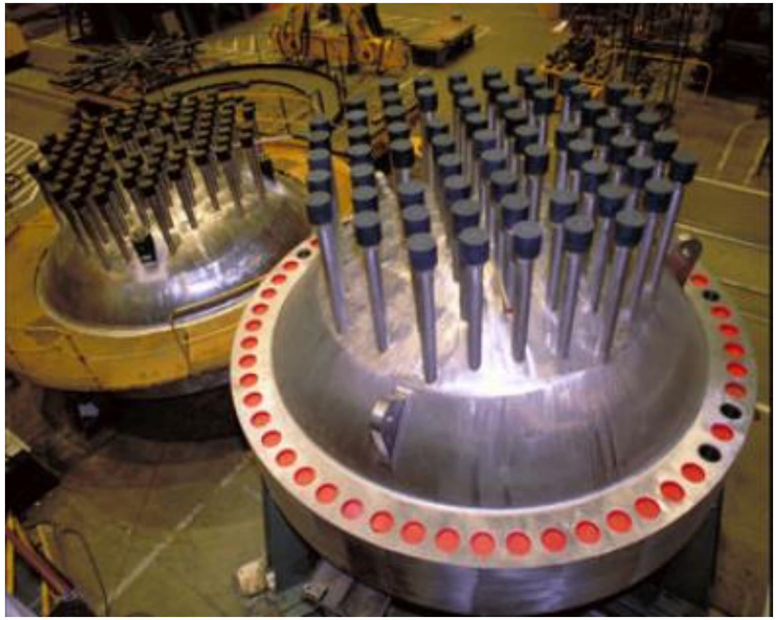
Cooling system :

- Removes the heat evaluated in the reactor core
- Coolant transfer the heat through the secondary thermal system



Control Rod :

- Control system enable the chain reaction to be controlled
- Usually made up of Cadmium or Boron , having a large neutron absorption cross section
- Control the reaction by the pushing up and down of the control rods



Safety system :

- This protect the intensive neutron flux and gamma ray existing in the reactor core
- The reactor with massive wall of concrete and lead which would absorb neutrons and gamma rays

Types of Nuclear Reactor

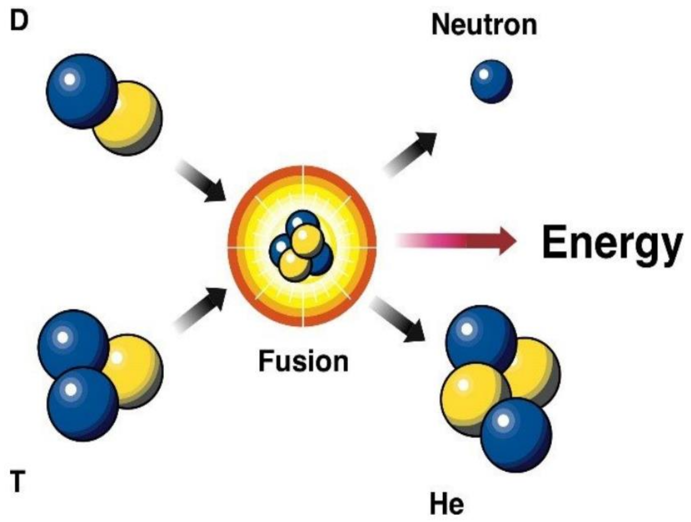
Reactor type	Main countries	Number	GWe	Fuel	Coolant	Moderator
Pressurised water reactor (PWR)	USA, France, Japan, Russia, China, South Korea	302	287.0	enriched UO_2	water	water
Boiling water reactor (BWR)	USA, Japan, Sweden	63	64.1	enriched UO_2	water	water
Pressurised heavy water reactor (PHWR)	Canada, India	49	24.5	natural UO_2	heavy water	heavy water
Advanced gas-cooled reactor (AGR)	UK	14	7.7	natural U (metal), enriched UO_2	CO_2	graphite
Light water graphite reactor (LWGR)	Russia	12	8.4	enriched UO_2	water	graphite
Fast neutron reactor (FBR)	Russia	2	1.4	PuO_2 and UO_2	liquid sodium	none

India Nuclear performance report -2020

- India has 22 operable reactors , both inland and coastal
- 7 more reactors under construction
- 2-3 % of India's electricity demand
- India has planned to increase the nuclear generation substantially
- DAE announced to India plans to build 21 new nuclear power reactor – including 10 PHWRs- with combined heart generating capacity of 15700 MW by 2031

Worlds nuclear association- 2020

Nuclear Fusion – sources of suns energy



- Two lighter nuclei combined to form single larger nuclei
- Barrier – coulomb repulsive force
- Higher the energy of the nuclei , greater the probability tunnel through the barrier
- The energy of the nuclei comes from thermal motion
  Thermonuclear reaction
- Sun able to control thermonuclear fusion in its core because of its gravity
- multistep process in which hydrogen burned to form helium (p-p cycle). First proposed by Bethe

$$^{1}\mathrm{H} + {}^{1}\mathrm{H} \rightarrow {}^{2}\mathrm{H} + e^{+} + \nu \quad (Q = 0.42\ \mathrm{MeV})$$
$$e^{+} + e^{-} \rightarrow \gamma + \gamma \quad (Q = 1.02\ \mathrm{MeV})$$

$$^{1}\mathrm{H} + {}^{1}\mathrm{H} \rightarrow {}^{2}\mathrm{H} + e^{+} + \nu \quad (Q = 0.42\ \mathrm{MeV})$$
$$e^{+} + e^{-} \rightarrow \gamma + \gamma \quad (Q = 1.02\ \mathrm{MeV})$$

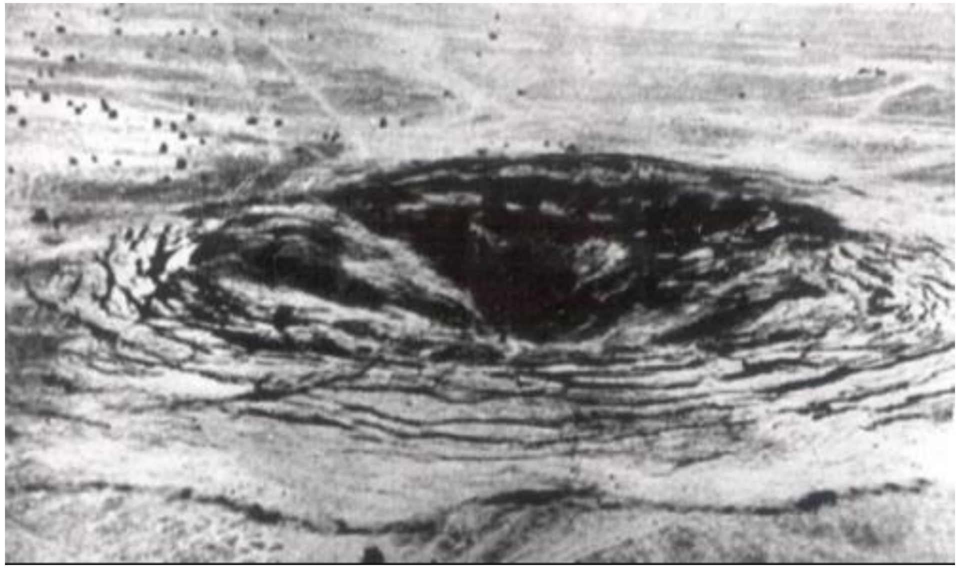
$$^{2}\mathrm{H} + {}^{1}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \gamma \quad (Q = 5.49\ \mathrm{MeV})$$

$$^{2}\mathrm{H} + {}^{1}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \gamma \quad (Q = 5.49\ \mathrm{MeV})$$

$$^{3}\mathrm{He} + {}^{3}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + {}^{1}\mathrm{H} + {}^{1}\mathrm{H} \quad (Q = 12.86\ \mathrm{MeV})$$

Hydrogen Bomb (uncontrolled thermonuclear reaction)

- Second generation nuclear weapon design
- Uncontrolled thermonuclear reaction
- Achieved by the detonation of atomic bomb
- Fission bomb produces the very high temperature at which thermonuclear reaction start
- Two stages
    - Primary explosive
    - Secondary explosive



Pokhran nuclear test - 1998

Fusion Reactor (controlled thermonuclear reaction)

- The large amount of energy released by the Hydrogen bomb
- The main problem is produced such a high temperature and container for the plasma which stands this temperature

Three challenges for the successful thermonuclear reactor

- **High Particle density n**: the number of density of interacting particle must be great enough. High temperature required , the deuterium would be completely ionized forming an electrically neutral *plasma*
- **A High plasma temperature T** : plasma must be hot otherwise the colliding deuterons will not be energetic enough to penetrate the coulomb barrier
- **Long confinement time τ** : to contain the hot plasma long enough to maintains it at a density

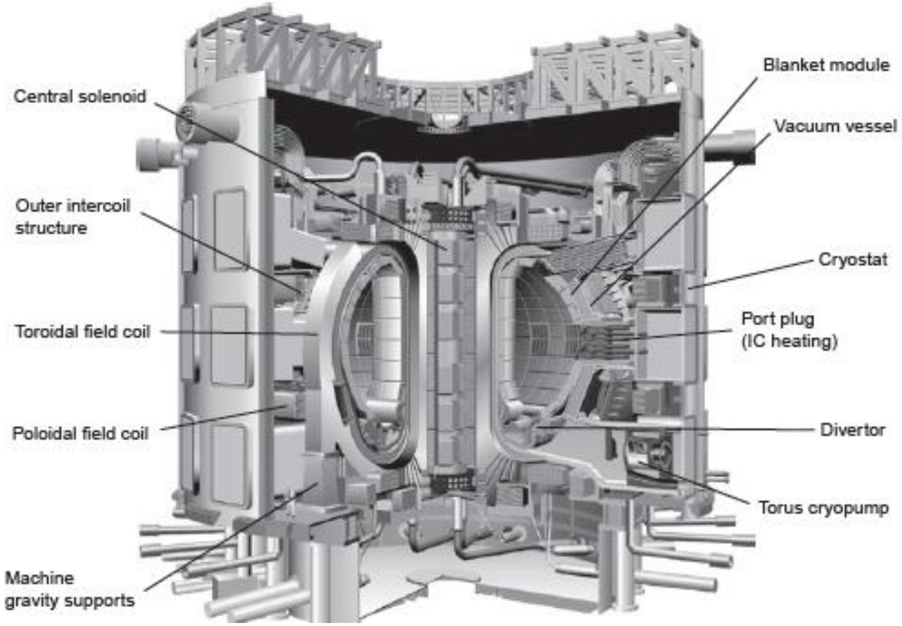
Two schemes for achieving Lawson's criterion :

Magnetic confinement

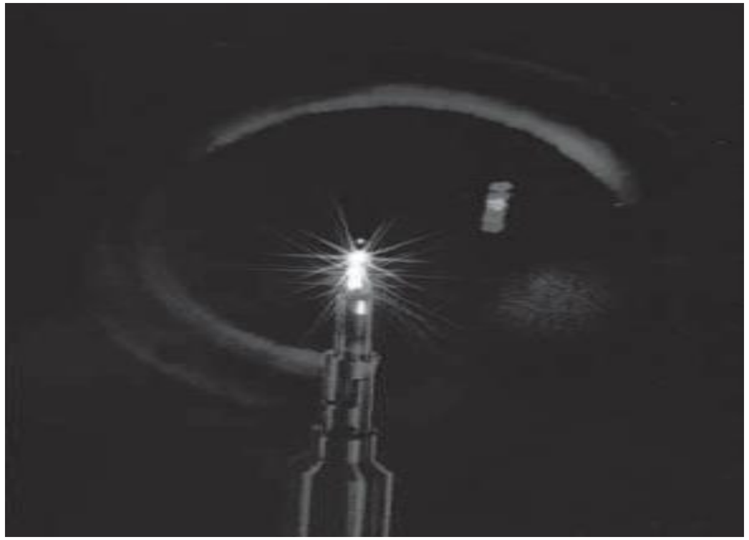
- the magnetic field used to confine the plasma
- Most common arrangement, first developed in Russia called *tokamak*
- The magnetic field is combination of doughnut-shaped magnetic field due to the current in the windings of the toroid
- The magnetic force acting on the charged particles that keep the plasma from touching the walls of the chamber

Inertial confinement

- The pellet of frozen –solid deuterium and tritium bombarded from all sides by pulsed laser beam
- Computer simulation indicate momentum absorbed by hydrogen nuclei from the beams
- It heat it to a temperature 10^8 K and produce 10^6 J of fusion energy in 10^{-10} s

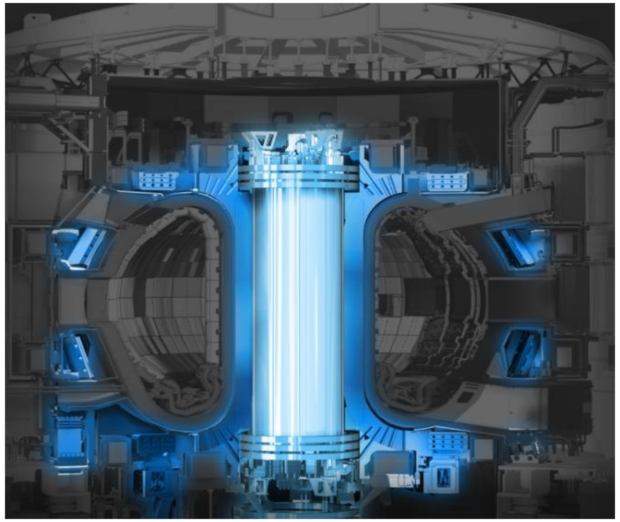


Tokamak fusion reactor



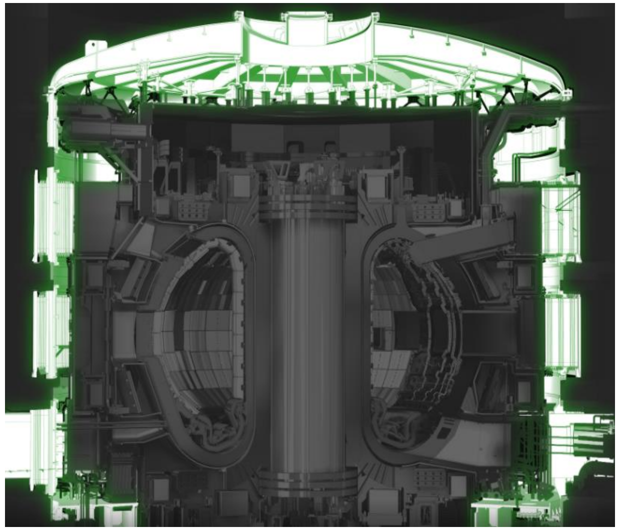
Nova inertial confinement fusion reactor uses powerful laser beam focused on H containing pellet 0.5 mm in diameter to make fusion reaction

ITER components



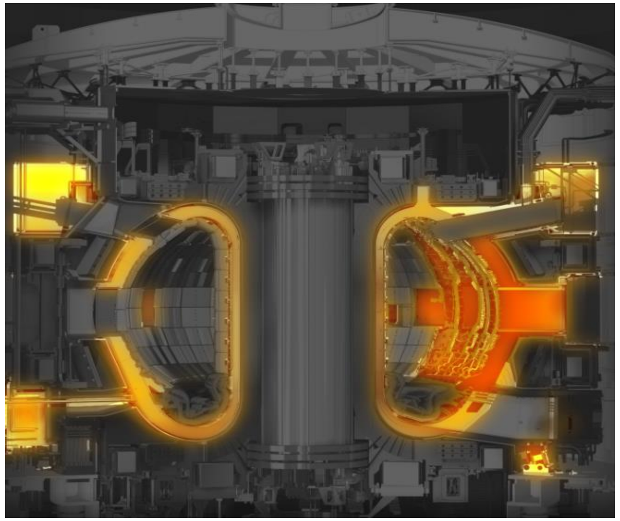
Magnets

- 10 thousand tonnes of superconducting magnet
- 51 KJ stored magnetic energy
- Magnetic temperature 4K (-269˚C) cooler than Pluto
- 100000km Nb3Sn superconducting stand



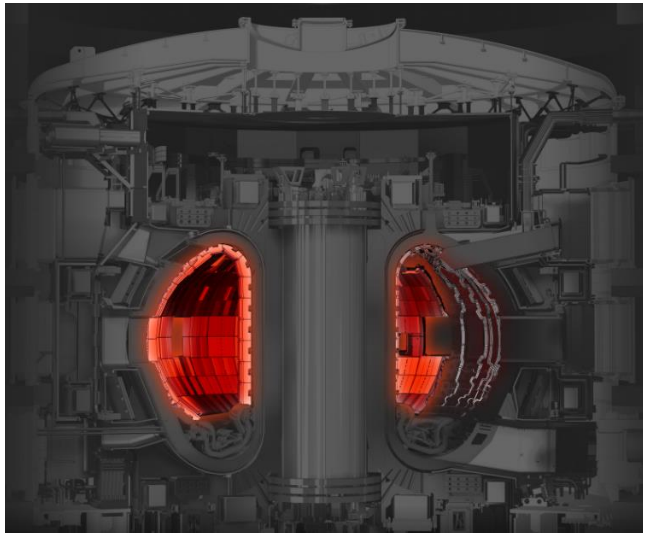
cryostat

- Stainless steel cryostat surrounded in a vacuum vessel and SC magnet
- 3800 T of steel
- 16000 m^3 total volume



Vacuum vessel

- Act as a first safety containment barrier
- 8000T steel plasma chamber
- 840 m^3 plasma volume
- 6m Plasma major radius

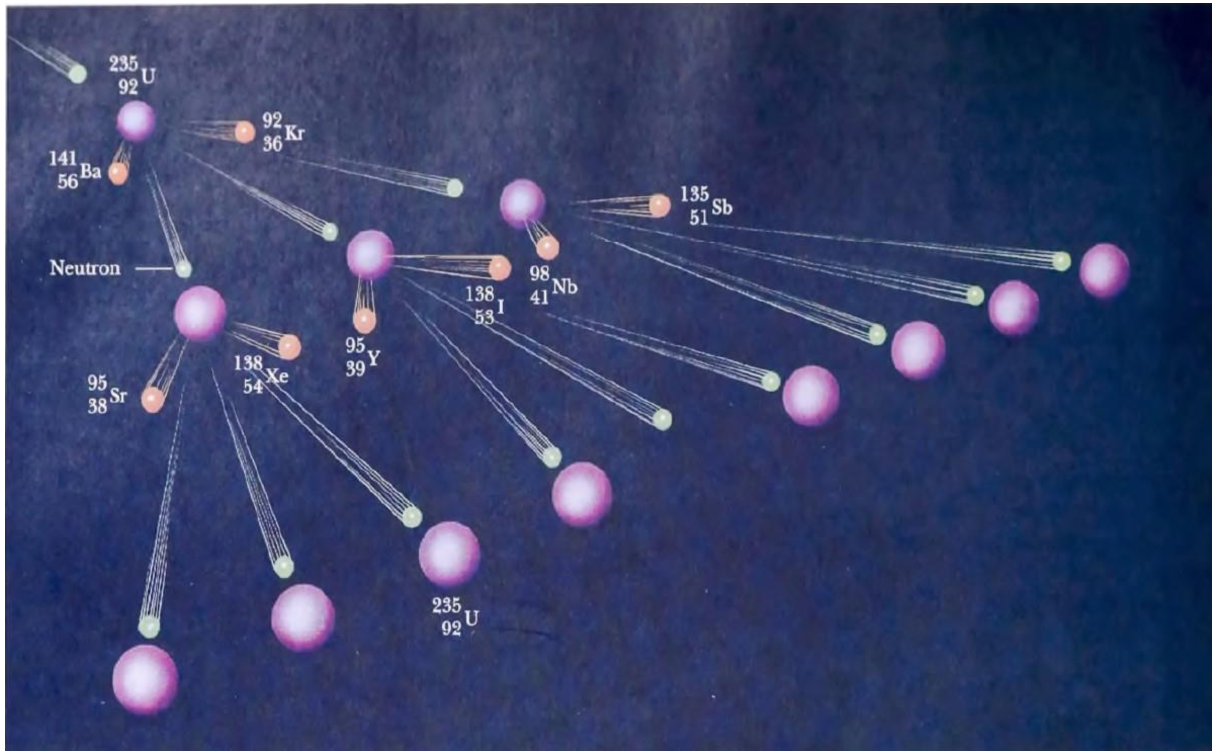


blanket

- The blanket shields the steel vacuum vessel and external machine components from high energy neutron produces

Discussion

Energy released when 1.00 kg of ^{235}U fissions, taking the disintegration energy per event to be $Q = 208$ MeV.



Number of nuclei in the 1 kg of ^{235}U ,
Molar mass of U isotope = 235g/mol
No.of nuclei in the sample,

$$N = \frac{m}{M} N_A$$

$$N = \frac{6.02\times10^{23}}{235} \times 1\times10^3 \text{ g}$$

$$N = 2.56\times10^{24} \text{ nuclei}$$

Disintegration energy E is

$$E = NQ$$

$$E = 2.56\times10^{24} \times 208$$

$$E = 5.32 \times 10^{26} \text{ MeV}$$

$$E = (5.32 \times 10^{26} \text{ MeV}) \left(\frac{1.6 \times10^{-13} \text{ J}}{1 \text{ MeV}}\right) \left(\frac{1 \text{ k}Wh}{3.60 \times10^{6}}\right) = 2.37\times 10^7 \text{ kWh.}$$

100-W lightbulb operating for 30 000 years
Equivalent to detonating about 20 000 tons of TNT.

Fusion of two Deuterons

Separation distance between two deuterons must be approximately 1.0×10^{-14} m.

Potential energy associated with two charges separated by a distance r for two deuterons

$$U = k_e \frac{q_1 q_2}{r} \qquad k_e = \text{Coulomb constant}, \ q_1 q_2 = +e$$

$$U = 8.99\times10^{9}\ \frac{\text{N.m}^2}{\text{C}^2}\left(\frac{(1.6\times10^{-19}\ \text{c})^2}{(1\times10^{-14}\ \text{m})}\right)$$

$$U = 2.3\times10^{-14}\ \text{J}$$

$$U = 0.14\ \text{MeV}$$

Temperature require for a deuteron overcome the potential barrier

Coulomb energy per deuteron is $0.07\ \text{MeV} = 1.1\times10^{-14}\ \text{J}$

Average energy per deuteron,

$$\frac{3}{2} k_B T = 1.1\times10^{-14}\ \text{J}$$

$$T = \frac{2\,(1.1\times10^{-14}\ \text{J}}{3 \times 1.38\times10^{-23}} = 5.3\times10^{8}\ \text{K}$$

Energy released in the fusion deuterium-deuterium reaction

$$ {}^{2}_{1}H + {}^{2}_{1}H \rightarrow {}^{3}_{1}H + {}^{1}_{1}H $$

Mass of single deuterium – 2.014 102 u

Total mass before reaction – 4.028 204u

Sum of mass after reaction : 3.016 049 u + 1.007 825u = 4.023 874u

Change in mass convert into energy : 4.028 204u – 4.023 874u = 0.004 33u

= 0.004 33u×931.494 MeV

= 4.03 MeV

Temperature require for D-D reaction ~ 4×10^{8} K

Temperature require for D-T reaction ~ 4.5×10^{7} K

Reference books:

- *Feynman lectures on Physics – Volume 1*
- *Physics for scientists and engineers with modern physics by Servey and Jewett*
- *Basic concepts in physics from cosmos to quarks by M.chaichian, H.perez rojas and A.Tureanu*
- *Concepts of Modern physics by Arthur Beiser*
- *Fundamental of Nuclear physics from Nuclear Structure to cosmology by James rich and Michel Spiro*
- *Fundamentals of Physics by Halliday and Resnick 10th Edition*
- *Modern Physics by Paul A.Tipler and Ralph A. Llewelyn*
- *Modern Physics by Murugeshan and Kiruthika sivaprasath*

Reference Article:

- *World nuclear association report - 2020*
- *Manhattan Project making the atomic bomb by F.G gosling, DOE*

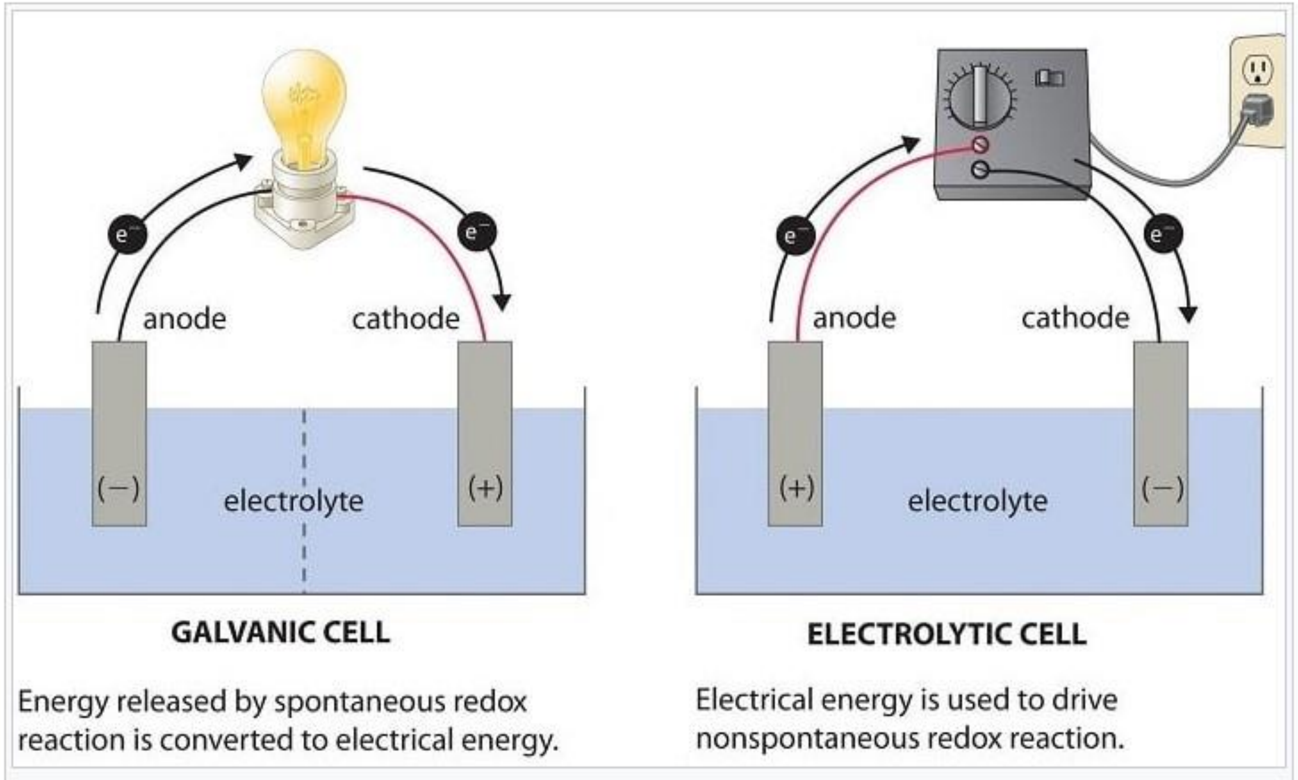
Website:

- *Iter.org*

Electrochemical energy conversion and storage

Electrochemical cell

In electrochemistry, electricity can be generated by movements of electrons from one element to another in a reaction known as redox or oxidation-reduction reaction



Galvanic or voltaic cell

- Driven by spontaneous chemical reaction, electrons will flow spontaneously from one side of the electrochemical cell to the other.
- Batteries and fuel cells

Electrolytic cell

- Non-spontaneous reaction takes place, electrons don't want to move.
- Requires an external source of chemical energy to force the electrons to flow
- Rechargeable batteries

Faraday's first law: The mass of a substance altered at an electrode during electrolysis is directly proportional to the quantity of electricity transferred at that electrode. Quantity of electricity refers to the quantity of electrical charge, typically measured in coulomb.

Faraday's second law: For a given quantity of electricity (electric charge), the mass of an elemental material altered at an electrode is directly proportional to the element's equivalent weight. The equivalent weight of a substance is its molar mass divided by an integer that depends on the reaction undergone by the material

Mathematically, Faradays Law

$$\mathbf{m} = \frac{Q}{F}\,\frac{M}{z}$$

m – mass of the substance in grams liberated at the electrode

Q – total electric charge passed through the substance

F – Faraday constant (96485 C mol^{-1})

M – molar mass of the substance

Z – electrons transferred per ion

Nernst equation : The potential of a single electrode or half-cell varies with the concentration of ions in the cell. In 1889 Walter Nernst derived a mathematical relationship that enabled us to calculate the half-cell potential, E, from the standard electrode potential, E°, and the temperature of the cell. This relation known as the Nernst equation can be stated as

$$E = E^{\circ} - \frac{2.303\,RT}{nF}\,\log K$$

Where,

E° = standard electrode potential

R = gas constant

T = Kelvin temperature

n = number of electrons transferred in the half-reaction

F = Faraday of electricity

K = equilibrium constant for the half-cell reaction as in equilibrium law

What is the potential of a half-cell consisting of a zinc electrode in 0.01M ZnSO4 solution at 25°C, E° =0.763 V

The half-cell reaction is $Zn \longrightarrow Zn^{2+} + 2e^-$ (oxidation)

The Nernst equation for the oxidation half-cell reaction is, (2.303 RT/F = 0.0591)

$$E = E^\circ - \frac{0.0591}{n} \log(Zn^{2+})$$

The number of electrons transferred n = 2 and E° =0.763 V.
Substituting these values in the Nernst equation we have

$$E = 0.763 - \frac{0.0591}{2} \log(0.01)$$

$$E = 0.763 - \frac{0.0591}{2} (-2)$$

$$E = 0.763 + 0.0591$$

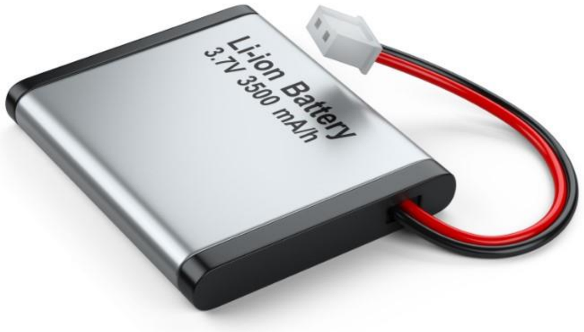
E = 0.8221 V

Primary batteries

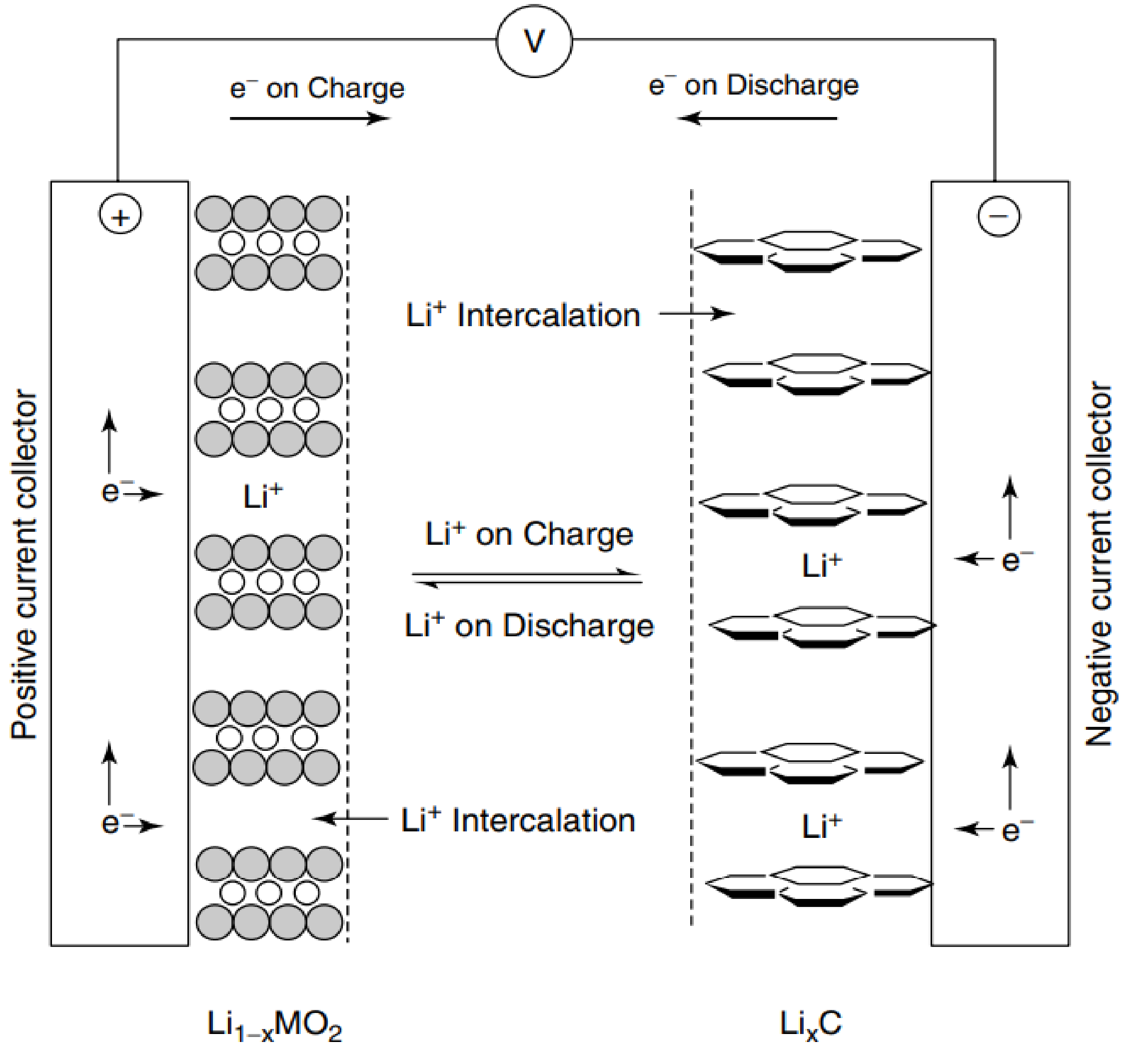
- Cannot be recharged once depleted
- Electrochemical reaction cannot be reversed
- Ranging from coin cells to AA batteries
- Example: Alkaline batteries, Zinc carbon batteries

Secondary batteries

- Rechargeable batteries
- Chemical reactions can reversed by applying a certain voltage to the battery in a reverse direction
- Example: Nickel Cadmium (Ni-Cd), Lead Acid, Lithium Ion



Li-ion battery



Cathode half-cell reaction

$$LiMO_2 \rightleftharpoons Li_{1-x}MO_2 + xLi^+ + xe^-$$

Anode half-cell reaction

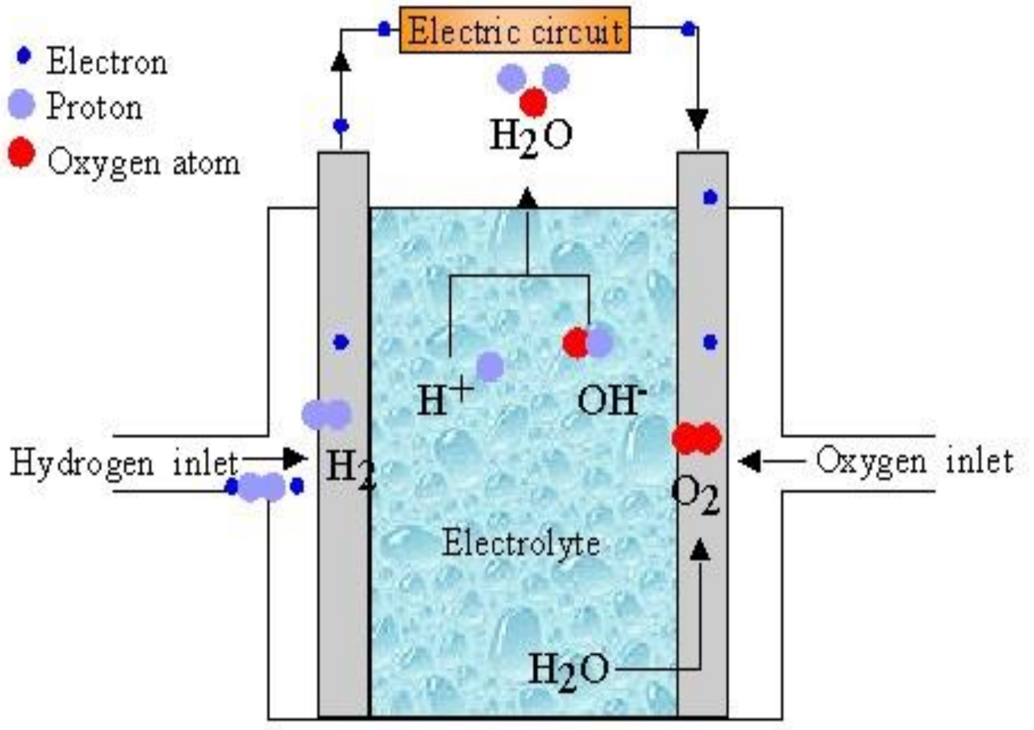
$$C + xLi^+ + xe^- \rightleftharpoons Li_xC$$

During discharge, lithium ions, Li+, carry the current from the negative to the positive electrode, through the nonaqueous electrolyte and separator

During charging, an external electrical power source (the charging circuit) applies a higher voltage (but of the same polarity) than that produced by the battery, forcing the current to pass in the reverse direction.

The lithium ions then migrate from the positive to the negative electrode, where they become embedded in the porous electrode material in a process known as intercalation

Fuel cells



Anode reaction: Facilitate electrochemical oxidation of fuel

$$H_2 = 2H^+ + 2e^-$$

Cathode reaction: Promote electrochemical reduction of oxidant

$$\frac{1}{2}O_2 + 2H^+ + 2e^- = H_2O$$

Over all reaction : $2H_2 + O_2 = 2H_2O$

Electrolyte: Ions generated during oxidation or reduction are transported from one electrode to the other through the ionically conductive but electronically insulating electrolyte

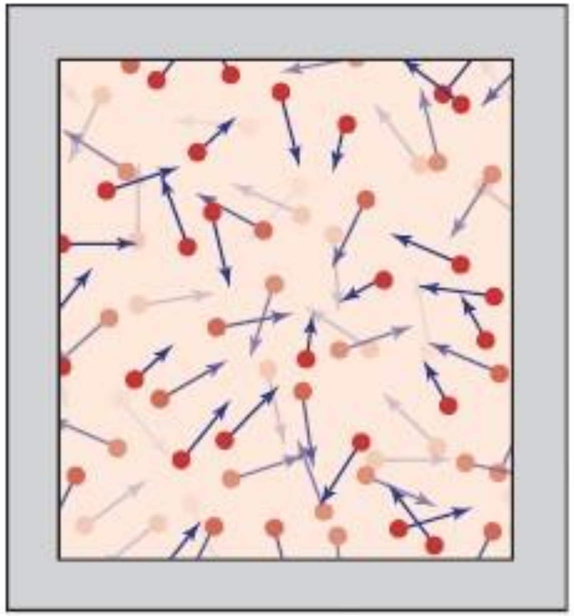
Electrons generated at the anode during oxidation pass through the external circuit (hence generating electricity) on their way to the cathode, where they complete the reduction reaction

Different types of fuel cells

Parameter	PEMFC	AFC	PAFC	MCFC	DMFC	SOFC
Electrolyte	Solid Polymer membrane (Nafion)	Liquid solution of KOH	Phosphoric Acid (H_2PO_4)	Li and K carbonate	Solid polymer membrane	Stabilized solid oxide electrolyte YSZ/SDC/GDC
Operating temperature	50-100°C	50-200°C	~ 200°C	~ 650°C	60-200°C	600-1000°C
Anode Reaction	$H_2 \rightarrow 2H^+ + 2e^-$	$H_2+2(OH^-) \rightarrow 2H_2O+ 2e^-$	$H_2 \rightarrow 2H^+ + 2e^-$	$H_2O+CO_3^{2-} \rightarrow H_2O+CO_2+2e^-$	$CH_3OH+H_2O \rightarrow CO_2+6H^+ +6H^-$	$H_2+O^{2-}-H_2O+2e^-$
Cathode reaction	$½O_2+2H^++2e^- \rightarrow H_2O$	$½O_2+H_2O+2e^- \rightarrow 2(OH)^-$	$½O_2+2H^++2e^- \rightarrow H_2O$	$½O_2+CO_2+2e^- \rightarrow CO_3^{2-}$	$3O_2+12H^++12H^- \rightarrow 6H_2O$	$½O_2+2e^- \rightarrow O_2^-$
Charge Carrier	H^+	OH^-	H^+	CO_3^-	H^+	O^-
Fuel	Pure H_2	Pure H_2	Pure H_2	H_2,CO,CH and Other Hydrocarbons	CH_3OH	H_2,CO,CH and Other Hydrocarbons
Oxidant	O_2 in air	O_2 in air	O_2 in air	O_2 in air	O_2 in air	O_2 in air
Efficiency	40-50%	~ 50%	40%	>50%	40%	>50%
Combined Heat and Power Efficiencies (CHP)	70-90%	>80%	>85%	>80%	80%	<90%

Thermal energy

Thermal Energy : Thermal energy refers to the collective energy contained in the relative motions of the large number of microscopic particles comprising a macroscopic whole.



Temperature : Relative measure of the amount of thermal energy in a system (or part of a system). Increasing the temperature of a system – making it hotter – generally requires adding thermal energy.

Heat : Thermal energy transit from a system at one temperature to a system that in contact with but is at a lower temperature.

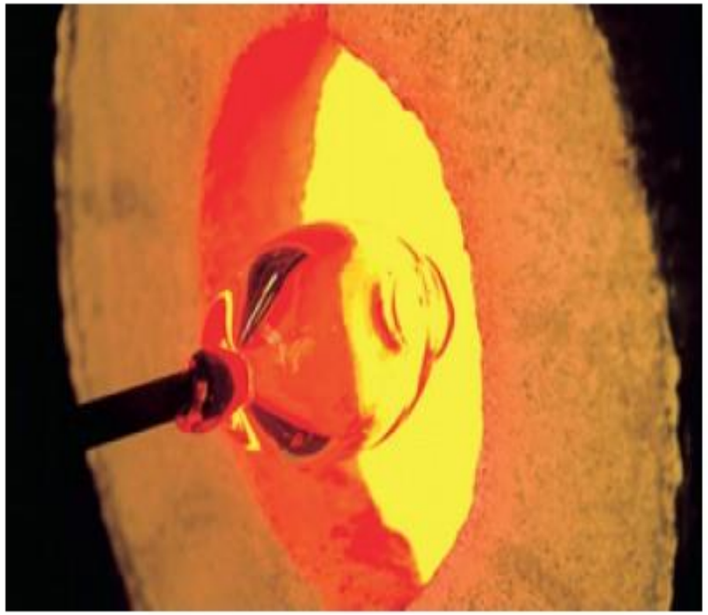
Specific heat : substance is the quantity of heat required to change the temperature of unit mass unit mass of the substance by one degree.

$$\mathrm{C} = \frac{\Delta Q}{m\,\Delta T}$$

ΔQ – Quantity of heat
ΔT – Temperature change
m – mass of the substance

Mechanism of heat transfer : Heat is transferred from one location or material to another in three primary ways

Conduction : Where energy of molecular motion is transferred between particles through materials



Convection : Where thermal energy carried by the collective motion of fluid

Radiation : Where the motion of hot molecules gives rise to radiation that carries away energy

Conduction : When thermal energy moves through the materials as a results of collision between free electrons, ions, atoms and molecules of the materials. The hotter a substance higher the average kinetic energy (KE) of the atom, when the temperature difference exists between materials in contact, the higher energy atoms in the warmer substance transfer energy to the lower energy atoms in the cooler substance.

Fourier's Law: The flow of heat through material is described by a heat flux q(x, t) with units W/m^2. For most materials and over a wide range of temperatures, the flux of heat follows Fourier's law of heat conduction

$$q(x, t) = -k \nabla T(x, t) \quad (x - \text{position}, t - \text{time})$$

The coefficient of proportionality k is the thermal conductivity, which ranges from very small (~0.02 W/m .K for excellent insulators) to very large (~300 W/m K for the best metallic conductors).

Convection : Collective motion of molecules within a fluid can effectively transport both mass and thermal energy

Forced convection : occurs when a fluid is forced to flow by an external agent.

Newtons law of cooling : A cold fluid forced to flow over a hot surface carries away heat efficiently

$$\frac{dQ}{dt} = \hat{h}\, A\, (T - T_0)$$

$\frac{dQ}{dt}$ - rate of heat transfer from object to fluid

A – object surface area

$\hat{h}$ – heat transfer coefficients

T and T_0 - Temperature of object and fluid

Free convection : occurs when a fluid rises or sinks because its temperature differs from that of its surroundings

Radiation : any material at a nonzero temperature radiates energy in the form of electromagnetic wave

Stefan–Boltzmann law : $\frac{dQ}{dt} = \varepsilon\, \sigma\, T^4 A$

$\frac{dQ}{dt}$ - Radiation power emitted by the object

T – temperature

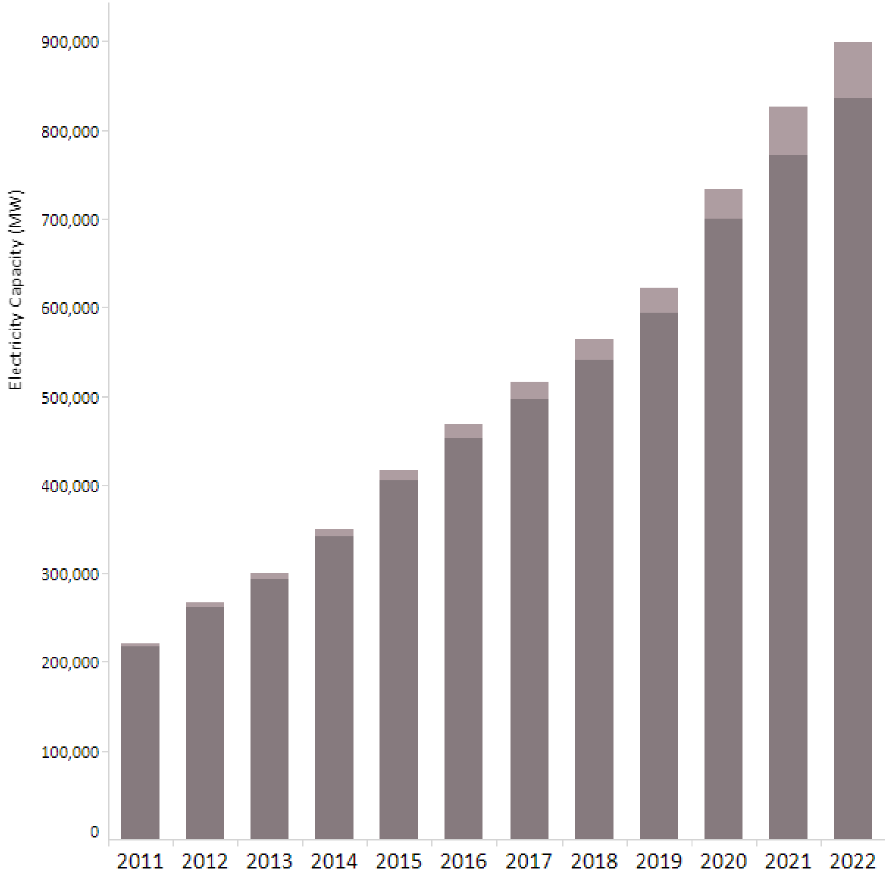
A- surface area

σ – Stefan-Boltzmann constant (5.67×10^{-8} W/m^2 . K^4)

Blackbody radiation : an object that absorbs all the radiant energy falling on it. At, thermal equilibrium, a body emits as much as energy as it absorbs.

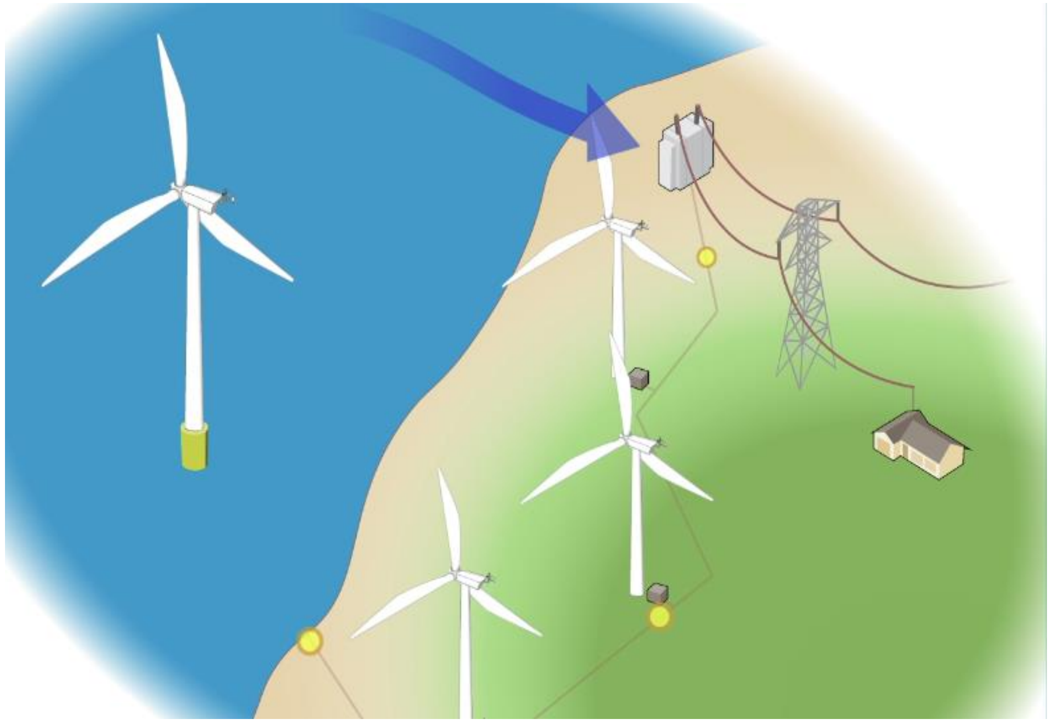
Wind energy

- Wind energy is **a byproduct of the sun**.
- The sun's **uneven heating of the atmosphere**, the earth's irregular surfaces (mountains and valleys), and the planet's revolution around the sun all combine to create wind.
- Since wind is in **plentiful** supply, it's a sustainable resource for as long as the sun's rays heat the planet.
- Wind energy describe the process by **which the wind is used to generate mechanical power or electricity**.
- This mechanical power can be used for specific tasks (such as grinding grain or pumping water) or a generator can convert this mechanical power into electricity.



Wind turbines

- A wind turbine turns wind energy into electricity using the **aerodynamic force from the rotor blades**, which work like an airplane wing or helicopter rotor blade.
- When wind flows across the blade, the **air pressure** on one side of the blade **decreases**.
- The **difference in air pressure** across the two sides of the blade creates both **lift and drag**.
- The force of the **lift is stronger than the drag** and this causes the rotor to spin.
- The **rotor connects to the generator**, either directly (if it's a direct drive turbine) or through a shaft and a series of gears (a gearbox) that speed up the rotation and allow for a physically smaller generator.
- This translation of aerodynamic force to rotation of a **generator creates electricity**.



Types of Wind Turbines

The majority of wind turbines fall into two basic types:

Horizontal-axis wind turbines:

They have **three blades** and operate "upwind," with the turbine pivoting at the top of the tower so the blades face into the wind.

Vertical-axis wind turbines:

- It comes in several varieties, including the eggbeater-style Darrieus model, named after its French inventor.
- These turbines are **omnidirectional**, meaning they don't need to be adjusted to point into the wind to operate.

Application of wind turbines

Modern wind turbines can be categorized by **where they are installed** and how they are connected to the grid:

Land-Based Wind:

- It ranges in size from **100 kilowatts** to as large as several megawatts.
- They are more **cost effective** and are grouped together into wind plants, which provide **bulk power** to the electrical grid.

Offshore Wind turbines:

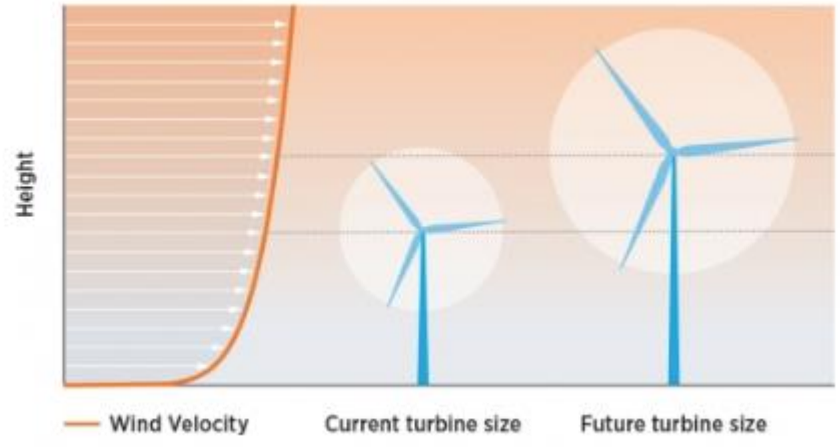
- They tend to be **massive**, and **tall**.
- Installation is easy compared to land based turbine as the large components can be transported on ships instead of on roads.
- These turbines are able to capture powerful ocean winds and generate vast amounts of energy.

Distributed Wind turbines:

- When wind turbines of any size are installed on the "customer" side of the electric meter, or are installed at or near the place where the energy they produce will be used, they're called "distributed wind.
- Many turbines used in distributed applications are small wind turbines. Single small wind turbines - **below 100 kilowatts** - are typically used for residential, agricultural, and small commercial and industrial applications.

Utility-Scale Wind Energy

- Utility-scale wind energy is a cornerstone in the realm of renewable energy sources, playing a pivotal role in the global transition towards sustainable and clean energy.
- It involves the generation of wind power at a large scale, typically using wind turbines that are capable of producing more than 1 MW of power.
- Utility-scale wind turbines are typically installed in large, multi-turbine wind farms connected to the nation's transmission system.



The Ecosystem of Utility-Scale Wind Energy

Utility-scale wind energy involves a complex ecosystem consisting of various components and stakeholders.

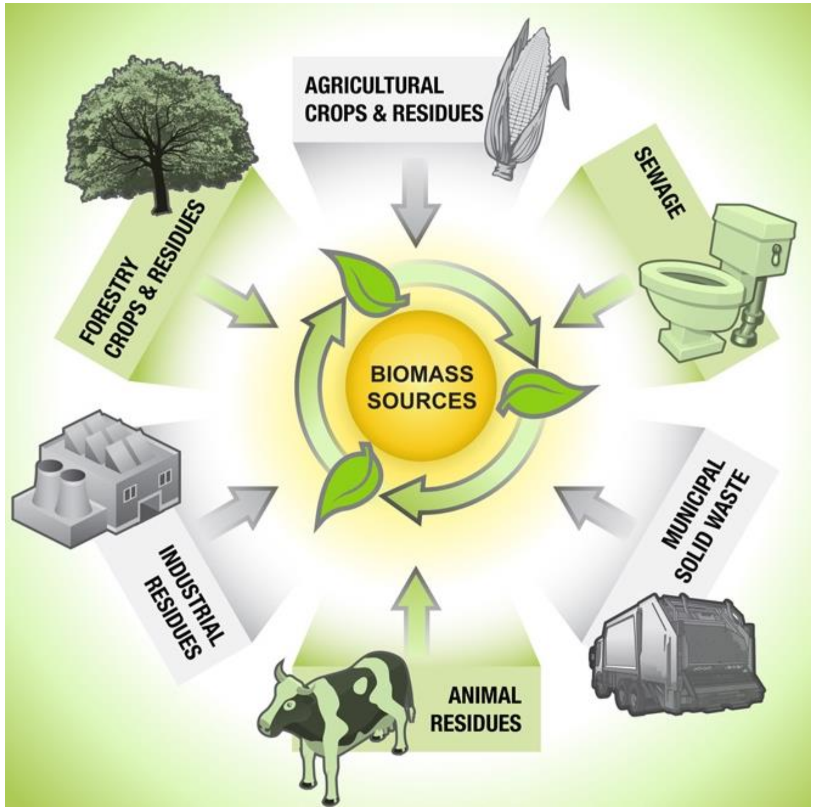
- **Wind Farms:** These are large installations of wind turbines, strategically located in areas with optimal wind conditions, often in remote or offshore locations.
- **Transmission Infrastructure**: Given the remote locations of many wind farms, extensive transmission lines and substations are required to transport the generated electricity to where it is needed.
- **Stakeholders:** The ecosystem involves myriad stakeholders including developers, investors, regulators, and consumers, each playing a crucial role in the development, deployment, and consumption of wind energy.
- **Policy and Regulation**: Government policies, incentives, and regulatory frameworks significantly impact the development and expansion of utility-scale wind energy projects.

Challenges in Utility-Scale Wind Energy

- **Siting and Environmental Concerns**: Identifying suitable locations that balance wind resource availability, environmental impact, and community acceptance is challenging.
- **High Capital Costs:** The initial investment required for land acquisition, turbine installation, and infrastructure development is substantial.
- **Intermittency and Reliability:** The variable and unpredictable nature of wind poses challenges in ensuring a consistent and reliable power supply.
- **Transmission and Integration:** Developing the necessary transmission infrastructure and integrating large-scale wind power into the grid are complex and often costly endeavors.

Bioenergy

- Bioenergy is one of many diverse resources available to help meet our demand for energy.
- It is a form of renewable energy that is derived from recently living organic materials known as biomass, which can be used to produce transportation fuels, heat, electricity, and products.



Biomass

- Biomass refers to any type of organic material derived **from plants, micro-organism grown on land and water and their derivatives**.
- Plants :trees, food crops, and other plants that can be used for energy, are forms of biomass
- Biomass also includes animals, animal waste, algae, and biological waste from agriculture and the food industry.
- Biomass is the largest renewable energy source.
- Biomass for **heat, light and cooking**
- Biomass can be converted into modern energy forms such as **liquid and gaseous fuels**, electricity, and process heat to provide energy services needed by rural and urban populations and also by industry.
- The conversion of biomass to liquid biofuels, primarily for use in transportation.

Types of Biomass

Type I

❖Biomass is from cultivated field, crops and forests.

❖In this type, the biomass is converted into bioenergy directly by burning the biomass(grasses, crops).

Type II

❖Biomass is from wastes like municipal waste, animal dung etc

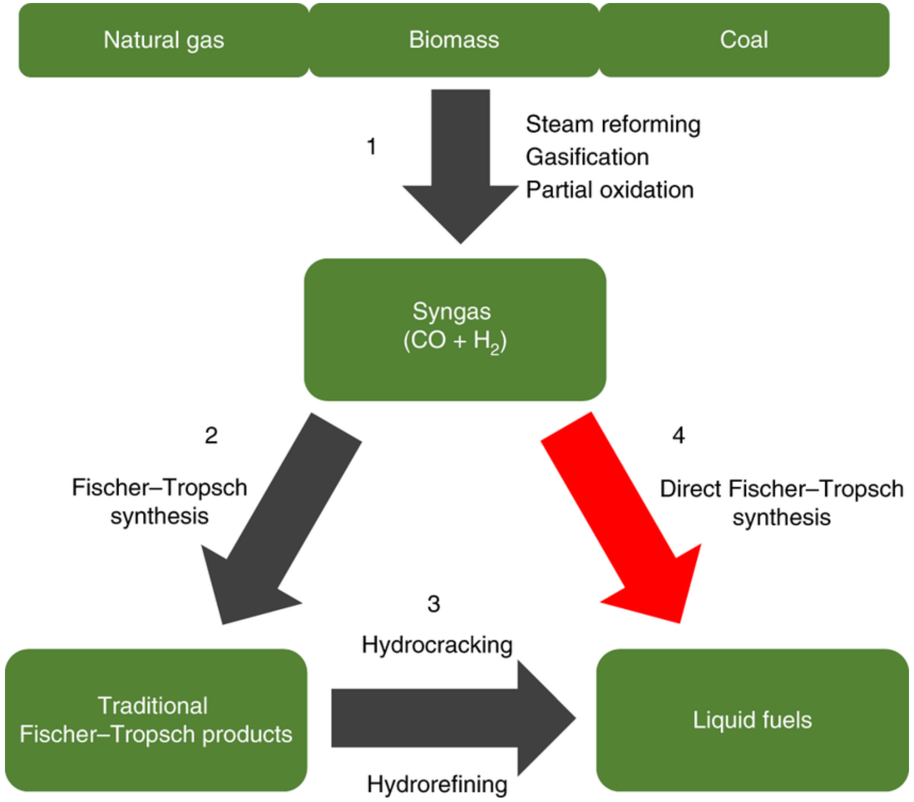
❖The biomass is fermented anaerobically to obtain gaseous fuel like bio-gas.

❖Anaerobic digestion

❖It is a multistep biological and chemical process that is beneficial in energy creation.

Type III

Biomass is converted into ethanol and methanol to use in a liquid fuels in engine.

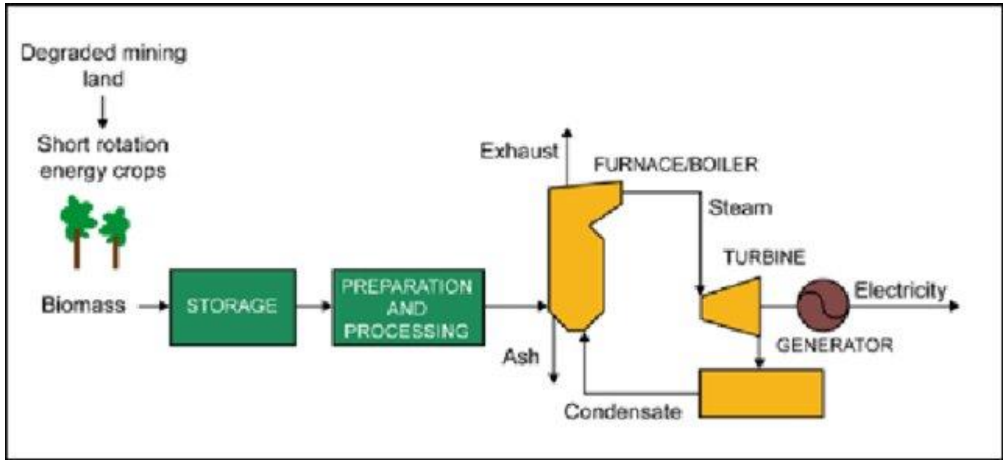


Direct Combustion

- According to IEA (International Energy Agency) estimates, in 2010 roughly 8% (or ~40 EJ/y) of global energy used came from the combustion of biomass.
- Burning of wood, brush, agricultural by-products, animal dung, and waste materials.
- Some of the energy produced by biomass combustion is used for electricity generation

Direct combustion

In a direct combustion system (shown in Figure), biomass is burned in a combustor or furnace to generate hot gas, which is fed into a boiler to generate steam, which is expanded through a steam turbine or steam engine to produce mechanical or electrical energy.



Direct combustion process

Thermal gasification

- Thermal gasification is carried out by heating biomass in the presence of oxygen, air, and/or water vapor.
- In this process, the molecular structure of the biological material is broken down and a gas is produced that contains varying fractions of methane, CO_2, CO, H_2, and water vapor depending upon the precise conditions and materials.
- If the amount of oxygen present is insufficient for complete combustion, the gas will contain substantial amounts of H_2 and CO.
- The gas produced in this fashion is known as biological syngas.

Pyrolysis

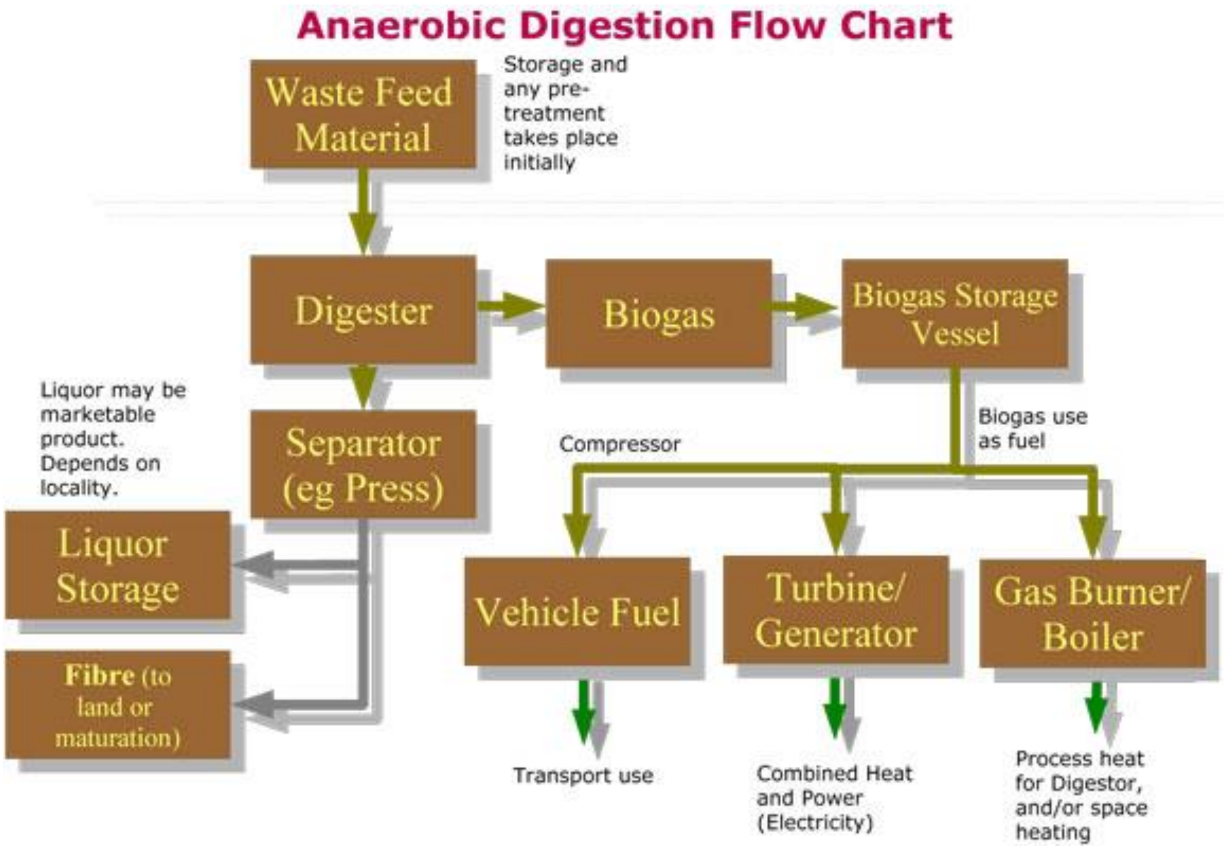
- Heating in the absence of oxygen or air, known as **pyrolysis**, similarly releases a gas containing H2, light hydrocarbons (methane, ethane, etc.), and liquid hydrocarbons depending on conditions.
- Pyrolysis can also transform solid biomass to char by increasing the carbon fraction of the material in a process similar to the production of coke from coal.
- The gases resulting from biomass gasification or pyrolysis can be combusted for heat or electric power, or can be converted into liquid fuels using liquefaction methods such as the **Fischer–Tropsch mechanism**.
- These uses of biologically produced syngas are closely parallel to methods used for gasification and liquefaction of coal and other fossil fuels, and produce similar gaseous and liquid hydrocarbon fuels.
- Biogas generally has higher oxygen, hydrogen, and moisture content, and a lower heating value; it also generally has less sulfur than gas and liquid fuels produced from coal

Anaerobic digestion

- Biological **processing of waste by bacteria** also releases methane in the natural process of decomposition that breaks down dead plant matter everywhere. This biological process can be harnessed for power.
- Biogas - distinct from biological syngas
- Organic material - breakdown without the presence of oxygen - by certain types of bacteria
- The main components of biogas are **methane and carbon dioxide**, with some water vapor and other gaseous components depending on circumstances.
- The two principal methods for biogas production currently in use are the capture of biogas from landfills and the production of biogas in closed containers known as anaerobic digesters.

- There are four fundamental steps of anaerobic digestion that include hydrolysis, acidogenesis, acetogenesis, and methanogenesis.
- **Hydrolysis**: enzymes in bacteria break down insoluble organic material into simple sugars and amino acids. The water is added to the glycosidic bonds in starches and other complex organic molecules.
- **Acidogenesis and Acetogenesis**: These are broken into simpler molecules by different bacteria to acetic acid, hydrogen, and car bon dioxide.
- **Methanogens**: resulting acetic acid, hydrogen, and car bon dioxide are finally converted into methane and carbon dioxide by primitive organisms.
- The time needed for the complete transformation from solid organic material to biogas depends upon the nature of the **organic material and temperature and chemical conditions**.

- There are two standard temperature ranges in which anaerobic digestion is carried out, in which different species of methanogens are operational:
- Mesophilic bacteria - 20–45◦ C
- Thermophilic bacteria - 50–70◦ C
- Soluble carbohydrates can be broken down in a few hours, while proteins, fats, and cellulosic material such as paper can take several days to break down.
- Thermophilic digesters act more rapidly, but are less stable and less widely used than mesophilic digesters



BioFuel

- Biofuels are liquid fuels produced from recently living organic material.
- The primary biofuels in use are ethanol and biodiesel, though other biofuels are under development.

Ethanol

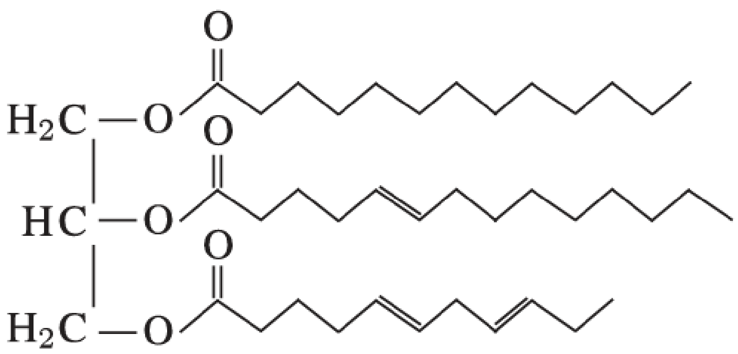
- Certain strains of **yeast** can process simple sugars through **fermentation** to produce ethanol.
- The term fermentation in general refers to the biological transformation of **sugars to alcohols, acids, and/or gases**.
- For glucose the chemical transformation is .

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$$

- Fermentation of sugars by yeast is the principal mechanism used to produce **ethanol from organic material**.
- Because yeast requires the presence of water and cannot tolerate an environment with too high a concentration of ethanol, the fermentation process yields a mixture of water and ethanol with a **maximum ethanol fraction of 10–15%**.
- A higher fraction of ethanol can be achieved through the process of **distillation**.
- Repeated distillation cannot raise the ethanol fraction beyond 96.4% (by volume).
- Further purification to 100% ethanol can be carried out in a variety of ways, including the use of molecular sieves such as zeolites or organic material such as cornmeal or sawdust to separate out the water.

Biodiesel

- Biodiesel is a liquid fuel produced from **vegetable oil and animal fat** using purely chemical processes.
- Vegetable seed oils and animal fats include molecules known as **triglycerides.**
- Triglycerides contain three hydrocarbon chains connected by an oxygen-containing structure based on glycerol, a simple compound ($C_3H_8O_3$) related to both alcohols and sugars.
- Triglycerides can be combined with alcohols such as methanol (CH_3OH) through a process known as **transesterification**.
- which breaks the triglycerides into three separate long-chain molecules known as **Fatty acid esters**.
- The resulting fatty acid esters have very **similar properties** to the hydrocarbons used in diesel fuel, and can be combusted directly in standard diesel engines



- Biodiesel can be produced from a wide range of different feedstocks.
- Typical biodiesel fuel has an enthalpy of **combustion of roughly 37 MJ/kg**, 10% lower than standard diesel fuel.
- The combustion quality of vegetable-oil based biodiesel is relatively good, and even higher for biodiesel from animal fat.
- While pure biodiesel (B100) can be used in many diesel engines without problems, biodiesel can dissolve rubber in components such as hoses and gaskets.
- Blends of 20% biodiesel (B20) or lower can be used directly in most diesel engines and are more widely distributed.