Energy Storage Technologies

UNIT 5

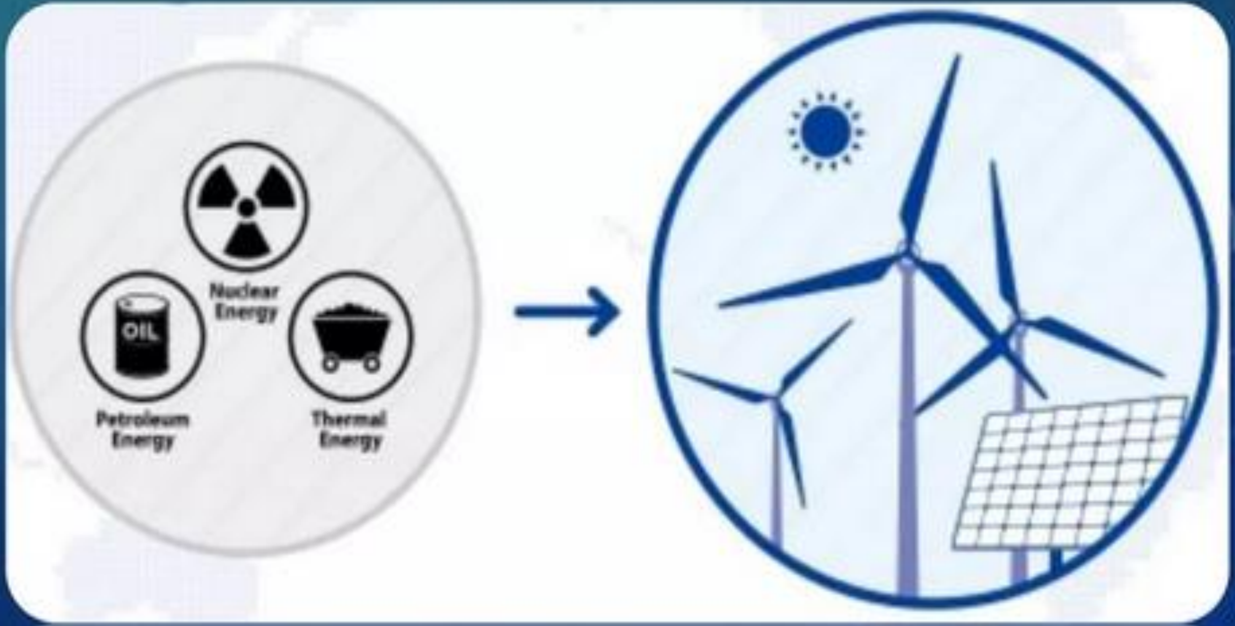
Introduction

It is particularly important for the development and integration of renewable energy technologies. Some renewable energy sources have intermittent generation profiles, which means that electricity is only produced when the sun is shining or when the wind is blowing. This creates supply and demand discrepancies because consumers may still require electricity when renewables sources are not producing.

Energy storage enables a lower-cost generating source to produce electricity at a different point in time to be stored and then used to meet times of peak demand. This 'flexibility' has the potential to transform how we produce and consume electricity.

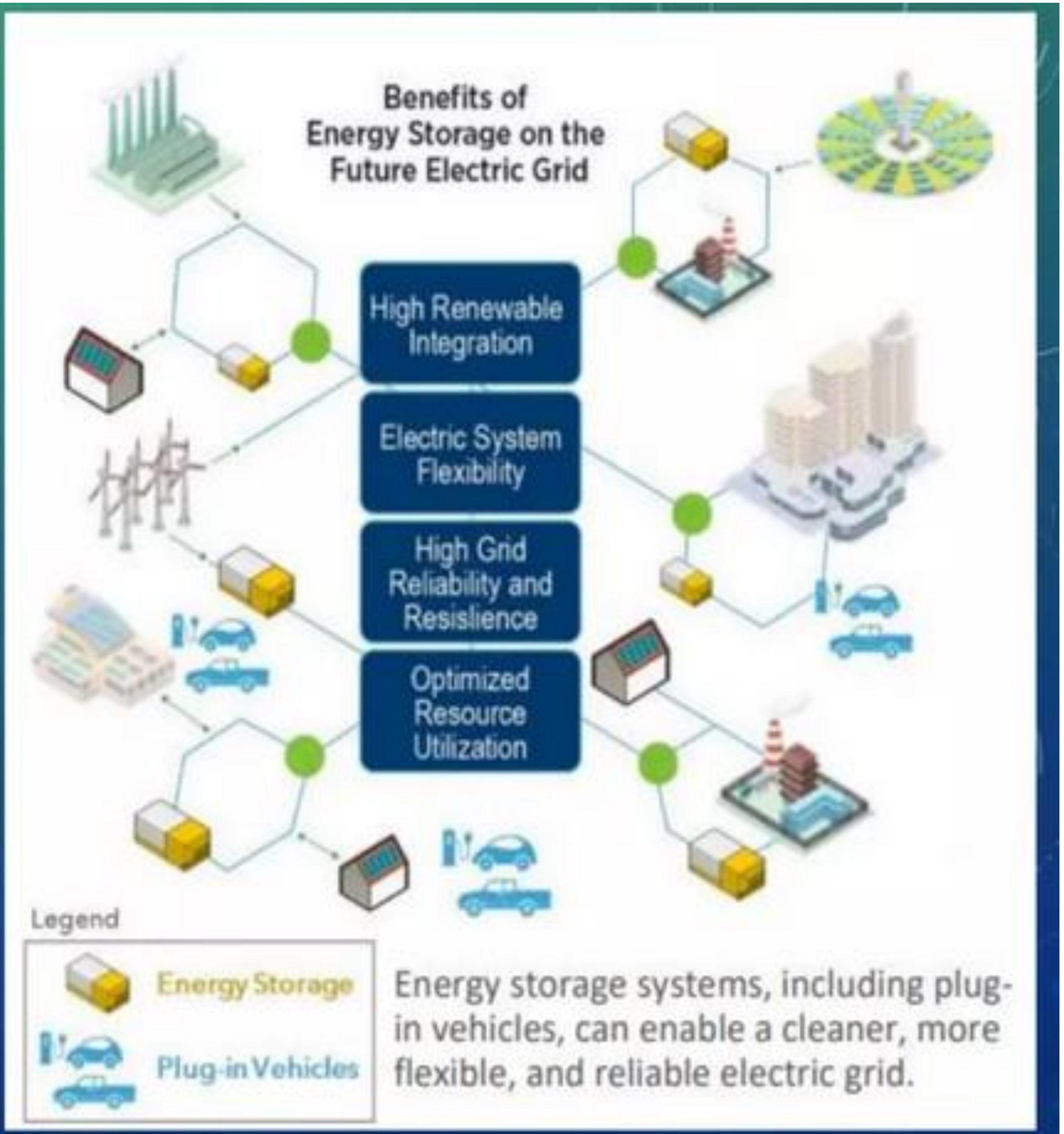
Energy Storage System(ESS)

- Energy storage system can actually store energy and use the stored energy whenever the need arises.
- As the need for clean energy arises, the need to replace current existing power plants have become a global issue.



Need for Energy Storage System(ESS)

- Supply and Demand mismatch
- Utilize storage for peak periods.
- Reliable power supply.
- Reduce the need for new generation capacity.
- Electrical vehicles
- Emergency support.



Need for Energy Storage System(ESS)

- The energy storage along with renewable energy generators/PV is required to increase the reliability and flexibility.
- The intermittent nature of renewable sources like solar and wind needs storage to deliver the right amount of power at right quality.
- To accommodate the projected high penetration of solar and wind energy in future grids with lower grid rejection loss.

Classification of Energy Storage System(ESS)

Energy storage Technology

Mechanical Energy storage

Potential Energy storage
-Compressed Air Energy storage
-Pumped Hydro energy storage

Kinetic Energy Storage
- Flywheel

Electrical Energy storage

Electrostatic Energy storage
-Capacitors
-Super-(Ultra) Capacitors

Superconducting Magnetic Energy Storage

Thermal Energy storage

Low Temperature Energy storage

High Temperature Energy storage

Chemical Energy storage

Electrochemical Energy storage
-Batteries
- Fuel Cells

Thermochemical Energy Storage

Classification of Energy Storage System(ESS)

Energy Storage Systems

- **Electrical Distribution Application**
  - Batteries
  - Flywheels
  - Compressed Air in Vessels
  - Fuel Cells
  - Thermal Energy Storage
  - Super-capacitors
- **Large-scale Power Grid Application**
  - Compressed Air Energy Storage
  - Flywheels
  - Pumped Hydro-electrical Energy Storage
  - Superconducting Magnetic Energy Storage
  - Super-capacitors

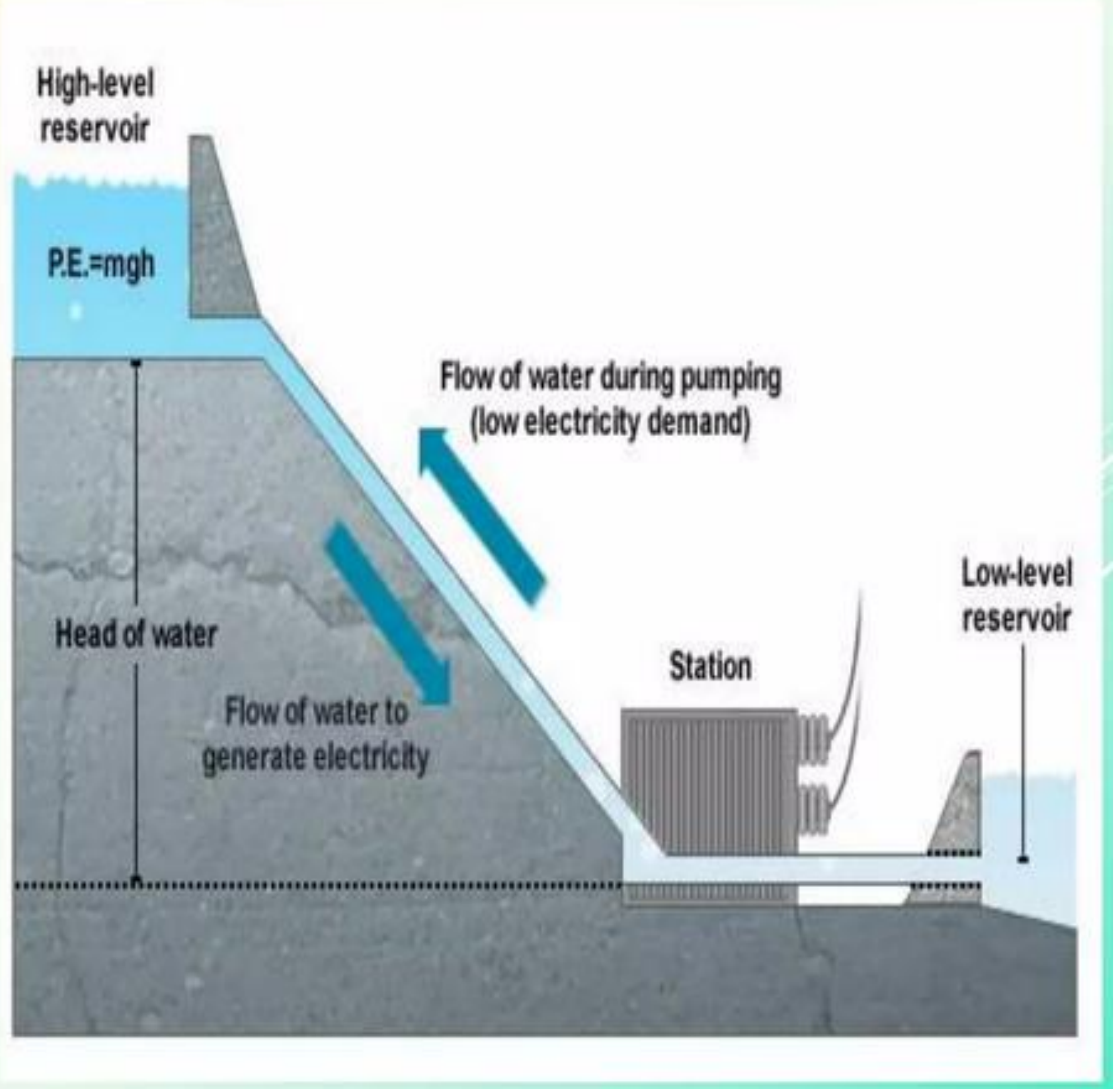
Benefits from Energy Storage System(ESS)

- **Major areas where energy storage systems can be applied as:**

  - **Voltage control:** Support a heavily loaded feeder, provide power factor correction, reducing the need to constrain DG, minimize on0-load tap charger operation, mitigating flicker, sags and swells.
  - **Power flow management:** Redirect power flows, delay network reinforcement, reduce reverse power flow and minimize losses
  - **Restoration:** Assist voltage control and power flow management in a post fault reconfigured network
  - **Energy market:** Arbitrage, balancing market, reduce DG variability, increase DG yield from non-firm connections, replacing spinning reserve.
  - **Commercial/regulatory aspects:** Assist in compliance with energy security standard, reducing customer minutes lost, while reducing generator curtailment.
  - **Network management:** assist islanded network, support black starts, switching ESS between alternative feeder at a normally open point.

Pumped Hydro Electric Storage

- A pumped storage system requires two water reservoirs – an upper and a lower – and water is moved between these two levels.
- By using surplus (or cheap) electricity to pump water from the lower reservoir to the upper reservoir, energy can be stored in the form of gravitational potential energy, which can then be converted back into electrical energy at a later time by allowing the water to flow back down from the upper to lower reservoir though a turbine and generator – just like conventional hydroelectric technology.
- In this manner energy is converted from electrical to kinetic to gravitational potential and then back to kinetic and finally back to electrical again.



Pumped Hydro Electric Storage

- The PHES systems are the largest energy storage systems of the world having 125 GW worldwide nearly 96% of the world's electric storage capacity and 3% of the global generation capacity.
- PHES stores the electrical energy in the form of potential energy by pumping the water from the lower side of reservoir up to the higher elevation of the reservoir. PHES power ratings ranging from 1 MW to 3000MWoperating at 76-85% efficiency having a very long life approximately 50 years or more and practically unlimited life cycles .
- However, it is a matured technology with limitations of site-specific social boundaries, large capital investment, lengthy project construction periods, issues of habitat species conservation and 10 to 15 minutes of reaction time.
- PHES size is another main constraint which can't be scale down to small sizes as compared to that of new emerging ESS technologies.
- The minimum average elevation of potential dam should be150 meter above the lower reservoir.
- Restricted geological implementations and negative environmental impacts make the future development of PHS limited.

Pumped Hydro Electric Storage

- To calculate the mass power output of a PHES facility, the following relation can be used

$$P_C = \rho g Q H \eta$$

Where

P_C – Power capacity in Watt, ρ – Mass density of water in kg/m^{3,} g- Acceleration due to gravity m/s^2 ,Q- Discharge through the turbines m^3/s, H- Effective head in meter, η- efficiency

- To evaluate the storage capacity of the PHES the following must be used

$$S_c = \frac{\rho g H V \eta}{3.6 \times 10^9}$$

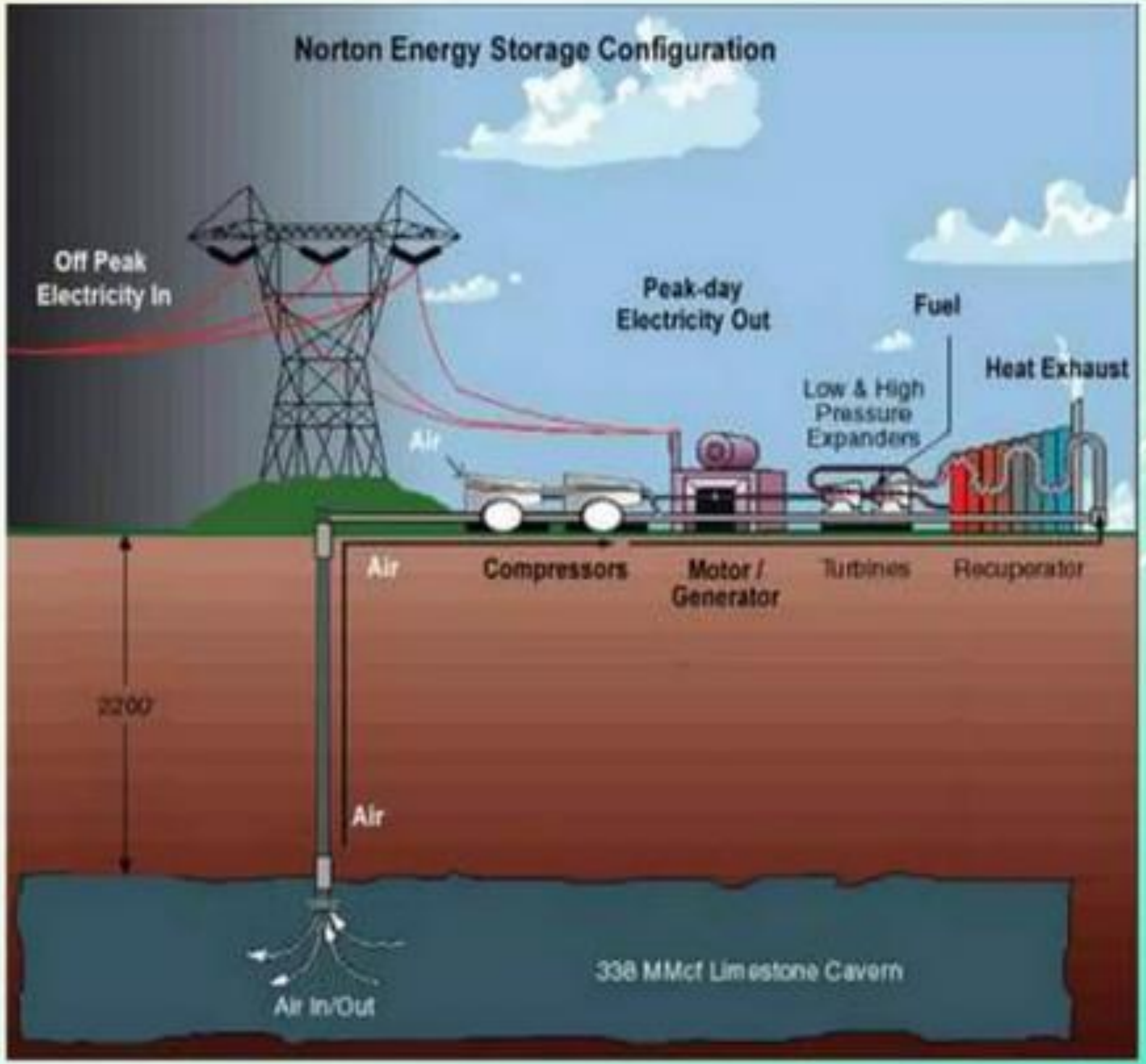
Where

S_C – Storage capacity in megawatt-hours (MWH),

V – Volume of water that is drained and filled each day in m^3

Compressed Air Energy Storage(CAES)

- Compressed air energy storage (CAES) uses surplus energy to compress air for subsequent electricity generation.
- It is possible to use electrical power during off-peak hours (storage hours) in order to compress the air, and then to produce power during peak hours (retrieval hours) by expanding the air in a combustion chamber before feeding it into the turbines.
- However, a good portion of the input energy is lost in this process, making CAES one of the least efficient storage technologies available.



Compressed Air Energy Storage(CAES)

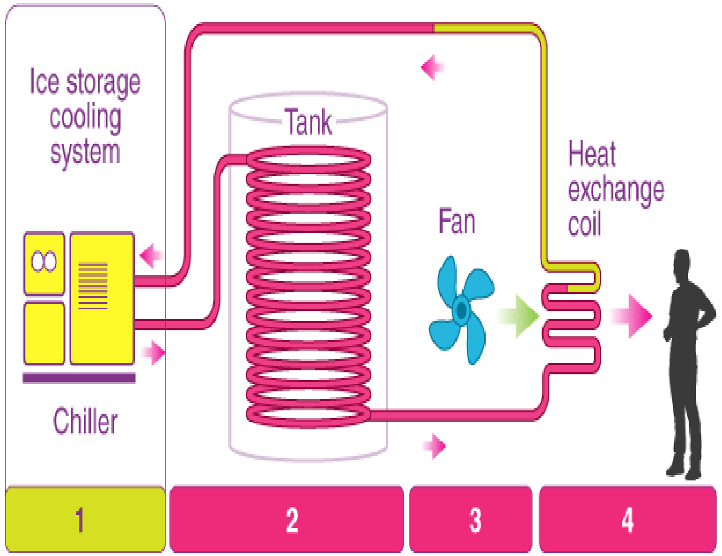
- The CAES system stores the energy in the form of intermolecular gas pressure with compression of air into the reservoir, then converts it into the modified gas. Compressed modified gas is expanded to rotate the turbine coupled with generator for producing electricity .
- CAES systems can be realistic alternative to the PHES systems because of their large capacity, intermediate geographical dependency, longer lifespan and low cost per kW.
- Based on the exothermic and endothermic processes involved, in the compression and expansion of the air and heat exchange, the complex designs of the CAES systems are classified into three types: Isothermal storage, adiabatic storage systems and diabatic storage systems.
- Isothermal and adiabatic systems work well for small power density requirements whereas diabatic storage systems are the most commercially implemented CAES systems due high-power density and great system flexibility.

Compressed Air Energy Storage(CAES)

- The installed commercial capacity of the CAES systems ranges from 35 to 300 MW with notable applications of grid support such as: load levelling and voltage and frequency control.
- The recent developments in the hybrid CAES plants with off shore and on shore wind plants shows increased overall efficiency with reduced fluctuations in the power output.
- The major barrier in CAES technology is the suitable geographical location of air storage tank or underground cavern. To overcome this limitation recently high pressure over ground carbon fibre tank air storage is proposed for small and medium scale advanced adiabatic CAES systems.
- Alternative low cost CAES solution could be achieved by decentralized small scale CAES systems, which is formed by collection of installations to serve as a virtual large power plant that is controlled by central unit of distribution system

Thermal Energy Storage(TES)

- TES can be defined as the temporary storage of thermal energy at high or low temperature. TES is significantly used technology around the world, according to U.S department of energy report the TES installed capacity is 3.3 GW accounting for 1.9% of the world energy storage in 2017
- As the heating and cooling necessities signify 45% of the total domestic and commercial energy usage, TES systems can be of significant support to load shifting and heating/cooling requirements of industrial and domestic sector, thus participating in demand side management of the respective micro grid
- The TES system consists of three major parts: thermal storage tank, heat transfer mechanism (refrigeration system, heat owing channels, pumps) and containment control system
- Depending upon the operating temperature of energy storage material, TES technologies are categorized into two groups: low temperature TES and high temperature TES .



Thermal Energy Storage(TES)

- Low temperature TES system consists of auriferous low temperature storage and cryogenic energy storage systems. Water cooling and reheating process is used in auriferous low temperature TES while liquid nitrogen or liquid air expansion ratio is used in cryogenic energy storage TES systems, such as liquid air energy storage (LAES).
- Low temperature TES is more suitable for high power density applications such as: load shaving, industrial cooling and future grid power management.
- Sensible heat and latent heat TES systems are most important in high temperature TES systems. In sensible heat storage system, the thermal energy is stored with change of temperature in storage medium without undergoing any form of phase change in the material.
- The capacity of sensible heat storage system depends upon the specific heat and mass of the storage medium, which may be of different form, such as liquid (water, molten salt or thermal oil) or solid (concrete, stone, metal or ground).
- Based on the combinations, phase change materials (PCMs) are classified into three types: solid-solid, solid-liquid and liquid-gas PCMs.

❑ Thermal Capacities at 20°C for Some Common TES Materials

S. No.	Material	Density (kg/m³)	Specific heat (J/kg.K)
1.	Aluminium	2710	896
2.	Brick	2200	837
3.	Clay	1460	879
4.	Concrete	2000	880
5.	Glass	2710	837
6.	Iron	7900	452
7.	Magnetite	5177	752
8.	Sandstone	2200	712
9.	Water	1000	4182
10.	Wood	700	2390

Electrochemical Energy Storage Systems

- Electrochemical energy storage systems (EcSS) are the oldest energy storing technologies where a reversible chemical reaction in the active material through electrolyte is used for producing/storing of DC power. All conventional secondary (rechargeable) battery energy storage (BES) and flow batteries (FBs) stores the electrical energy in the form of chemical energy comes under EcSS.
- EcSS are the largest group of electrical energy storage systems available with wide range of energy densities in the range of 10 Wh/kg up to 13 kW/kg having efficiencies of 70-80% for various methods without any harmful emissions and minimum maintenance.
- In order to get the desired voltage/power rating, a number of electrochemical cells are connected in series or in parallel in BES system. Each cell has two electrodes: anode (participating in oxidation reaction by losing electrons) and cathode (simultaneously participating in reduction reaction by gaining electrons) along with an electrolyte in the form of solid, liquid or viscous state according to requirement.

Electrochemical Energy Storage Systems

- Electrochemical energy storage systems (EcSS) are the oldest energy storing technologies where a reversible chemical reaction in the active material through electrolyte is used for producing/storing of DC power. All conventional secondary (rechargeable) battery energy storage (BES) and flow batteries (FBs) stores the electrical energy in the form of chemical energy comes under EcSS.
- EcSS are the largest group of electrical energy storage systems available with wide range of energy densities in the range of 10 Wh/kg up to 13 kW/kg having efficiencies of 70-80% for various methods without any harmful emissions and minimum maintenance.
- In order to get the desired voltage/power rating, a number of electrochemical cells are connected in series or in parallel in BES system. Each cell has two electrodes: anode (participating in oxidation reaction by losing electrons) and cathode (simultaneously participating in reduction reaction by gaining electrons) along with an electrolyte in the form of solid, liquid or viscous state according to requirement.

- In discharging mode, electrochemical reactions of oxidation and reduction flows the electrons to external power circuit.
- While in charging mode the external voltage applied between electrodes restores the chemical energy by reversible reaction
- In order to get the required potential in standard electrochemical cell, selecting the appropriate anode (oxidizing material) and cathode (reducing material) is vital part of cell design.

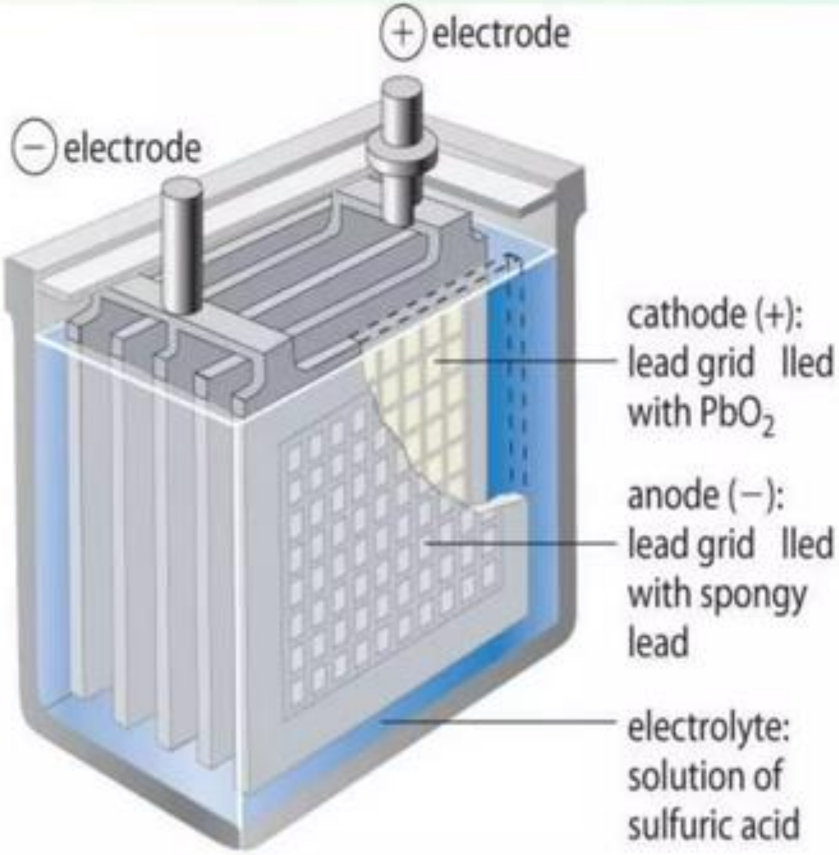
Electrochemical Energy Storage Systems

- Batteries store energy in chemical form during charging and discharge electrical energy when connected to a load. In its simplest form a battery consists of two electrodes, a positive and a negative placed in an electrolyte.
- Lead acid and Sodium Sulfur (NaS) batteries are used at present for large utility applications in comparable numbers.

  - Lead-acid (L/A) batteries
  - Sodium-sulfur (NaS) batteries
  - Lithium-ion (Li-ion) batteries
  - Flow batteries
    - Sodium bromide sodium polysulfide
    - Zinc bromine (Zn/Br)
    - Vanadium-redox (V-redox)

LEAD ACID Batteries

- Lead-acid batteries are used in stationary energy storage applications, especially as a DC auxiliary.
- Lead-Acid batteries consist of two electrodes: Lead and lead-dioxide immersed in sulfuric acid.
- It offers large life cycle and about 97% of lead can be recycled and reused in new batteries.
- The drawbacks of lead-acid batteries are primarily to do with low cycling capacity, high charge time and careful maintenance requirements coming largely from the evolution of H_2 and water loss.
- They also have a low energy density to weight ratio (currently around 40 Wh/kg), due to the high density of lead.

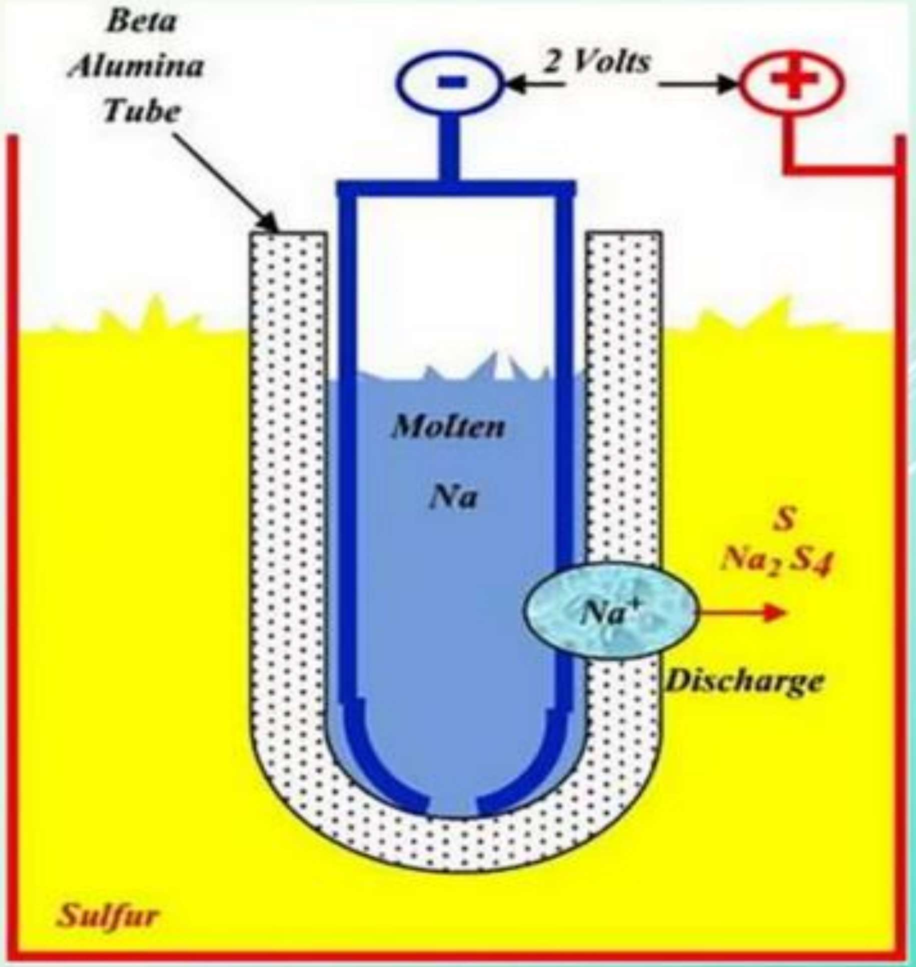


cell reaction:

$$Pb(s) + PbO_2(s) + 2HSO_4^-(aq) + 2H^+(aq) \rightarrow 2PbSO_4(s) + 2H_2O(l)$$

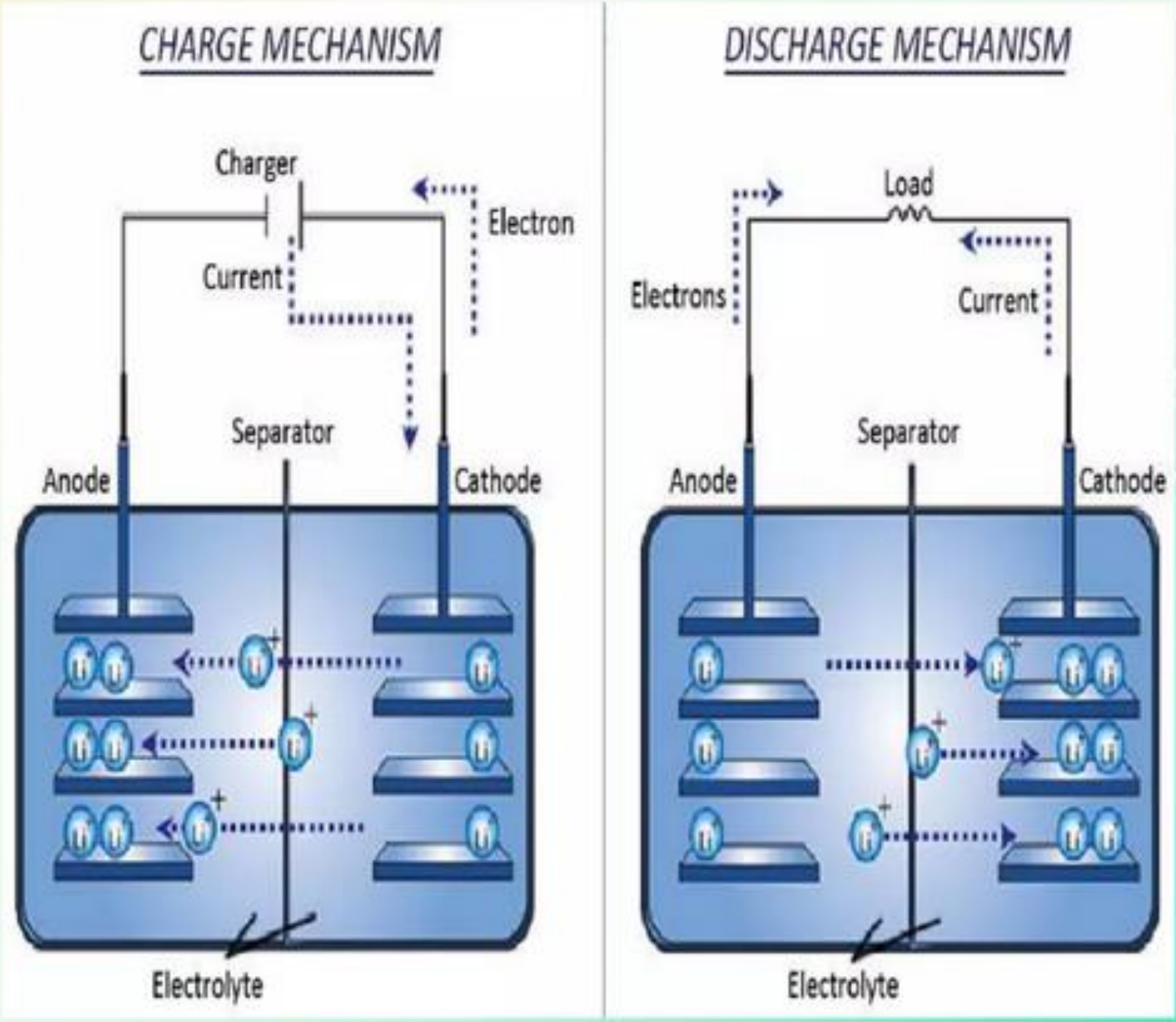
SODIUM-SULPHUR BATTERIES

- Sodium Sulphur (NaS) batteries are high temperature molten metal batteries.
- The negative electrode is made of liquid sodium while the electrolyte is solid beta-aluminium (a type of aluminium oxide).
- Na-S batteries have high efficiencies (85-92%) and high energy and power densities (150-240 Wh/kg and 150-230 W/kg).
- They are most suited to stationary grid applications due to high operating temperatures and corrosive nature of sodium polysulphide.
- Safety is also an issue as elemental sodium will ignite in contact with air or moisture.



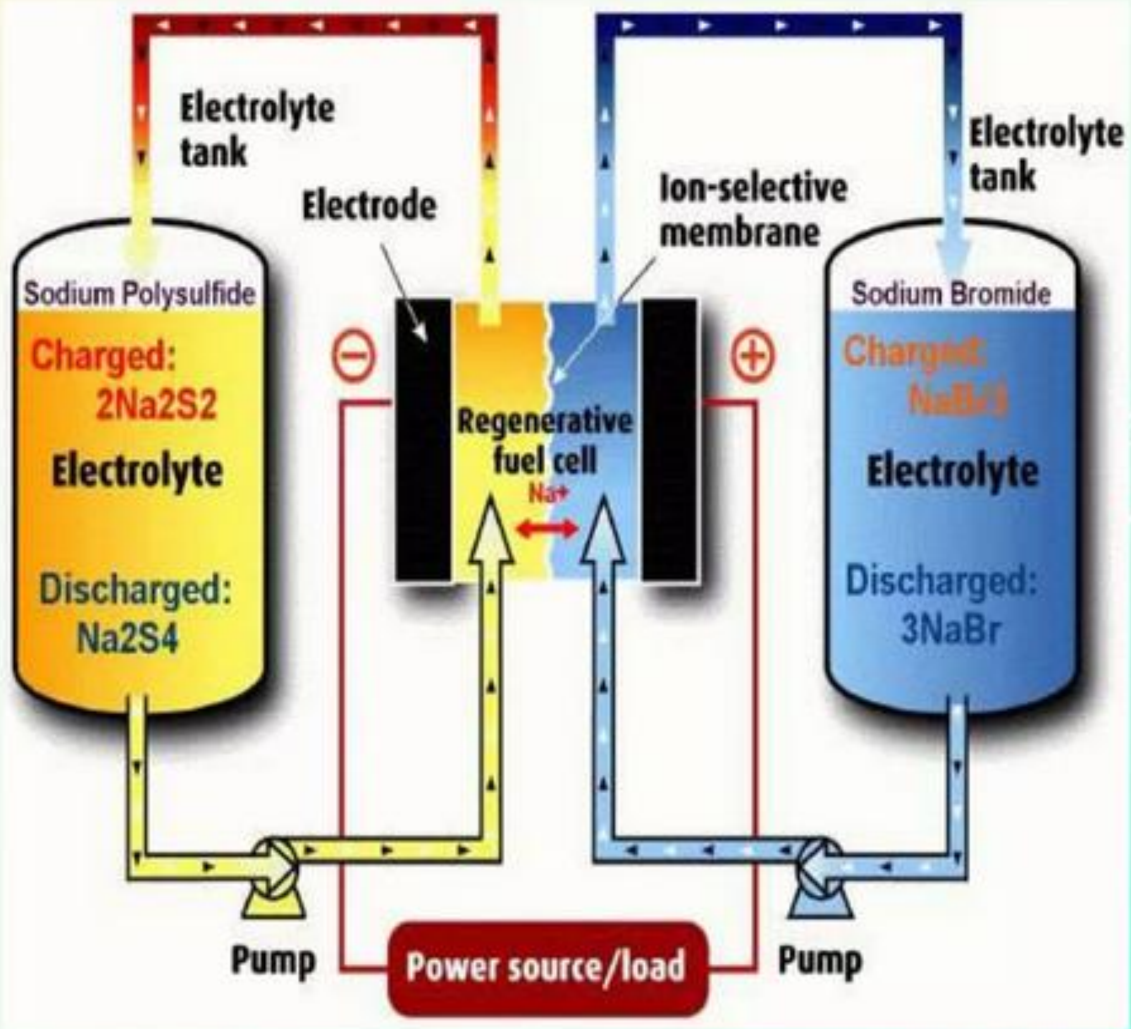
LITHIUM-ION BATTERIES

- Lithium ion batteries are now the dominant type of batteries found in small portable electronic applications due to their high energy density, light-weight and high efficiencies.
- The negative electrode in these batteries is a lithiated metal oxide (($LiCoO_2$, $LiMO_2$, $LiNiO_2$) and the positive electrode is made of graphitic carbon with a layered structure. Electrolytes generally consist of lithium salts dissolved in organic carbonates, i.e. $LiPF_6$ in ethylene carbonate.
- These batteries have high energy densities (in excess of 150Wh/kg), high efficiency, a low rate of self-discharge (around 5% per month) and a good cycle life provided they aren't fully discharged. Their disadvantages are a higher cost than other battery technologies and a limited lifespan.



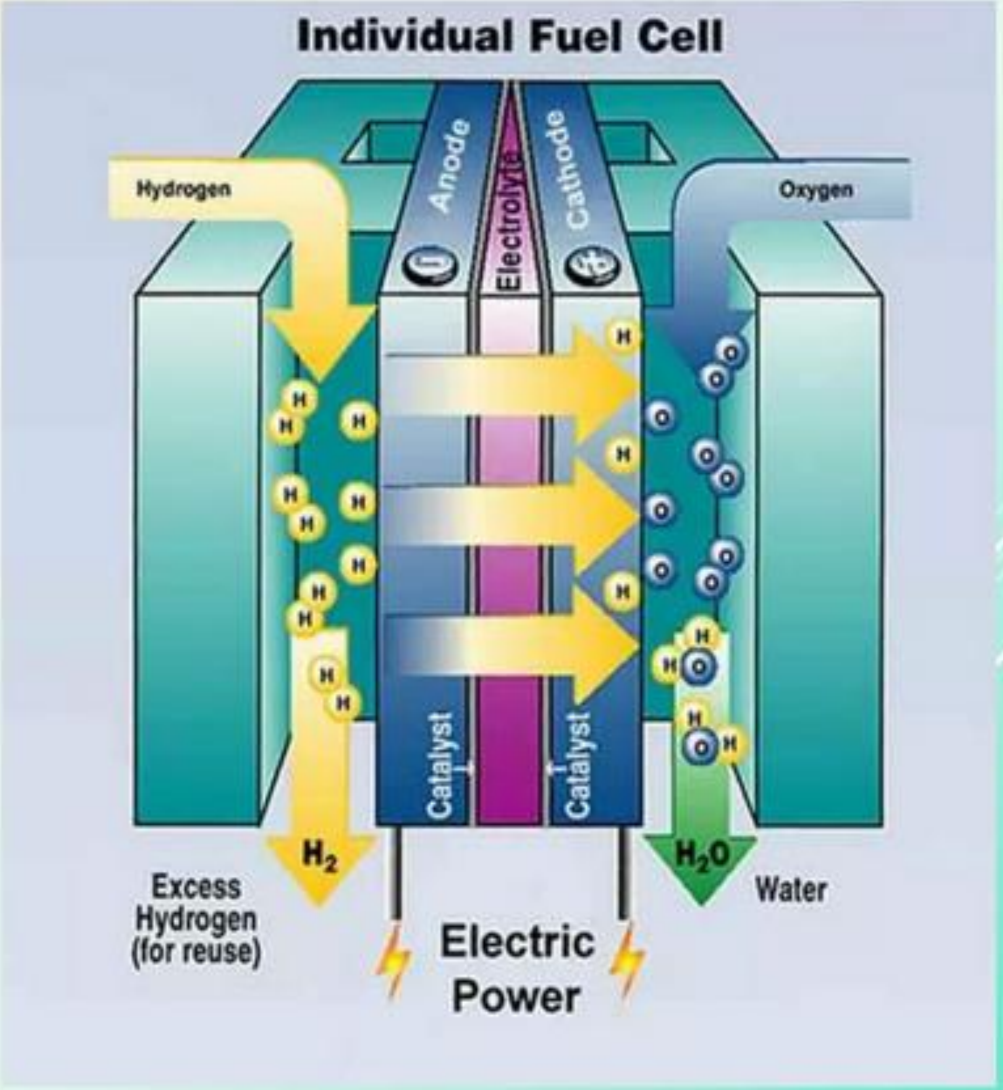
FLOW BATTERIES

- Flow Batteries (RFB) are a form of a battery in which the electrolyte contains one or more dissolved electro-active species which flow through a power cell/reactor where the chemical energy is converted to electricity.
- They are based on the reduction-oxidation reaction between two electrolytes. The reaction is reversible allowing the battery to be charged, discharged and recharged.
- The electrolytes are stored in external tanks and pumped through separate circuits for positive and negative species, while an ion exchange membrane separates them within the reaction chamber.
- Flow batteries can release energy continuously at a high rate of discharge for up to 10 h. They also have no self-discharge as there is no reaction outside of the reaction chamber.



Fuel Cells and Hydrogen Energy Storage Systems

- Most fuel cells use H2 and O2 as their main fuel
- A single fuel cell consists of two catalyst-coated electrodes (a porous anode and cathode) and an electrolyte in between, similar to a battery.
- Unlike batteries, FCs will continue to generate electricity as long as a source of fuel is supplied. FCs do not burn fuel, making the electricity generation process quiet, pollution-free and two to three times more efficient than combustion.
- The electrons flow through the external electrical circuit whereas the hydrogen ions move towards the positive electrode through the electrolyte. The positive electrode is made from a porous material coated with a catalyst. At that electrode, the hydrogen ions combine with oxygen to produce water.

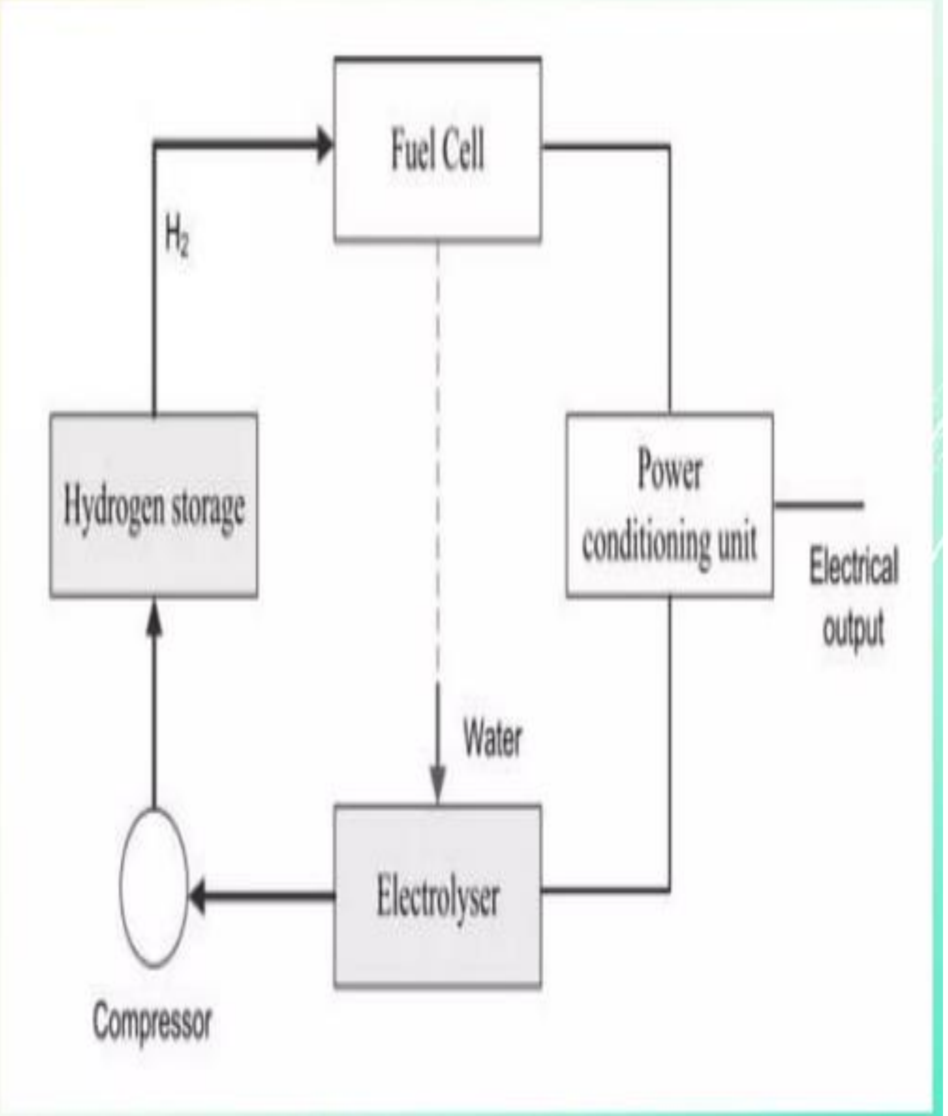


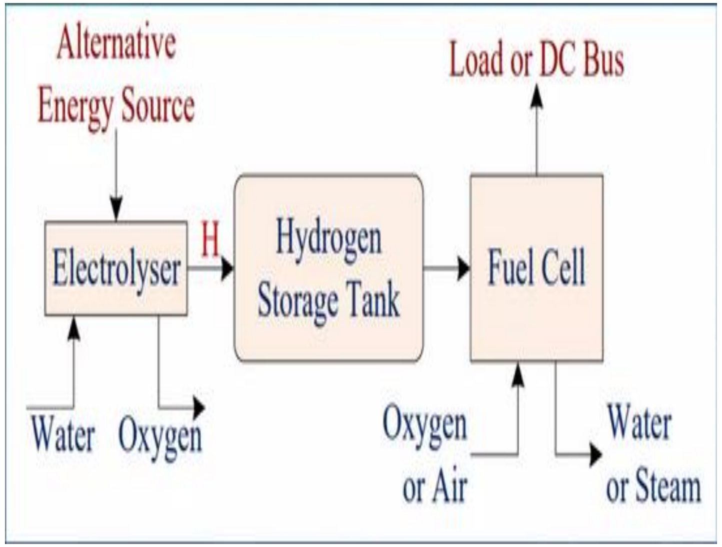
Hydrogen Energy Storage Systems

- Hydrogen-based energy storage systems consist of an electrolyser, hydrogen storage and a fuel cell.

- The electrolyser uses electrical energy to produce H2 from water.

- One of the potential applications of this device is to store H2 when there is excess wind energy generation and then use the stored H2 to support the power system during peak demand periods.





Flywheel or Inertial Energy Storage Systems

- In FES system angular momentum of the flywheel mass is used to store the power in the form of kinetic energy. They are typically employed in short duration with short discharge time applications such as the requirement of power over 80 kW within a period of 1-100 s .

- They have high power and energy density with an infinite number of charge-discharge cycles and used for stabilizing voltage and frequency . The ``state of charge (SoC)'' of FES is a function of moment of inertia and angular speed which are readily available to measure as shown below:

$$E = \frac{1}{2} mr^2 (w_{max}^2 - w_{min}^2)$$

where E is a useful energy of the flywheel in range of maximum angular speed (w_{max}) and minimum angular speed (w_{min}). Mass of flywheel concentrated at rim and radius is given by m and r respectively.

- The efficiency of FES system is in between 85% to 90% due to decreased mechanical friction by using magnetic bearing and very low aerodynamic resistance achieved through vacuum enclosure.

- The modern high speed flywheel systems have five main components: a flywheel, a set of bearings, an electrical motor/generator, power electronics unit and the containment system that provides high vacuum environment.

Flywheel or Inertial Energy Storage Systems

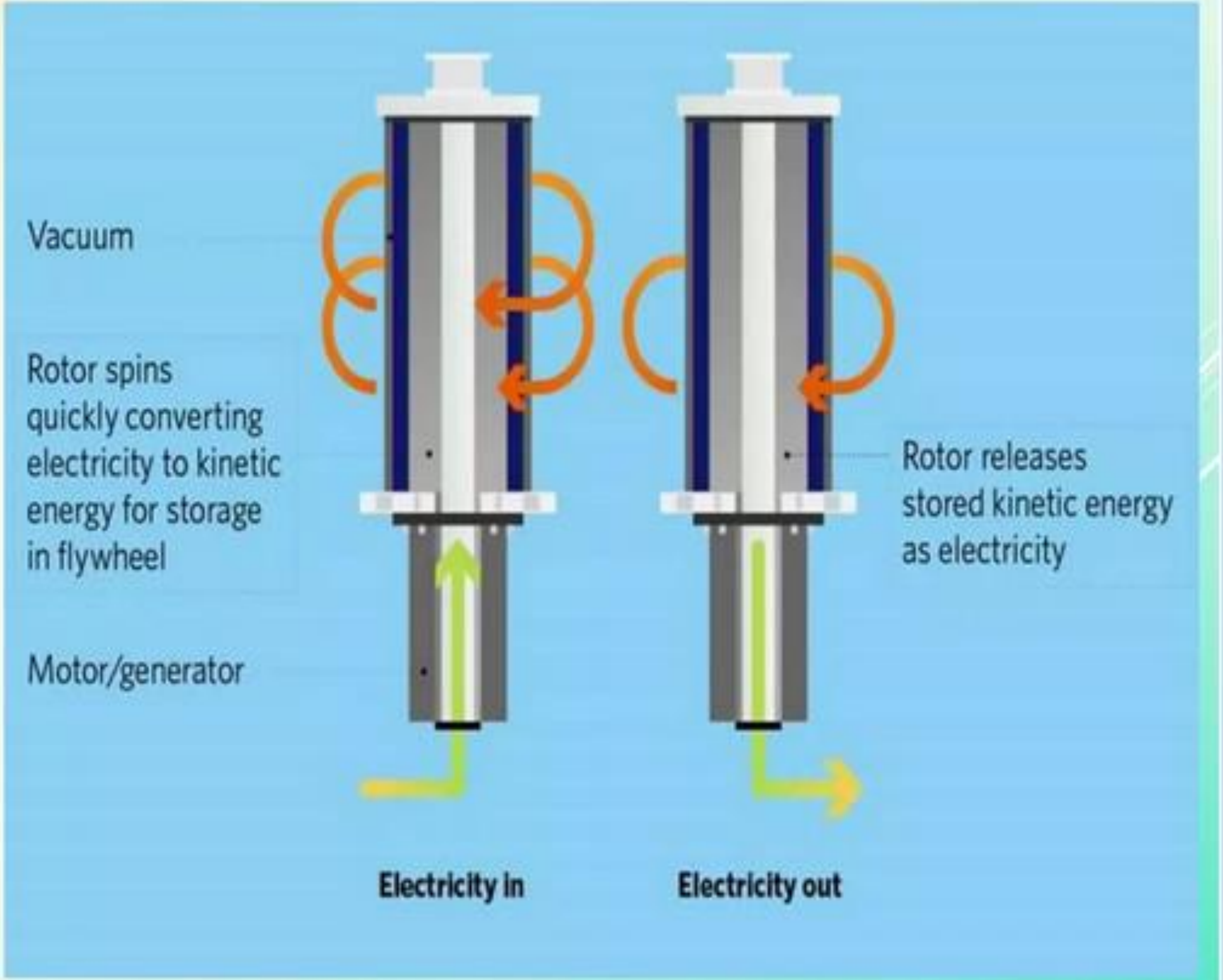
- The amount of energy that can be stored in the flywheel is a function of moment of inertia of rotor and the speed at which it can be rotated along with its tensile strength and stress restrictions. Based on these properties they are classified into two groups: low speed steel FES systems with speeds upto 10000 rotations per minute and high-speed FES systems with speeds up to 1 lakh rotations per minute. As shown in table below, high speed FES systems are manufactured from advanced high speed composite materials such as carbon-fiber .

- **Comparison of low speed and high speed flywheel.**

Specifications	*Low speed FES*	*High speed FES*
Material	Steel	Composite
Electrical machine	Induction, permanent magnet synchronous and reluctance machine	Permanent magnet synchronous and reluctance machine
Quarantine atmosphere	Partial vacuum and partial gas	Absolute vacuum
Required weight of enclosure	Double of flywheel weight	Half of flywheel weight
Applications	Power quality improvement	Aerospace and traction
Economy	Low cost and commercial	High cost and specific usage

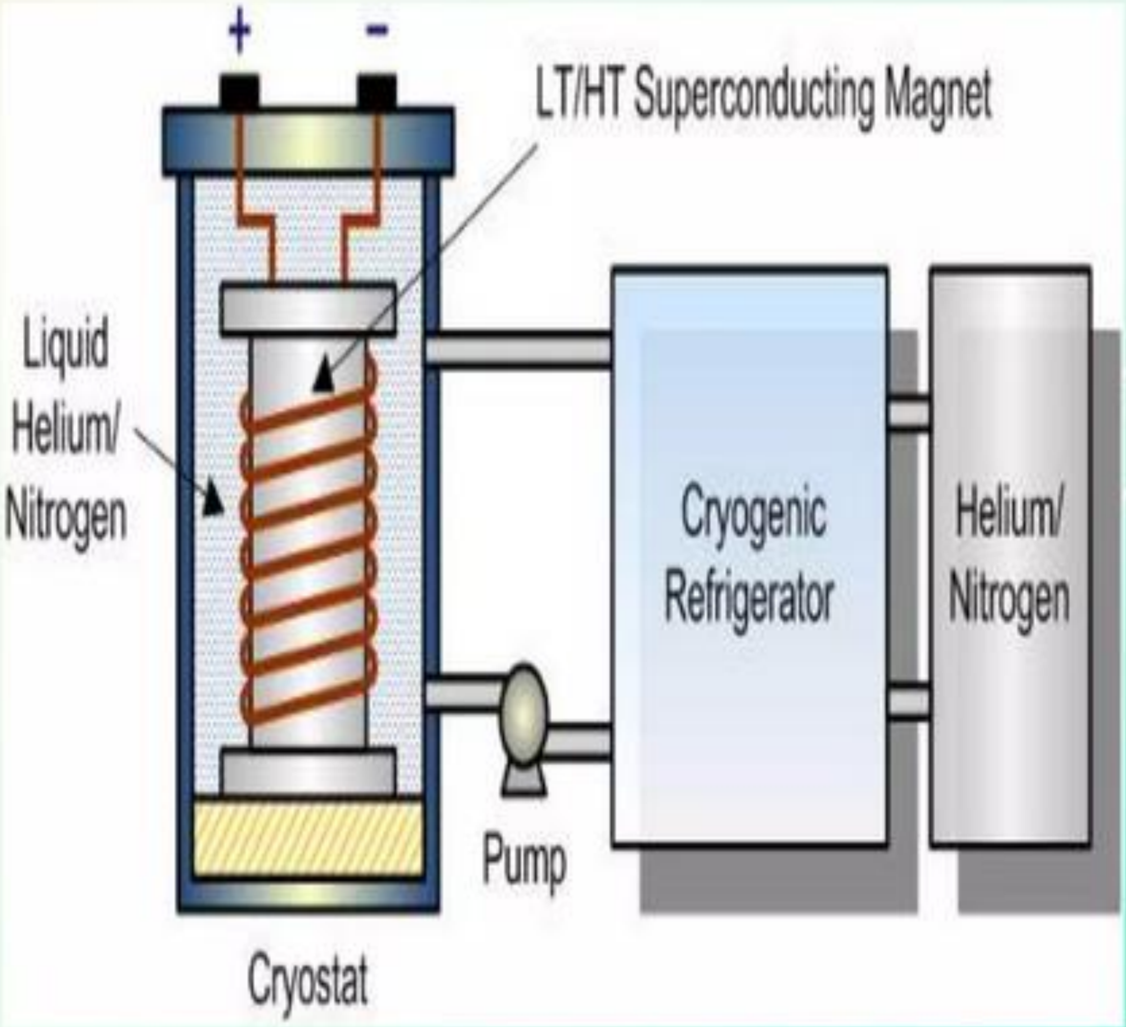
Flywheel or Inertial Energy Storage Systems

- The principle behind flywheel energy storage is to store energy in the form of rotational kinetic energy.
- To charge the flywheel, useful energy is used to increase the rotational speed of the flywheel- thus increasing its energy content.
- To discharge, kinetic energy is extracted from the flywheel (the flywheel is slowed) and converted into electricity via a generator (driven by the flywheel).
- Flywheels have long lifetimes (and require very little maintenance), can be very rapidly cycled and have good efficiency over short timescales, often quoted well in excess of 95%.
- Their application to date has mainly been for power quality and to provide energy for UPS.



Superconducting Magnetic Storage Systems(SMSE)

- Superconducting Magnetic Energy Storage (SMES) is a method of energy storage based on the fact that a current will continue to flow in a superconductor even after the voltage across it has been removed.
- In a SMES system, a magnetic field is created by direct current passing through a superconducting Coil.
- In a superconducting coil, resistive losses are negligible and so the energy stored in the magnetic field (equal to ½ $L*i$^2 where L is the inductance of the coil and I is the current passing through the coil) does not reduce with time.
- However, in order to maintain the superconductivity of the SMES coil, a cryostat which can keep the temperature of the coil below the superconductor temperature limit is required.

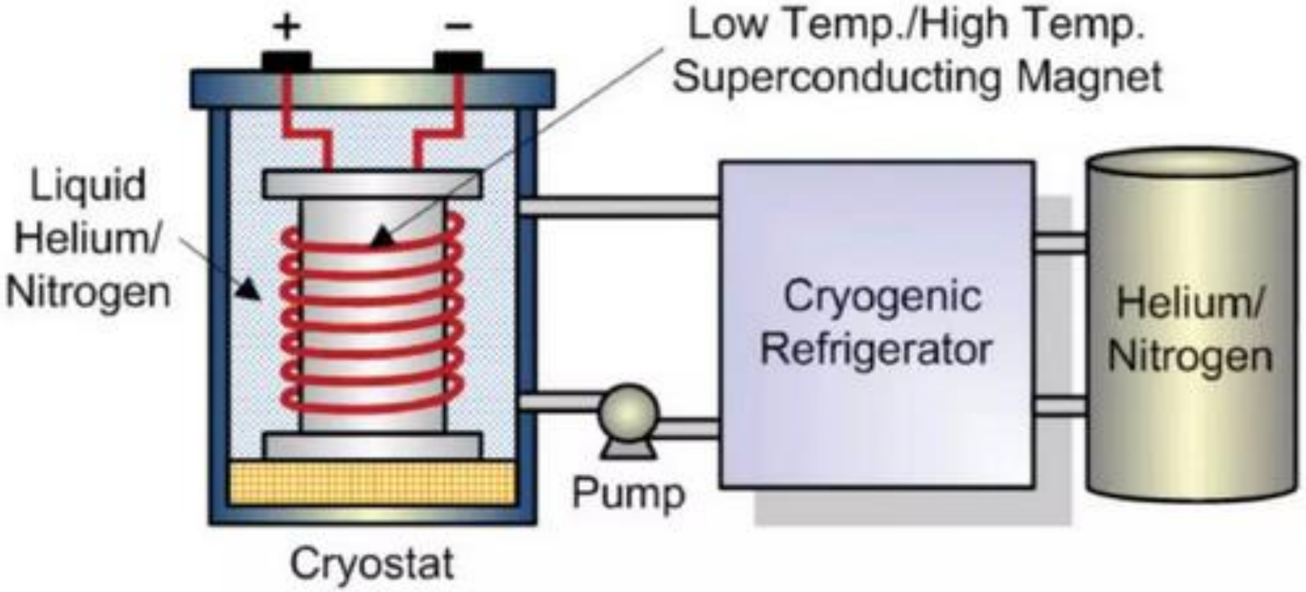


Superconducting Magnetic Storage Systems(SMSE)

- SMES exploits advances in materials and power electronics technologies to achieve novel means of energy storage based on three principal of physics:
    a) Some materials (superconductors) carry current with no resistive losses
    b) Electric currents induce magnetic fields and
    c) Magnetic field are a form of energy that can be stored.
- The combination of these principles provides the potential for the highly efficient storage of electrical energy in a superconducting coil.
- The electrical energy stored in SMES is in the form of magnetic field of superconducting coil formed due to flow of direct current. The ohmic losses in SMES once charged are virtually zero due to negligible resistance of superconducting coil.
- The cryogenic cooling of coil is employed in SMES to cool it below its superconducting critical temperature. While in discharging mode, the SMES is capable of releasing very high power (several megawatts) into the electric network within few milliseconds time.

Superconducting Magnetic Storage Systems(SMSE)

- Advanced low temperature and high ductile characteristic superconductor material such as niobium-titanium (NbTi) ne coils together with liquid helium coolant or superfluid helium coolant at 4.2 K are. employed in SMES design
- In accordance with the basic principle of SMES, when superconductor is charged while the cryogenic temperature is kept below the critical value, the energy will be stored permanently without any current decay.



Design of Super magnetic energy storage (SMES) system

Superconducting Magnetic Storage Systems(SMSE)

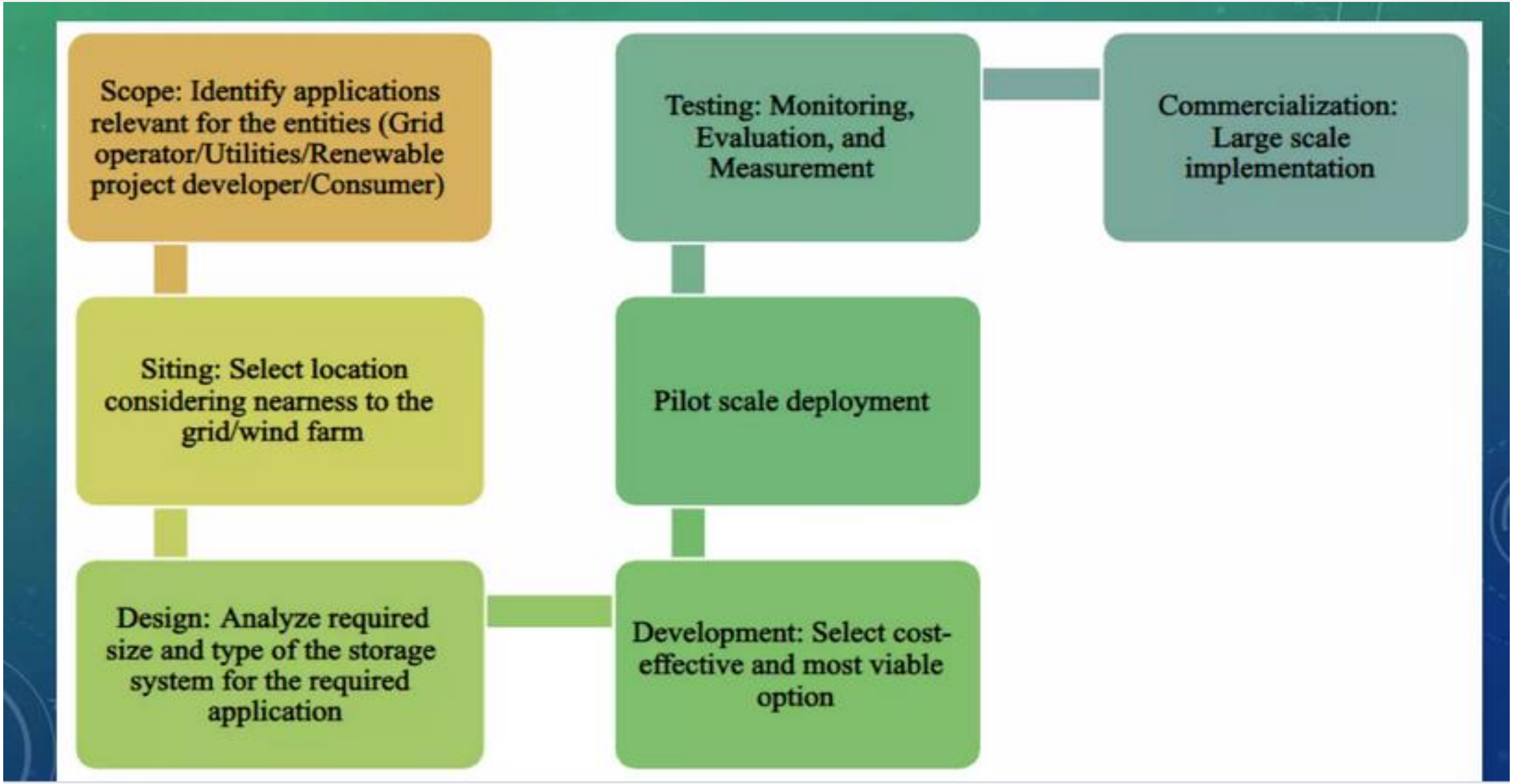
- Based on type of superconductor material and cryogenic conditioning system the SMES are classified into two groups:
- low temperature superconductor (LTS) SMES systems built with NbTi superconductor and liquid helium coolant at 4.3 K,
- whereas high temperature superconductor (HTS) SMES systems are built from ceramic oxide superconductor and liquid nitrogen coolant at 77 K. HTS SMES systems are cost effective and economical than the LTS SMES systems .

- The overall energy stored in superconductor coil of SMES is given by:

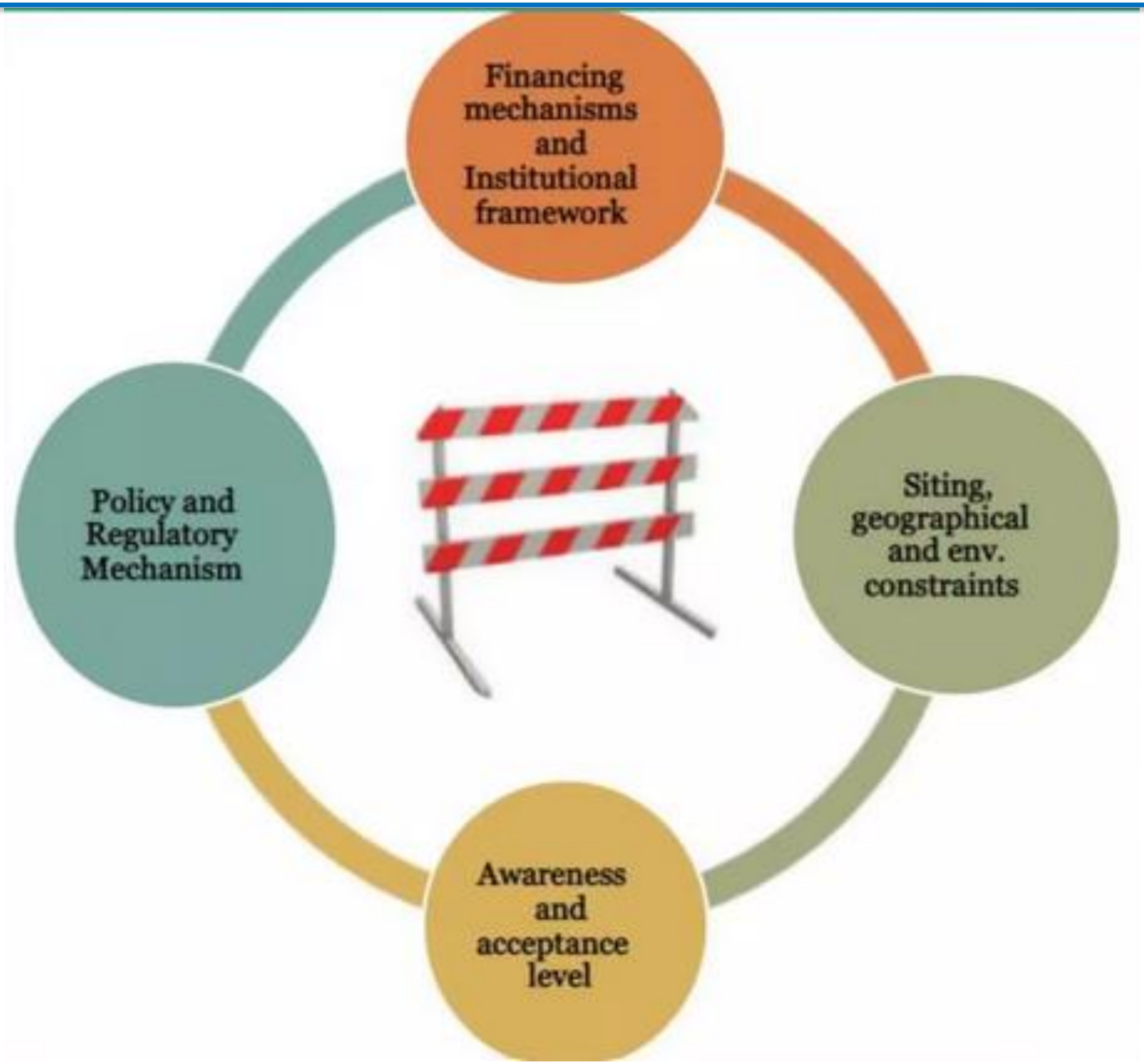
$$E_{SMES}=\frac{1}{2}LI^2$$

where, L is the coil inductance based upon the geometry and cross-sectional area of the wire, i is the amount of current owing in the coil having energy E.

Strategic Approach for Energy Storage Systems



Barriers for Energy Storage Systems



Conclusion on Energy Storage Systems

- ESS for balancing grid is a long term solution.
- Research centers should be established to carry out the research and for testing in this field.
- Countries who have not yet explored their renewable energy potential should explore potential of storage in parallel.
- Proper policies should be developed.
- Explore public private partnership

Thank you