Energy Storage

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1. Why Energy Storage ?

1.1. Flexibility on ***WHERE*** to use energy

1.2. Flexibility on ***WHEN*** to use energy

1.3. Peak shaving & Peak shifting

1.4. Reliability Issues

1.5. Smart Grids

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1.1.1. Electric Vehicles

- Mobile energy source
- Stable energy source
- Large power density
- Large energy density

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1.1.2. Mobile Devices

- Small size , Low weight
- Low temperature
- Accessible
- Mobile energy source
- Stable energy source

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1.1.3. Remote Locations

- Off-grid
- Daily demand
- Inter-seasonal storage
- Accessible
- Stable energy source

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1.2.1. Store Solar Energy

- No access to sun during night
- No access to sun when cloudy
- Short-term storage
- Thermal or electricity storage

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1.2.2. Store Wind Energy

- Limited to windy days
- Drastically fluctuating
- Short-term storage

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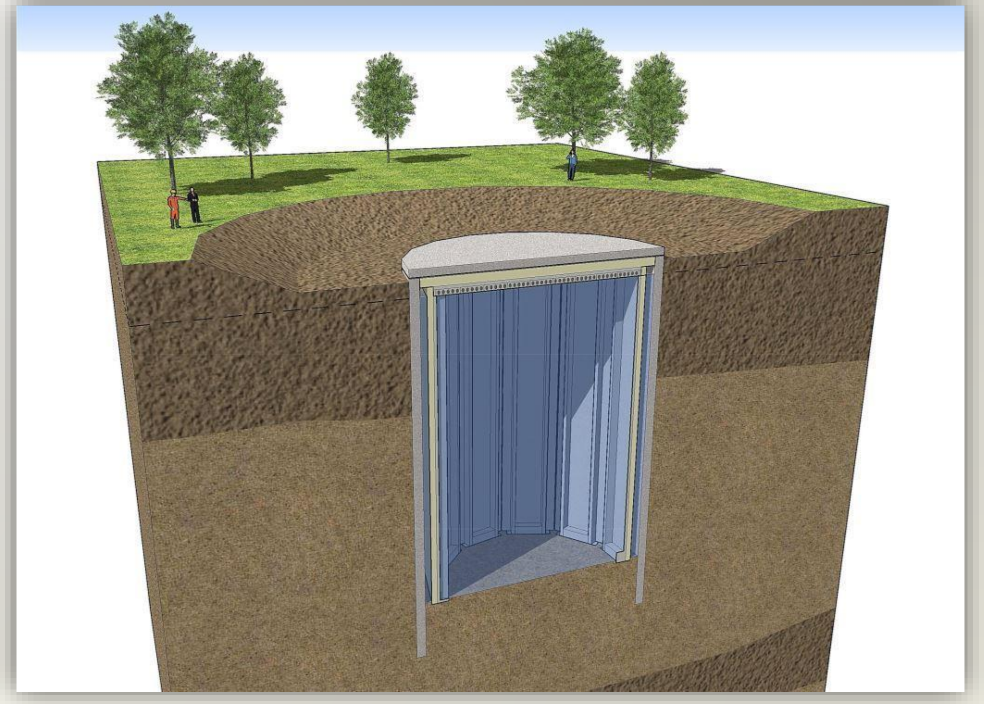
1.2.3. Seasonal Storage

- Store heat for winter
- Store coolth for summer
- Long-term storage



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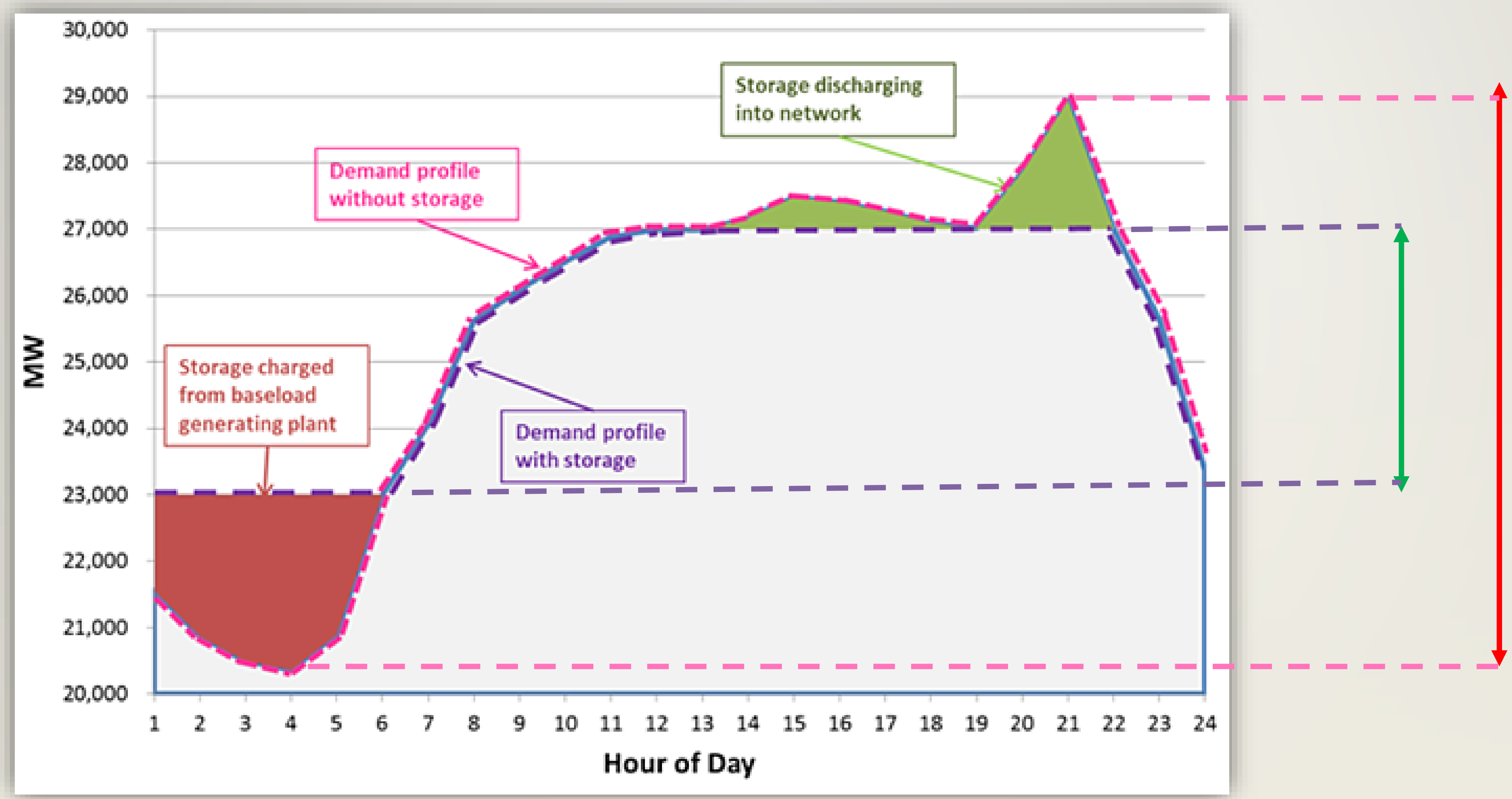
1.3. Peak Shaving & Peak Shifting



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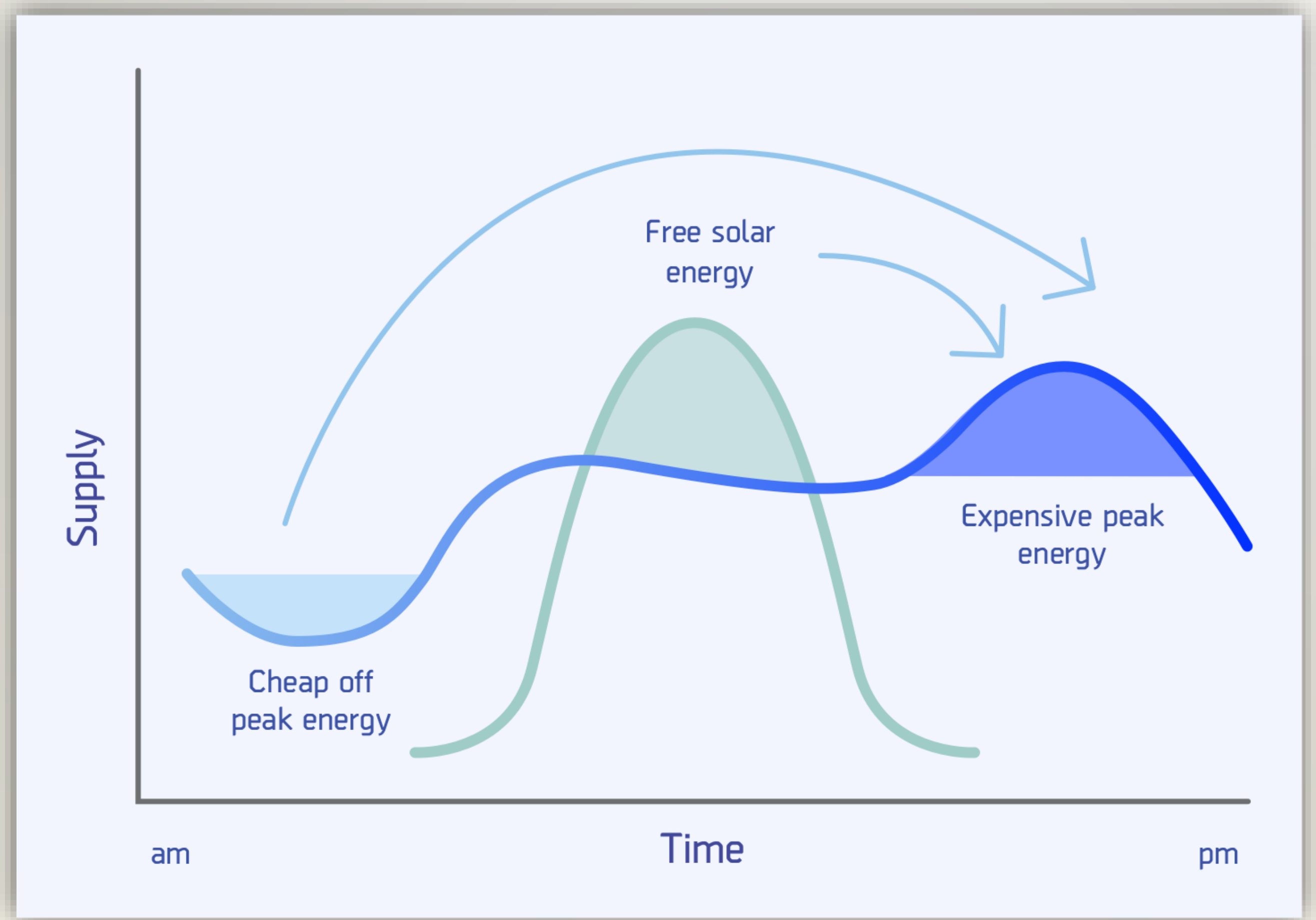
1.3. Peak Shaving & Peak Shifting



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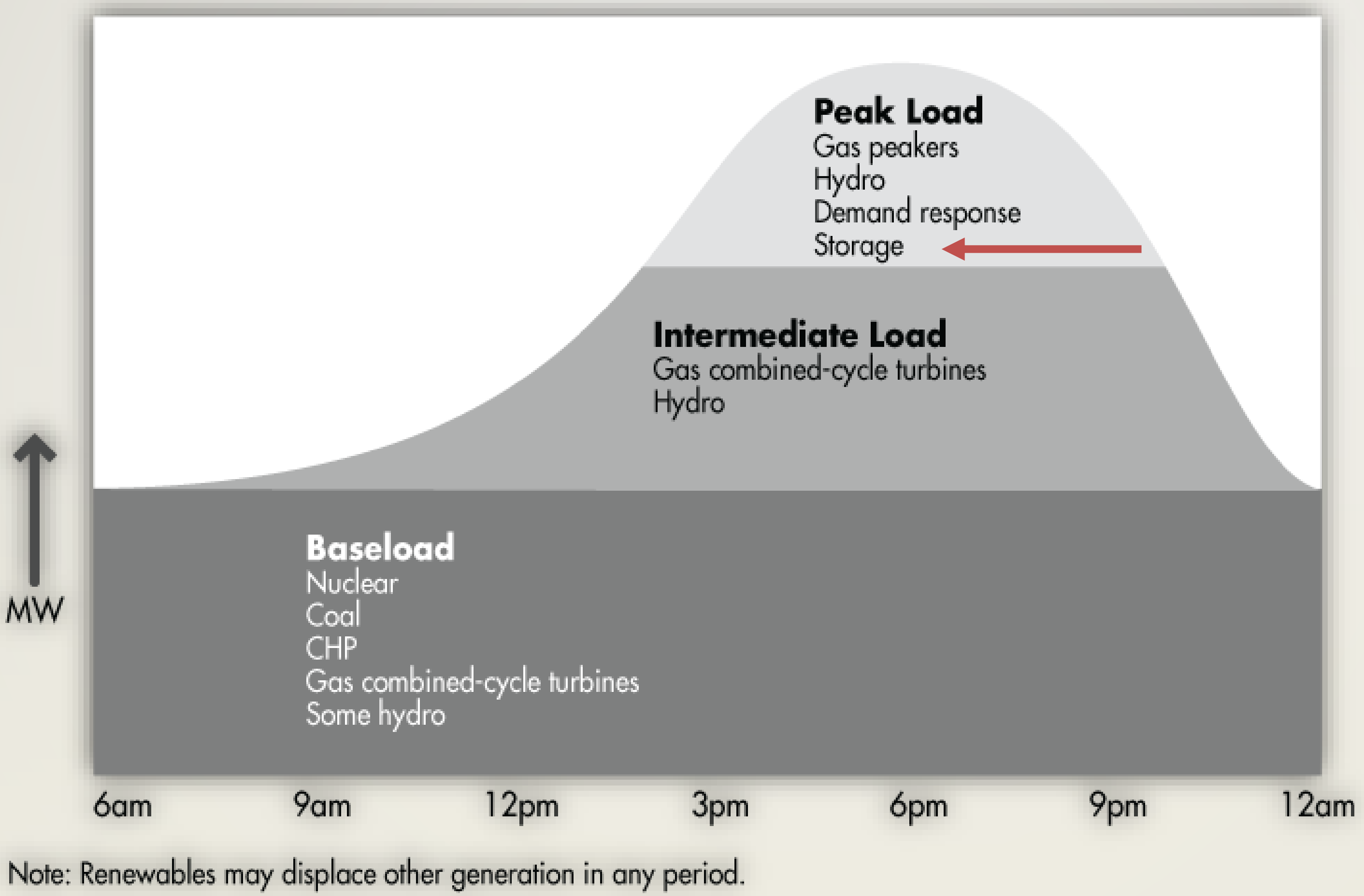
1.3. Peak Shaving & Peak Shifting



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1.3. Peak Shaving & Peak Shifting

- Decrease in peak demand
- Decrease in costs
- Balance in supply-demand
- Decrease in need for peak load power plants

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1.4.1. Black-outs (Power Outage/Failure)

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1.4.1. Black-outs (Power Outage/Failure)

- Severe weather
- Sudden spikes in demand
- Overdue maintenance
- Damage to parts of the delivery system
- Large scale

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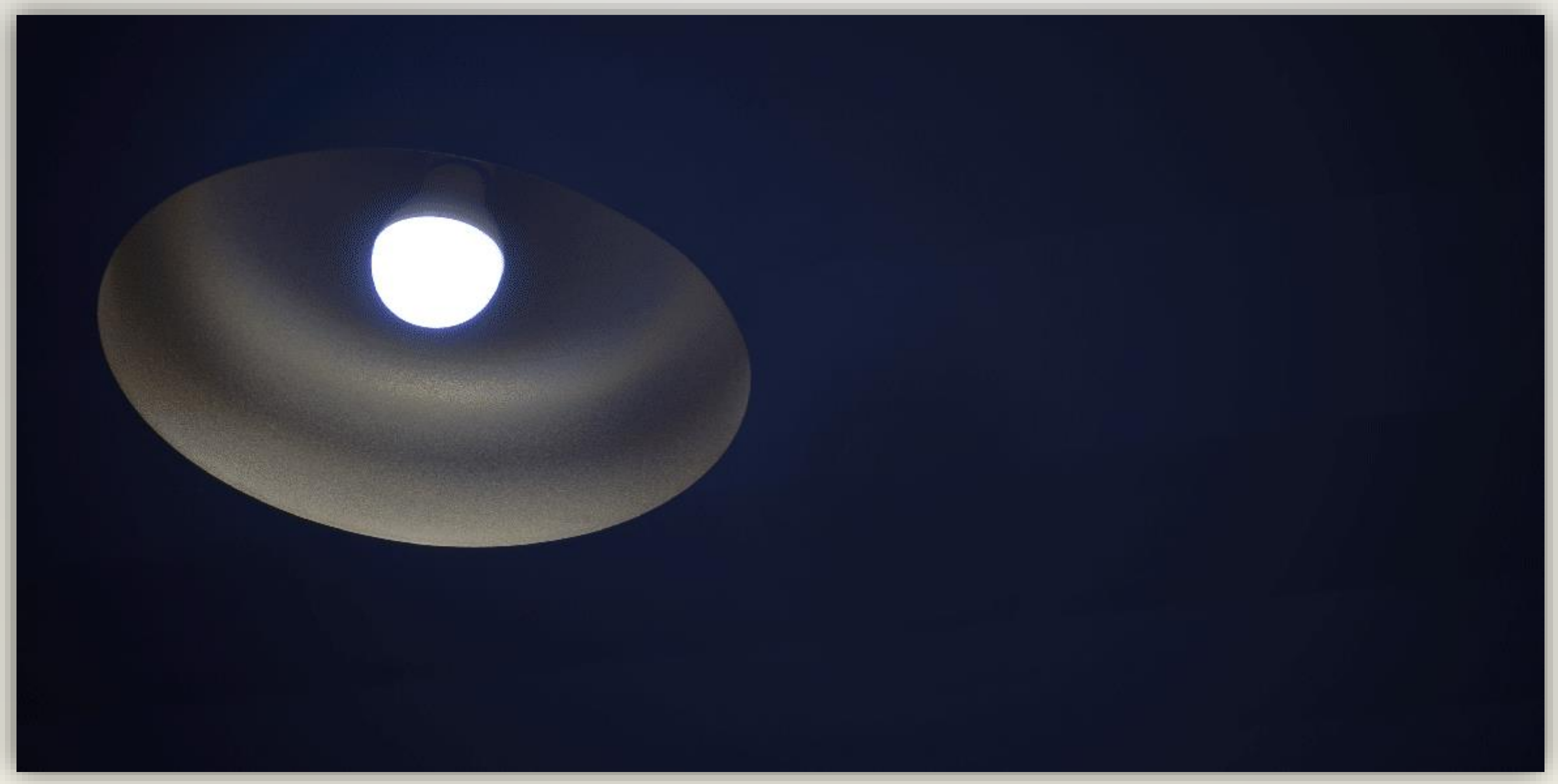
1.4.2. Brown-outs



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1.4.2. Brown-outs

- High electricity demand
- Near or above a utility's production capacity
- Reduce the flow of electricity
- To prevent a blackout

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1.4.3. Nonstop Need for Electricity

- One hour of downtime can cost a business up to $5 million
- Loss of unsaved data on PC
- Damage to sensitive equipment
- Missed deadlines
- Interrupted production runs
- No access to e-commerce websites

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1.4.3. Nonstop Need for Electricity

The most susceptible industries:

- ***Big Data***: Data centers store their customers' critical data.
- ***Healthcare***: Medical facilities rely on electricity to support patients' lives, e.g. ICU, ER.
- ***Military***
- ***Control Tower***

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1.4.3. Nonstop Need for Electricity

- ***Retail***: Most transactions are electronic. Just a few minutes of a power outage can cost hundreds of thousands - or even millions - of lost sales revenue.

- ***Finance***: Financial transactions require electricity to move money around. For example, the stock market can lose millions of dollars in just a fraction of a second during a power outage.

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1.5. Smart Grids

- Smart grid is another alternative way to achieve maximum benefit from energy storage in renewable energy systems.
- Smart grids ensure communication between supplier and consumer to manage demand, reduce losses in the energy transmission lines, protect the distribution network and reduce costs.
- Energy storage is an essential component of smart grids to maintain energy balance between supply and demand. Integration of energy storage systems to smart grids is important for energy sustainability.

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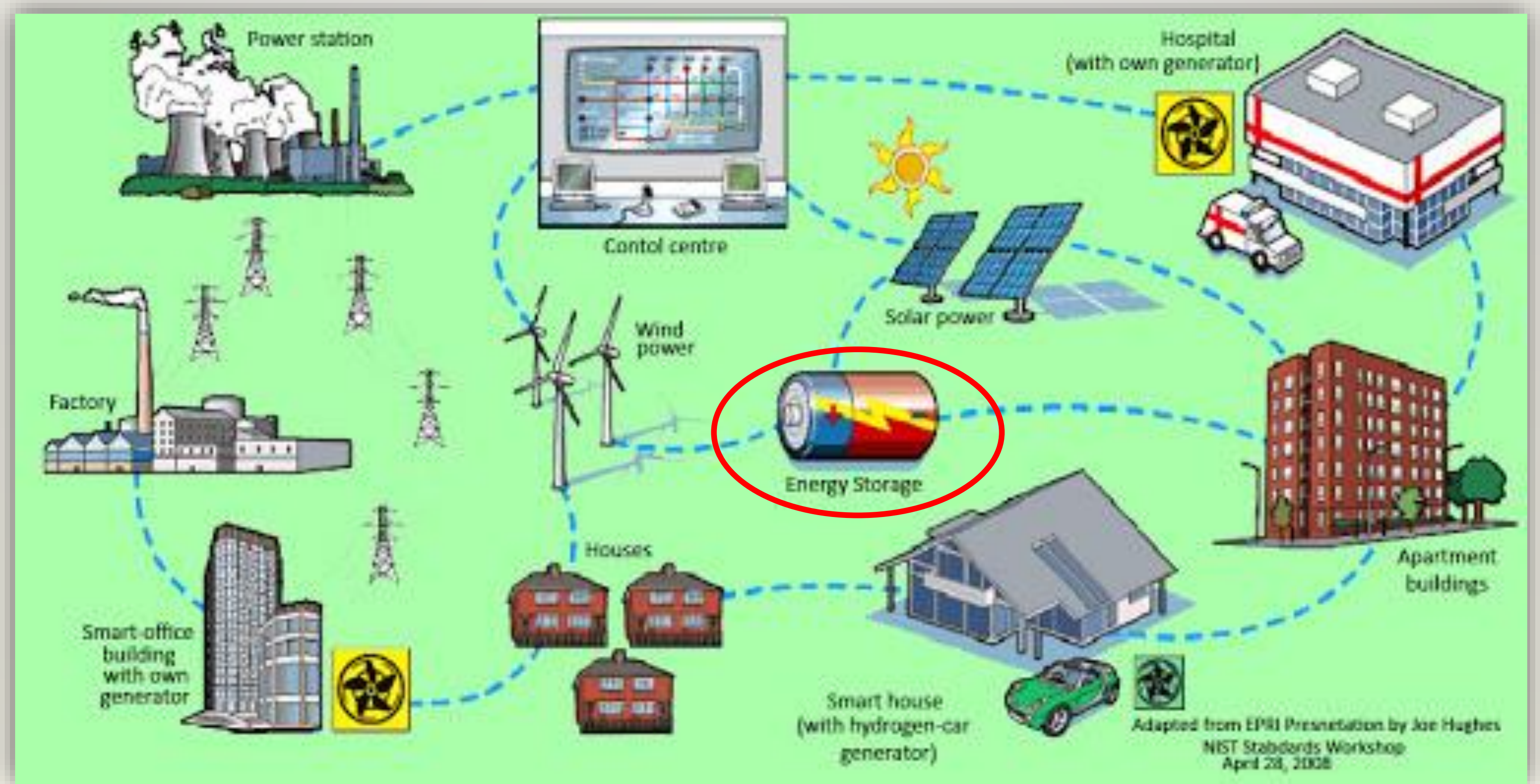
1.5. Smart Grids



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2. How Energy Storage ?

2.1. Thermal

2.2. Hydrogen

2.3. Electrical

2.4. Mechanical

2.5. Electrochemical

2.6. Magnetic

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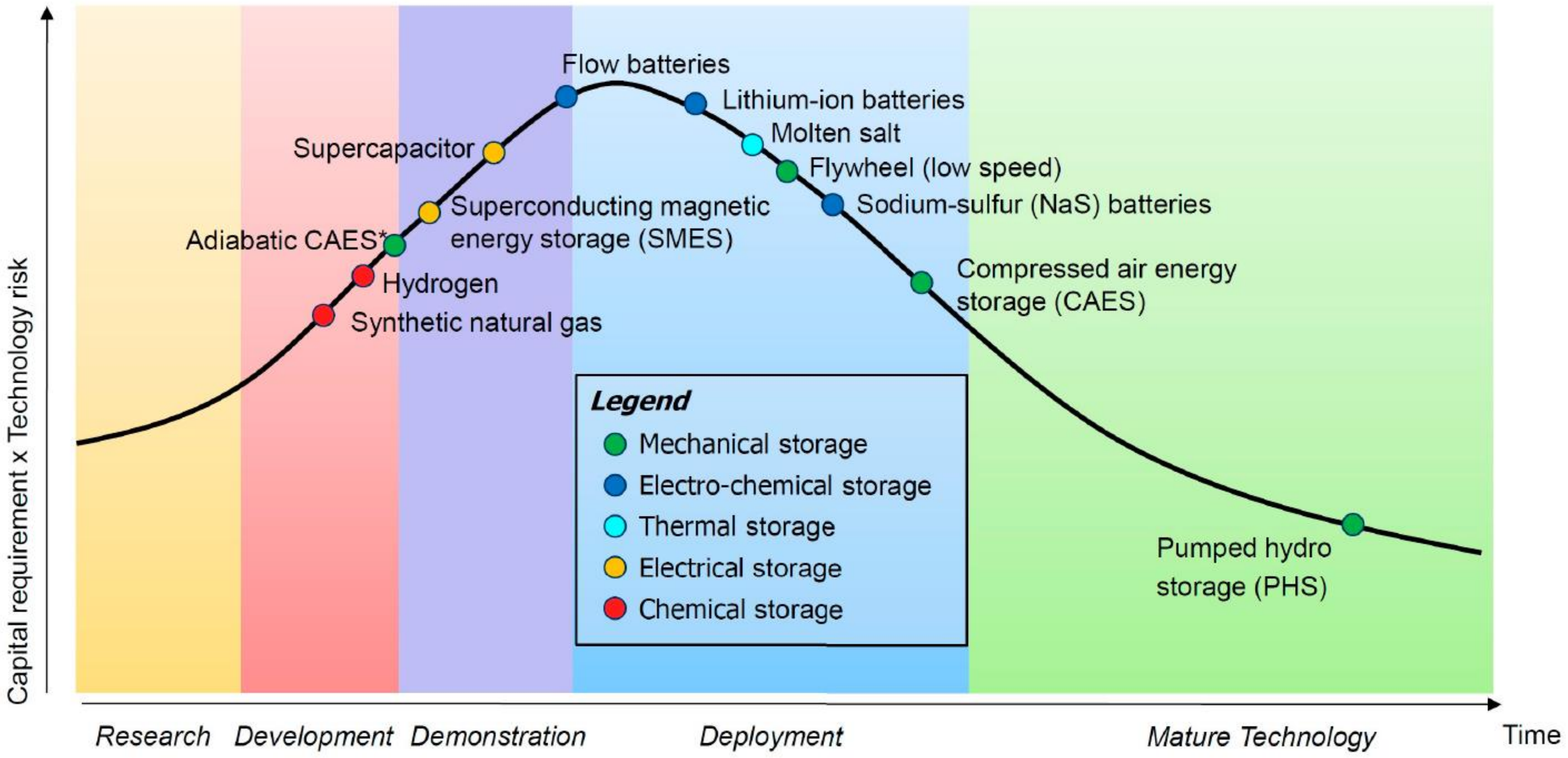

Figure 1. Maturity of energy storage technologies

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2.1. Thermal Energy Storage (TES)

2.1.1. Thermal mass

2.1.2. Concentrated Solar Power (CSP)

2.1.3. Sensible heat thermal

2.1.4. Ice storage

2.1.5. Solar pond

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2.1.1. Thermal mass

Thermal mass materials absorb energy (during day) as a heat sink and release it later (during night) as a heat source.

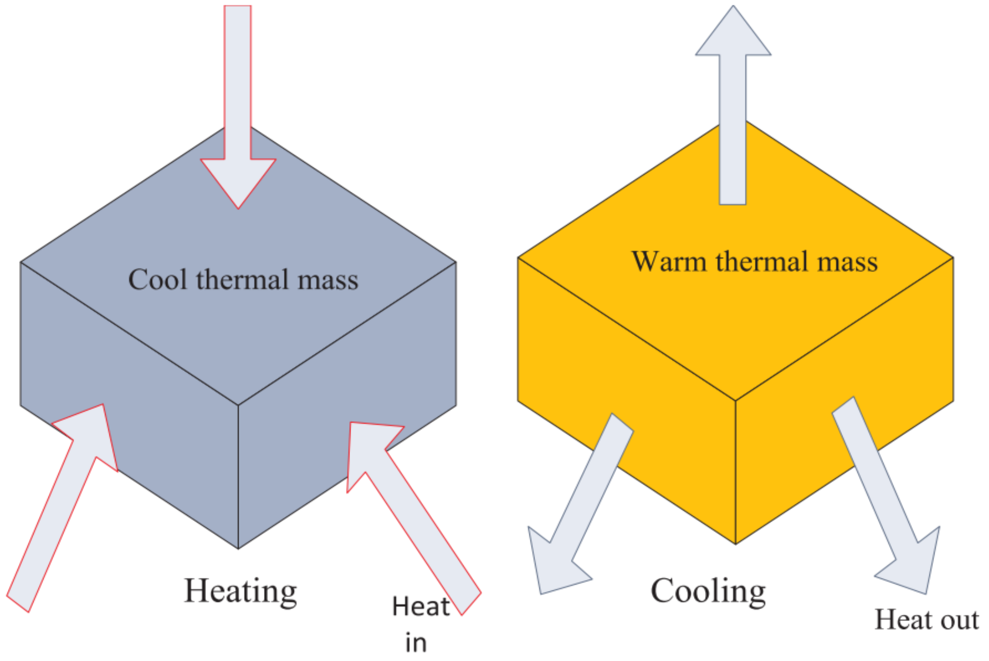

Fig. 2. Thermal behavior of thermal mass materials [13].

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2.1.1. Thermal mass

Specific heat capacity is the amount of heat required to increase the temperature of substance having mass 1kg or 1g by 1 degree Celsius (°C) or 1 Kelvin.

Specific latent heat of a substance is the amount of energy needed to change the state of 1 kg of the substance without changing its temperature.

Thermal conductivity, k (or λ), measured in W/m.K. It is a measure of a substance's ability to transfer heat through a material by conduction. $K=(\dot{q}\,d)/A\Delta T$

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2.1.1. Thermal mass

Globally, buildings are responsible for 40% of the total world annual energy consumption which is responsible for one-third of green-house gas (GHG) emissions around the world.

*A quad is a unit of energy equal to 10^15(a short-scale quadrillion) BTU or 1.055 × 10^18 joules (1.055 exajoules or EJ) in SI units.

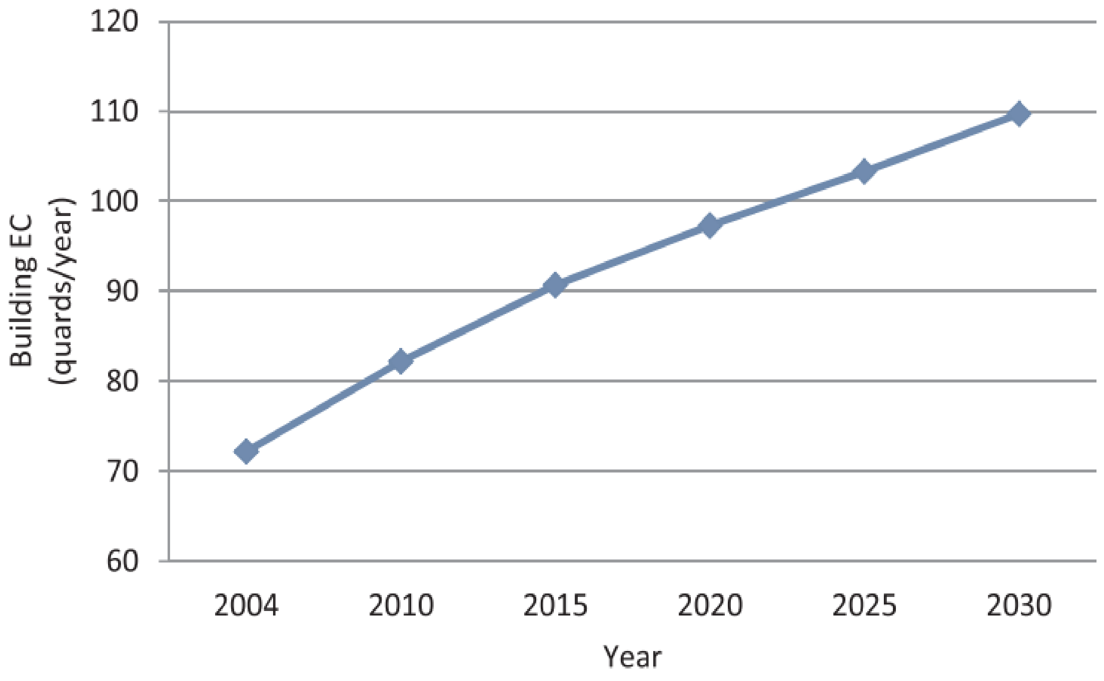

Fig. 1. Worldwide building energy consumption

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2.1.1. Thermal mass

PCMs (Phase Change Material) are used to store and balance energy in construction sector.

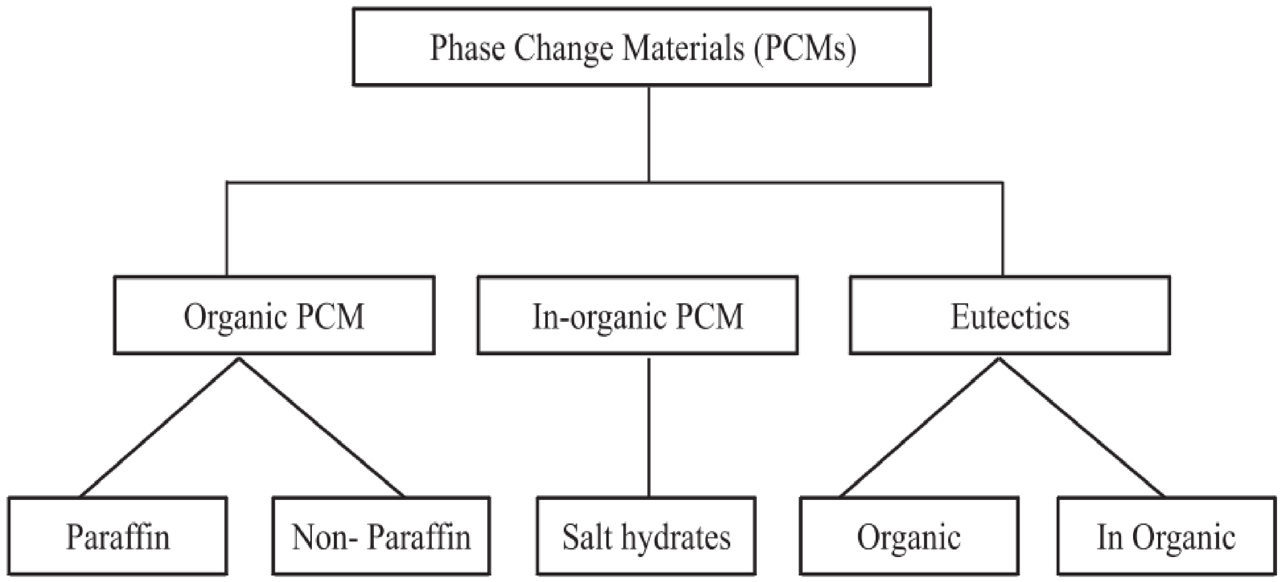

Fig. 15. Types of phase change materials

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2.1.1. Thermal mass

An ideal PCM will have high heat of fusion, high thermal conductivity, high specific heat and density, long term reliability during repeated cycling, and dependable freezing behavior.

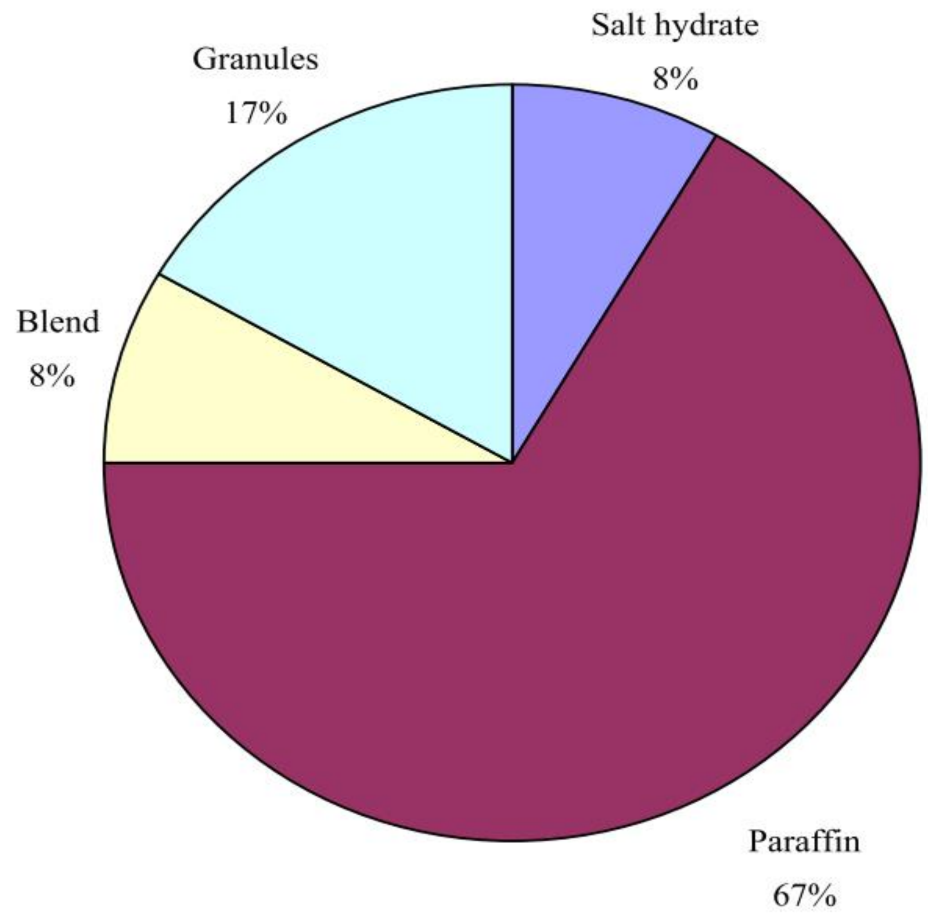

Fig. 16. Type of PCMs used for free cooling in different studies.

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2.1.1. Thermal mass

Desirable thermal mass: low thermal conductivity and high heat capacity like concrete.

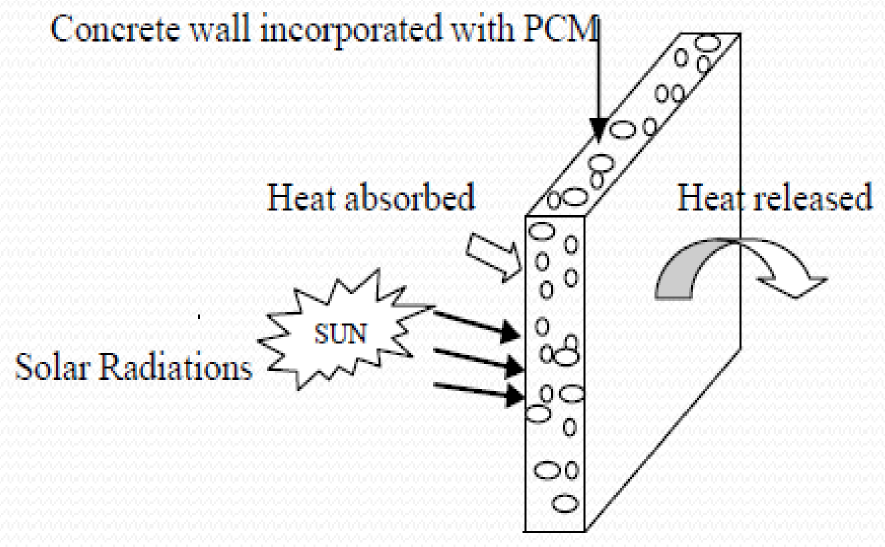

Figure . Heating and cooling function of concrete wall incorporated with PCM.

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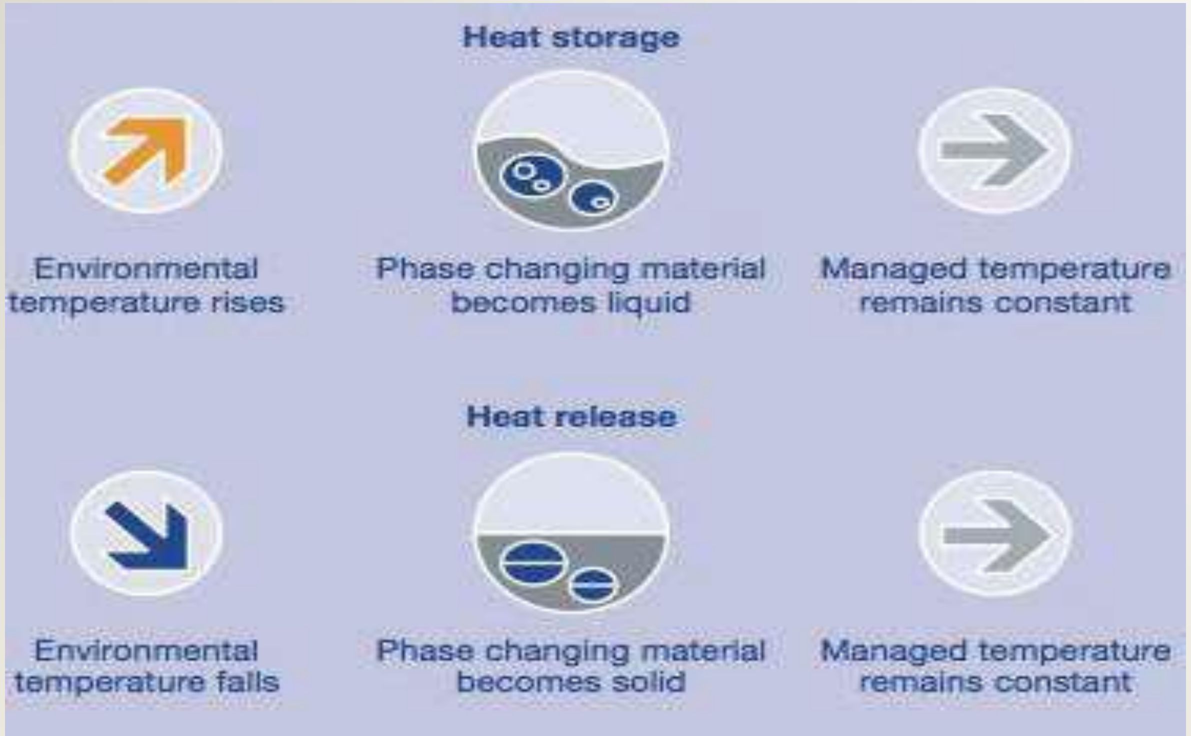
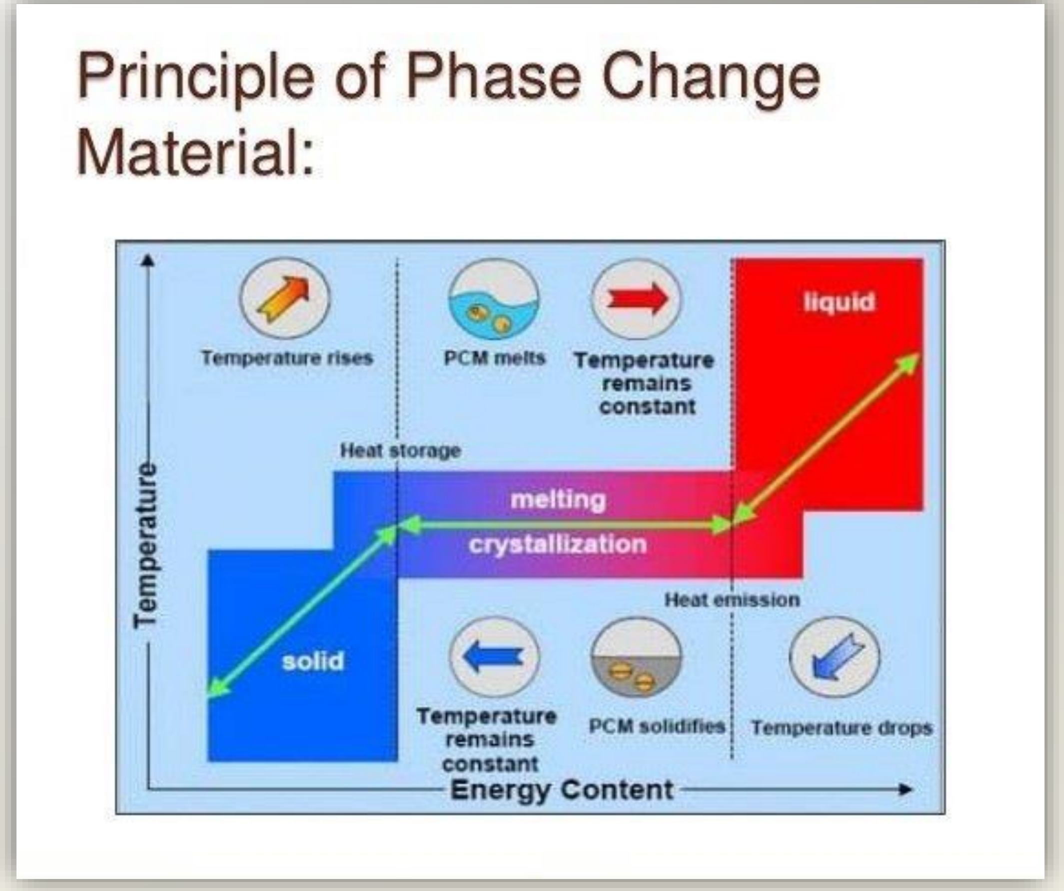
2.1.1. Thermal mass





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2.1.1. Thermal mass

Advantages

1) Decrease in demand costs

2) Use of off-peak lower tariffs

3) Lower mechanical conditioning due to use of cooler night time air

4) Increased mechanical efficiency due to better use of equipment part loads.

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2.1.2. Concentrated Solar Power (CSP)

CSP technologies generate electricity by *concentrating* the solar radiation beam onto a small area, where a heat transfer fluid (*HTF*) is heated up and this energy is ultimately transferred to the steam.

Electricity is then generated by an electric generator which is driven by a steam turbine with the efficiency limited by the Carnot cycle.

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2.1.2. Concentrated Solar Power (CSP)

Solar heat industrial processes are classified in 3 groups according to temperature range:

- Low temperature (below 150 °C)
- Medium temperature (150–400 °C)
- High temperature (above 400 °C).

Current solar industrial applications are generally for low-temperature processes due to availability of inexpensive solutions by flat plate collectors.

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2.1.2. Concentrated Solar Power (CSP)

- Spain (48%) and the U.S. (40%) are pioneers of STE*.

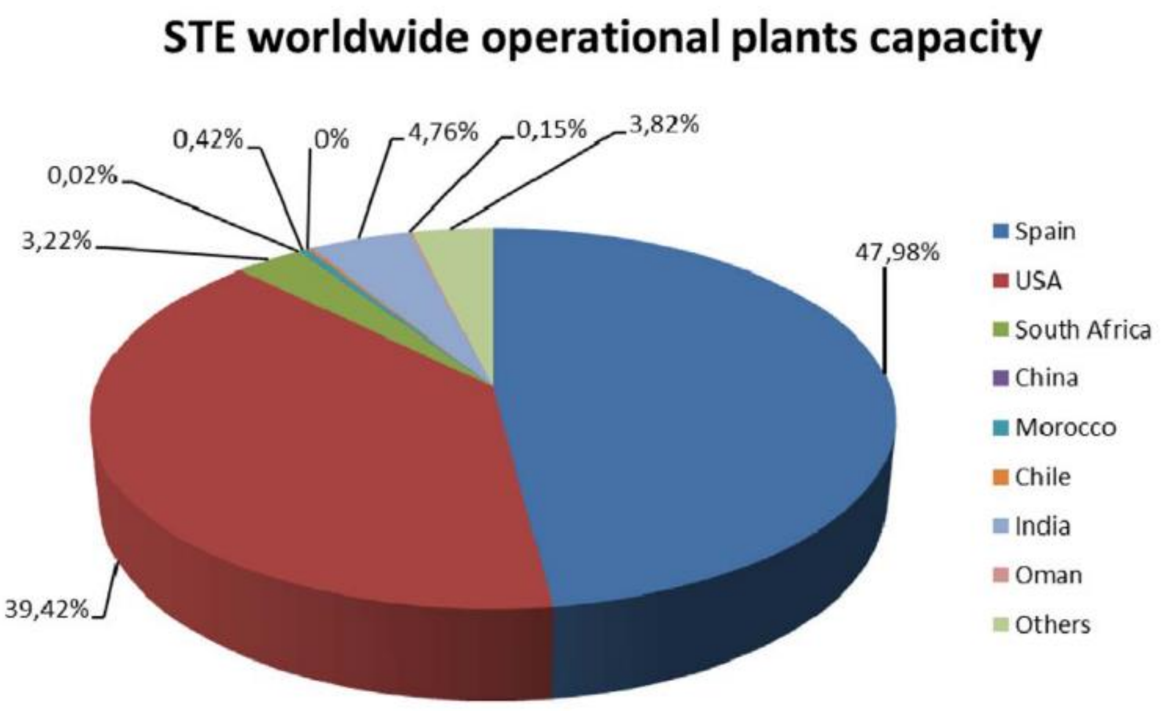

Fig. 3. STE worldwide operational plant capacity (January 2016)

*STE: Solar Thermal Electricity

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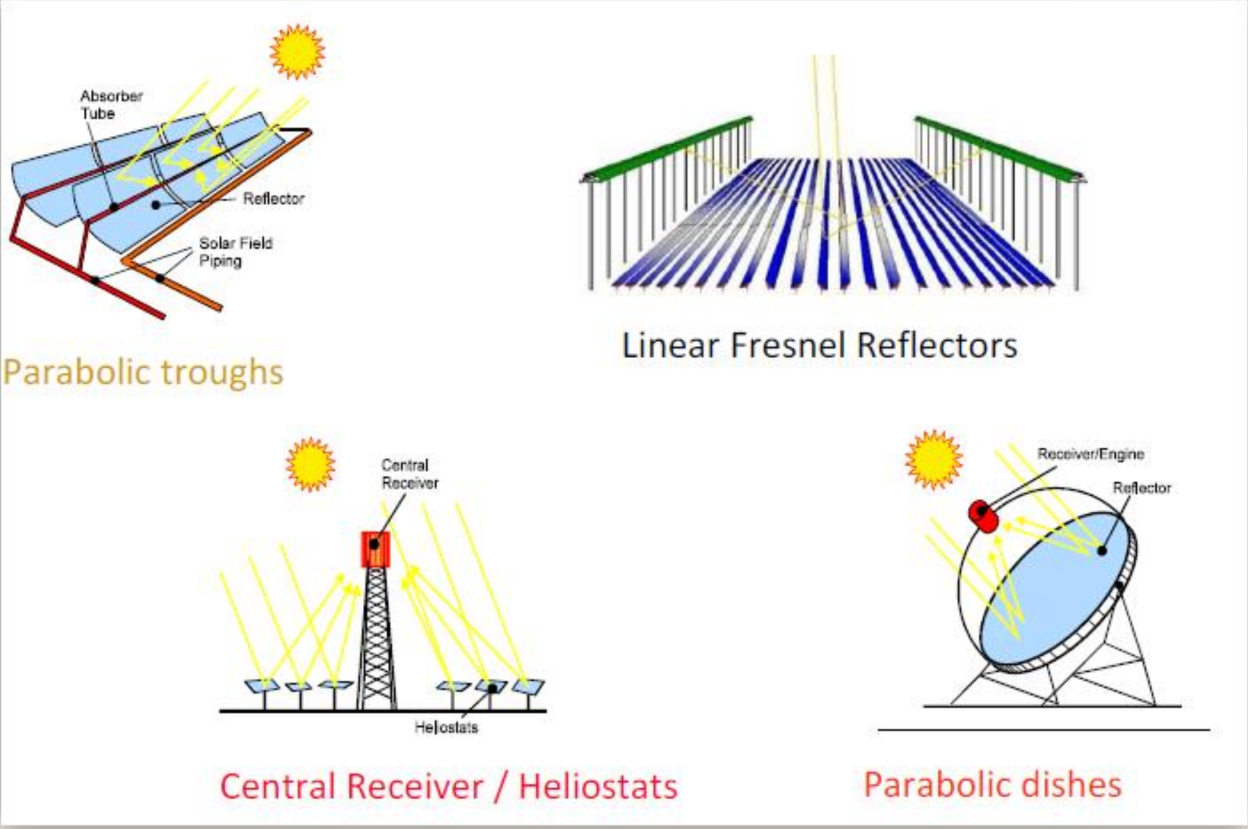
2.1.2. Concentrated Solar Power (CSP)

Different Types of CSP

- Parabolic Troughs
- Linear Fresnel Reflectors
- Central Receiver
- Parabolic Dish



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2.1.2. Concentrated Solar Power (CSP)

- Parabolic trough systems, installed in more than 80% of the CSP plants in operation and under construction.
- Tower systems have just started to be introduced in to commercial applications.
- Linear Fresnel plants are currently making the transition to commercial applications.
- Half the installed CSP has thermal storage and
- Over 80% of under construction CSP capacity does.

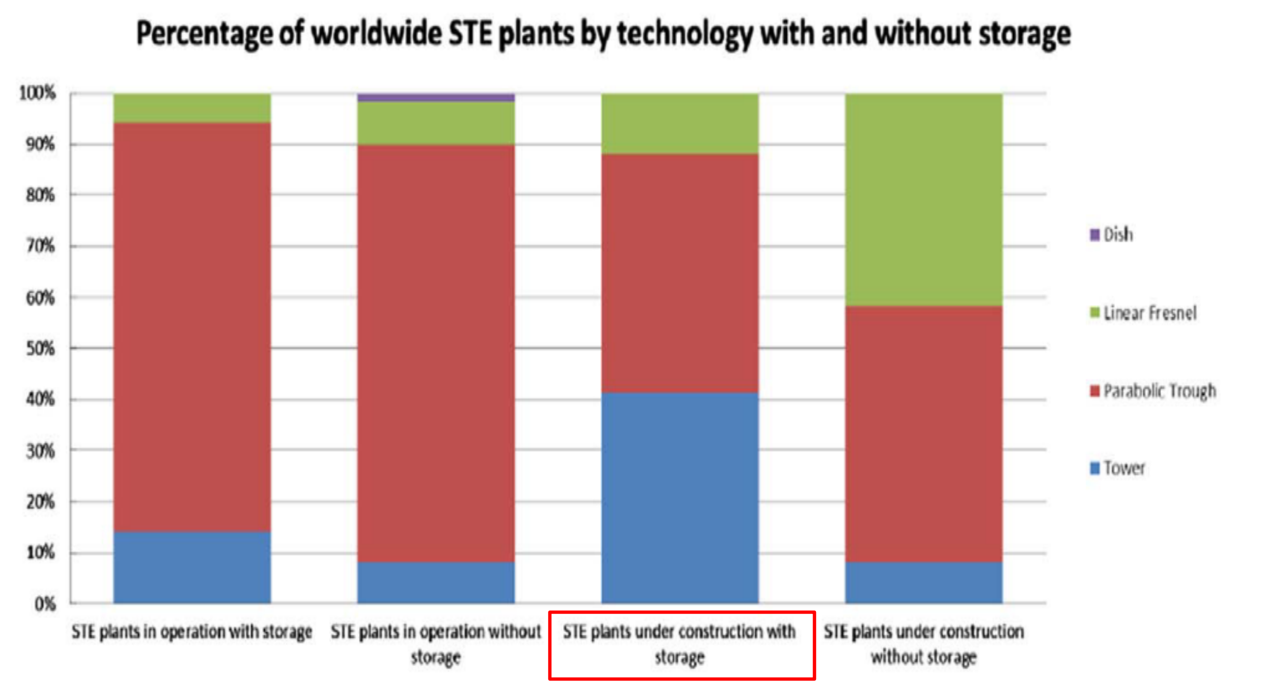

Fig. 7. STE worldwide capacity categorized by technology and with/without storage (January 2016)

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2.1.2. Concentrated Solar Power (CSP)

Thermal energy for CSP systems can be stored in:

- sensible heat storage by using either solid or liquid storage media,
- latent heat storage by using phase change materials (PCMs) and
- thermo-chemical storage through reversible chemical reactions.

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2.1.2. Concentrated Solar Power (CSP)

To achieve more cost-effective TES systems:

- New nitrate/nitrite molten salts (wider temp range)
- Cheap solid heat storage media with good physical properties
- New PCMs and highly efficient latent energy storage system
- identification of thermo-chemical processes suitable for the temperature range of CSP plant

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2.1.2. Concentrated Solar Power (CSP)

Desirable features of the storage media/HTF*s

- Low freezing temperature and/or high maximum operational temperature
- High heat capacity, thermal conductivity and density
- Good thermal stability
- Low corrosion to the containment material
- Low cost

*HTF: Heat Transfer Fluid

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2.1.2. Concentrated Solar Power (CSP)

- In sensible TES systems, the energy is stored/released by raising/lowing the temperature of the storage medium in either a solid or liquid. $Q=mCp\Delta T$
- All TES systems currently installed in CSP plants are using sensible storage materials, e.g. oil, molten salt, steam, ceramic and graphite.
- The state-of-the-art storage material is molten salts.
- Two-tank molten salt sensible storage is the most common.

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2.1.2. Concentrated Solar Power (CSP)

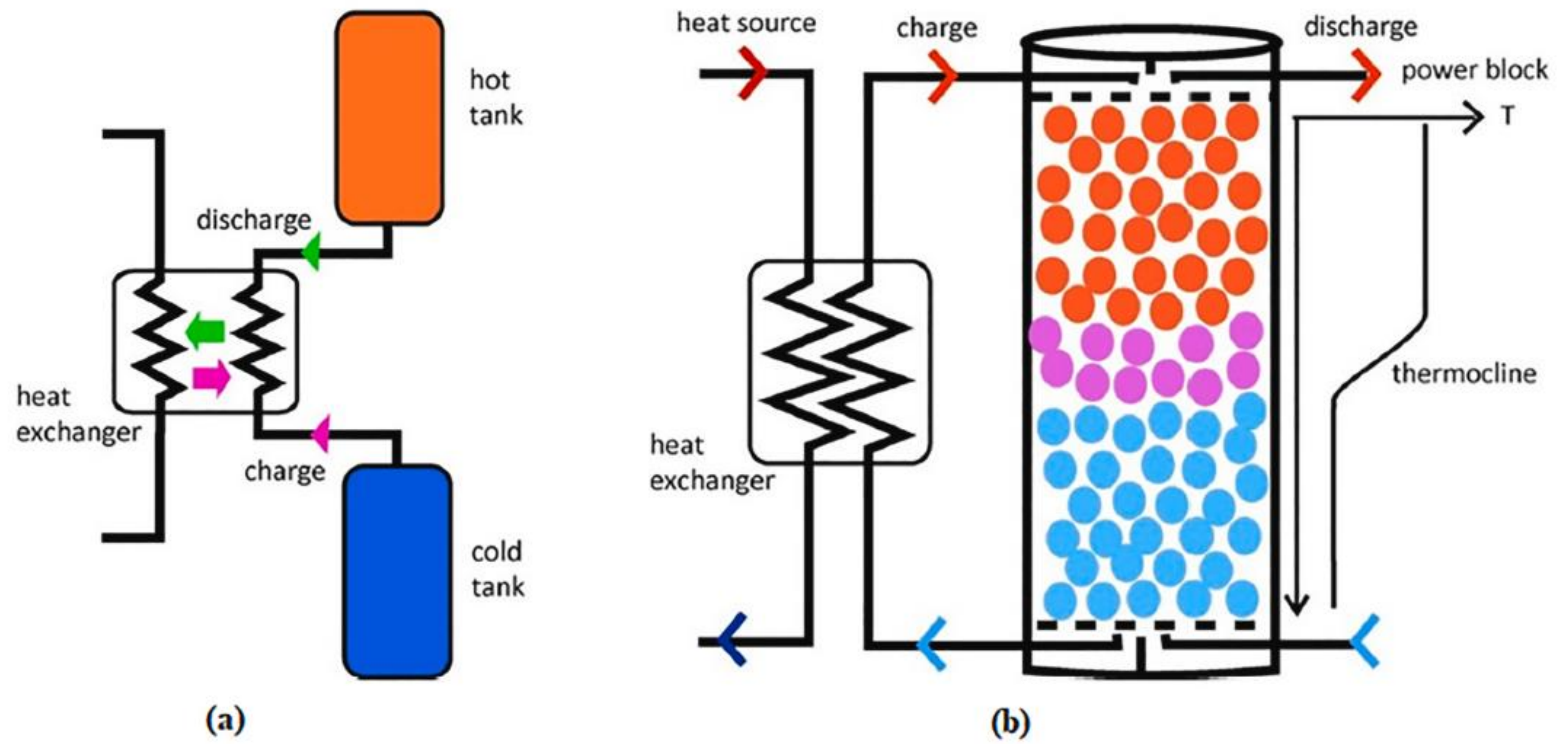

Fig. 10. Sensible heat storage systems a) Two-tank storage system b) Single-tank thermocline storage system

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2.1.2. Concentrated Solar Power (CSP)

- The same fluid operates as the HTF and the storage medium in the *direct* storage system.
- In the *indirect* storage system, the HTF operating in the solar field is coupled by means of an intermediate heat exchanger to a different storage medium.

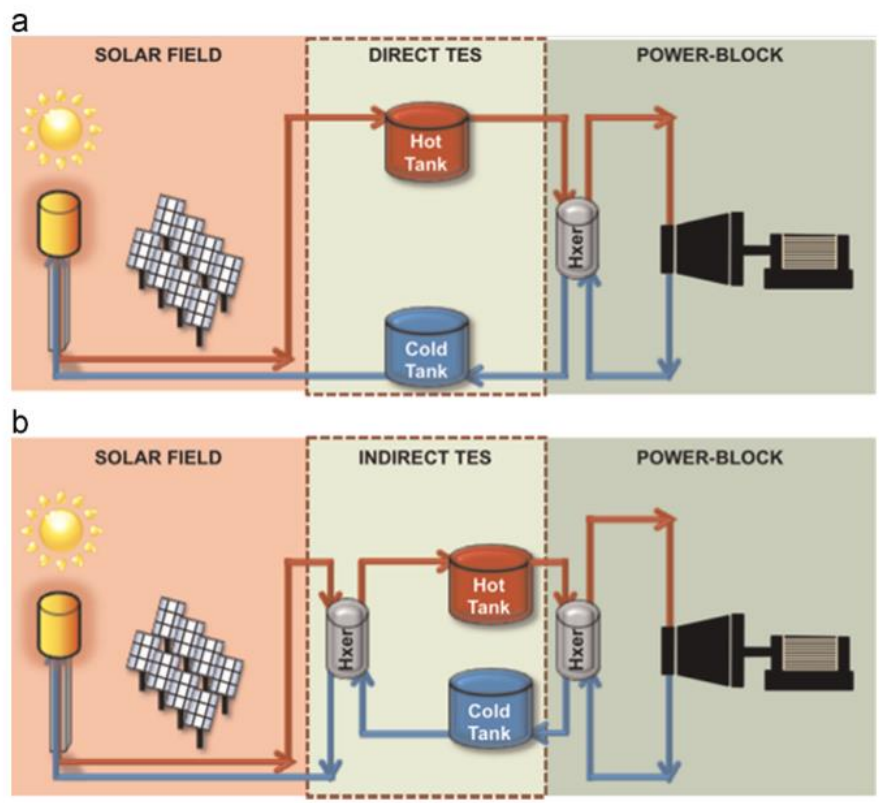

Fig. 4. Thermal storage system integrated in the CSP plant with solar field and power block [1]: (a) direct heat storage and (b) indirect heat storage.

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2.1.2. Concentrated Solar Power (CSP)

- In latent heat storage, PCMs are used.
- Take advantage of large latent heat
- *solid ↔ liquid* (generally)
- Has been attractive over the past decade.

$$Q = m[C_{p,s}(T_m - T_s) + h + C_{p,l}(T_l - T_m)]$$

$C_{p,s}$: average specific heat of the PCM in solid phase

$C_{p,l}$: average specific heat of the PCM in liquid phase

T_m : melting temperature

h : phase change enthalpy

T_s : temperature of the solid PCM

T_l : temperature of the liquid PCM

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2.1.2. Concentrated Solar Power (CSP)

latent heat thermal storage is more desirable than the sensible one due to high energy density and the isothermal behavior.

Problem : low thermal conductivity of the inorganic salt PCMs → obstructs the heat transfer between the PCM and the HTF.

Solution : Composing high thermal conducting materials into the PCM, e.g. magnesium oxide and graphite.

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2.1.2. Concentrated Solar Power (CSP)

- In thermochemical storage, the energy is stored by means of the reversible chemical reaction

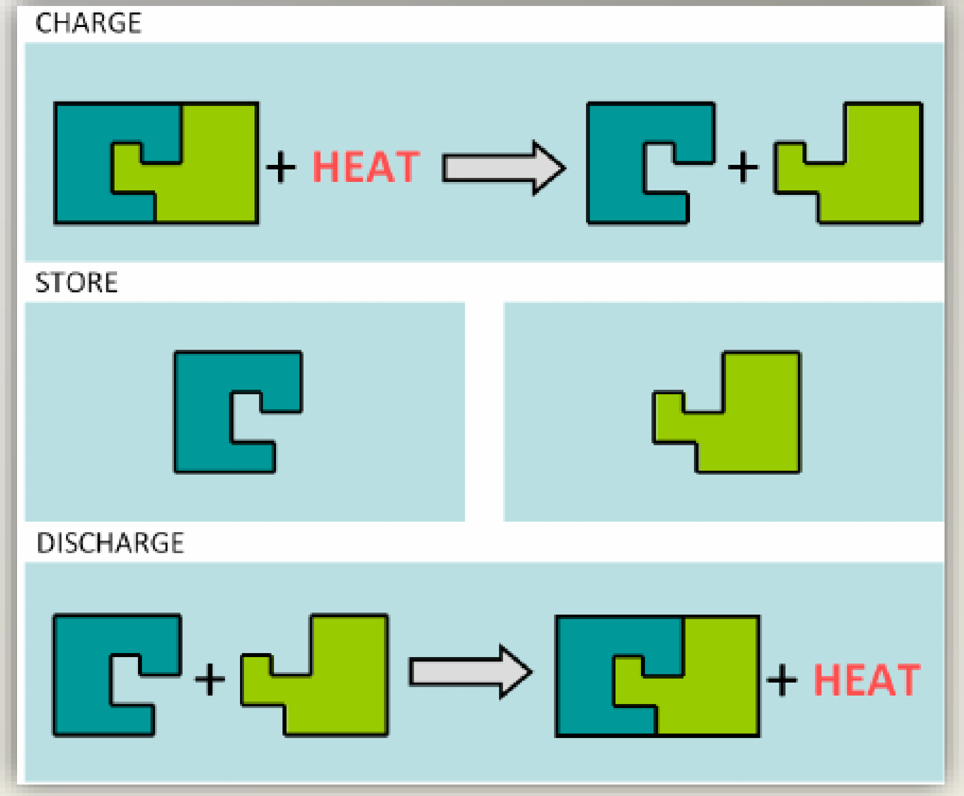
- AB + Heat ↔ A+B

- $\boldsymbol{Q = m a_r \Delta H}$

a_r : fraction reacted

m : mass of the reactant AB

ΔH : heat of reaction per unit mass



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2.1.2. Concentrated Solar Power (CSP)

Current research efforts in the area of sensible TES

- Developing new molten salts with lower freezing temperatures and higher decomposition temperatures

- Developing ionic liquids for next generation HTFs

- Utilizing nano-based technology to improve the specific heat capacity and thermal conductivity

- Developing low-cost solid storage media and evaluating them through compatibility testing with molten salts

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2.1.2. Concentrated Solar Power (CSP)

High temperature corrosion of the containment material is a severe problem experienced by all types of TES.

Corrosion in molten salts is a very complex issue, encompassing many aspects of chemistry, metallurgy and thermodynamics.

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2.1.3. Sensible Heat Thermal

- Industry is one of the leading energy consumers with a global share of 37%. (2016)
- Fossil fuels are used to meet more than 80% of this demand.
- Solar heat industrial plants (567 MWth) cover very small share of total global capacity.
- Industrial sector is responsible for 19% of CO_2 emissions. (2016)
- Sensible thermal energy storage, which is the oldest and most developed, has recently gained interest due to demand for increased sustainability in energy use.

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2.1.3. Sensible Heat Thermal

Key criteria to select suitable storage method :

- ✓ Usage period
- ✓ Cost
- ✓ temperature range
- ✓ storage capacity
- ✓ availability of storage material
- ✓ heat loss rates and installation area

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2.1.3. Sensible Heat Thermal

According to usage period :

- short-term storage (day/night)
- seasonal storage (summer/winter)

According to temperature range :

- heat storage
- cold storage
- both heat and cold storage

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2.1.3. Sensible Heat Thermal

- Sensible Thermal Energy Storage (STES) is the simplest and the most mature way to store heat.
- STES systems are 50–100 times cheaper than electrical storage systems.

Criteria :

- ✓ Storage capacity
- ✓ Power
- ✓ Charge/discharge time
- ✓ Cost
- ✓ Efficiency

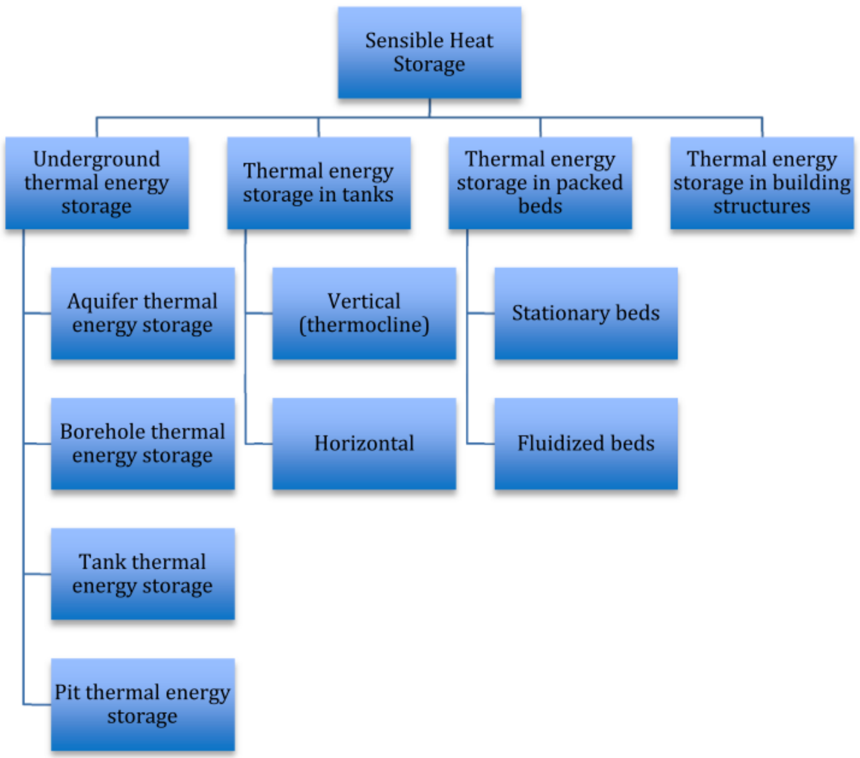

Fig. 4. Classification of sensible heat storage technologies.

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2.1.3. Sensible Heat Thermal

- Latent heat storage and thermochemical heat storage systems have higher energy densities than sensible thermal energy storage systems.
- But cost-effective solutions for especially medium-high temperature industrial applications can be achieved by only STES systems.

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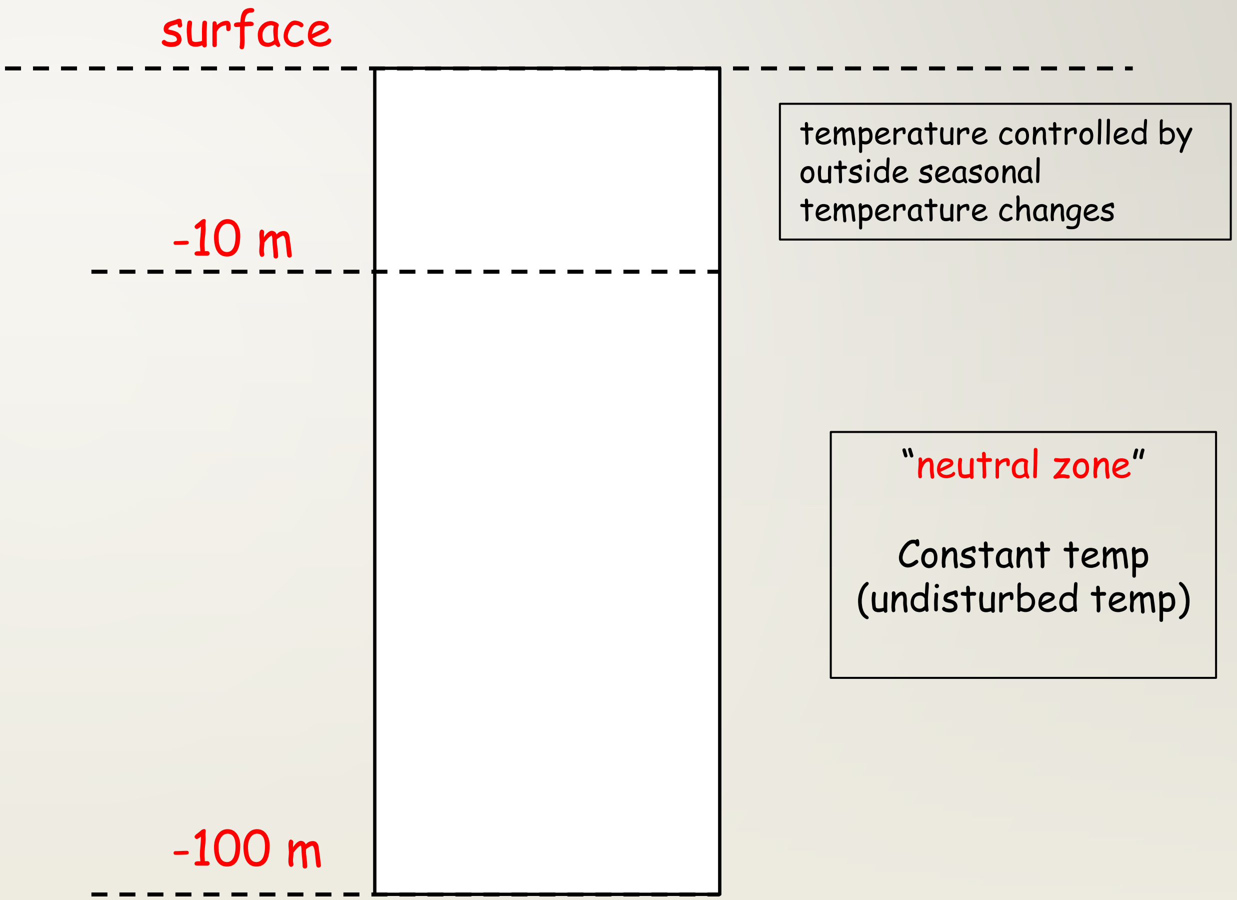
Underground Thermal Energy Storage (UTES)

- UTES technologies use the heat capacity of the underground to store thermal energy from any natural or artificial source for seasonal or diurnal applications.

- Seasonal storage systems are very popular sensible TES systems due to high efficiency and low cost.



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Underground Thermal Energy Storage (UTES)

Different Types of UTES

- Tank Thermal Energy Storage (TTES)
- Pit Thermal Energy Storage (PTES)
- Borehole Thermal Energy Storage (BTES)
- Aquifer Thermal Energy Storage (ATES)

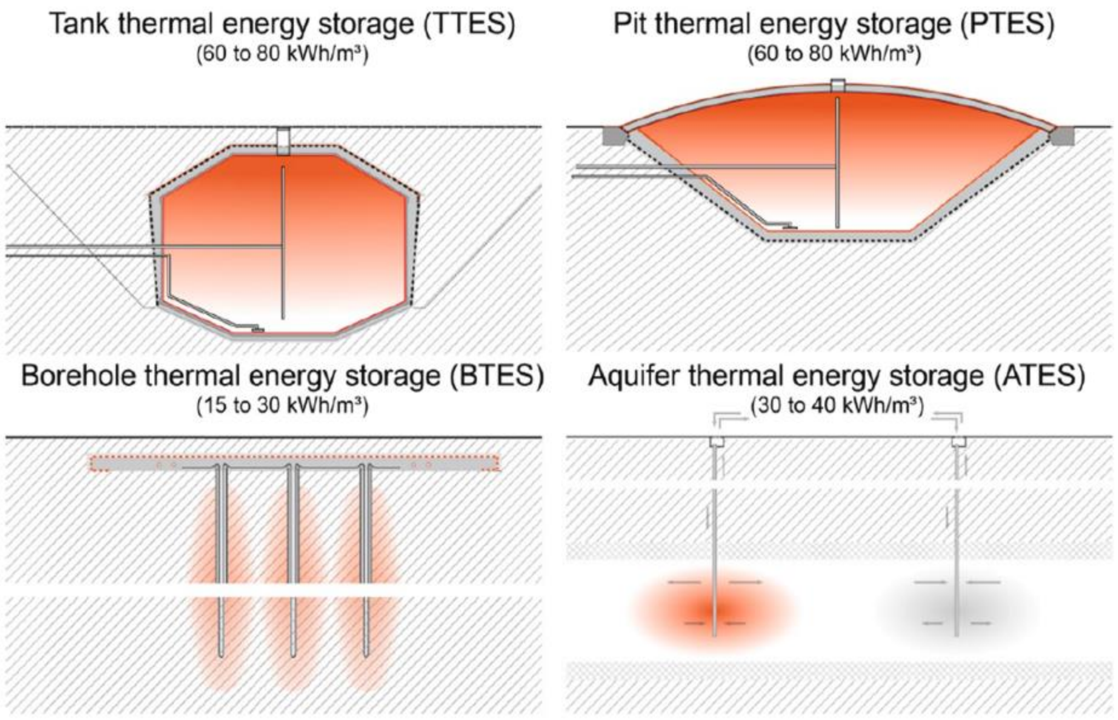

Fig. 5. Seasonal thermal energy storage methods (IEA, 2015).

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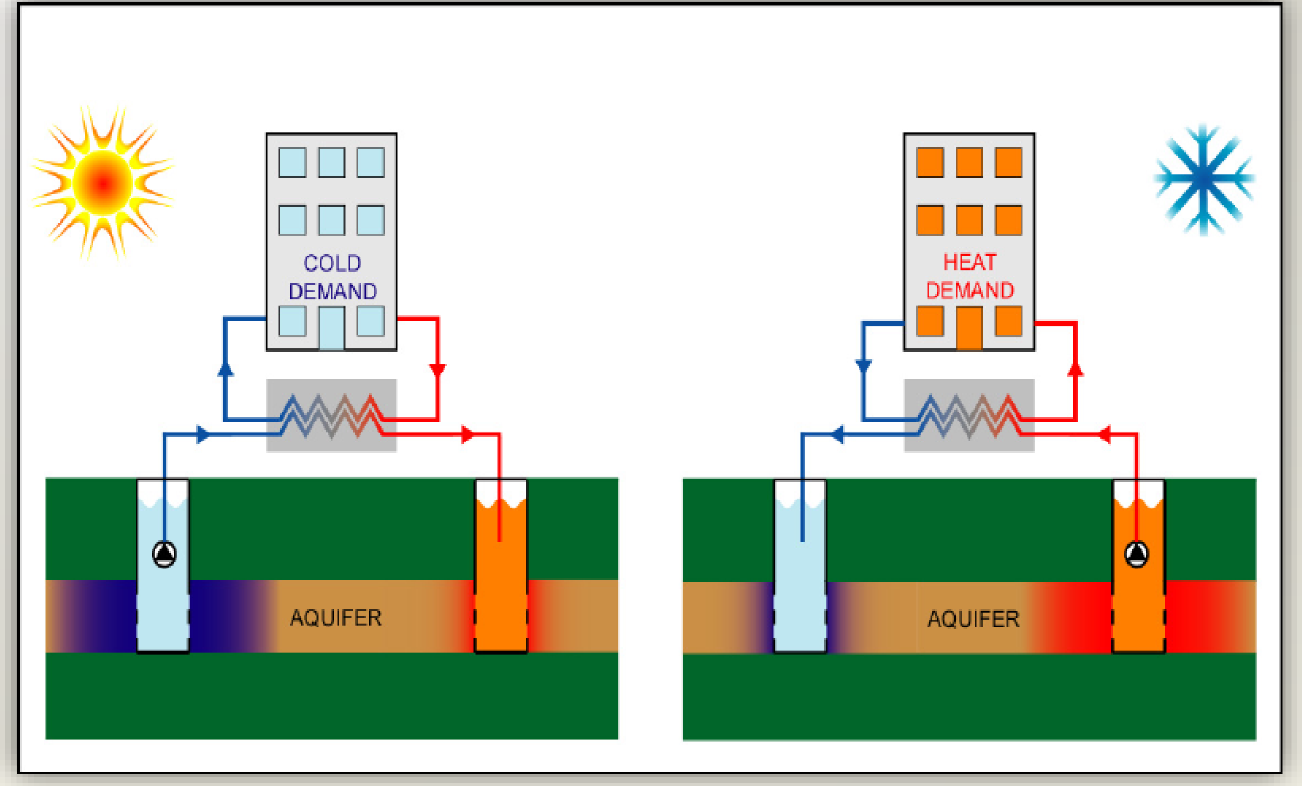
Aquifer Thermal Energy Storage (UTES)

- The development of ATES in the Netherlands started in the early 1980s.
- ATES systems employ large groundwater basins – aquifers – through wells that use groundwater as the medium of heat transfer between an external energy source such as solar energy and the aquifer.



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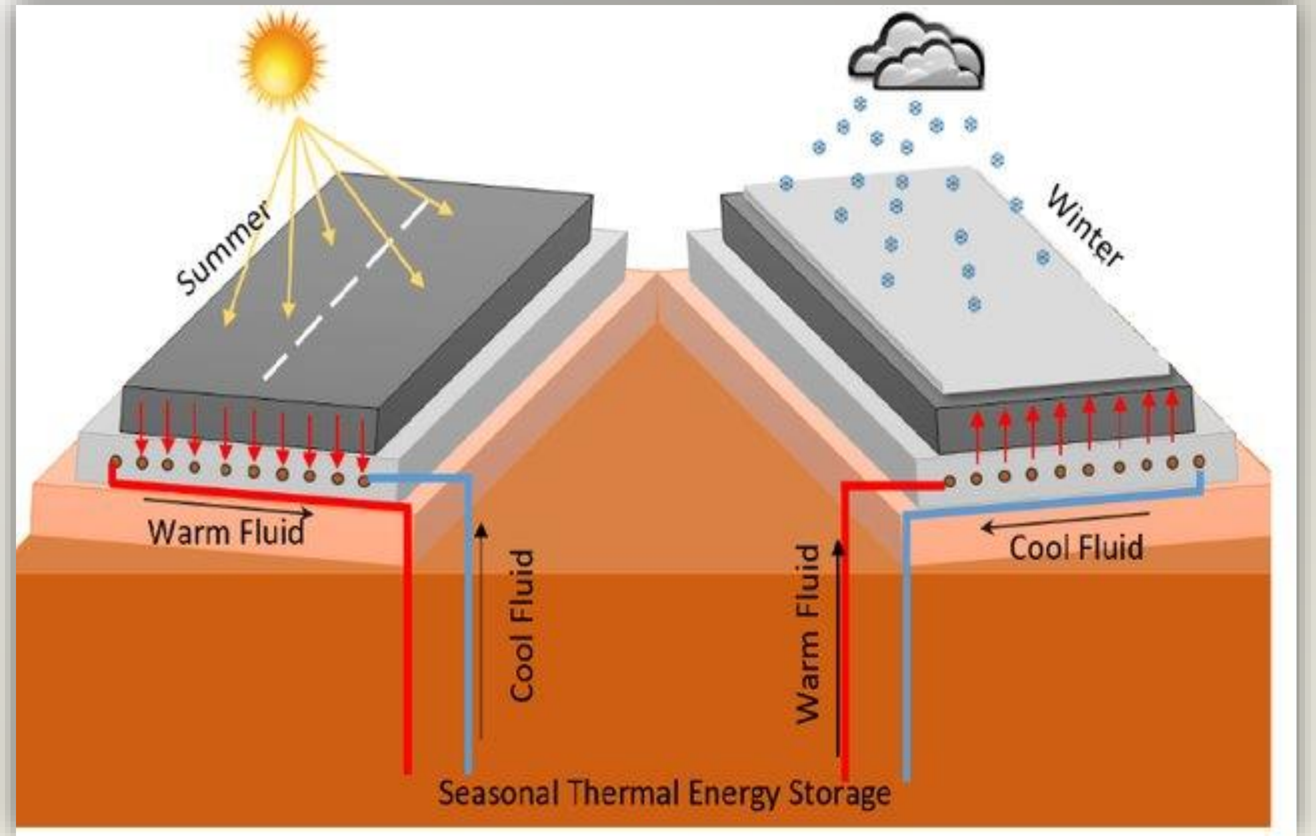
Aquifer Thermal Energy Storage (UTES)

- By installing heat exchangers just below the surface of asphalt roads, heat can be stored in the summer and the road can be de-iced in the winter.
- The excess heat can be used for heating residential areas or other buildings along the road.
- Advantage of this technology is that the degradation of the road is slowed down.



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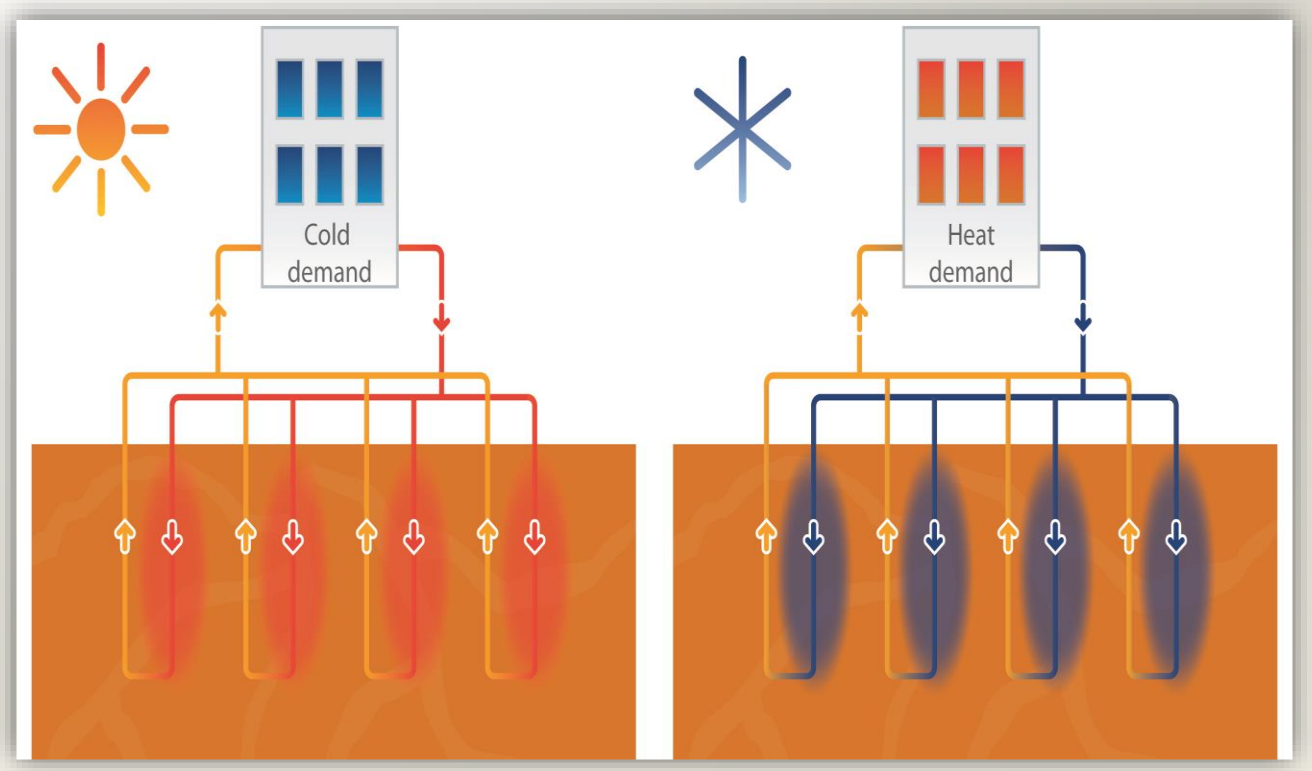
Borehole Thermal Energy Storage (UTES)

- In a BTES system thermal energy is transferred to the underground by means of conductive flow from a number of closely spaced boreholes.
- Heat is stored underground by circulating heat transfer fluid such as water, glycol-water mixture in high-density polyethylene pipes used as ground heat exchangers, which can be vertical or horizontal.



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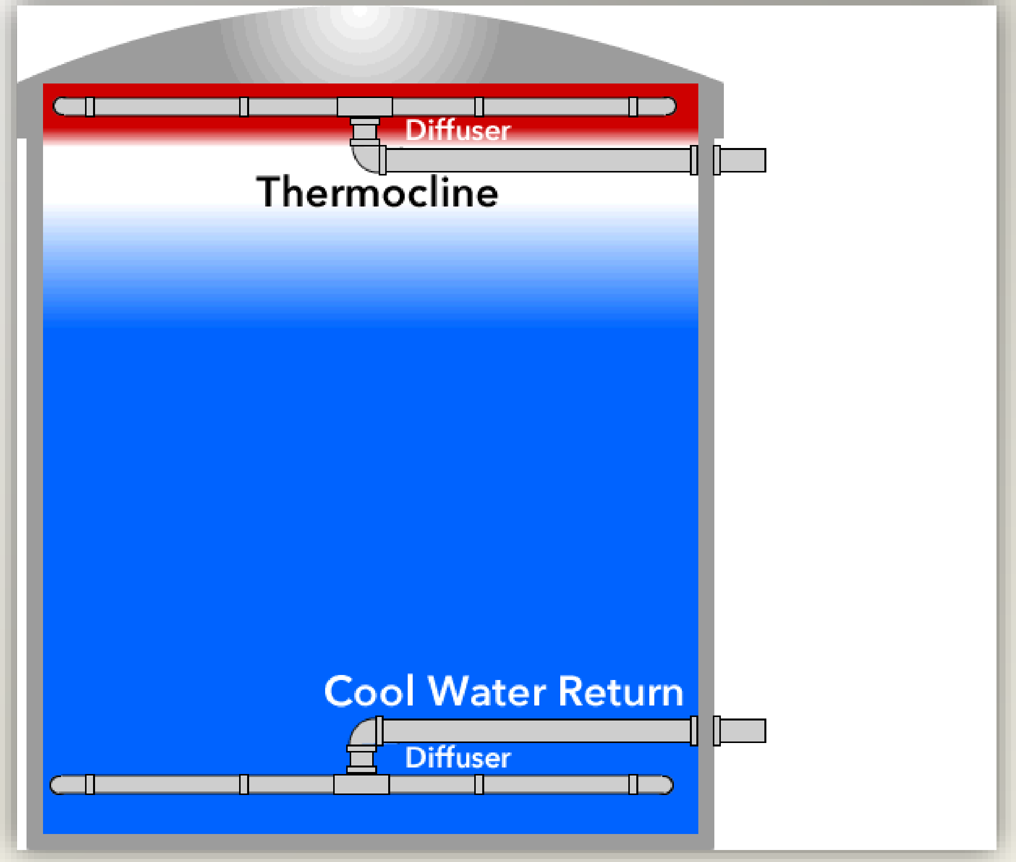
Water Tank Energy Storage (UTES)

- The most well-known and widely used systems in sensible heat storage
- Made of steel, stainless steel, concrete or plastic
- Warm and chilled water enters and exits the tank through diffusers located at the top and bottom of the tank. These diffusers provide a stable, clearly-defined transition layer, or "thermocline" that keeps warm water at the top of the tank and chilled water at the bottom.



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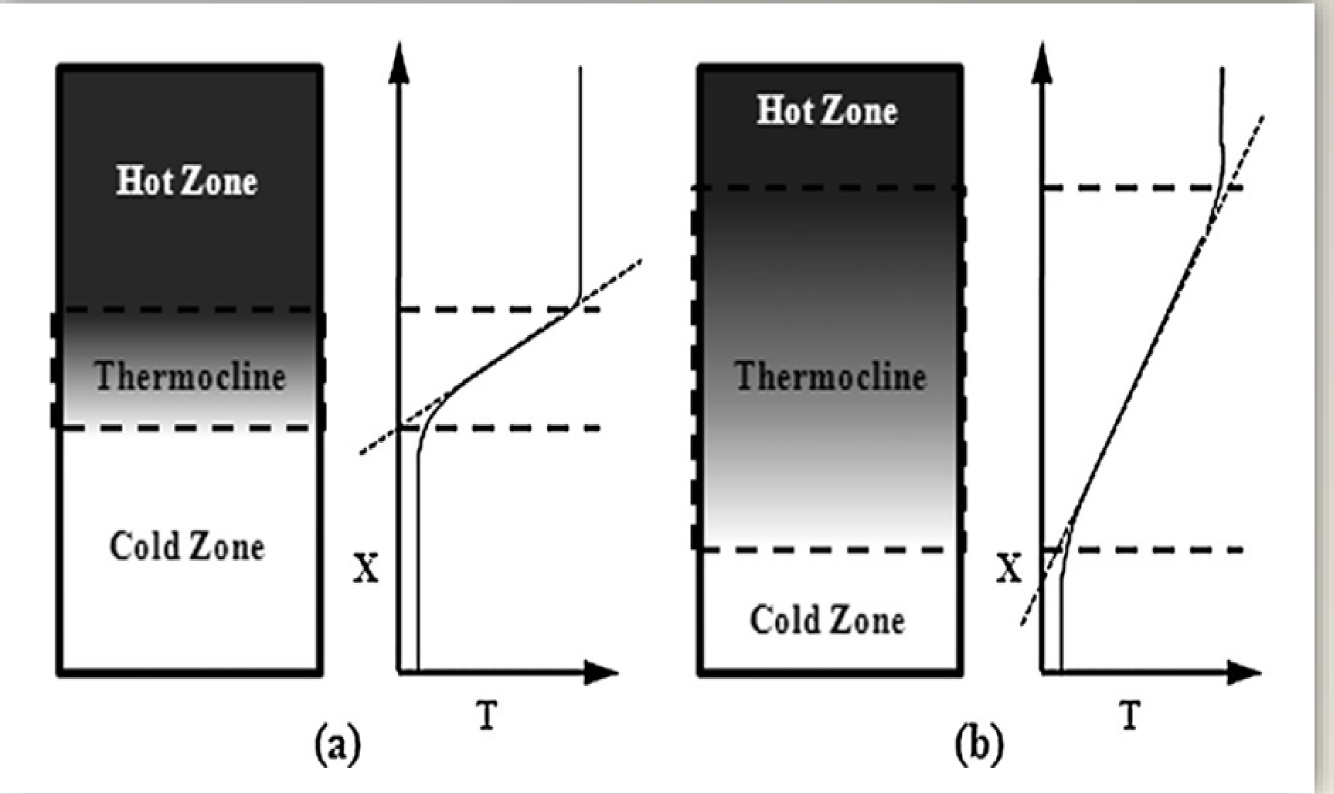
Water Tank Energy Storage (UTES)

- At the end of a distribution phase, the tank will contain mostly warm water. To "recharge" or cool the water, warm water exits through the top diffuser where it is sent to the cooling plant. It is then cycled back into the tank as chilled water through the bottom diffuser where it is ready to be used by the cooling system.



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Packed Beds Energy Storage (PBES)

- Packed beds consist of a tank filled with packing material and a heat transfer fluid that is circulated through the bed to store or recover heat. Water and thermal oil are common heat transfer fluids.
- At elevated temperatures, thermal oils and steam are preferred. Solid materials such as rocks pebbles, metals, ceramics and recycled materials can be used as packing materials. Rock bed is the cheapest packed bed.

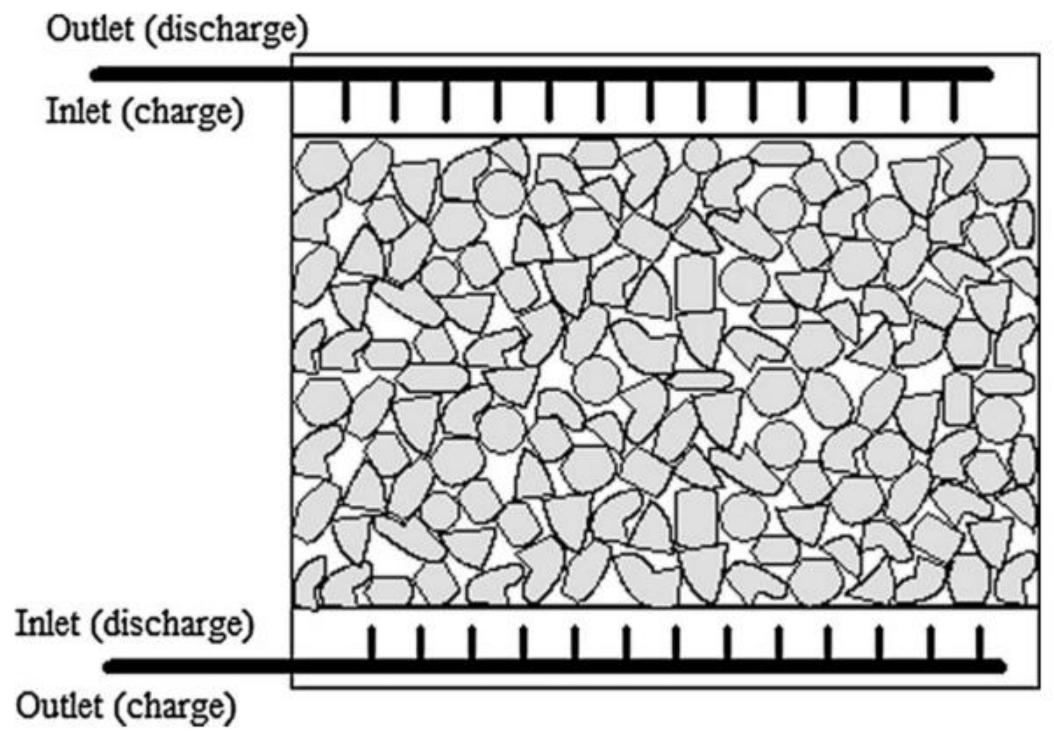

Fig. 9. Rock bed storage system (Pinel et al., 2011).

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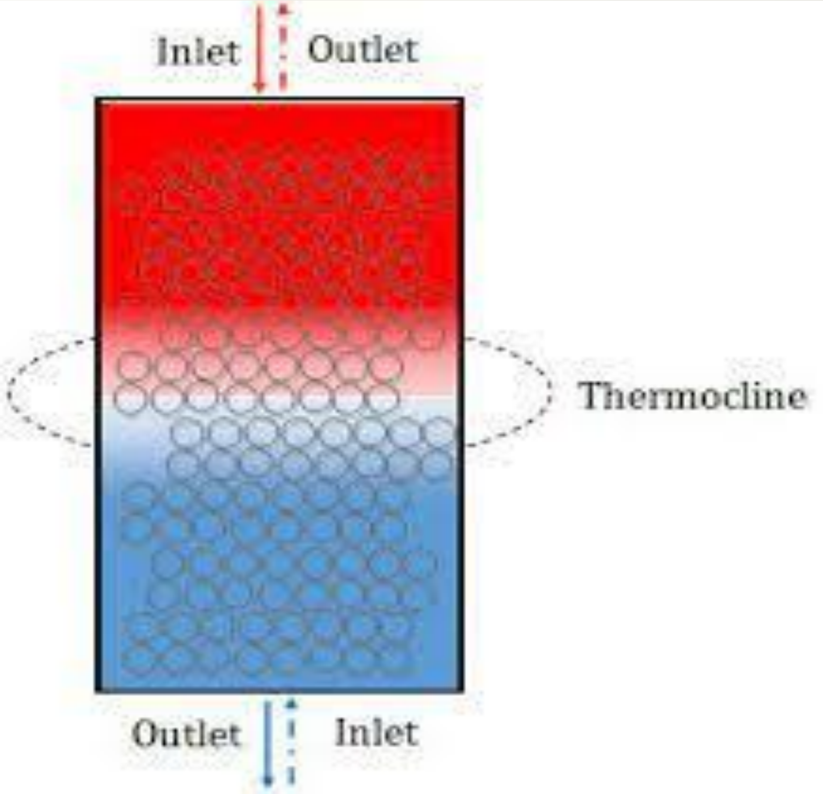
Packed Beds Energy Storage (PBES)

- During charge, hot fluid flows in from top to heat packing material.
- During discharge, hot fluid is extracted from top. Then it is pumped into the bed.
- As in water tanks, thermocline moves downward during charge and vice versa during discharge.



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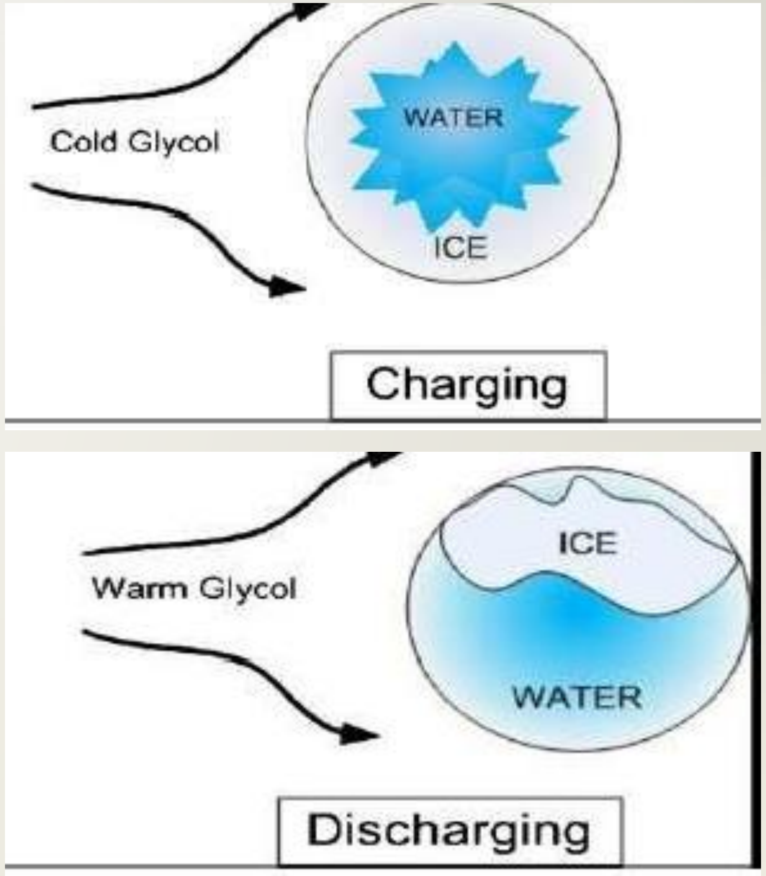
Ice Thermal Energy Storage (ITES)

- To mitigate high energy dependence of HVAC systems, on-site ice storage and cooling can be proposed. Ice and slush usage for cooling purposes is a well-understood, mature concept that dates back many years ago.
- Uses water as a phase change material to store energy for cooling.

Advantages of ice-cooling :

- ✓ pumping cost savings
- ✓ easy transportation
- ✓ high cooling capacity
- ✓ thermal performance over transportation



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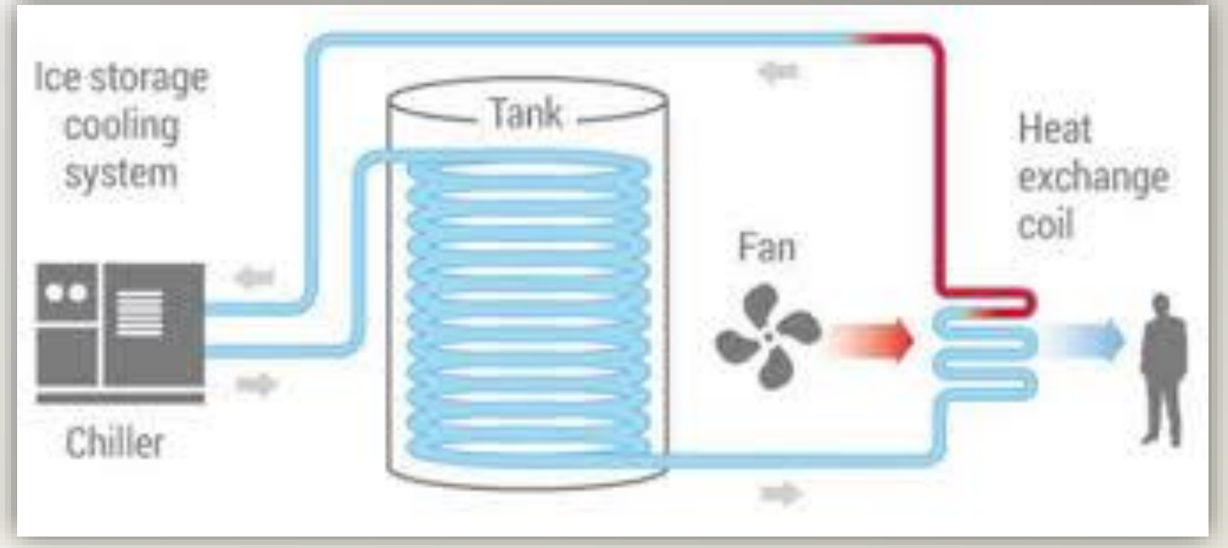
Ice Thermal Energy Storage (ITES)

1. A chiller operates during off-peak hours cooling a glycol solution to sub-freezing temp
2. Then the solution is circulated through the ice storage coils
3. Ice forms around external surface of coils
4. Full storage is reached when the ice is 2.8 cm to 3.8 cm thick
5. Then ice is melted and used as a cooling agent



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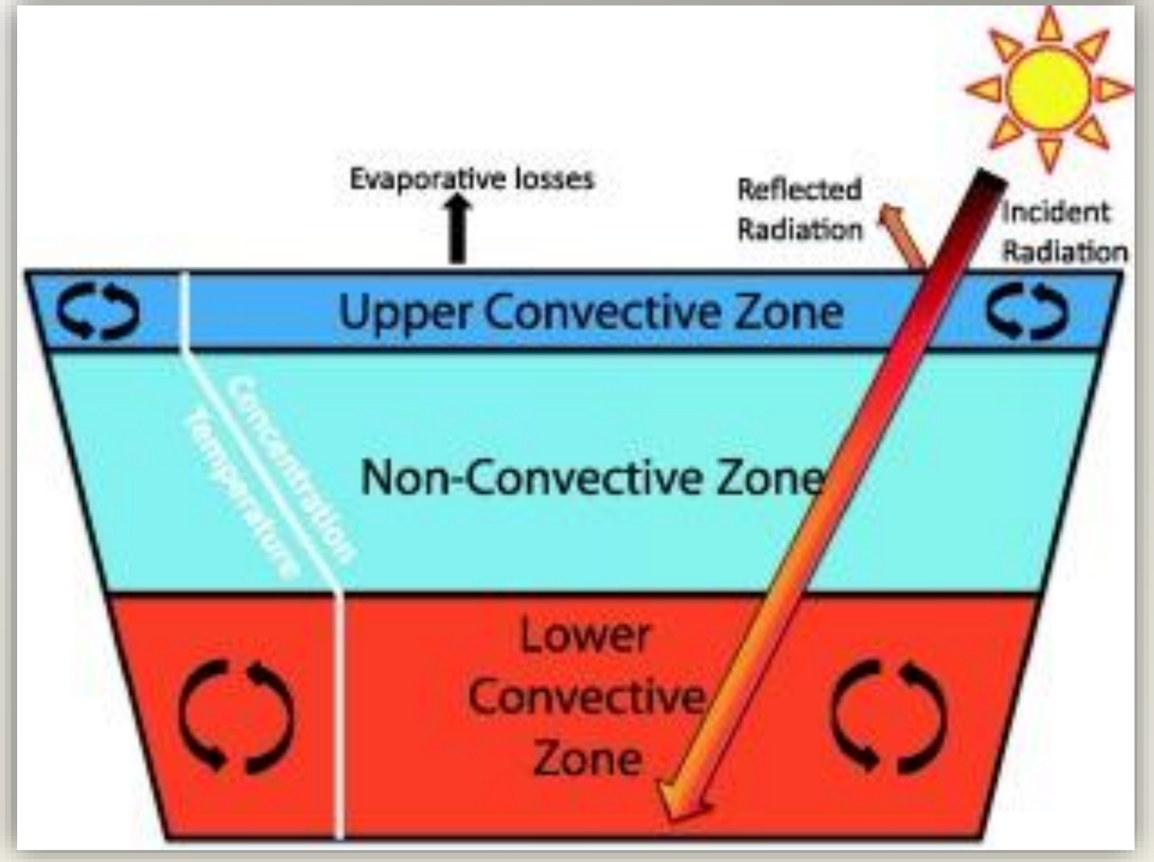
Solar Pond Energy Storage (SPES)

- Ponds of salt water
- Salient gradient
- Low salinity water floats on high salinity water
- They do not mix readily
- Bottom section can reach 90 °C
- None-Convective zone act as insulator
- NaCl and $MgCl_2$ used as salt
- Salt dissolution system used



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Solar Pond Energy Storage (SPES)

Salt Dissolution :

1. Top layer of pond is pumped into a mixing tank
2. Salt is added in the mixing tank
3. Concentrated brine is pumped into the bottom part

Site Criteria :

- ✓ Access to water
- ✓ Access to salt
- ✓ Low wind speed
- ✓ Relatively flat site
- ✓ Soil with good cohesion for walls

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2.2. Hydrogen Storage

- Use of hydrogen as a clean fuel for road and marine traffic
- As a long-term flexible energy storage option for backing up intermittent renewable sources
- Used in industrial, transport, and power generation sectors
- lowest-cost electricity storage options throughout days, weeks, and even months
- Suitable for long-distance transmission

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2.2. Hydrogen Storage

- Hydrogen is considered a clean fuel that produces zero emissions during use (except for water vapor).
- But its production is currently neither clean nor sustainable !
- It is accountable for around 830 million tons of CO_2 emissions per year.
- In the future, water electrolysis powered by RES* would be a clean way to produce
- Hydrogen.
- At the current market cost, this is still considerably more expensive than the route from fossil sources.
- High energy density (140 MJ/kg)

*RES: Renewable Energy Sources

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2.2. Hydrogen Storage

Hydrogen can be stored as:

- Compressed gas
- Liquid
- Chemical structure
- Geological storage

Compressed gas:

- High energy requirement (low specific gravity)
- Challenges pertaining to the materials of the storage tanks

Liquid:

- Requires a 64% higher amount of energy than that of compressed gas
- hydrogen does not liquefy until -253 °C, and cooling that far is an energy-intensive process.

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2.2. Hydrogen Storage

Chemical structure:

- Metal hydrides (esp. MgH_2) are one of the most common types of hydrogen chemical storage.
- have the ability to store hydrogen at high densities that can exceed that of liquid hydrogen.
- Hydrogenation and dehydrogenation processes require high temperature and pressure.

Geological storage:

- Salt caverns
- Depleted natural gas or
- Oil reservoirs
- Aquifers

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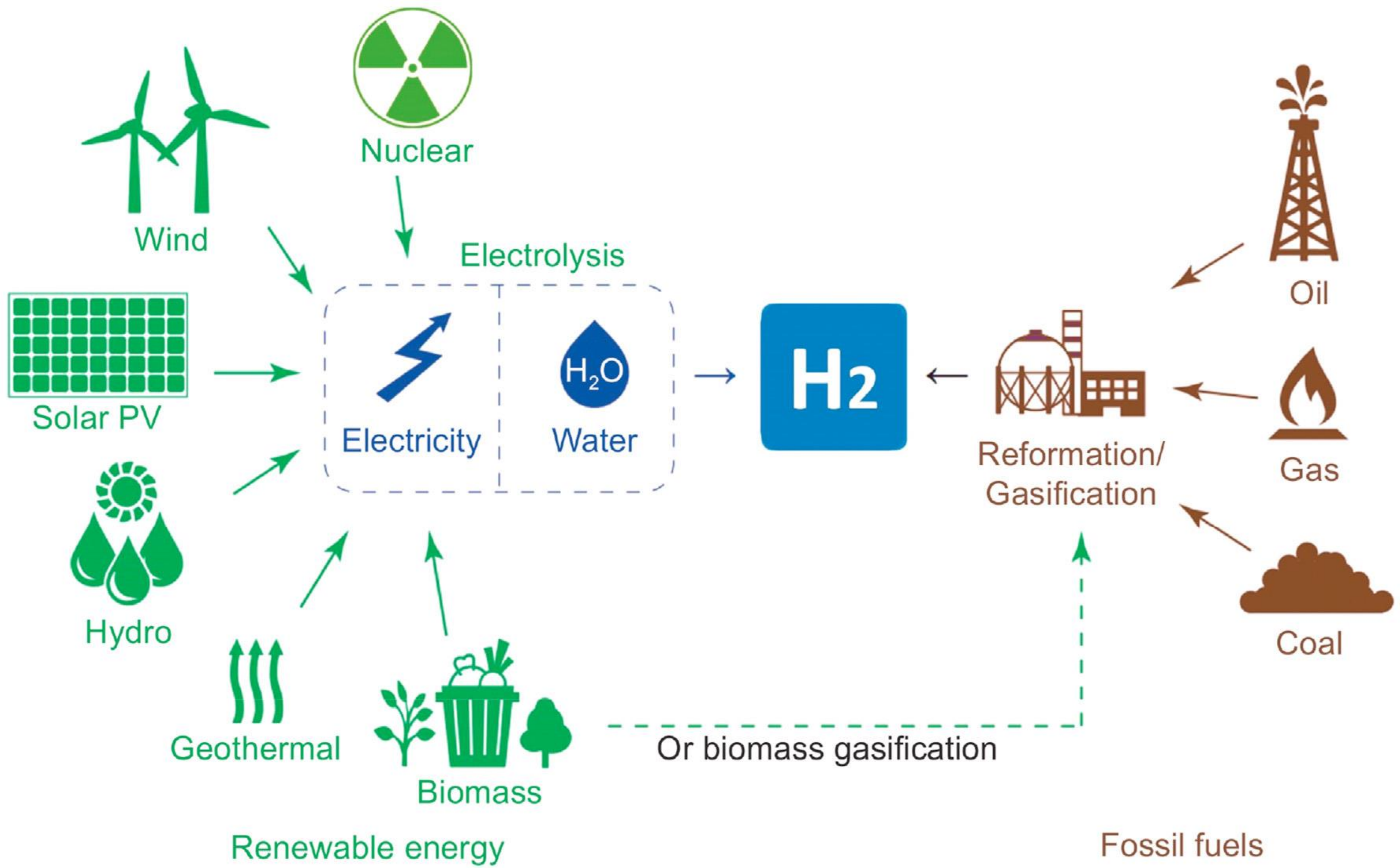

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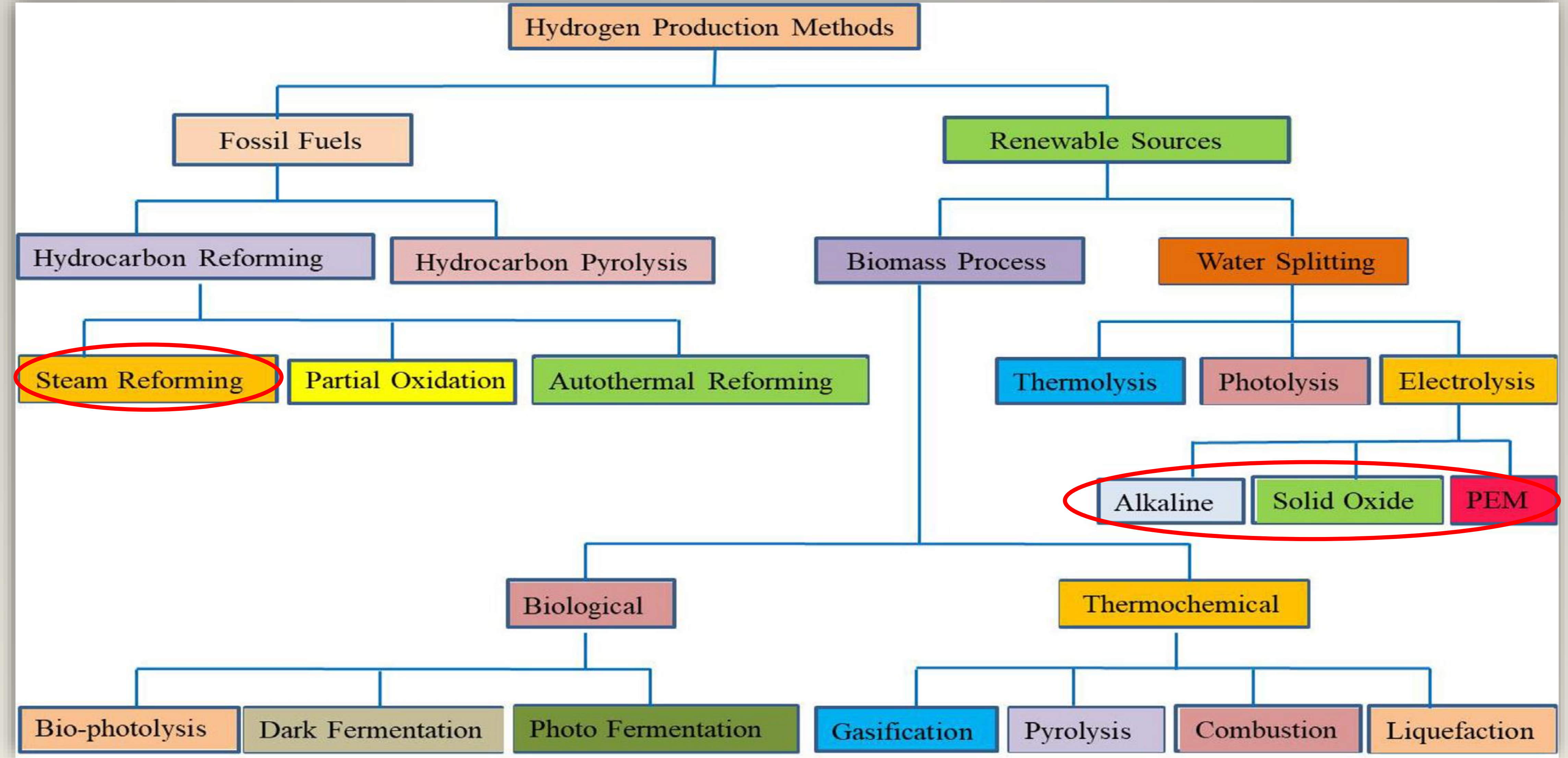

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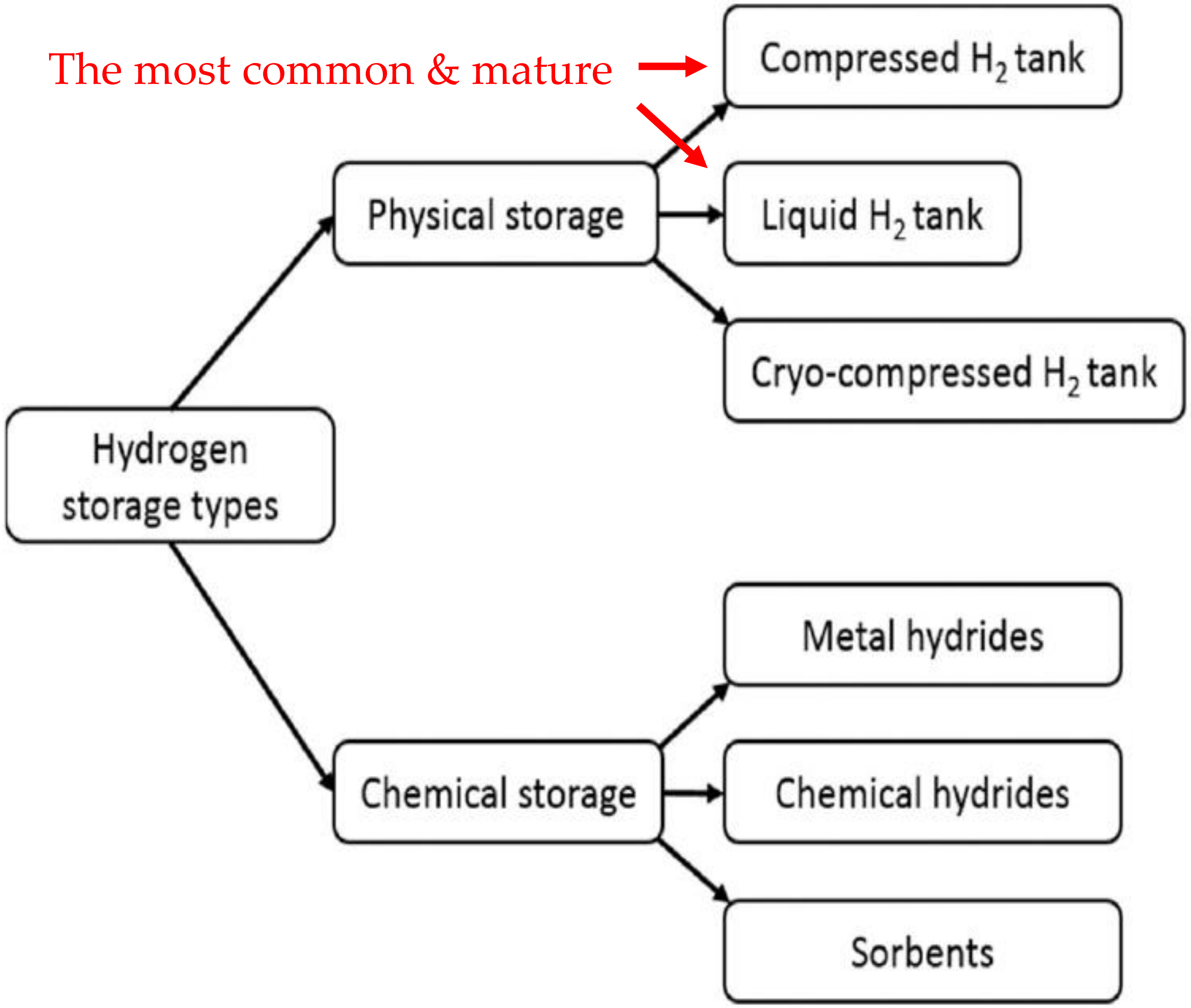

Table 2
Global hydrogen production by source.

Source	Billion m^3/year [30]	Share (%) [30]	Advantages	Disadvantages
Natural gas	240	48%	Low production cost; accessible infrastructure	Environmental impacts during extraction of natural gas; production of greenhouse gases
Oil	150	30%	Low production cost; accessible infrastructure	Environmental impacts during extraction of oil; production of greenhouse gases
Coal	90	18%	Low production cost; accessible infrastructure	Environmental impacts during extraction of coal; production of greenhouse gases
Electrolysis	20	4%	Can be produced with low greenhouse gas emissions when using renewable energy sources	Low efficiency, high cost of production, limited infrastructure, production of greenhouse gases when powered with fossil fuels
Total	**500**	**100%**		

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2.2. Hydrogen Storage

Another classification:

1. Electrolysis
2. Photolysis
3. Biolysis
4. Thermolysis

Hydrogen color:

1. Grey (polluting)
2. Blue (grey + CCS*)
3. Green (RES)

color codes does NOT necessarily indicate cleanness (low carbon emission)

Cryogenic freeze/liquify

- require up to 30% of the potential energy of the hydrogen stored as a result of the high energy consumption required to freeze or liquefy the hydrogen

*Carbon Capture and Storage

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Table 1
Various Hydrogen production methods along with their advantages, disadvantages efficiency and cost [Refs. [2,4,5]].

Hydrogen production Method	Advantages	Disadvantages	Efficiency	Cost [$/kg]
Steam Reforming	Developed technology & Existing infrastructure	Produced CO, CO_2 Unstable supply	74–85	2.27
Partial Oxidation	Established technology	Along with H_2 Production, produced heavy oils and petroleum coke	60–75	1.48
Auto thermal Reforming	Well established technology & Existing infrastructure	Produced CO_2 as a byproduct, use of fossil fuels.	60–75	1.48
Bio photolysis	Consumed CO_2, Produced O_2 as a byproduct, working under mild conditions.	Low yields of H_2, sunlight needed, large reactor required, O_2 sensitivity, high cost of material.	10–11	2.13
Dark Fermentation	Simple method, H_2 produced without light, no limitation O_2, CO_2-neutral, involves to waste recycling	Fatty acids elimination, low yields of H_2, low efficiency, necessity of huge volume of reactor	60–80	2.57
Photo Fermentation	Involves to waste water recycling, used different organic waste waters, CO_2-neutral.	low efficiency, Low H_2 production rate, sunlight required, necessity of huge volume of reactor, O_2-sensitivity	0.1	2.83
Gasification	Abundant, cheap feedstock and neutral CO_2.	Fluctuating H_2 yields because of feedstock impurities, seasonal availability and formation of tar.	30–40	1.77–2.05
Pyrolysis	Abundant, cheap feedstock and CO_2-neutral.	Tar formation, fluctuating H_2 amount because of feedstock impurities and seasonal availability	35–50	1.59–1.70
Thermolysis	Clean and sustainable, O_2-byproduct, copious feedstock	High capital costs, Elements toxicity, corrosion problems.	20–45	7.98–8.40
Photolysis	O_2 as byproduct, abundant feedstock, No emissions.	Low efficiency, non-effective photocatalytic material, Requires sunlight.	0.06	8–10
Electrolysis	Established technology Zero emission Existing infrastructure O_2 as byproduct	Storage and Transportation problem.	60–80	10.30

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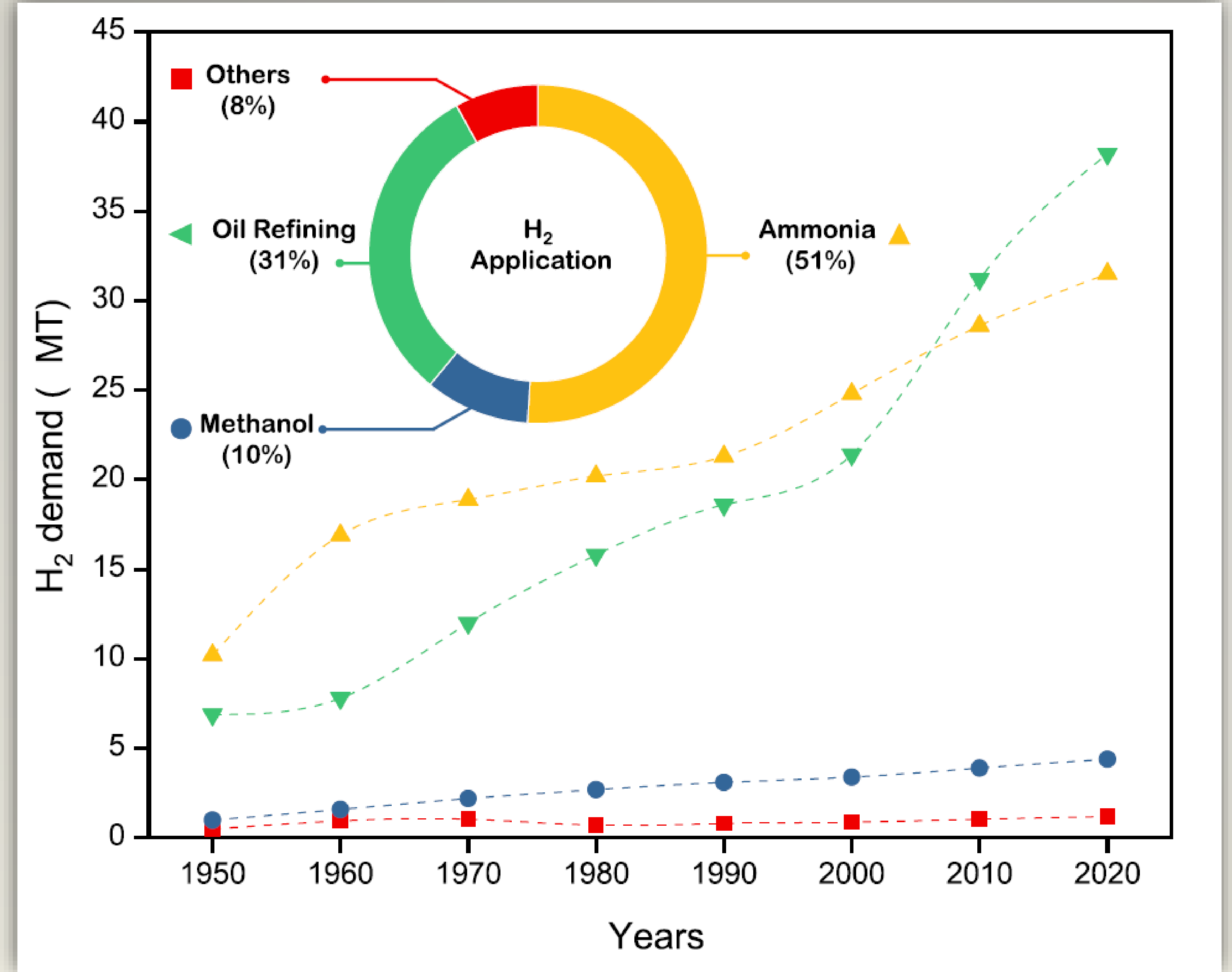

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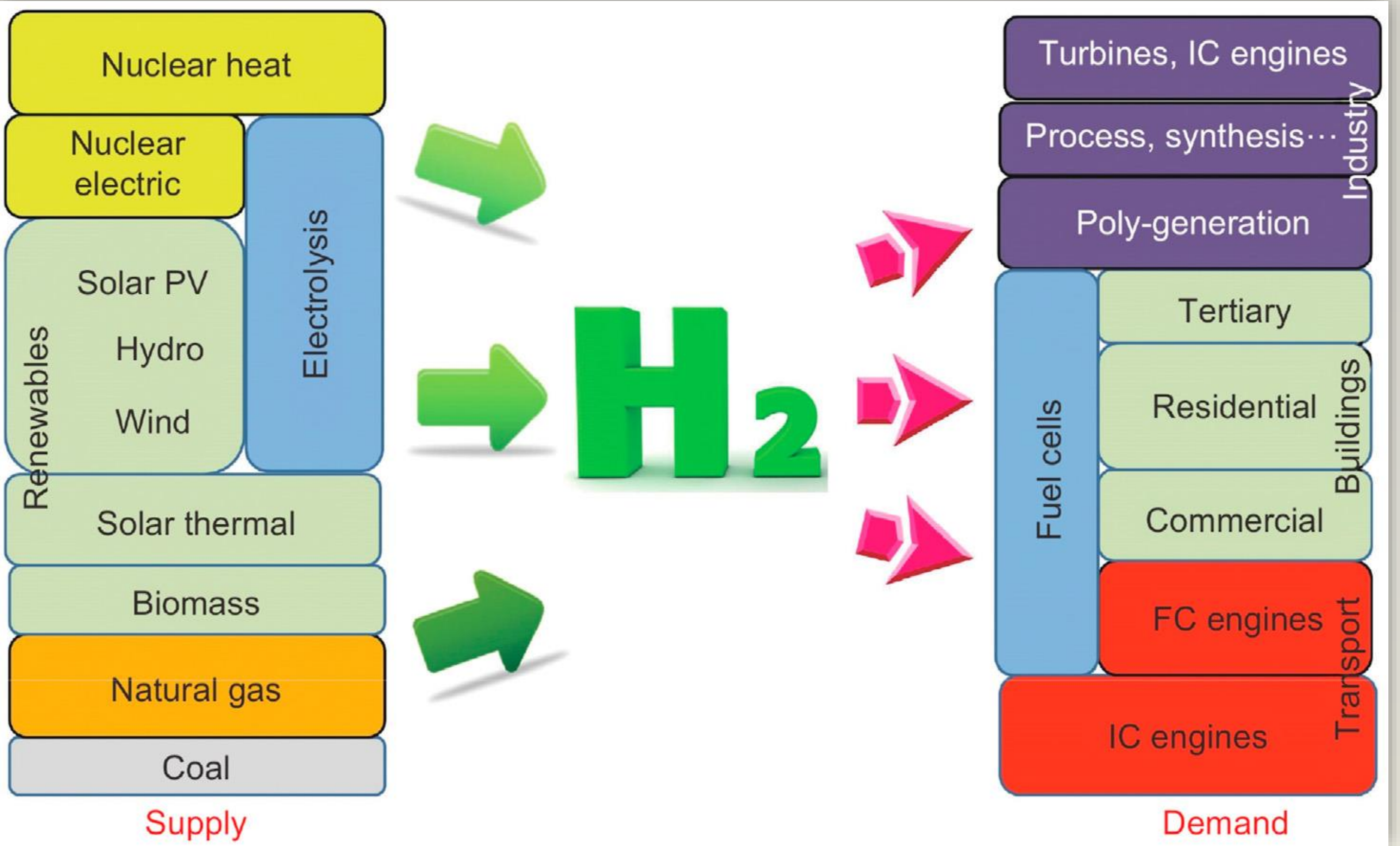

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2.2. Hydrogen Storage

Water Electrolysis

- Eco-friendly
- High-purity hydrogen (% 99.999)
- Only 4% of H_2 production
- Uses DC power
- Four types: 1. Alkaline, 2. Solid oxide, 3. Microbial electrolysis cells, 4. PEM electrolysis
- $1\ \boldsymbol{H_2O} + Electricity\ (237.2\ kJ) \rightarrow 1\ \boldsymbol{H_2} + \frac{1}{2}\ \boldsymbol{O_2} + Heat\ (48.6\ kJ)$

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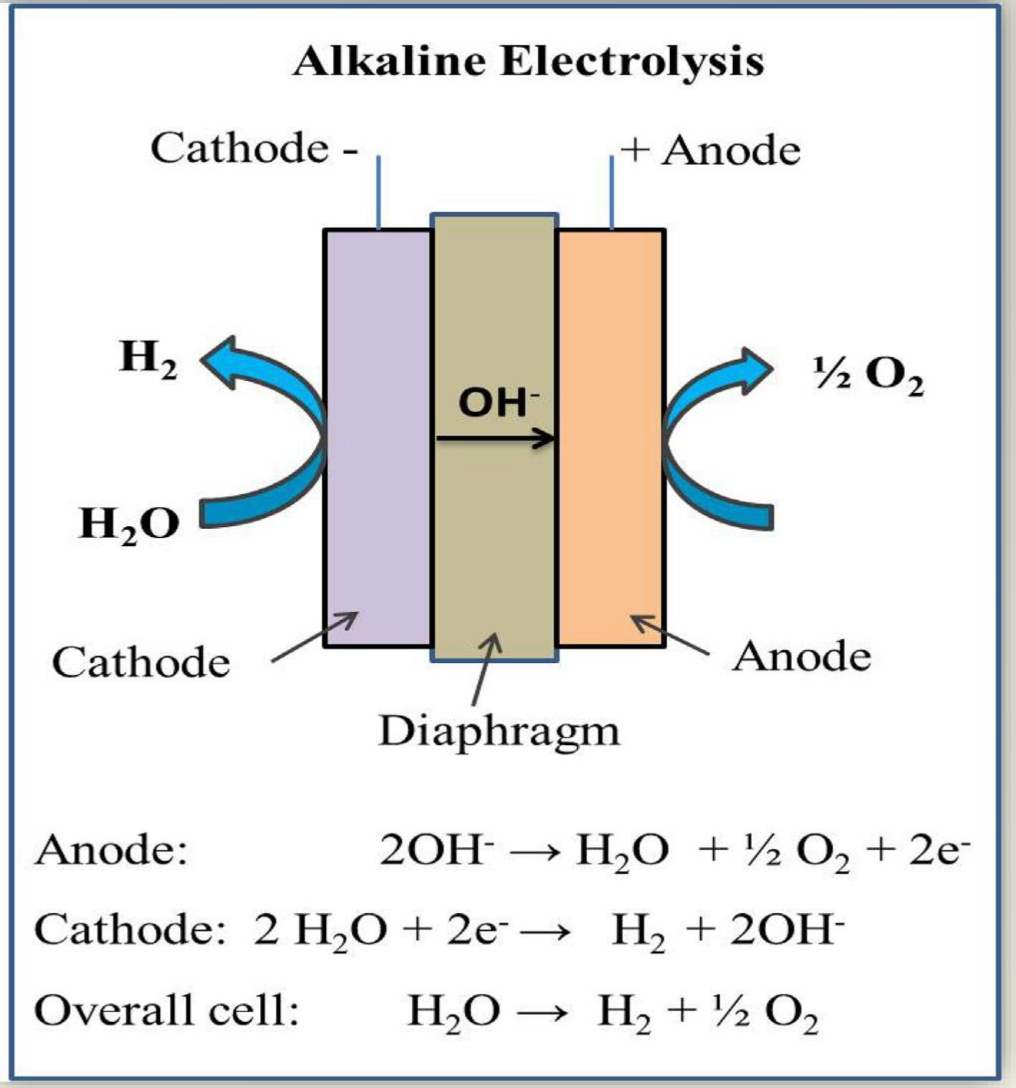
2.2. Hydrogen Storage

Alkaline Water Electrolysis (AWE)

- Well established technology up to the megawatt range
- Operates at low temperatures such as 30–80 °C
- Aqueous solution (KOH/NaOH) as the electrolyte
- Asbestos diaphragm
- Nickel materials are used as the electrodes



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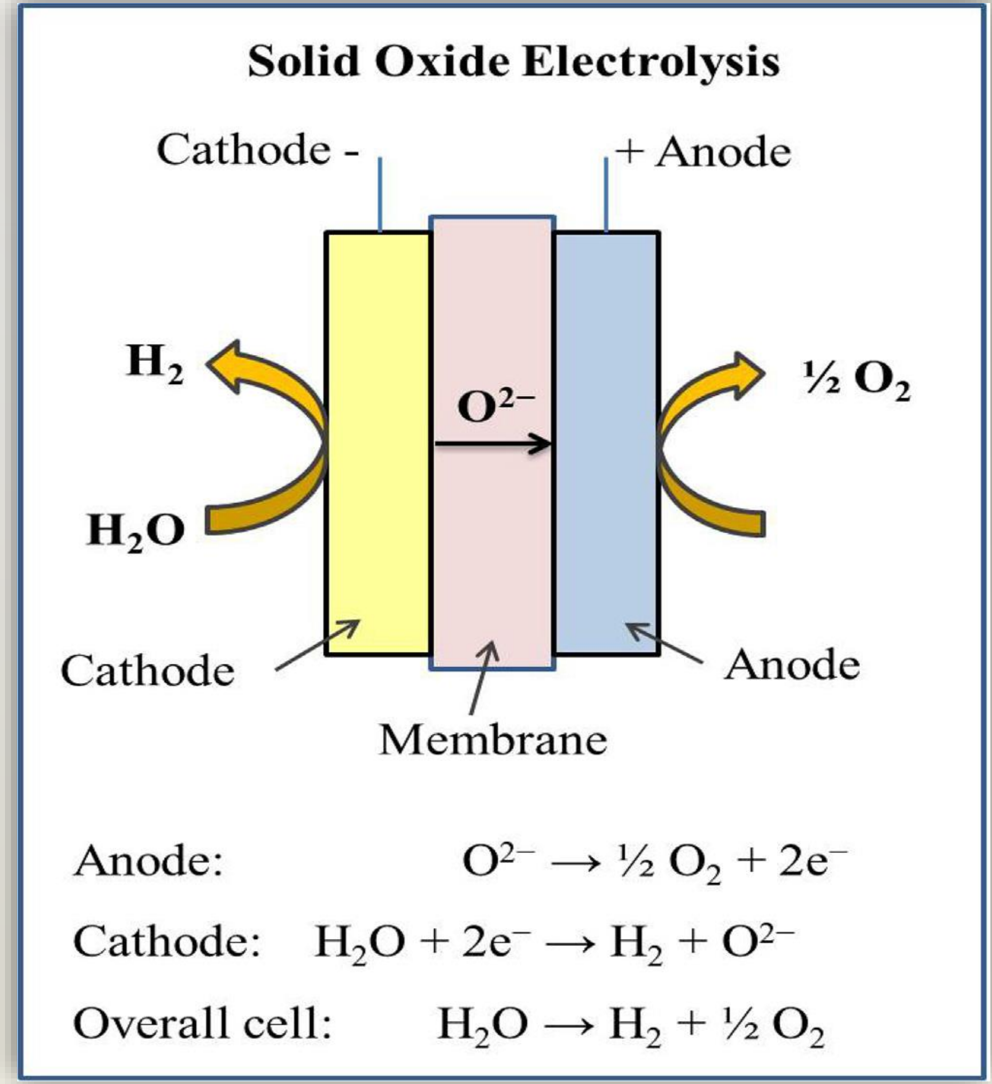
2.2. Hydrogen Storage

Solid Oxide Electrolysis (SOE)

- High pressure and high temperatures 500-850 °C
- Uses the O^{2-} conductors which are mostly from nickel/yttria stabilized zirconia
- Ceramic proton conducting materials have been developed and studied
- Lack of stability and degradation



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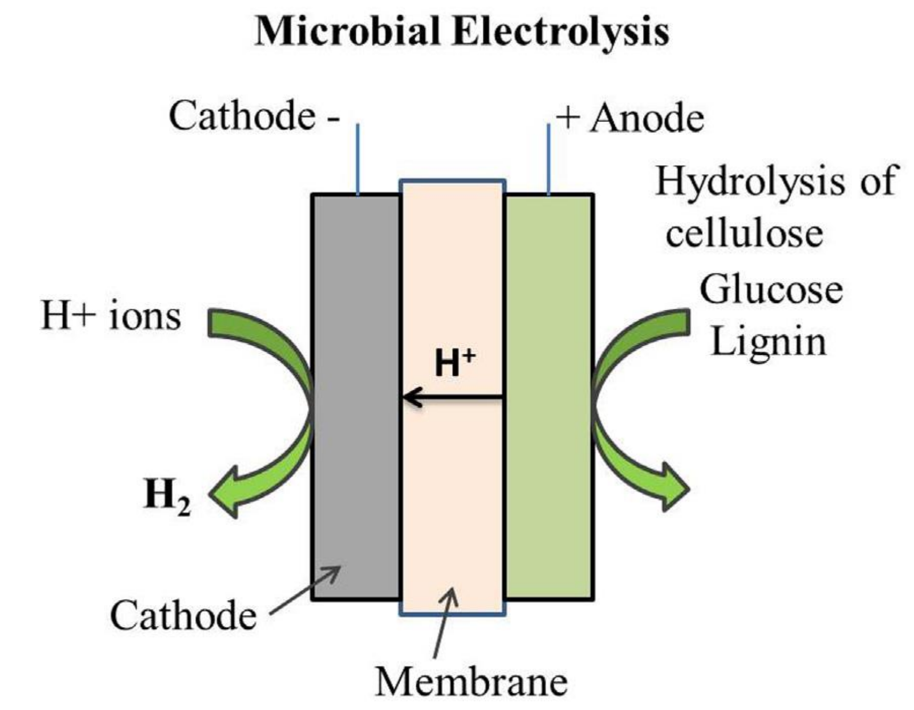
2.2. Hydrogen Storage

Microbial Electrolysis Cell (MEC)

- Uses organic matter including renewable biomass and wastewaters
- Electrical energy converted into chemical energy
- Still under development

Challenges:

- Hydrogen production rate
- High internal resistance
- Electrode materials
- Complicated design



Anode: $CH_3COO^- + 4H_2O \rightarrow 2HCO^{3-} + 9H^+ + 8e^-$

Cathode: $8H^+ + 8e^- \rightarrow 4H_2$

Overall cell: $CH_3COO^- + 4H_2O \rightarrow 2HCO^{3-} + H^+ + 4H_2$

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2.2. Hydrogen Storage

PEM water electrolysis

- Favorable method for conversion of renewable energy
- Compact design
- High current density
- High efficiency
- Fast response
- Small footprint
- Lower temperatures (20–80 °C)
- Ultrapure hydrogen
- Noble metals such as Pt/Pd at the cathode
- IrO_2/RuO_2 at the anode
- More expensive than alkaline
- approaching commercial markets

Challenges:

- Reduce costs
- Maintain high efficiency

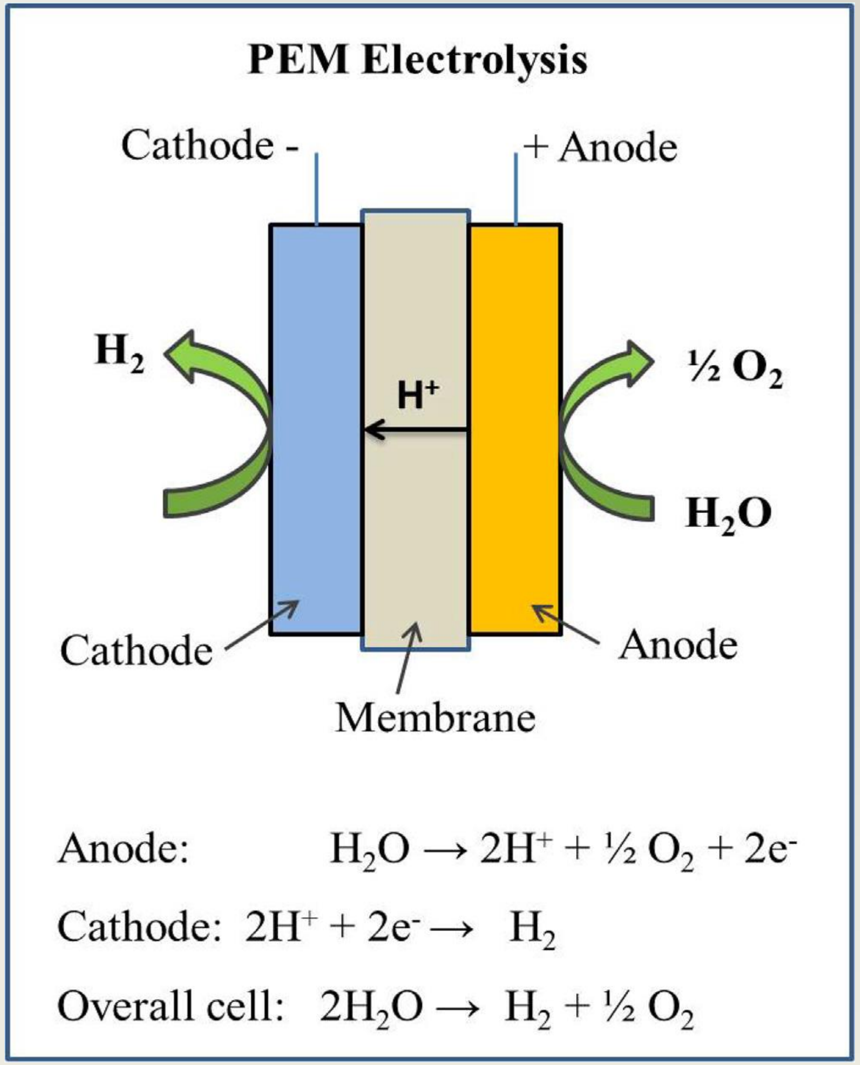

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Table 2
Advantages and Disadvantages of different water electrolysis technologies.

Electrolysis process	Advantages	Disadvantages
Alkaline Electrolysis	Well established technology Non-noble electro catalysts Low cost technology The energy efficiency is (70–80%) Commercialized	Low current densities Formation of carbonates on the electrode decreases the performance of the electrolyser Low purity of gases Low operational pressure (3–30 bar) Low dynamic operation
Solid Oxide Electrolysis	Higher efficiency (90–100%) Non-noble electro catalysts High working Pressure	Laboratory stage Large system design Low durability
Microbial Electrolysis	Used different organic waste waters	Under development Low hydrogen production rate Low purity of hydrogen
PEM Electrolysis	High current densities Compact system design and Quick Response Greater hydrogen production rate with High purity of gases (99.99%) Higher energy efficiency (80–90%) High dynamic operation	New and partially established High cost of components Acidic environment Low durability Commercialization is in near term

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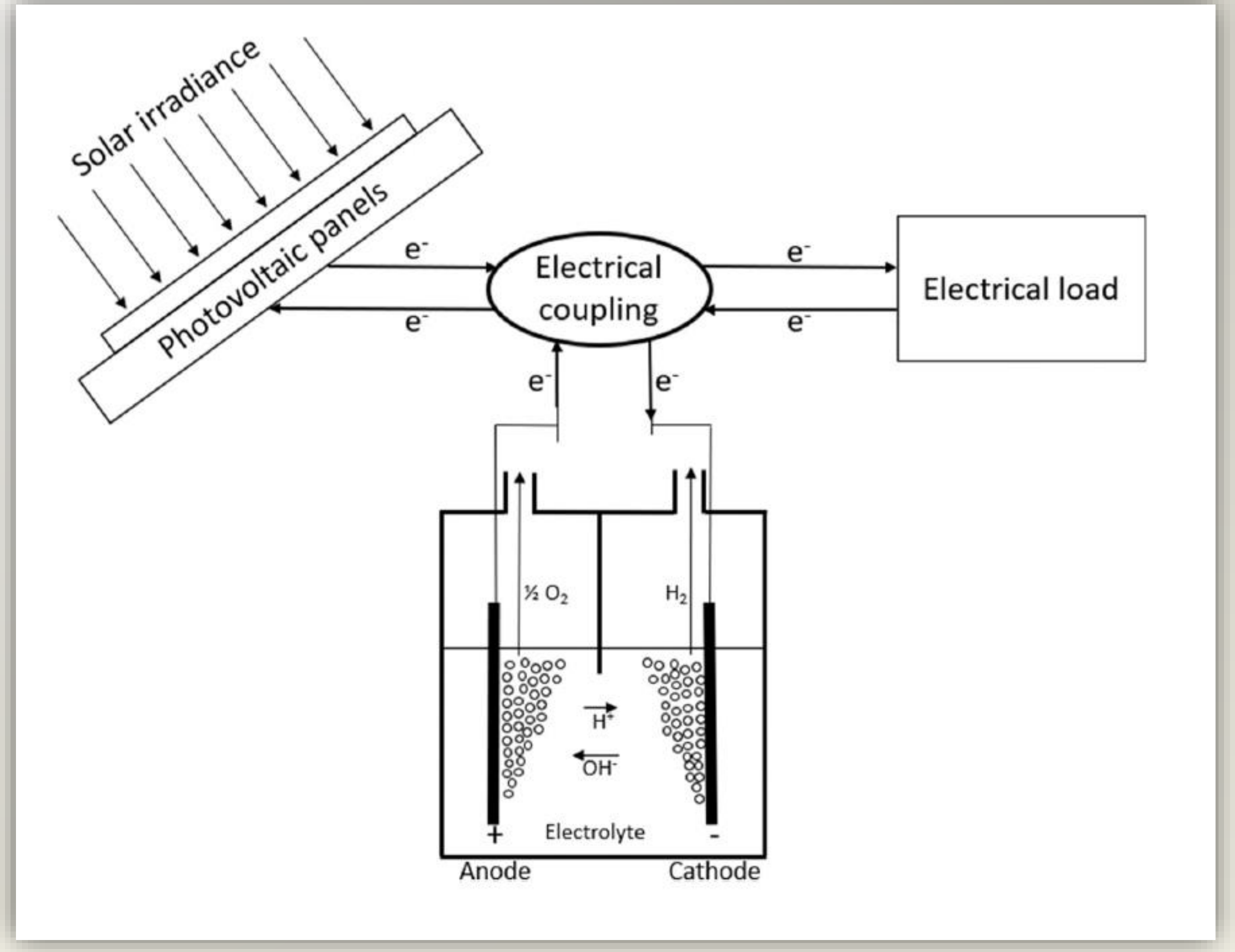
2.2. Hydrogen Storage

Solar Hydrogen

- ➢ Currently, low efficiency (31%)
- ➢ How to increase efficiency ?
- Magnetic fields
- Light energy
- Ultrasonic fields
- Pulsating electric fields



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2.2. Hydrogen Storage

Conclusion

- ✓ Small scale (low demand) investment : water electrolysis $<$ natural gas steam reforming
- ✓ Large scale (large demand) investment : water electrolysis $>$ natural gas steam reforming
- ✓ Trend toward the diversification of the hydrogen-production scale
- ✓ Scope: green, efficient, convenient, safe, and low-cost hydrogen-production technologies
- ✓ Investigate the steam reforming of hydrocarbons from the microscopic perspective of atomic engineering methods
- ✓ Development of raw materials such as: biomass, residual waste, plastic waste, and seawater
- ✓ The use of sustainable energy + combining different technologies

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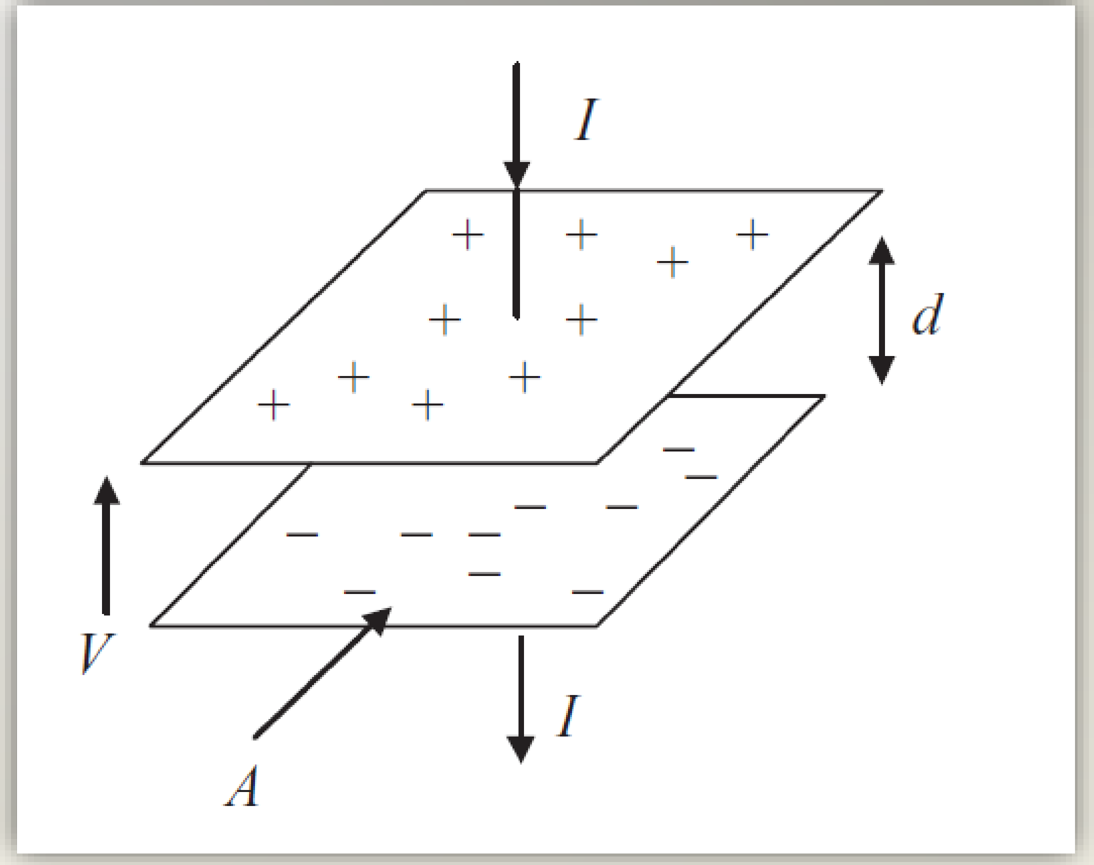
2.3. (Super) Capacitors

- A capacitor is a device that stores electrical charge and releases them when it is required by the circuit.
- $C = \frac{Q}{V} = \frac{\varepsilon A}{d}$

  C : Capacitance ε : absolute permittivity of the dielectric

  Q : Charge A : Plate area

  V : Voltage d : Plates distance
- The electric energy is stored statically in the electric field between two electrodes.



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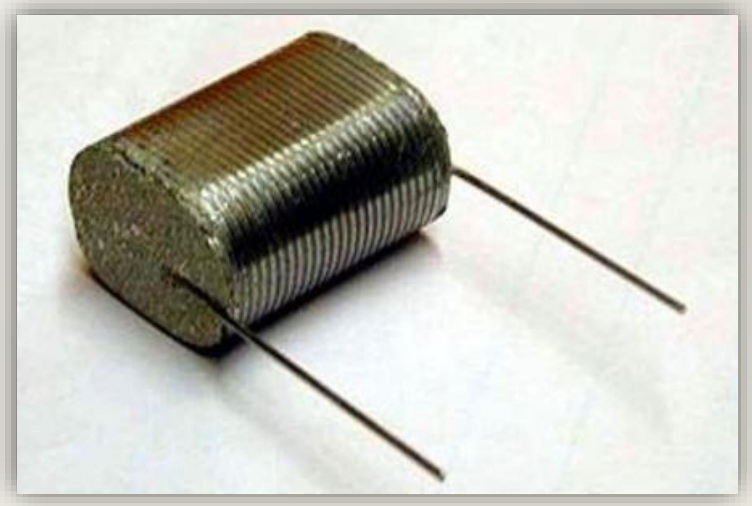
2.3. (Super) Capacitors

- Small capacitors: 5 pF to 1 F
- Large capacitors: up to 100 mF
- $U = \frac{CV^2}{2} = \frac{QV}{2} = \frac{Q^2}{2C}$
- Common capacitor types:
  1. Film capacitors
  2. Ceramic capacitors
  3. Electrolytic capacitors

Film Capacitors:

- Fixed-value capacitors
- Tight capacitance tolerances
- Very low leakage currents
- Large sizes and weights
- AC or DC voltage



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2.3. (Super) Capacitors

Ceramic Capacitors:

- Fixed-value capacitors
- composition of the ceramic material
- AC voltage

Electrolytic Capacitors:

- Aluminum, tantalum, and niobium

Aluminum:

- Less than 1 mF to 1 F
- Up to several hundred DC volts
- More capacitance and energy storage per unit volume

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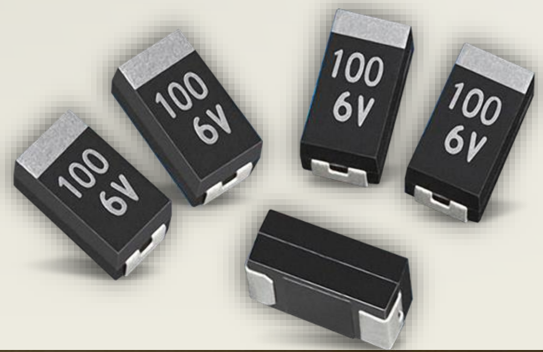
2.3. (Super) Capacitors

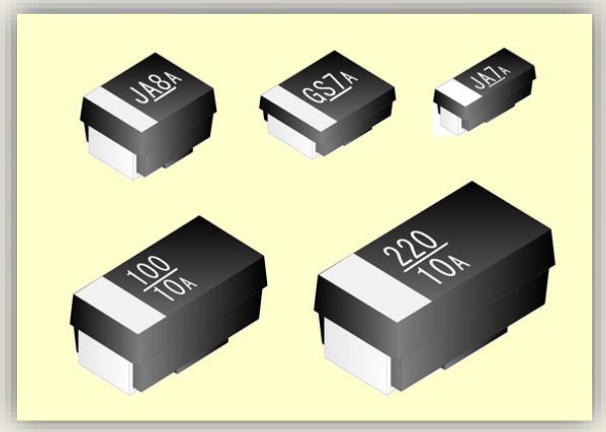
Tantalum:

- Low voltage
- Up to several hundred μF
- Smaller size → miniature applications
- Lower energy density



Niobium:

- Lower efficiency
- Lower voltage range
- Higher DC leakage



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	Aluminum	Tantalum	Niobium	Ceramic	Film
Dielectric	Aluminum oxide	Tantalum pentoxide	Niobium pentoxide	Based on barium titanate, etc.	Polyester, polypropylene, etc.
Shape	Screw terminal type, snap-in type, lead terminal type, chip type	Chip type, Dip type	Chip type	Chip type, Dip type	Dip type, case type for SMD
Advantages	Cheap, small-size and large-capacity	Small size and comparatively large capacitance, semi-permanent service life	Small size and comparatively large capacitance, semi-permanent service life	Small-size, no polarity	Good characteristics, can be made for low- to high-voltage applications, high reliability
Disadv.	Short service life in hot environment, large tolerance, polarized	Can be used with some voltage leeway, polarity	Can be used with some voltage leeway, polarity	Large changes in capacitance due to changes in temperature and DC voltage	Large outside dimensions

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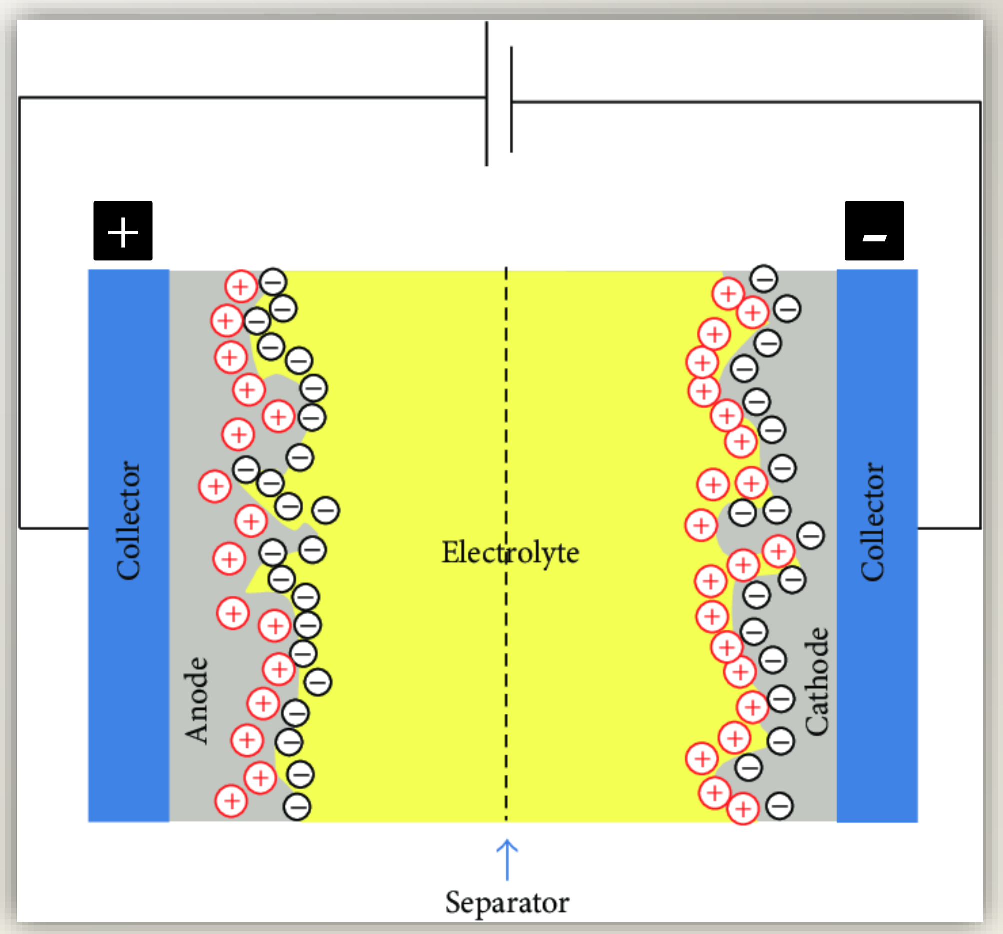
2.3. (Super) Capacitors

Electrochemical Capacitors* (EC):

- Energy storage application
- Low voltage (DC)
- Short-duration power bursts
- life cycles of half a million to several millions
- More power density but less energy density (vs batteries)



* = supercapacitors = ultracapacitors = electrochemical double-layer capacitors (EDLCs)

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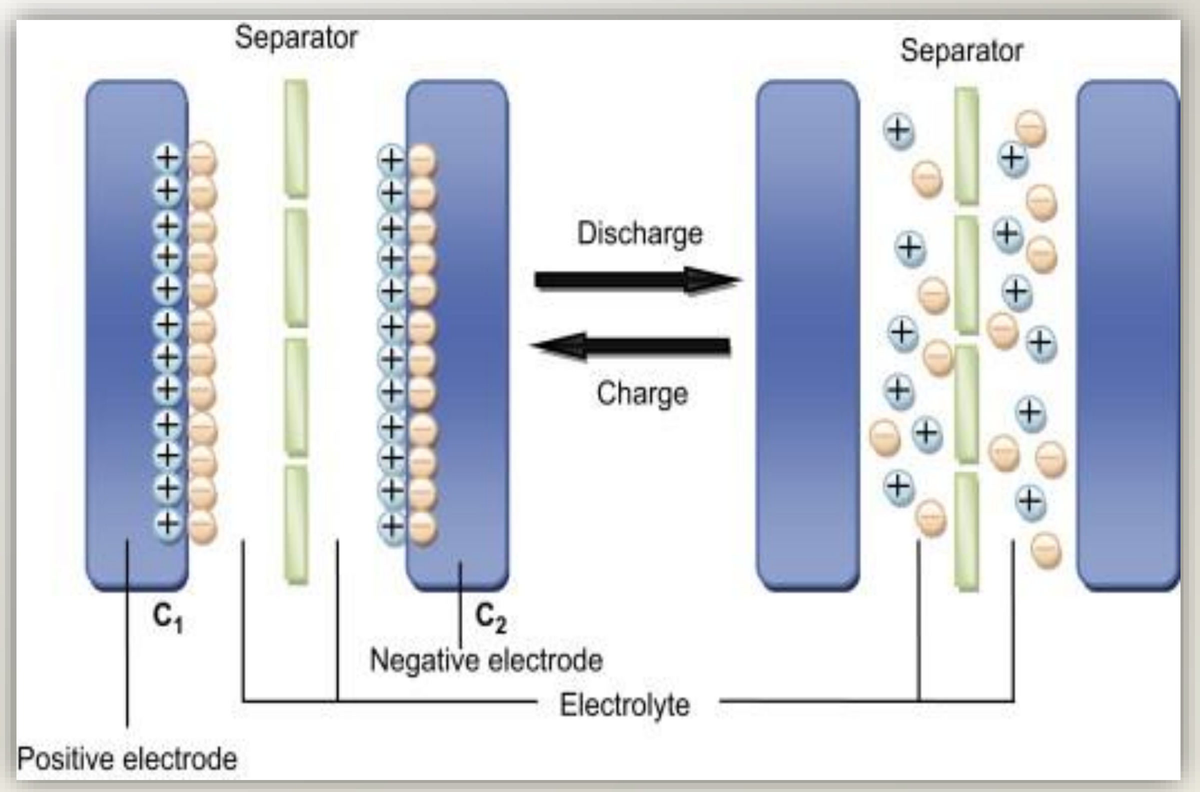
2.3. (Super) Capacitors

Charge:

1. Electrons move from the positive electrode to the negative one via the external power source
2. Ions from the electrolyte bulk move to the electrodes

Discharge:

1. Electrons move from the negative electrode to the positive one through the load
2. Ions return from the surface to the bulk of electrolyte



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2.3. (Super) Capacitors

Application:

1. Transmission lines: improve power transfer and enhance power quality and provide stability in voltage and frequency
2. UPS: combined with the storage batteries to provide power over short period of interruption (increase battery life)
3. Telecommunications: fast response, avoid interruption of the communication system
4. Diesel engines: hard to start up in cold weather, a bank of supercapacitor that isn't affected by low temp
5. Hybrid EVs: transient power demand → high power density → supercapacitors → battery life increase

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2.3. (Super) Capacitors

Advantages:

1. Long cycle life
2. Fast charge/discharge
3. Low impedance
4. Large power density
5. Maintenance free
6. Completely pollution free (environmentally friendly)
7. Explosion risk is minimal

Disadvantages:

1. Low energy density
2. High self-discharge rate
3. Need to be combined with other energy storage devices

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2.4. Mechanical Storage

2.4.1. Compressed air

2.4.2. Pumped hydro

2.4.3. Flywheel

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2.4.1. Compressed Air (CAES)

- Stores energy by pressurizing air into special containers or reservoirs
- Expands it in air turbines coupled with electrical generators
- Depleted oil/gas well, salt mine, Porous rocks, cavern reservoirs, aquifers
- Large-scale applications have greater heat losses
- Heat storage during compression (charge)
- Heat addition (stored heat) during discharge

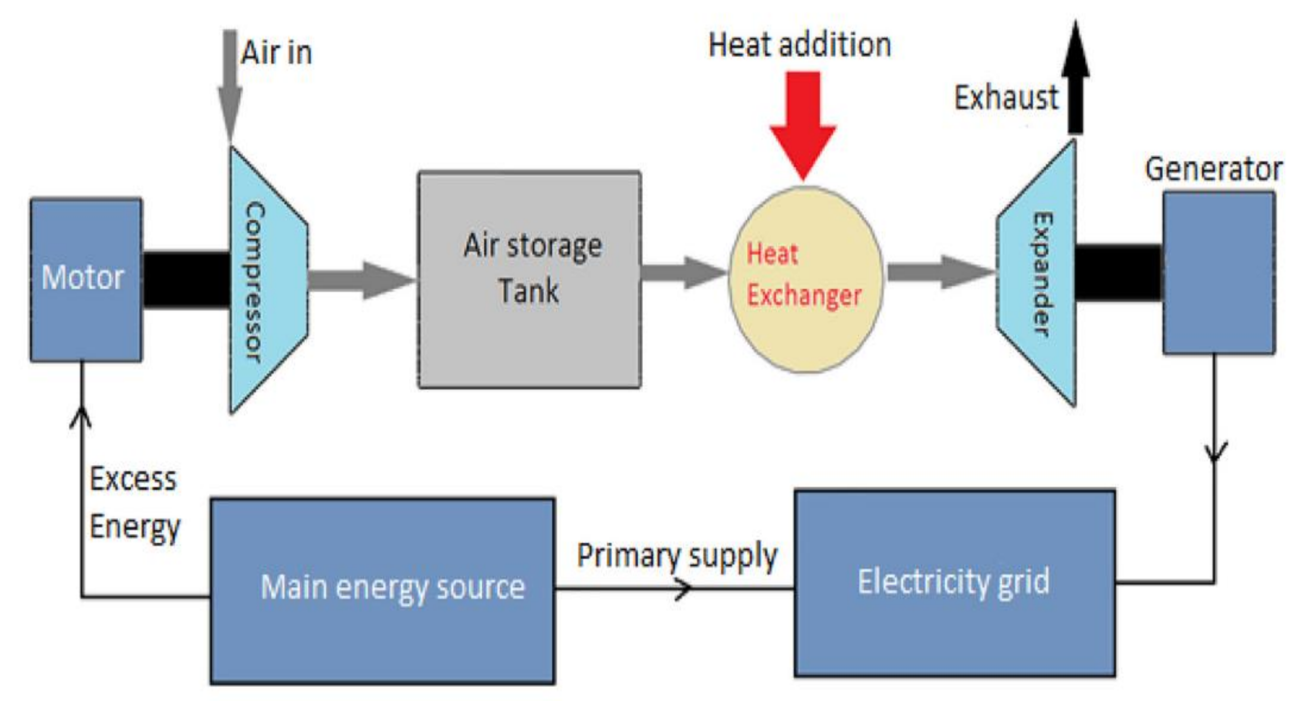

Fig. 8. Schematic diagram of a conventional CAES.

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2.4.1. Compressed Air (CAES)

Energy conversion in CAES:

1. Air compression
2. Heat extraction
3. Air & heat storage
4. Heat addition
5. Air to turbines

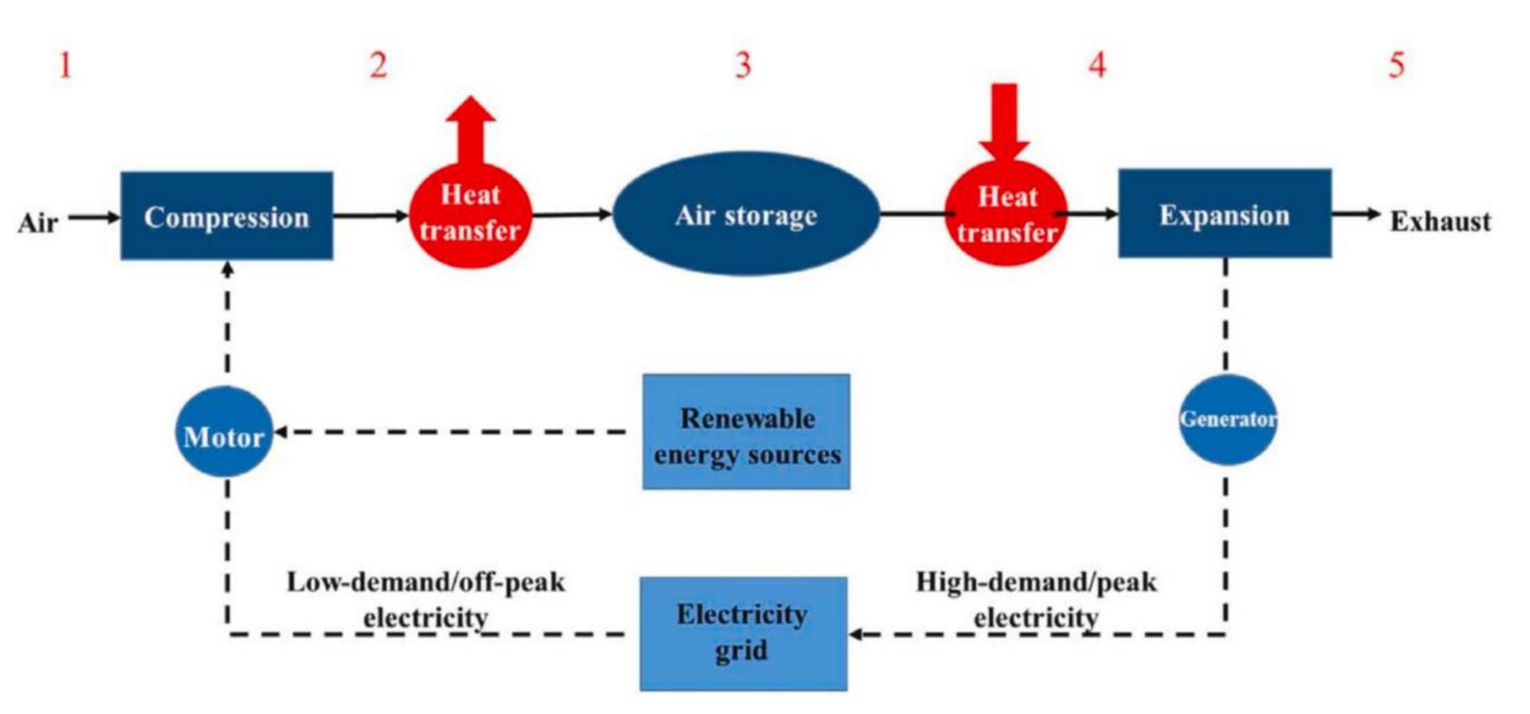

Fig. 4. Operational stages of CAES.

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2.4.1. Compressed Air (CAES)

CAES:

1. Large-scale ($\geq 100\ MW$)
2. Small-scale ($\leq\ 10\ kW$)

Small-scale

- Ideal
- RESs

Large-scale

- Grid app
- Load shifting
- Uninterrupted supply
- Accessible and impermeable cavern
- Modular canisters
- Efficiency: ≥ %90

CAES processes:

1. Adiabatic
2. Diabatic
3. Isothermal

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2.4.1. Compressed Air (CAES)

- ✓ In the development and demonstration stage
- ✓ Complex
- ✓ Low efficiency
- ✓ Construction costs
- ✓ Different hydrocarbons underground → potential fire hazard
- ✓ Turbine blade corrosion
- ✓ Long start-up time

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2.4.2. Pumped Hydro

- 96% of global storage power capacity
- 99% of global storage energy volume
- Water is pumped from a lower to an upper reservoir during times of low demand
- The stored energy is recovered during times of high demand
- Now : river-based in conjunction with hydroelectric generation
- Future : closed loop off-river pumped hydro systems

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2.4.2. Pumped Hydro

- Hydroelectricity since 1880
- Pumped hydro more than a century
- 1310 GW capacity in 2019
- 17% of electricity production in 2018
- Fast response (charge/discharge)
- Cheaper in large-scale
- Technical lifetime : 50-100 years
- Long storage periods (hours to weeks)

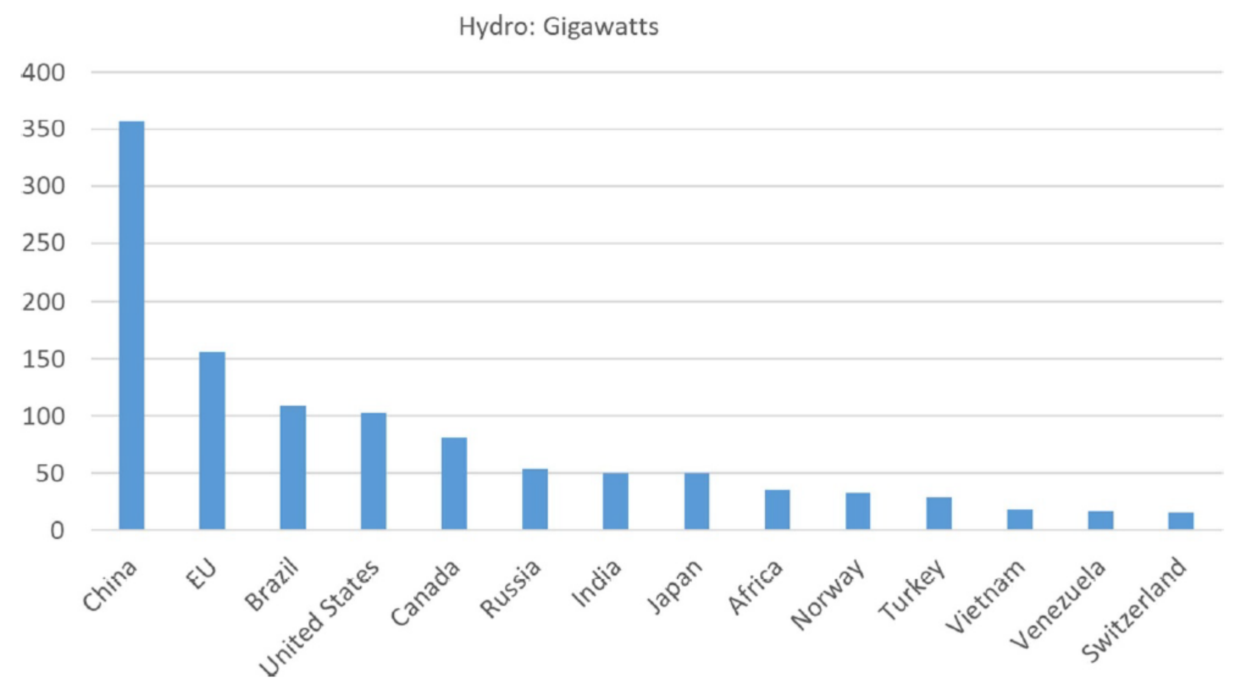

Figure 1. Hydropower capacity (Gigawatts) for selected countries and regions in 2019 [1].

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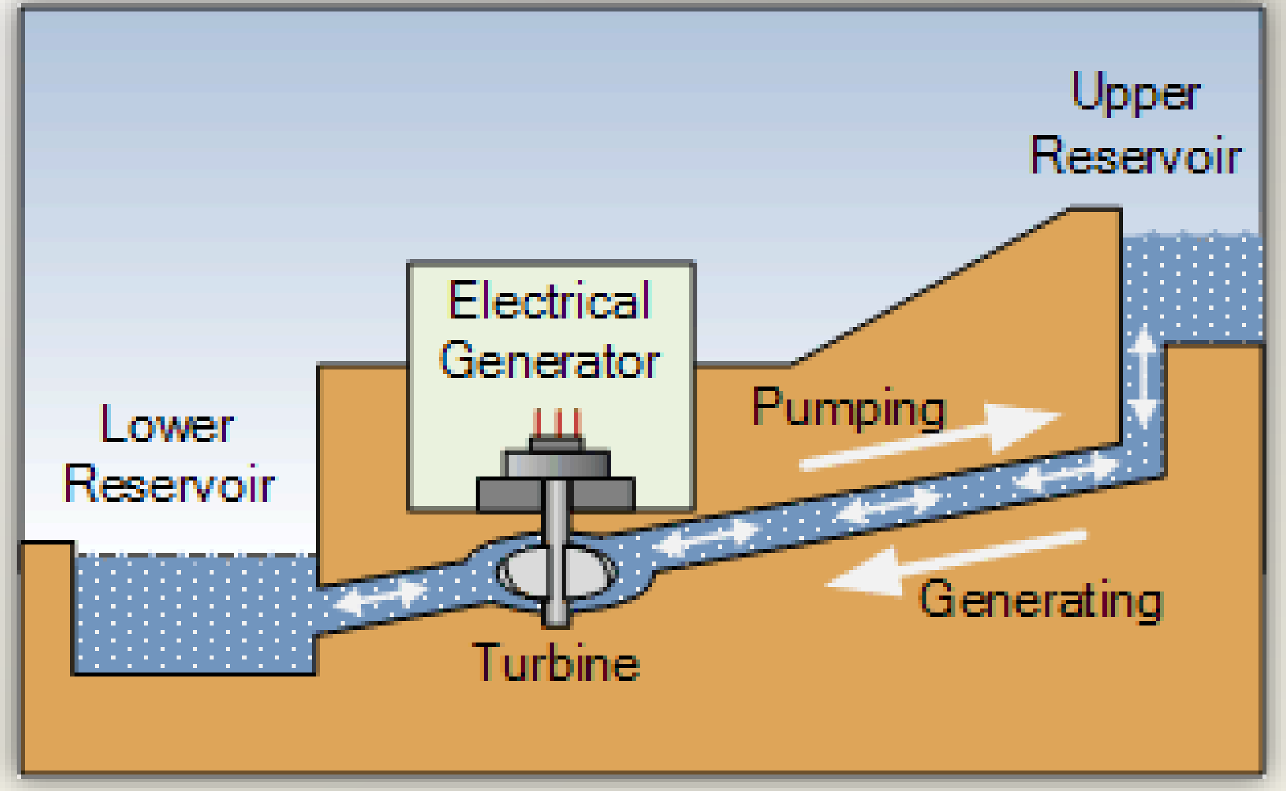
2.4.2. Pumped Hydro

1. The turbine spins in response to flow of high-pressure water
2. The generator spins to produce electricity
3. Electricity is sent to the switchyard for voltage transformation and transmission
4. The turbine & the generator acts reversely
5. Electricity is supplied to the generator
6. The generator and turbine spin in the reverse direction
7. Pump water from a lower to an upper reservoir



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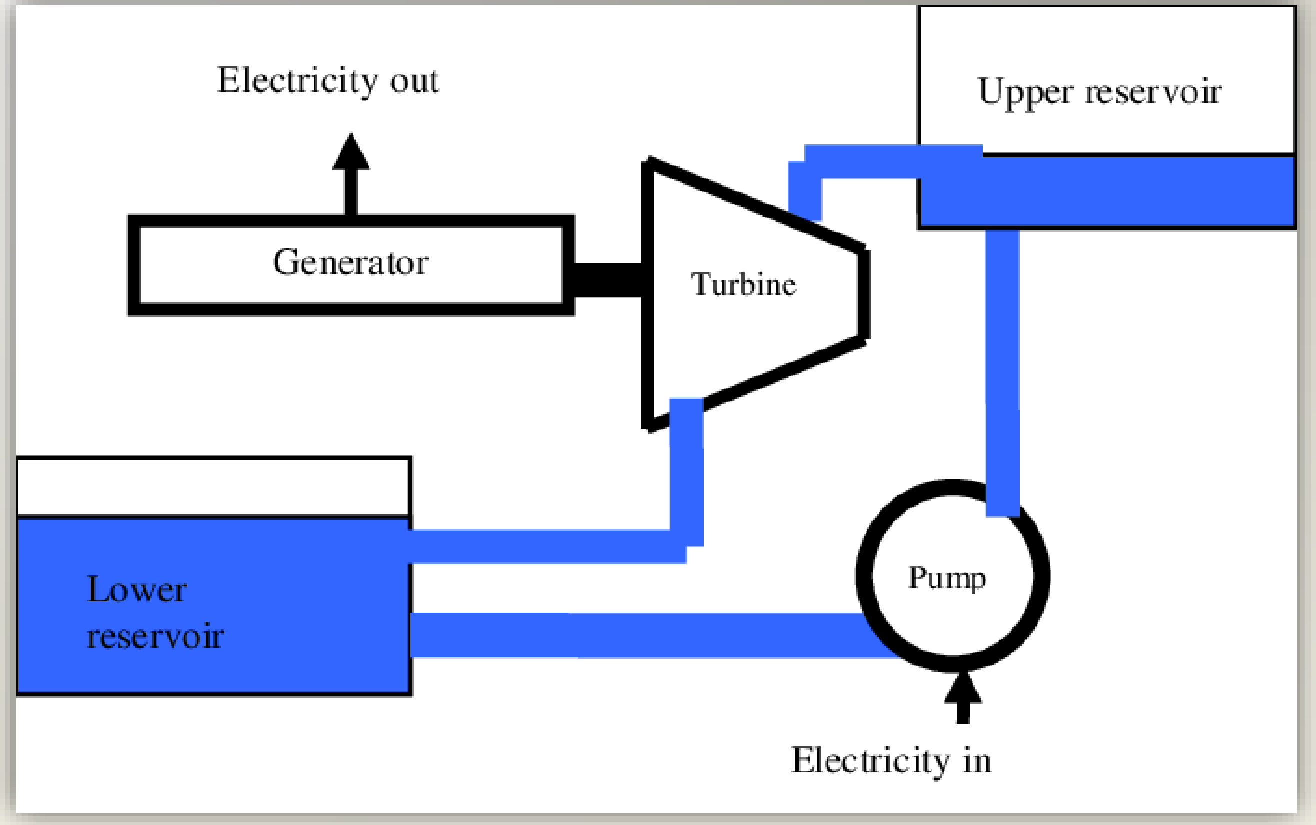
2.4.2. Pumped Hydro

- Sometimes the pump and the turbine are separate items of equipment, but more commonly they are combined
- The power capacity: the maximum rate of energy production
- The energy of a hydroelectric system: the amount of potential energy in the upper reservoir
- The head: the altitude difference between the water intake and the water egress (100-800m)



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2.4.2. Pumped Hydro

- $P = \eta \, \dot{m} \, g \, \Delta H$

P : power

η : generation efficiency (~ 90%)

$\dot{m}$: mass flow rate

ΔH : head

- Round-trip efficiency : ~ 80%
- Dams : earth, rock, concrete and including a layer that is impervious to water such as concrete, asphalt, clay, plastic or steel

Figure 9. Tumut 3 on-river hydroelectric system (Snowy Hydro Ltd). Reproduced with permission from Snowy Hydro Ltd.

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2.4.2. Pumped Hydro

River-based PHES*

- Almost all existing PHESs
- Lower reservoir : larger, substantial
- Upper reservoir : smaller, same river or in a high tributary or parallel valley
- Pumping : cheap electricity, low demand, excess power (solar, wind)
- Generation : high electricity price, high demand (evening)
- Arbitrage = buy-low and sell-high

*PHES = Pumped Hydro Energy Storage

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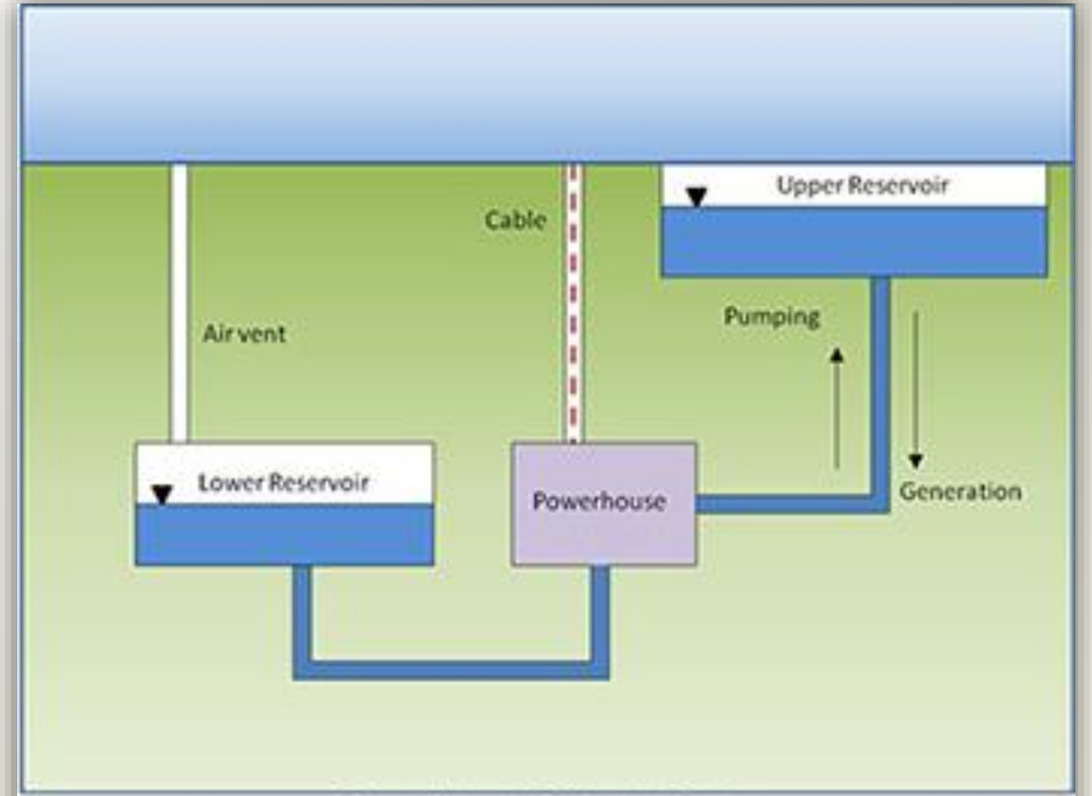
2.4.2. Pumped Hydro

(off-river/closed-loop/underground) PHES

- Environmental opposition to river-based PHESs
- Connect closely spaced existing reservoirs using underground tunnels and powerhouses
- Low disturbance at the surface
- Example: 2 Gigawatt, 350 Gigawatt-hour system, Australia
- Lower energy storage (than river-based)
- Faster construction
- Bigger heads
- More sites available



Source: University of Colorado at Boulder

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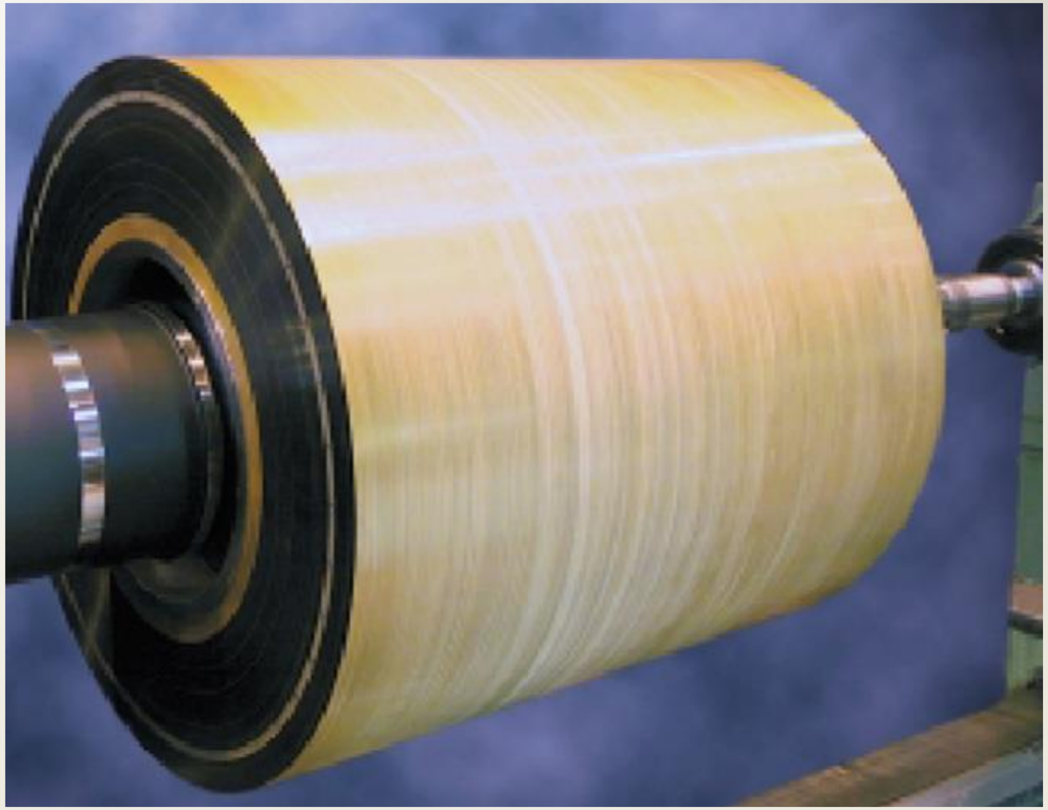
2.4.3. Flywheel

- Called mechanical battery
- Saves the kinetic energy in a high speed rotational disk
- First use of FW was to make fire
- High energy efficiency
- Fast response
- Low maintenance
- Long life-time
- environment-friendly
- Low-speed (< 6000 rpm) & high-speed (> 100,000 rpm)



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2.4.3. Flywheel

Low-speed flywheels:

- Hundreds of megawatts
- Implemented in high-energy physics facilities
- High reliability
- Rugged construction

High-speed flywheels:

- Faster response
- More efficient
- High energy density
- Low power rating*
- Harder to cool

Applications:

- Electric vehicle
- Railway
- Wind power system
- Hybrid power generation system
- Power network
- Marine
- Space

- *max input power allowed

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2.4.3. Flywheel

$$E = \frac{1}{2} J \omega^2$$

E : kinetic energy stored

J : moment of inertia

ω : angular velocity

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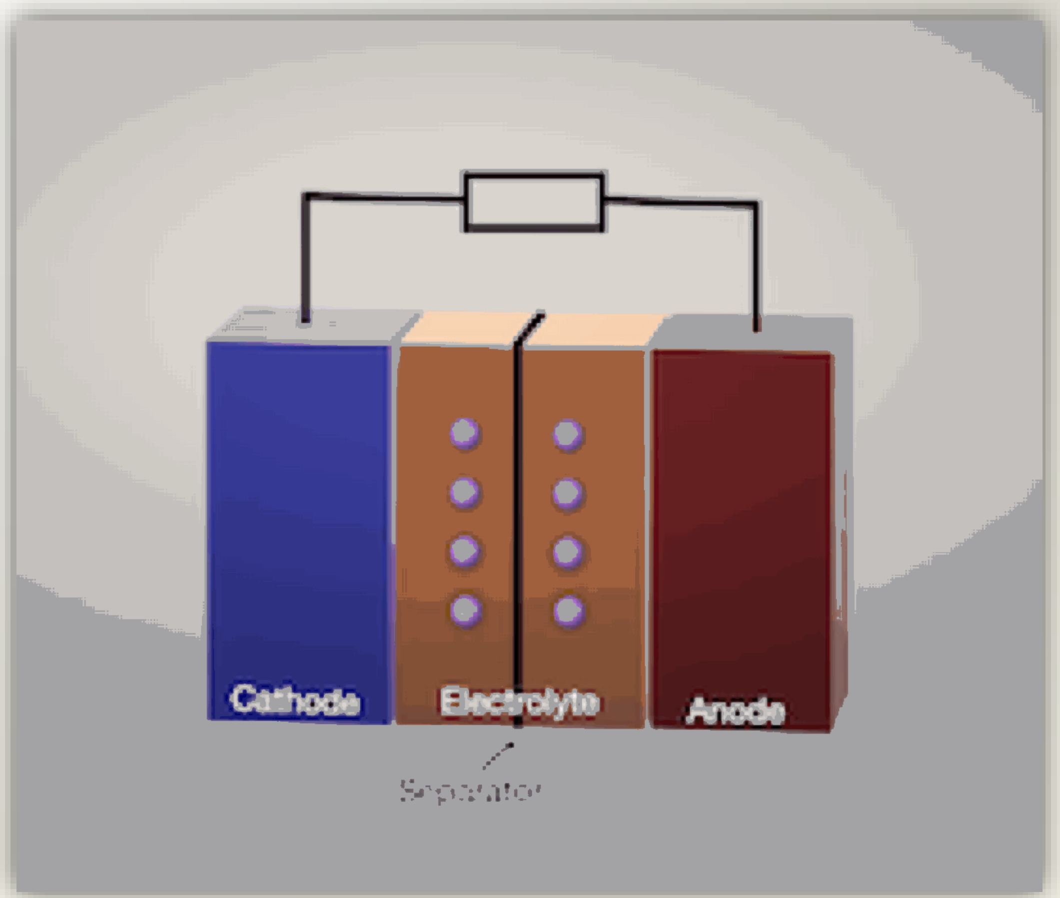
2.5. (Rechargeable) Battery

- Electrochemical devices
- = Galvanic cells
- lead-acid, NiCd, Li-ion, NaS
- Two electrodes (anode (+) & cathode(-))
- Electrolyte (ion conducting)
- Chemical reaction → electricity
- Each cell : 0.5 - 4 V → series connection → high voltage



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2.5. (Rechargeable) Battery

Applications :

- Automobiles (starting, lighting, ignition)
- Backup supply
- In-house transport vehicles
- Aircraft, submarine, military
- Renewable energy sources
- Hybrid/full EVs

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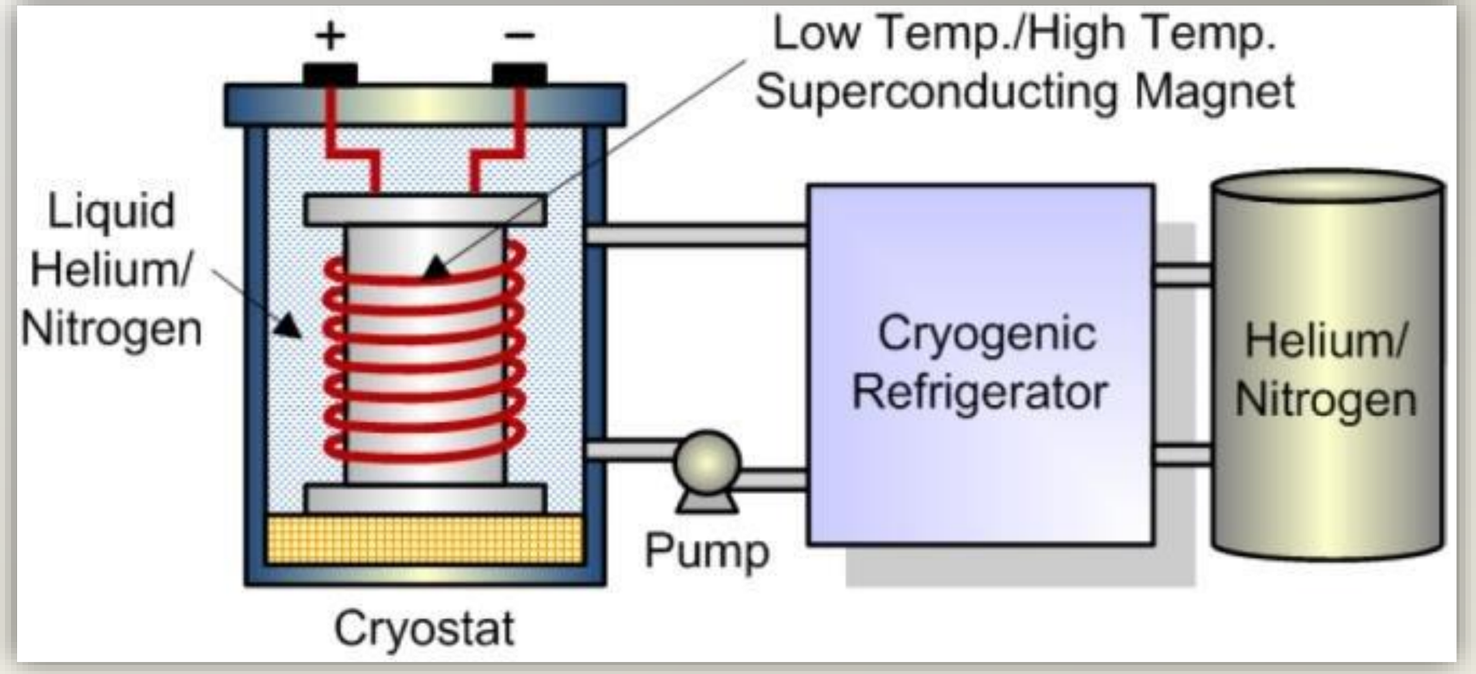
2.6. Superconducting Magnetic

- DC current across a coil
- Energy stored in magnetic field
- Superconductor → R ~ 0 → RI^2 ~ 0 → non-stop current
- High-speed charge/discharge
- High efficiency
- $\boldsymbol{U = \frac{LI^2}{2}}$, $\mathbf{L} = \boldsymbol{\frac{\mu A N^2}{l}}$



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2.6. Superconducting Magnetic

Applications :

- Backup device
- Micro grid
- Plug-in hybrid EVs
- RE sources

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References

1. Ahmed M. Elberry, et al, *Large-scale compressed hydrogen storage as part of renewable electricity storage systems*, International Journal of Hydrogen Energy, 2021 (Link)
2. Binjian Nie, et al, *Review on phase change materials for cold thermal energy storage applications*, Renewable and Sustainable Energy Reviews, 2021 (Link)
3. A.M. Foley, et al, *A long-term analysis of pumped hydro storage to firm wind power*, Applied Energy, 2015 (Link)
4. Amiryar ME, Pullen KR. *A Review of Flywheel Energy Storage System Technologies and Their Applications*, Applied Sciences, 2017 (Link)
5. Adeel Waqas, Zia Ud Din, *Phase change material (PCM) storage for free cooling of buildings—A review*, Renewable and Sustainable Energy Reviews, 2013 (Link)
6. Dave Olsthoorn, et al, *Abilities and limitations of thermal mass activation for thermal comfort, peak shifting and shaving: A review*, Building and Environment, 2017 (Link)

7. Wenjin Ding, Thomas Bauer, *Progress in Research and Development of Molten Chloride Salt Technology for Next Generation Concentrated Solar Power Plants*, Engineering, 2021 (Link)

8. A. Palacios, et al, *Thermal energy storage technologies for concentrated solar power – A review from a materials perspective*, Renewable Energy, 2020 (Link)

9. Edouard González-Roubaud, et al, *Review of commercial thermal energy storage in concentrated solar power plants: Steam vs. molten salts*, Renewable and Sustainable Energy Reviews, 2017 (Link)

10. Ming Liu, et al, *Review on concentrating solar power plants and new developments in high temperature thermal energy storage technologies*, Renewable and Sustainable Energy Reviews, 2016 (Link)

11. Fenil Desai, et al, *Thermochemical energy storage system for cooling and process heating applications: A review*, Energy Conversion and Management, 2021 (Link)

12. Zhiqiang Kang, et al, *Research Status of Ice-storage Air-conditioning System*, Procedia Engineering, 2017 (Link)

13. Seyed Ali Ghoreishi-Madiseh, et al, *Ice versus battery storage; a case for integration of renewable energy in refrigeration systems of remote sites*, Energy Procedia, 2019 (Link)

14. Linbin Zeng, et al, *Design and experimental performance of an off-grid ice storage system driven by distributed wind energy*, Energy and Buildings, 2020 (Link)

15. Amin Sepehri, Brent Nelson, *Energy and emissions analysis of ice thermal energy storage in the western US*, Energy and Buildings, 2019 (Link)

16. Burcu Koçak, et al, *Review on sensible thermal energy storage for industrial solar applications and sustainability aspects*, Solar Energy, 2020 (Link)

17. Nasiru I. Ibrahim, et al, *Solar absorption systems with integrated absorption energy storage–A review*, Renewable and Sustainable Energy Reviews, 2018 (Link)

18. Geoffrey J. May, et al, *Lead batteries for utility energy storage: A review*, Journal of Energy Storage, 2018 (Link)

19. Edward Barbour, et al, *Adiabatic Compressed Air Energy Storage with packed bed thermal energy storage*, Applied Energy, 2015 (Link)

20. Marcus Budt, et al, *A review on compressed air energy storage: Basic principles, past milestones and recent developments*, Applied Energy, 2016 (Link)

21. Gayathri Venkataramani, et al, *A review on compressed air energy storage – A pathway for smart grid and polygeneration*, Renewable and Sustainable Energy Reviews, 2016 (Link)

22. Mehdi Jalili, et al, *Stochastic optimal operation of a microgrid based on energy hub including a solar-powered compressed air energy storage system and an ice storage conditioner*, Journal of Energy Storage, 2021 (Link)

23. Montaser Mahmoud, et al, *A review of mechanical energy storage systems combined with wind and solar applications*, Energy Conversion and Management, 2020 (Link)

24. Elby Titus, *Clean hydrogen energy*, International Journal of Hydrogen Energy, 2021 (Link)

25. Hari Bhakta Sharma, et al, *Downstream augmentation of hydrothermal carbonization with anaerobic digestion for integrated biogas and hydrochar production from the organic fraction of municipal solid waste: A circular economy concept*, Science of The Total Environment, 2020 (Link)

26. Ahmed Zayed AL Shaqsi, et al, *Review of energy storage services, applications, limitations, and benefits*, Energy Reports, 2020 (Link)

27. A.G. Olabi, et al, *Compressed air energy storage systems: Components and operating parameters – A review*, Journal of Energy Storage, 2021 (Link)

28. R. Saidur, et al, *A review on compressed-air energy use and energy savings*, Renewable and Sustainable Energy Reviews, 2010 (Link)

29. S. Shiva Kumar, V. Himabindu, *Hydrogen production by PEM water electrolysis – A review*, Materials Science for Energy Technologies, 2019 (Link)

30. Suratsawadee Anuphappharadorn, et al, *Comparison the Economic Analysis of the Battery between Lithium-ion and Lead-acid in PV Stand-alone Application*, Energy Procedia, 2014 (Link)

31. Furat Dawood, et al, *Hydrogen production for energy: An overview*, International Journal of Hydrogen Energy, 2020, (Link)

32. Samuel Wicki, Erik G. Hansen, *Clean energy storage technology in the making: An innovation systems perspective on flywheel energy storage*, Journal of Cleaner Production, 2017 (Link)

33. Ahmed M. Elberry, et al, *Large-scale compressed hydrogen storage as part of renewable electricity storage systems*, International Journal of Hydrogen Energy, 2021 (Link)

34. Amro M. Elshurafa, *The value of storage in electricity generation: A qualitative and quantitative review*, Journal of Energy Storage, 2020 (Link)

35. Bing Zhang, et al, *Progress and prospects of hydrogen production: Opportunities and challenges*, Journal of Electronic Science and Technology, 2021 (Link)

36. D.O. Akinyele, R.K. Rayudu, *Review of energy storage technologies for sustainable power networks*, Sustainable Energy Technologies and Assessments, 2014 (Link)

37. Yasaman Balali, Sascha Stegen, *Review of energy storage systems for vehicles based on technology, environmental impacts, and costs*, Renewable and Sustainable Energy Reviews, 2021 (Link)

38. N.A. Burton, et al, *Increasing the efficiency of hydrogen production from solar powered water electrolysis*, Renewable and Sustainable Energy Reviews, 2021 (Link)

39. Moslem Uddin, et al, *A review on peak load shaving strategies*, Renewable and Sustainable Energy Reviews, 2018, (Link)