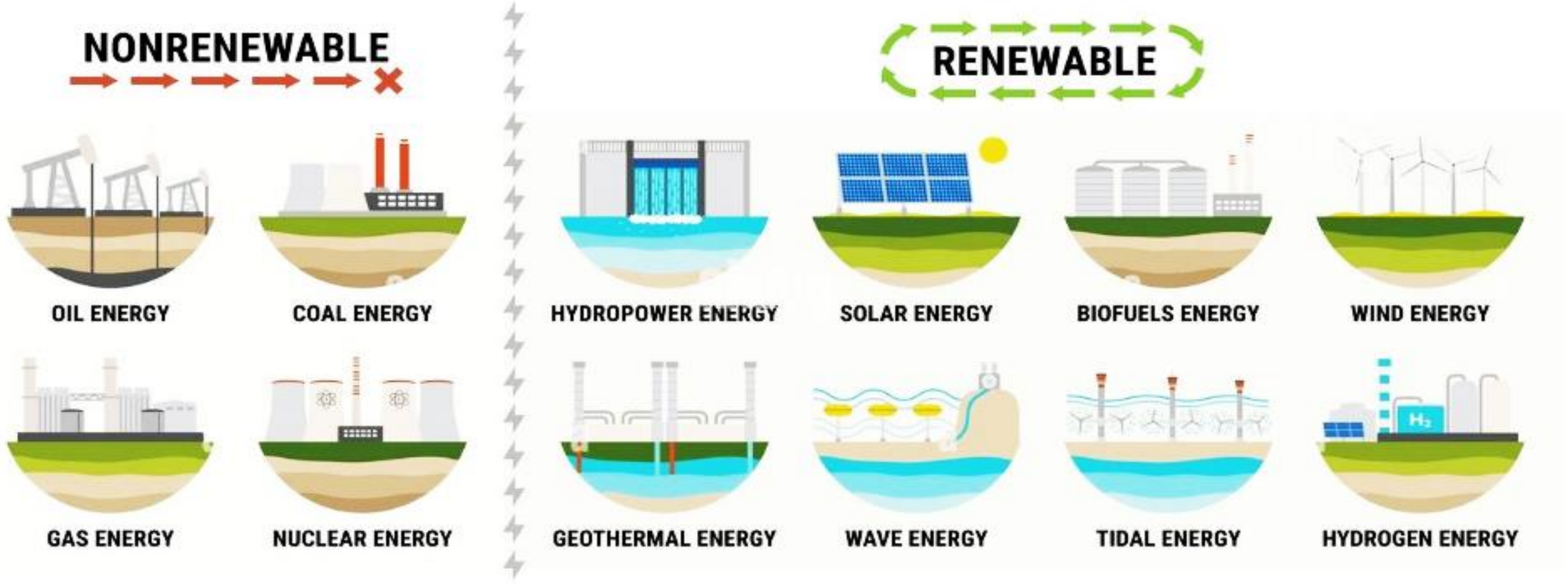
“TIIAME”
National Research University

ENERGY STORAGE METHODS AND DEVICES



Dilshod KODIROV
Professor, Doctor of Science

Head of the Department of Power Supply and Renewable Energy Sources

kodirov.dilshod@gmail.com
d.kodirov@tiiame.uz

INTRODUCTION

a. **Electrochemical Storage**: Batteries, such as lithium-ion, flow batteries, and emerging solid-state batteries, are key for grid and mobile applications. They are highly versatile and efficient but require material innovation to address cost and sustainability challenges.

b. **Thermal Energy Storage (TES)**: Systems like molten salts or phase change materials store heat or cold for later use, particularly useful in industrial processes and concentrated solar power plants.

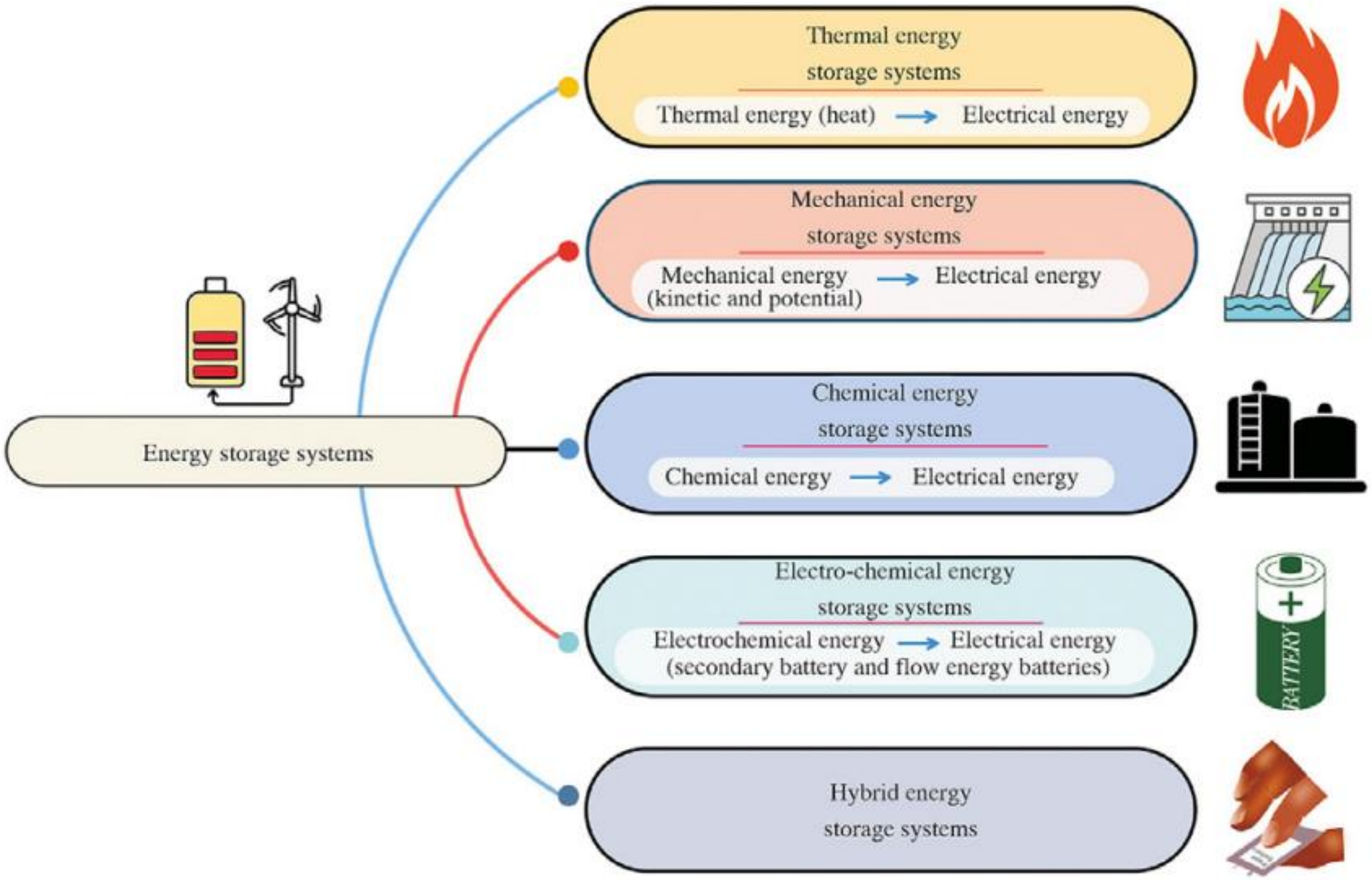
c. **Mechanical Storage:** Includes pumped hydro storage, flywheels, and compressed air energy storage. These methods excel in large-scale energy management with long lifespans and high cycle efficiency.

d. **Chemical Storage:** Hydrogen production and storage, such as in ammonia, serve both as an energy carrier and fuel for a hydrogen economy, vital for decarbonizing transport and industry.

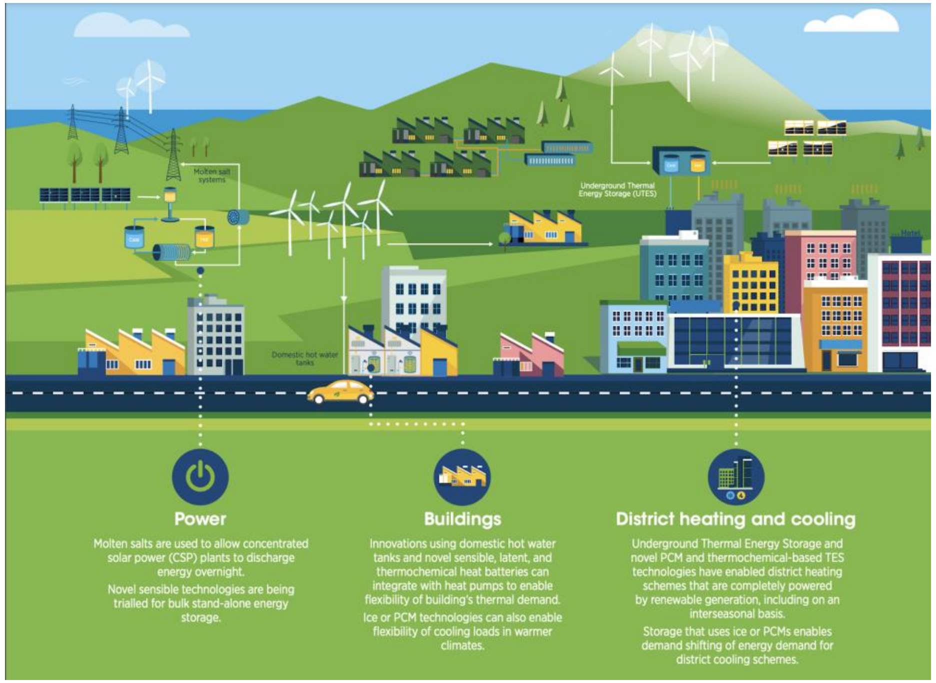
e. **Capacitors and Supercapacitors:** These offer rapid energy discharge capabilities, ideal for applications requiring quick power bursts like grid stabilization and electric vehicles.

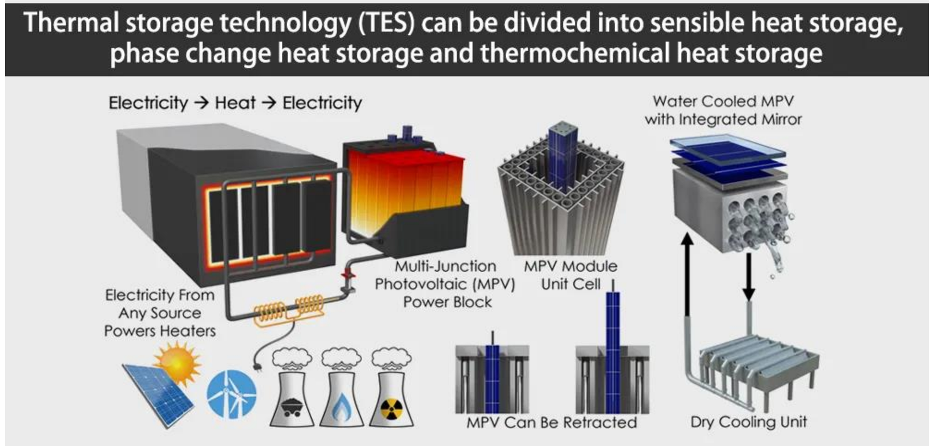
f. Recent developments include **hybrid systems** integrating multiple storage types and advanced materials for enhanced performance and reduced costs.

CLASSIFICATION OF MAJOR ENERGY STORAGE SYSTEMS



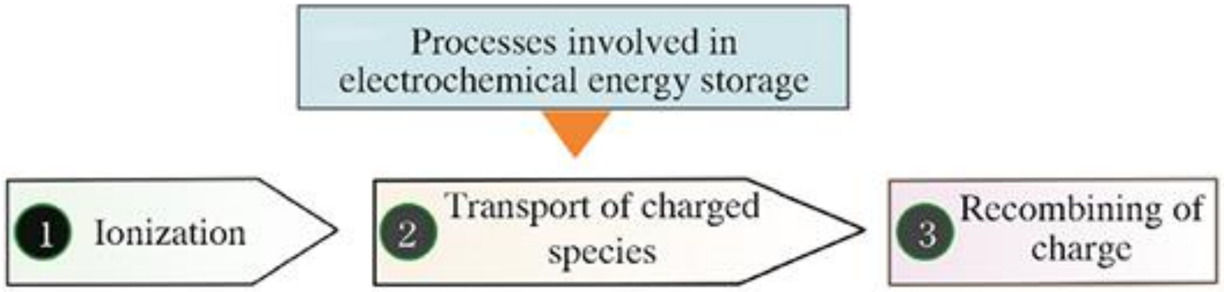
Source: http://www.keaipublishing.com/en/journals/energy-storage-and-saving/

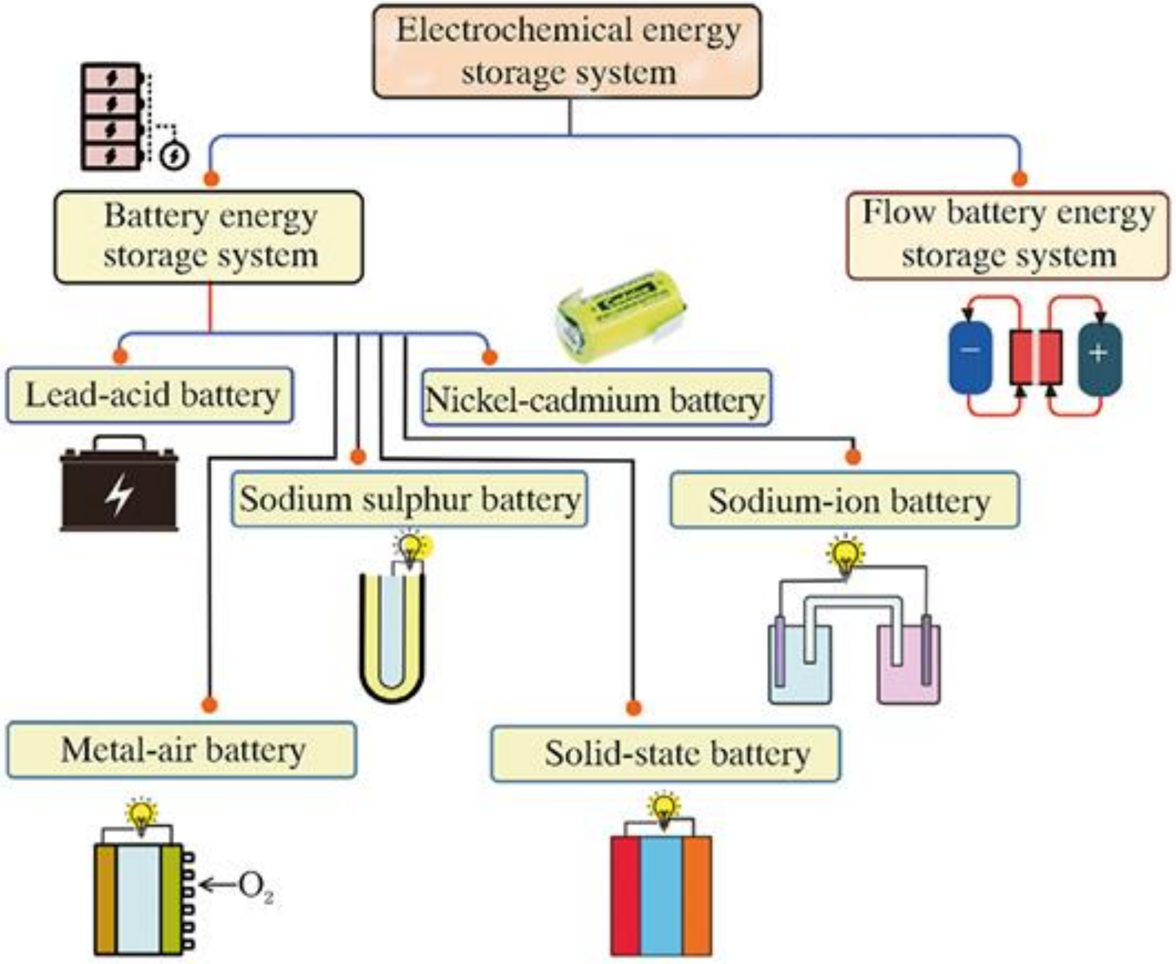




Source: https://www.weforum.org/stories/2021/04/renewable-energy-storage-pumped-batteries-thermal-mechanical/

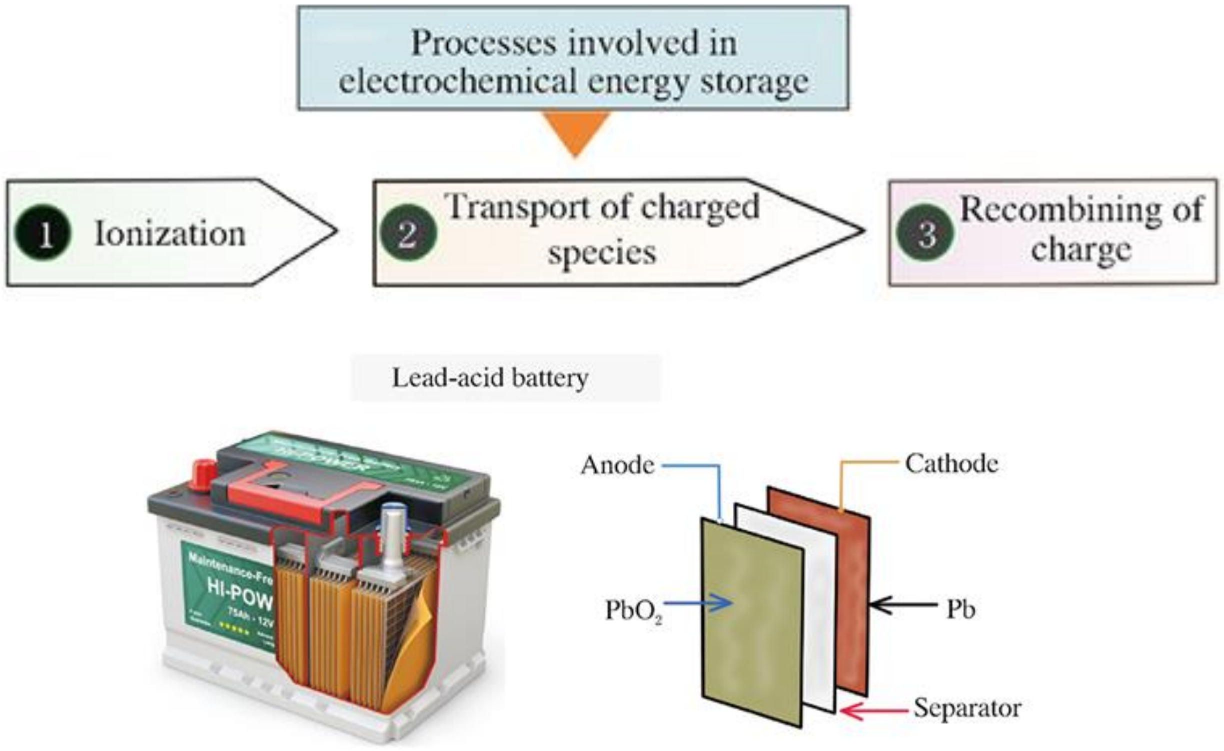
ELECTROCHEMICAL STORAGE



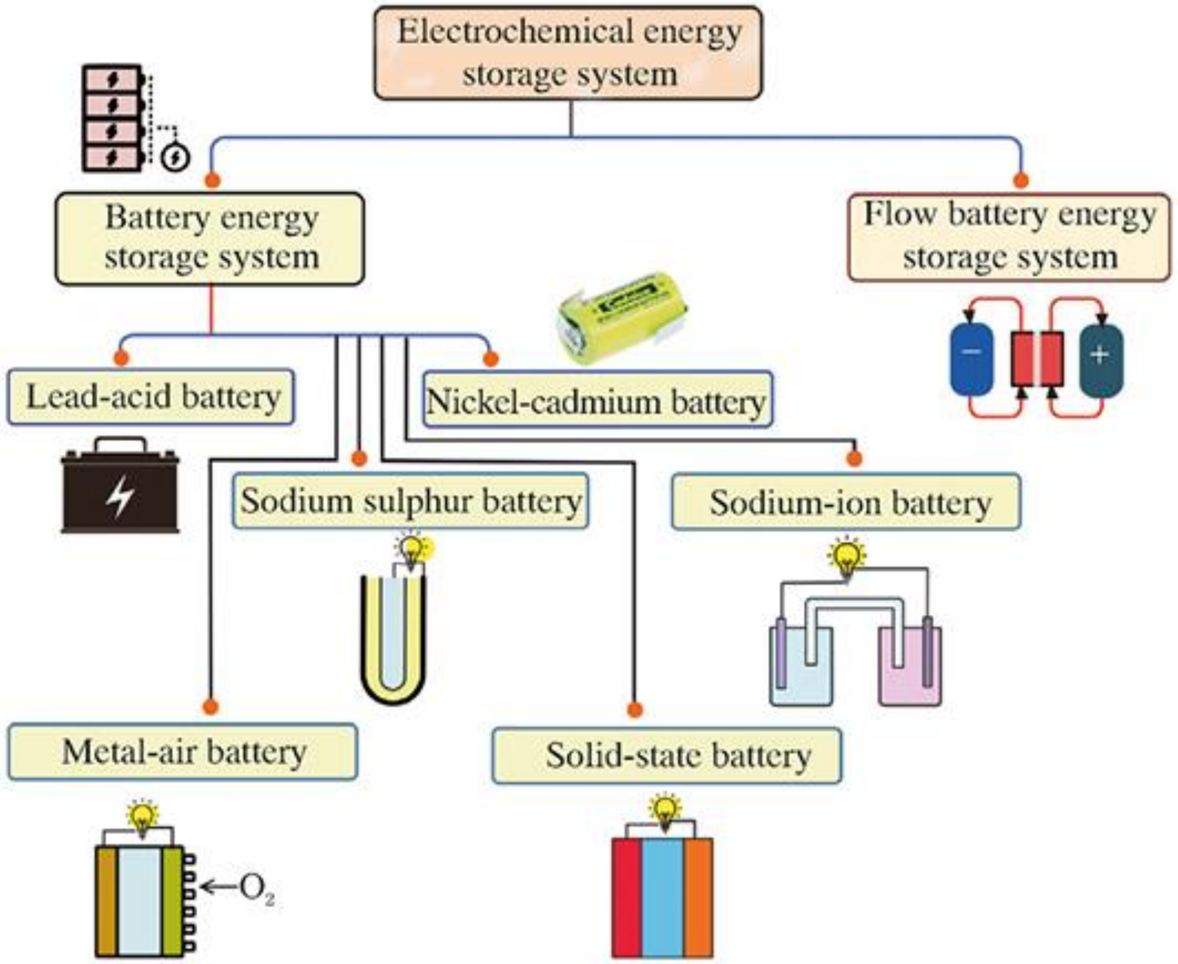


http://www.keaipublishing.com/en/journals/energy-storage-and-saving/

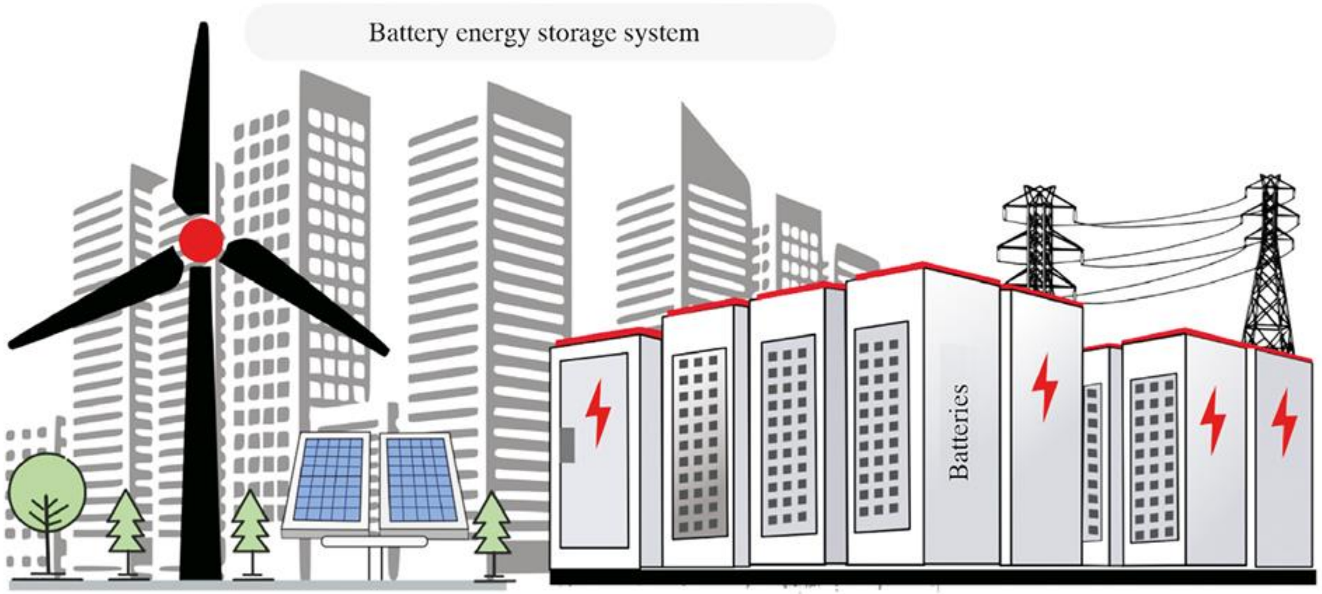
ELECTROCHEMICAL STORAGE

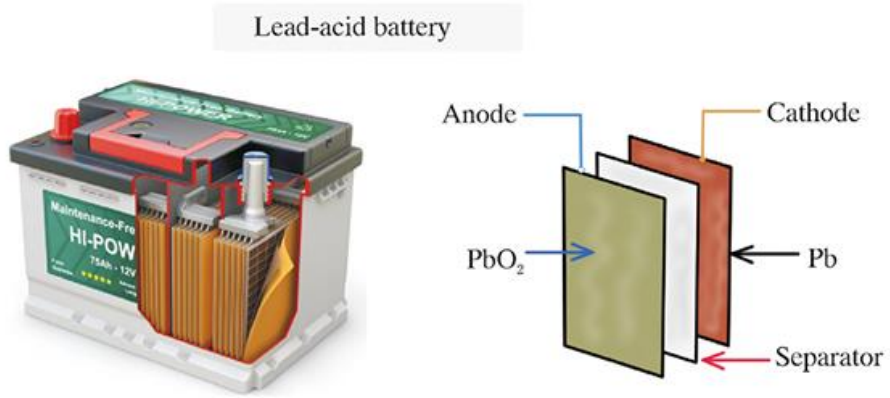


Principal components of a lead-acid battery. It is made up of an anode made of metallic sponge lead, a cathode made of lead dioxide and an electrolyte consisting of 37% sulphuric acid and 63% water.



http://www.keaipublishing.com/en/journals/energy-storage-and-saving/





Principal components of a lead-acid battery. It is made up of an anode made of metallic sponge lead, a cathode made of lead dioxide and an electrolyte consisting of 37% sulphuric acid and 63% water.

BATTERIES

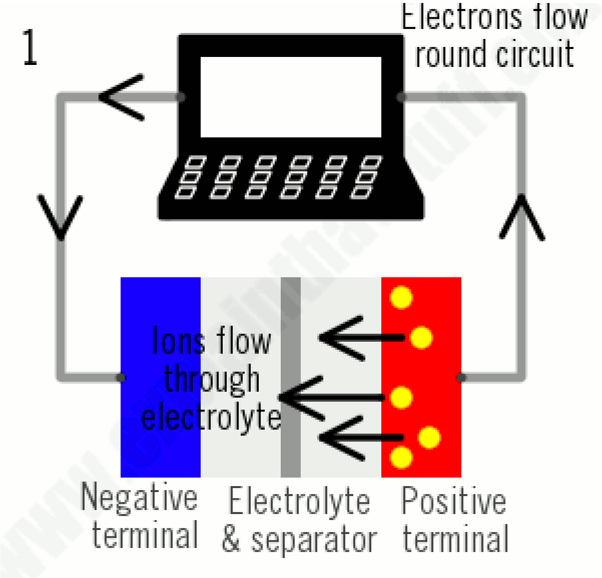
•**Lithium-Ion Batteries (LIBs)**: These are widely used due to their high energy density and versatility. However, challenges like safety risks (thermal runaway), material sourcing (lithium and cobalt), and recycling hurdles call for improvements. Research focuses on increasing stability and sustainability while reducing reliance on critical raw materials

•**Flow Batteries**: Particularly promising for grid-scale storage, these systems separate energy storage capacity from power output, making them ideal for long-duration storage. Vanadium is commonly used, but its high cost and supply chain issues have driven exploration of alternative chemistries. These alternatives must balance cost,

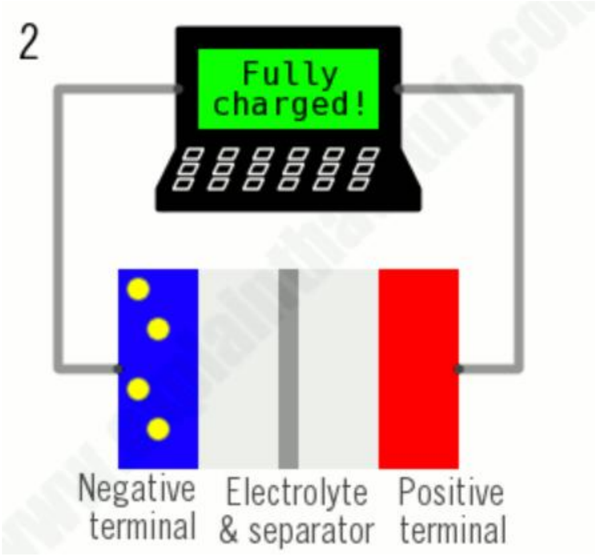
•stability, and scalability

•**Solid-State Batteries (SSBs)**: These represent a shift from liquid to solid electrolytes, enhancing safety by eliminating flammable materials. They also offer higher energy density and longevity, making them ideal for electric vehicles and grid storage. Research focuses on improving solid electrolytes and lithium-metal anodes to address interface compatibility and ionic conductivity challenges

LITHIUM-ION BATTERY



1. During charging, lithium ions flow from the positive electrode (red) to the negative electrode (blue) through the electrolyte (gray). Electrons also flow from the positive electrode to the negative electrode, but take the longer path around the outer circuit. The electrons and ions combine at the negative electrode and deposit lithium there.

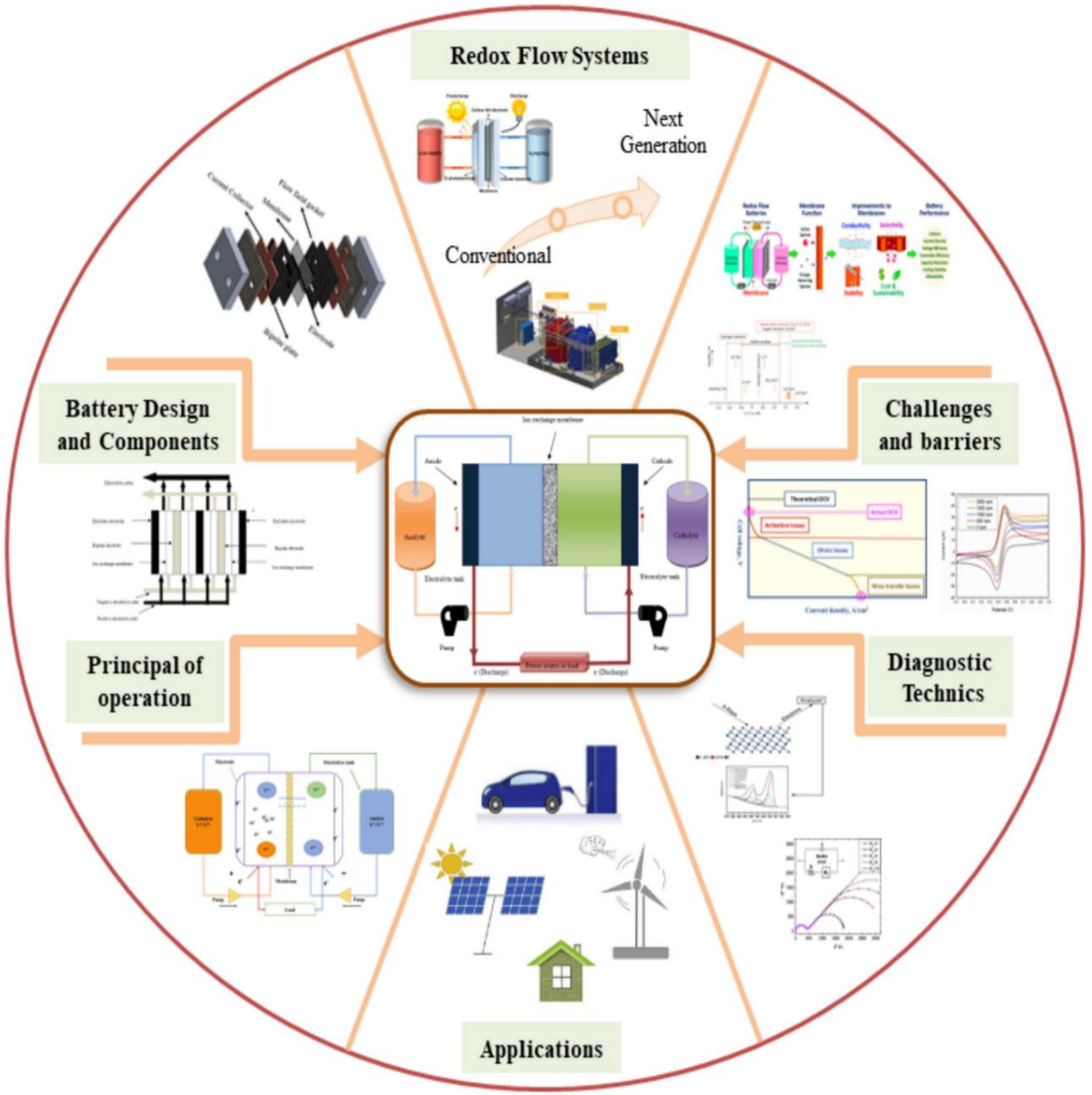


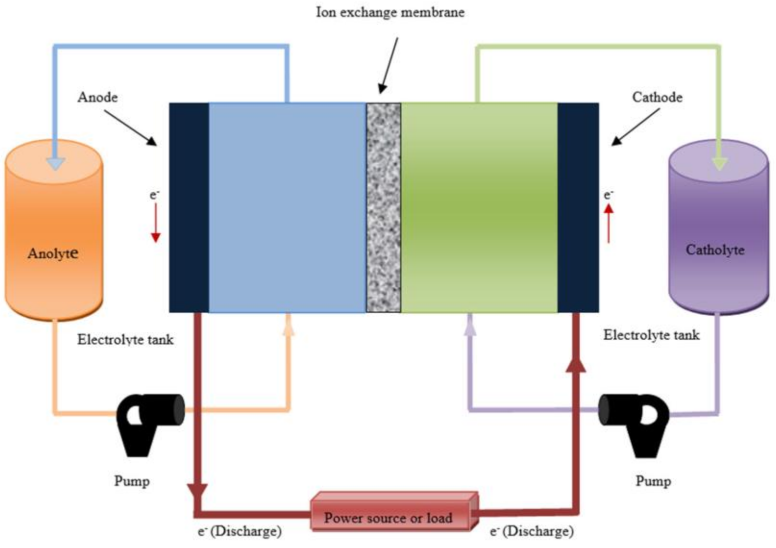
2. When no more ions will flow, the battery is fully charged and ready to use.

Lithium-ion battery is made of one or more power-generating compartments called **cells**. Each cell has essentially three components: a **positive electrode** (connected to the battery's positive or + terminal), a **negative electrode** (connected to the negative or − terminal), and an **electrolyte** in between them. The positive electrode is typically made from a chemical compound called **lithium-cobalt oxide** ($LiCoO_2$—often pronounced "lyco O2") or, in newer batteries, from **lithium iron phosphate** ($LiFePO_4$). The negative electrode is generally made from **carbon** (graphite) and the electrolyte varies from one type of battery to another

Lithium-ion batteries can also work at scale to store power produced by wind turbines and solar cells. Here's an experimental 1MWh battery storage

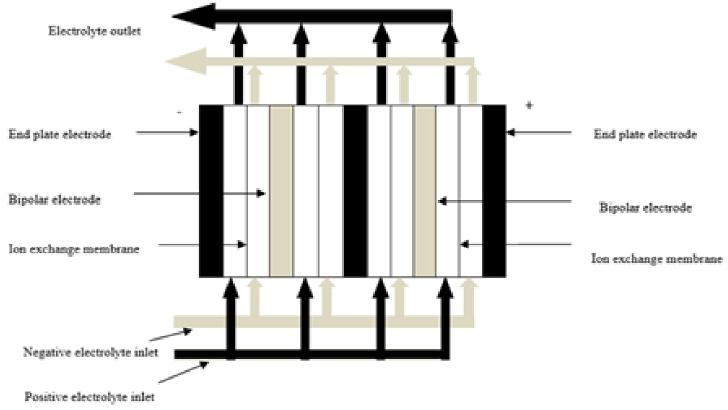
ENERGIES ON EARTH





(a)

(a) Schematic of a single cell RFB, depicting electrolyte flowing from storage tanks. The blue side (B^{m+}/B^{m+x}), the green side (A^{n}/A^{n-x}),

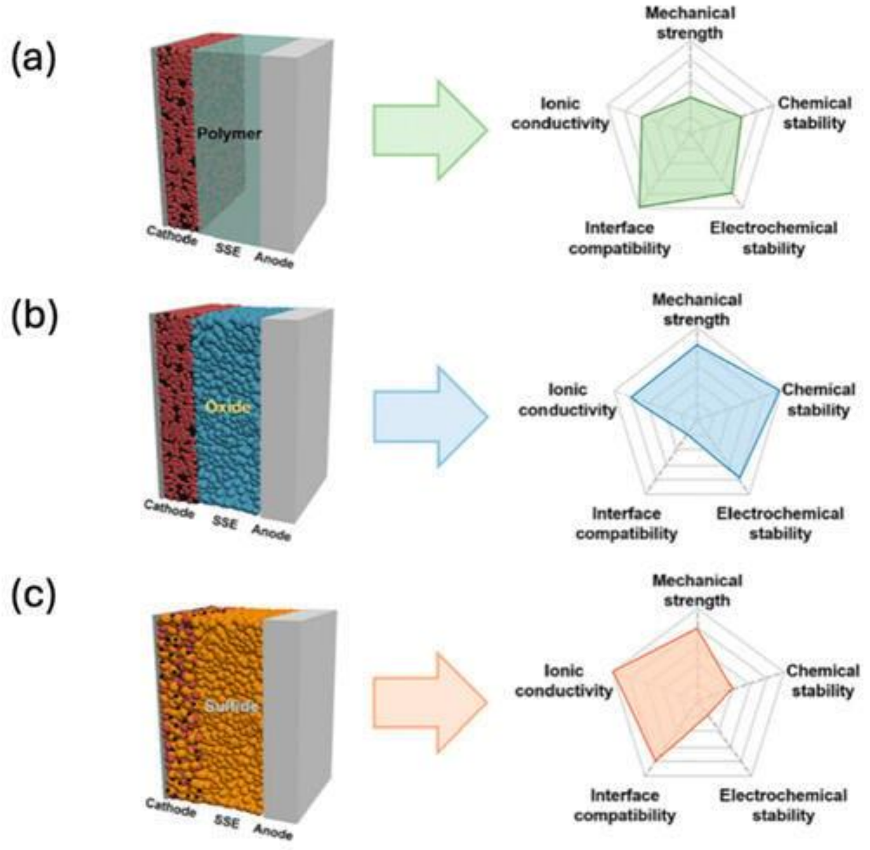


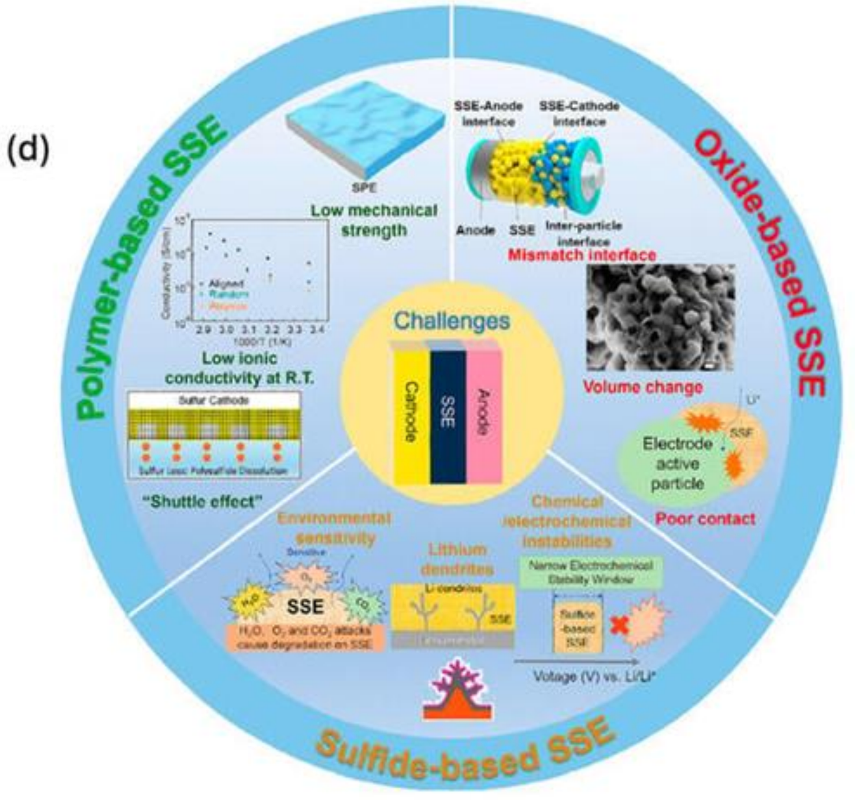
(b) Stack combined four redox flow cells accompanied by bipolar electrodes

SOLID-STATE BATTERIES (SSBS)

The different types of SSBs are categorized as follows:

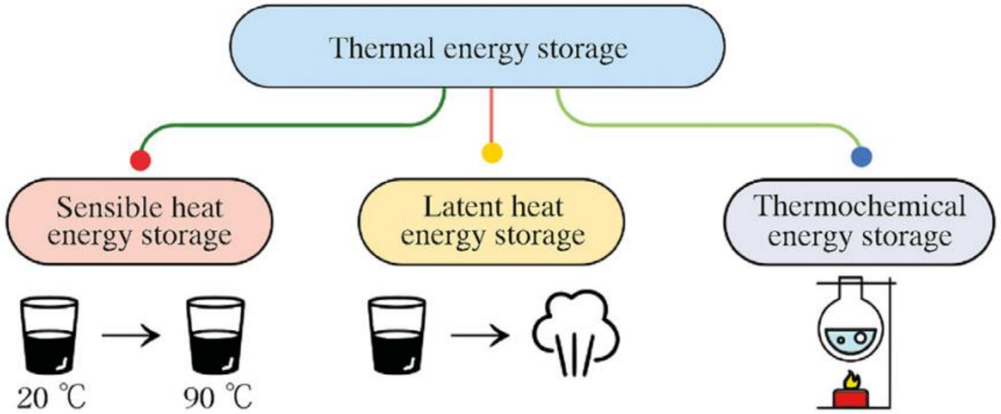
- Oxide Electrolytes: LIPON, NASICON, and Garnet Type;
- Sulfide Electrolytes: LPS and Argyrodites;
- Polymer Electrolytes;
- Halide Electrolytes;
- Composite Electrolytes;
- Hybrid Solid–Liquid Electrolytes.





Comparison of SSBs using polymer (a), oxide (b), and sulfide (c) SSEs; and the challenges for SSBs depending on the SSEs used (d).
Source: https://doi.org/10.3390/batteries10010029

THERMAL ENERGY STORAGE (TES)



TES systems: store heat energy by ***cooling, heating, melting, condensing, or vaporising a substance***.

TES systems USE: industrial cooling below –18 °C, building cooling between 0 and 12 °C, heating buildings between 25 and 50 °C and industrial heat storage over 175 °C [17].

TES systems:

✓**low temperature energy storage (LTES) system**

✓**high temperature energy storage (HTES) system**, based on the operating temperature of the energy storage material in relation to the ambient temperature .

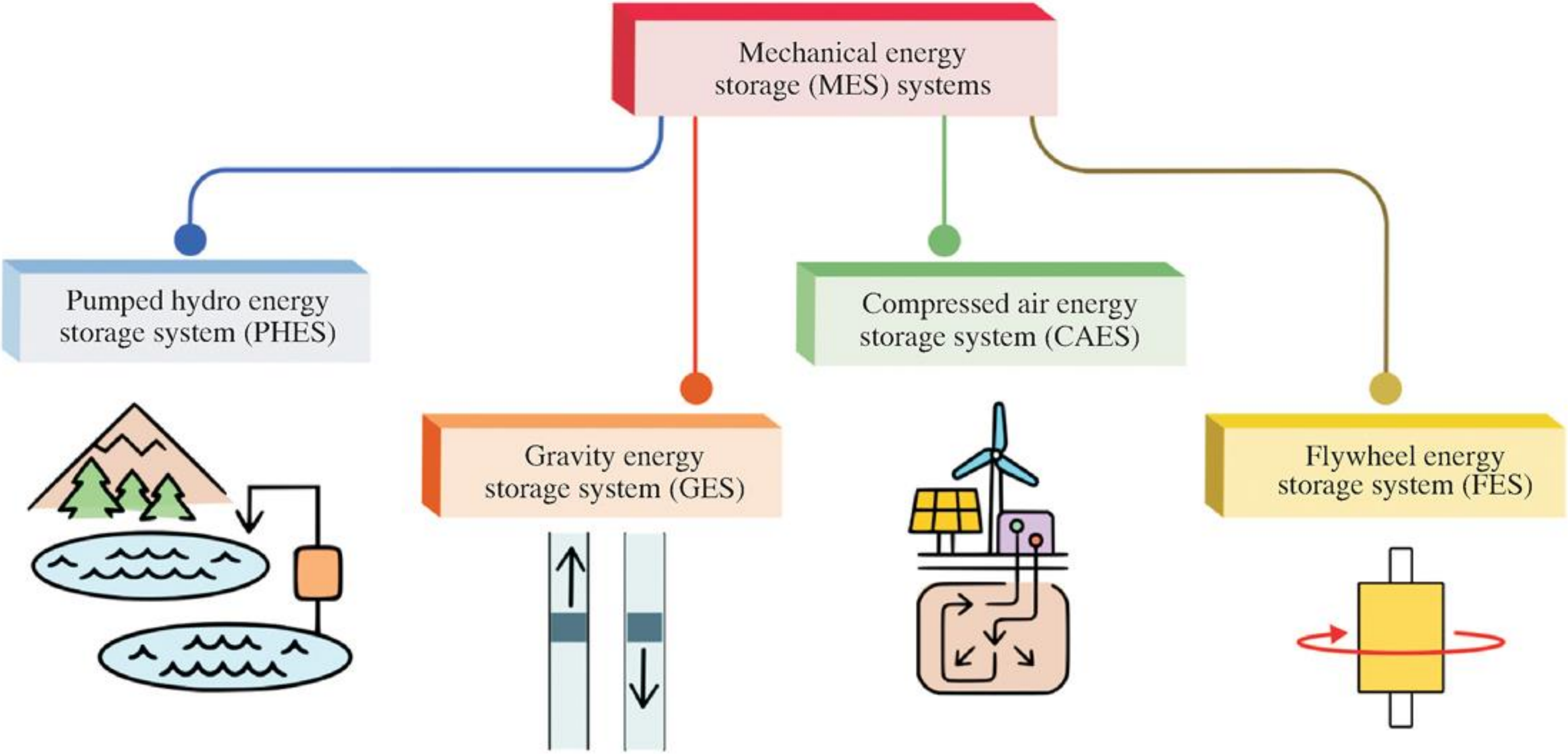
LTES is made up of two components: aquiferous low-temperature TES (ALTES) and cryogenic energy storage.

In ALTES, water is cooled/iced using a refrigerator during low-energy demand periods and is later used to provide the cooling requirements during peak energy demand periods. In cryogenic energy storage, the cryogen, which is primarily liquid nitrogen or liquid air, is boiled using heat from the surrounding environment and then used to generate electricity using a cryogenic heat engine.

LTES is better suited for high power density applications such as load shaving, industrial cooling and future grid power management

http://www.keaipublishing.com/en/journals/energy-storage-and-saving/

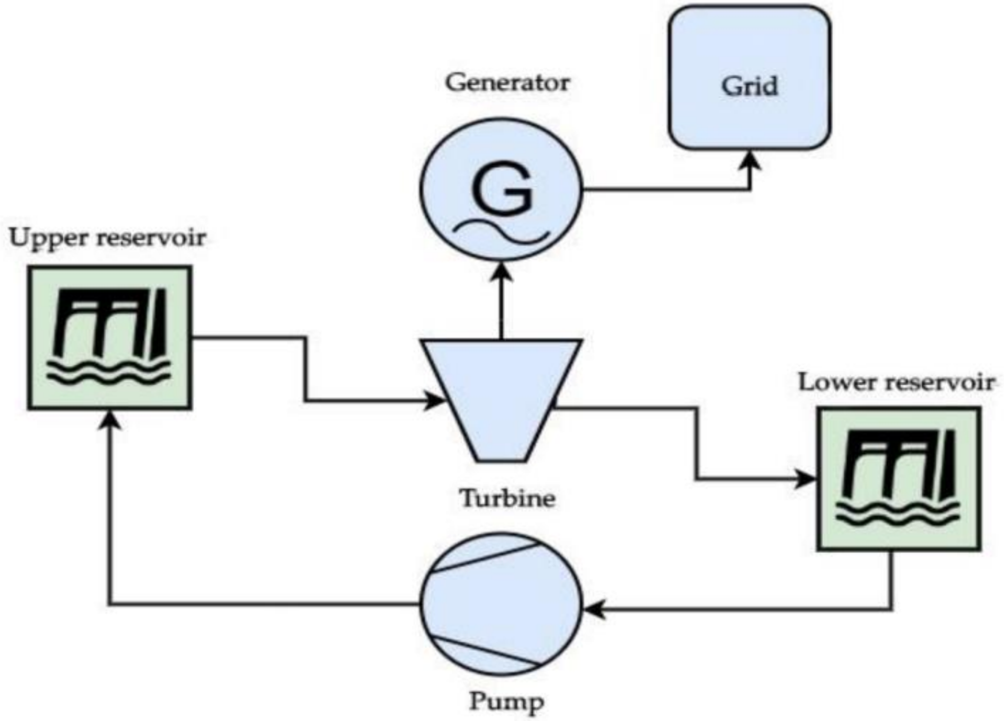
MECHANICAL STORAGE

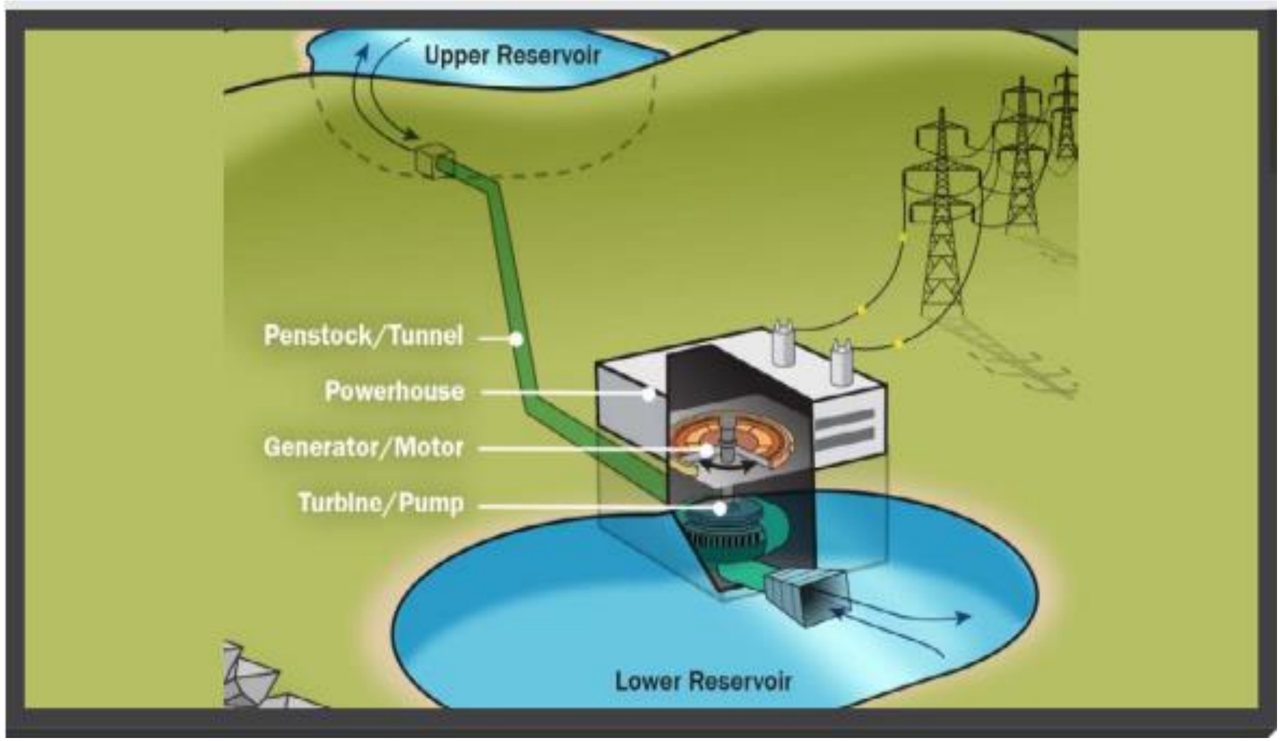


Classification of mechanical energy storage systems

PUMPED HYDRO STORAGE (PHS)

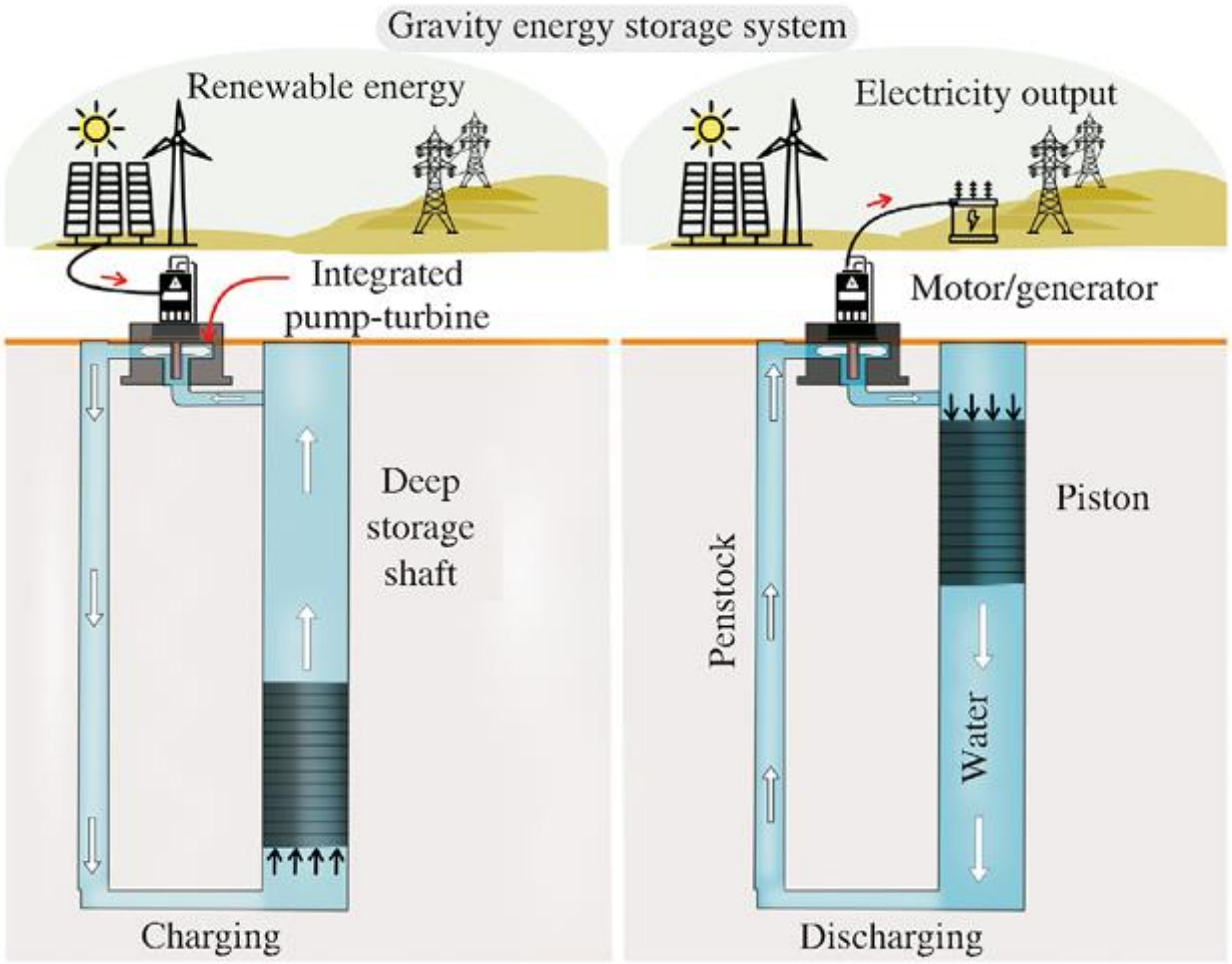
- **Principle**: PHS uses **gravitational potential energy by pumping water to an elevated reservoir during low-demand periods and releasing it through turbines to generate electricity during peak demand.**
- **Applications**: Long-term storage for grid stabilization, especially in regions with significant elevation differences.
- **Efficiency**: Round-trip efficiency ranges between 70-85%.
- **Novel Variants**: Coastal PHS systems, like STENSEA, employ the ocean floor for reservoirs, utilizing underwater turbines





Novel mechanical energy storage methods https://lutpub.lut.fi/bitstream/handle/10024/167409/; https://netl.doe.gov/sites/default/files/2021-02/Mechanical_Storage.pdf

ENERGIES ON EARTH



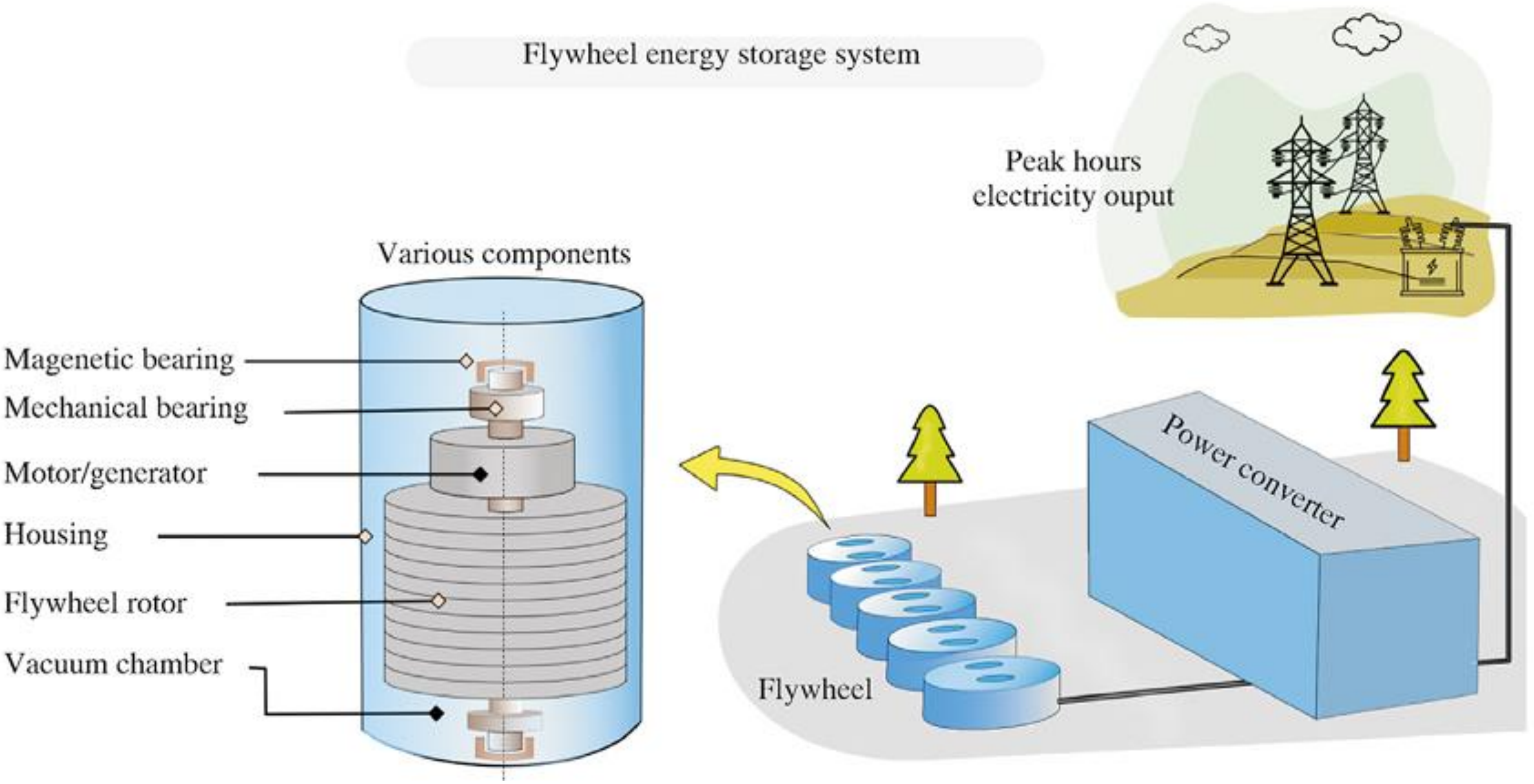
Working principle of gravity power module:

Surplus energy is stored during the charging cycle by pumping water to elevate the piston, and excess energy is released during the discharging cycle by pushing water through the turbine, which spins the generator and provides required energy

Energy Storage and Saving 1 (2022) 166–216

FLYWHEEL ENERGY STORAGE

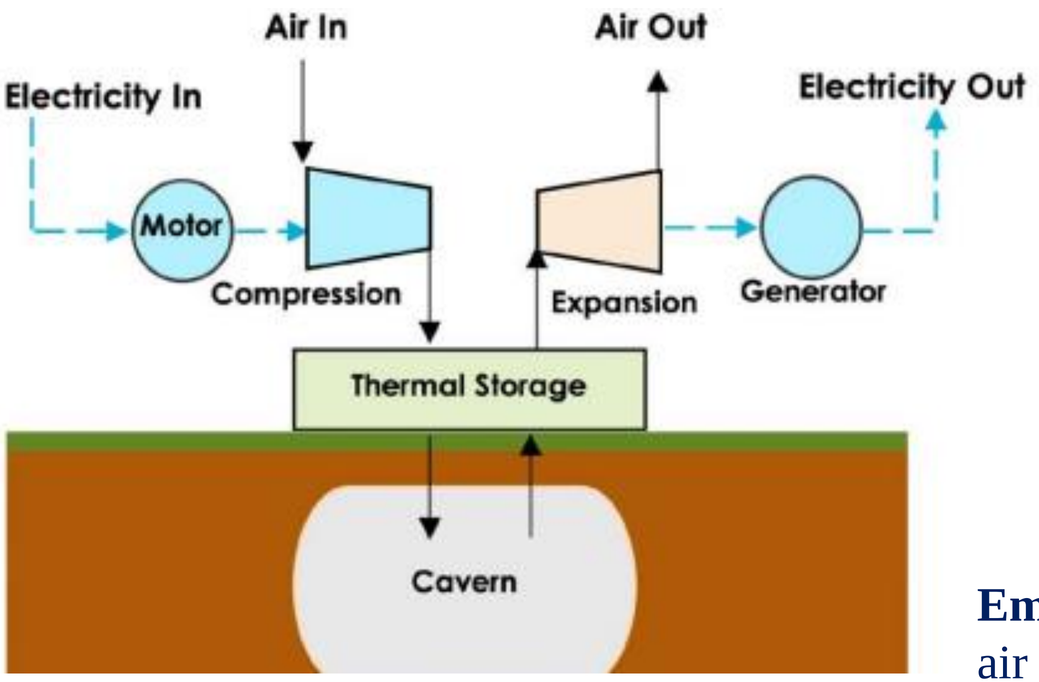
- **Principle**: Flywheels store energy as **rotational kinetic energy in a spinning mass. Energy is retrieved through regenerative braking.**
- **Applications**: Ideal for short-term energy balancing, grid stability, and backup power for rapid response scenarios.
- **Benefits**: High power output, rapid response times, and long service life (millions of cycles). However, energy retention is limited to a few hours due to frictional losses

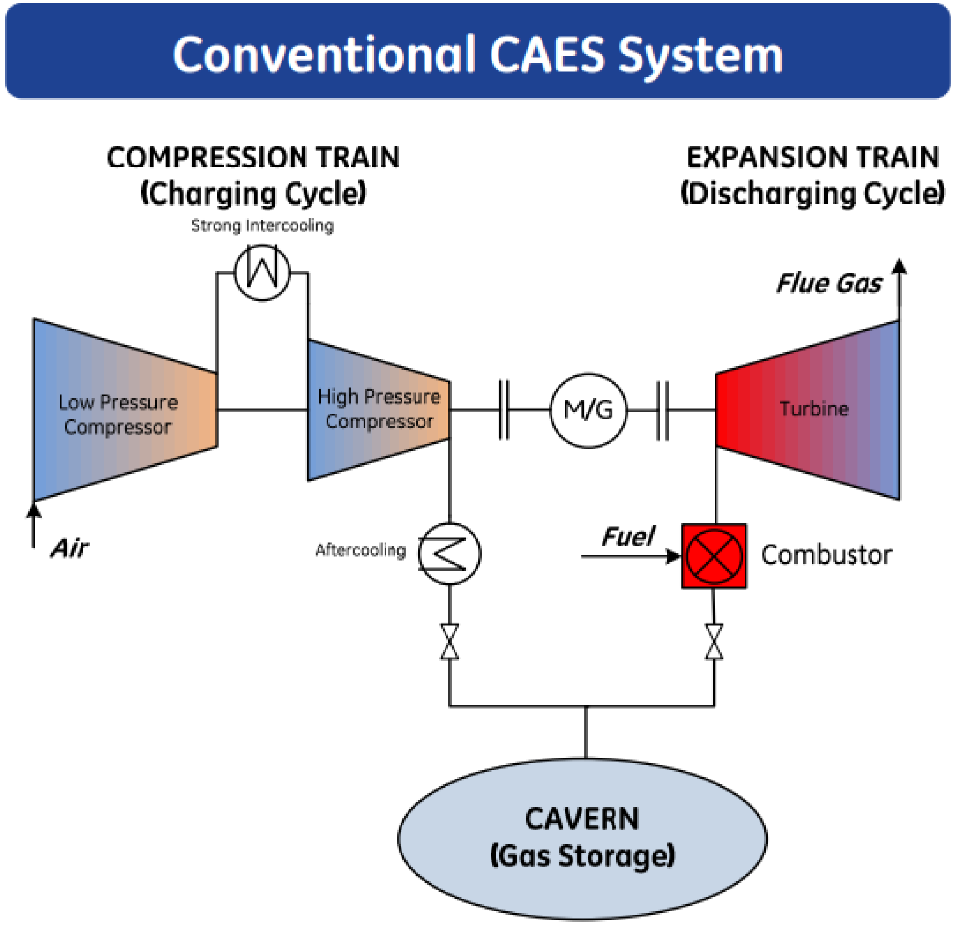


Schematic diagram of flywheel energy storage (FES) system.
During the **charging cycle**, excess electrical energy from the grid is used to rotate the flywheel system using a reversible electrical machine that functions as a motor.
The **rotational energy** of a rotating cylinder is stored in the form of mechanical energy. In the discharging cycle, the reversible machine acts as a generator, converting the kinetic energy stored in the flywheel back to electrical energy.

COMPRESSED AIR ENERGY STORAGE (CAES)

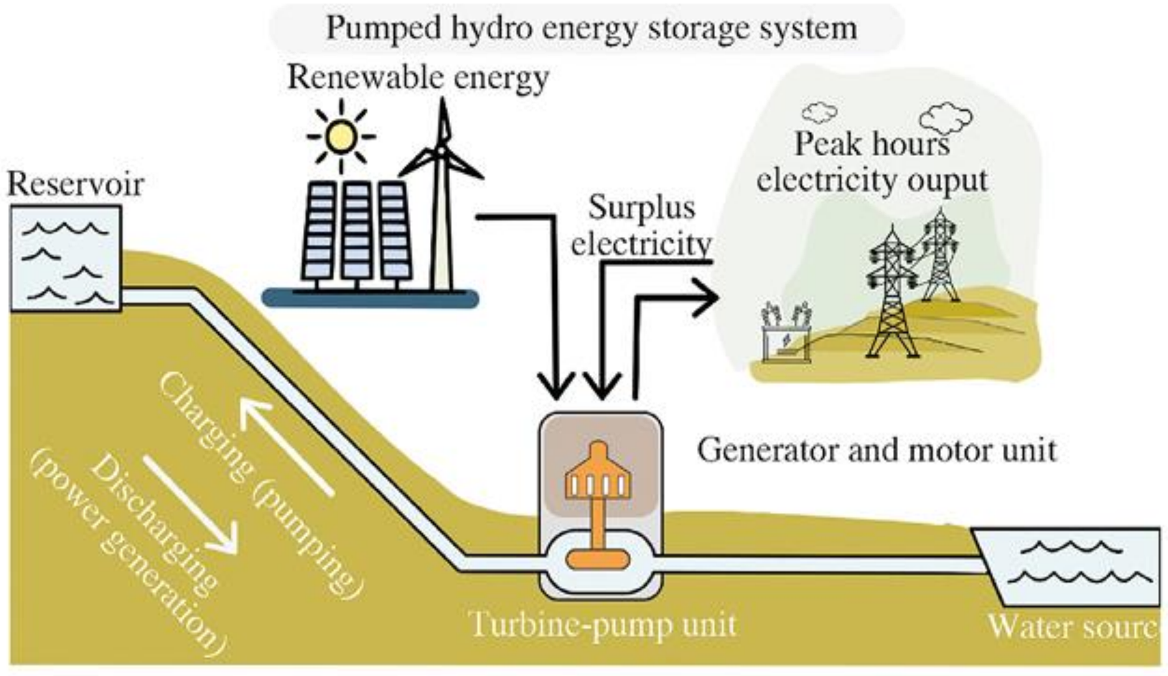
- **Principle**: **Air is compressed and stored in underground caverns or tanks. During discharge, the air is heated and expanded to drive turbines.**
- **Applications**: Suitable for medium- to long-term storage.
- **Efficiency**: 60-80%, with advanced systems using thermal energy storage
 for improved performance.

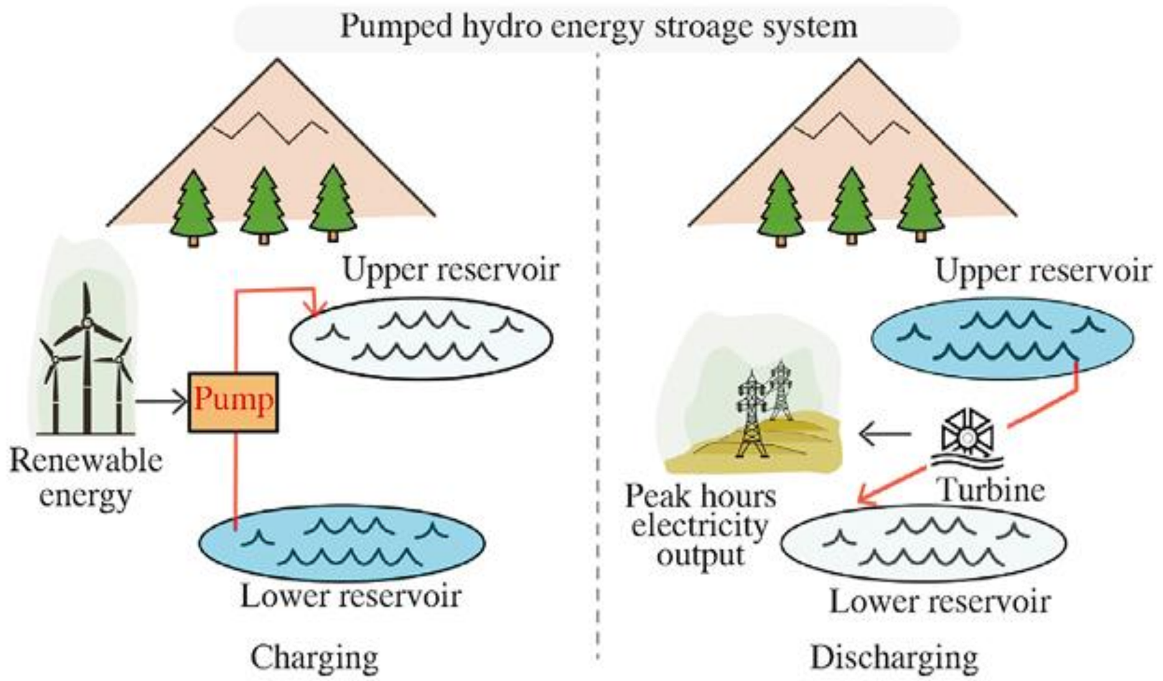




Emerging Technologies: Liquid air energy storage by storing air as a cryogenic liquid

SCHEMATIC DIAGRAM OF PUMPED HYDRO ENERGY STORAGE SYSTEM

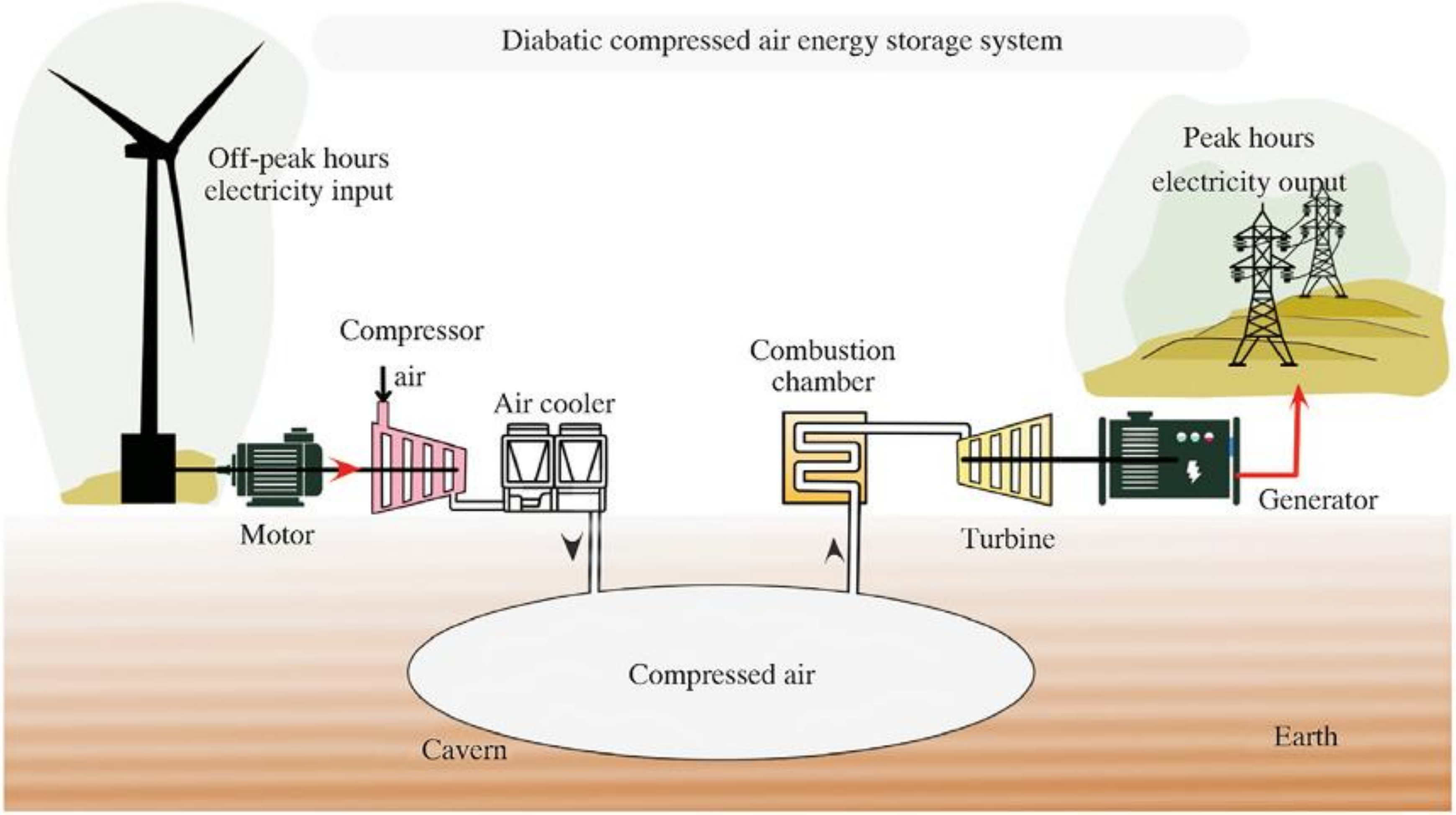




The **potential energy is stored and extracted** by transferring water between two reservoirs located at different elevations.
During the **charging cycle, excess electrical energy from the grid or renewable energy sources is transformed into mechanical energy**, which is then converted into potential energy by pumping and storing water from the lower reservoir to the higher reservoir.
The **stored water from the higher reservoir is released back into the lower reservoir** during the **discharging cycle**, which drives the turbines and generates electricity via generators.

Energy Storage and Saving 1 (2022) 166–216

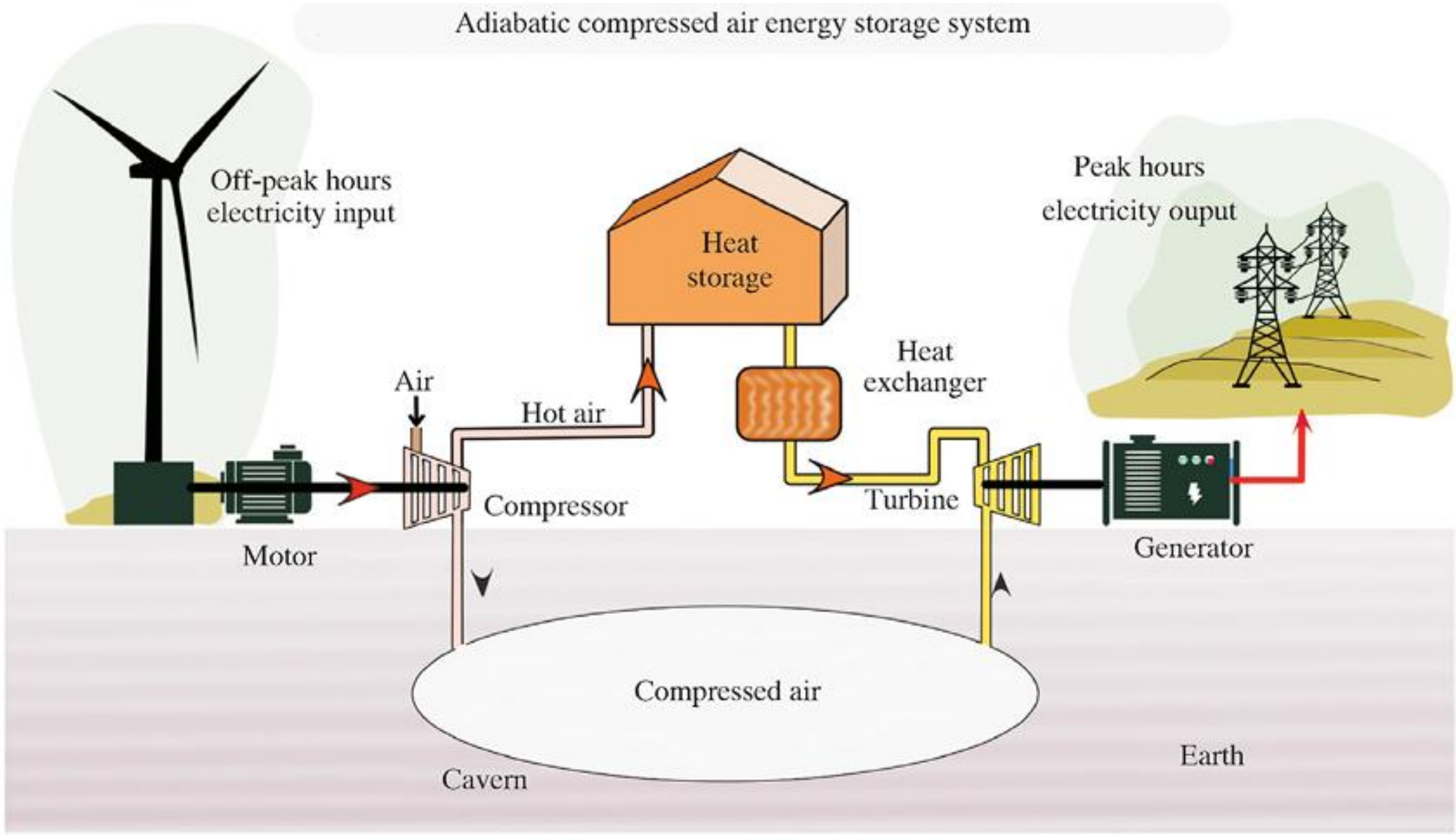
SCHEMATIC DIAGRAM OF DIABATIC COMPRESSED AIR ENERGY STORAGE (D-CAES) SYSTEM



During the **charging cycle**, **excess electricity from the grid is used to power the motor**, which generates **mechanical energy and drives the multi-stage compressor**.

After removing the heat with the help of an air cooler, the compressed atmospheric air is stored in the underground cavern. The stored cooled compressed air in the cavern is then heated in a combustion chamber and expanded to release the energy as needed during the discharging cycle.

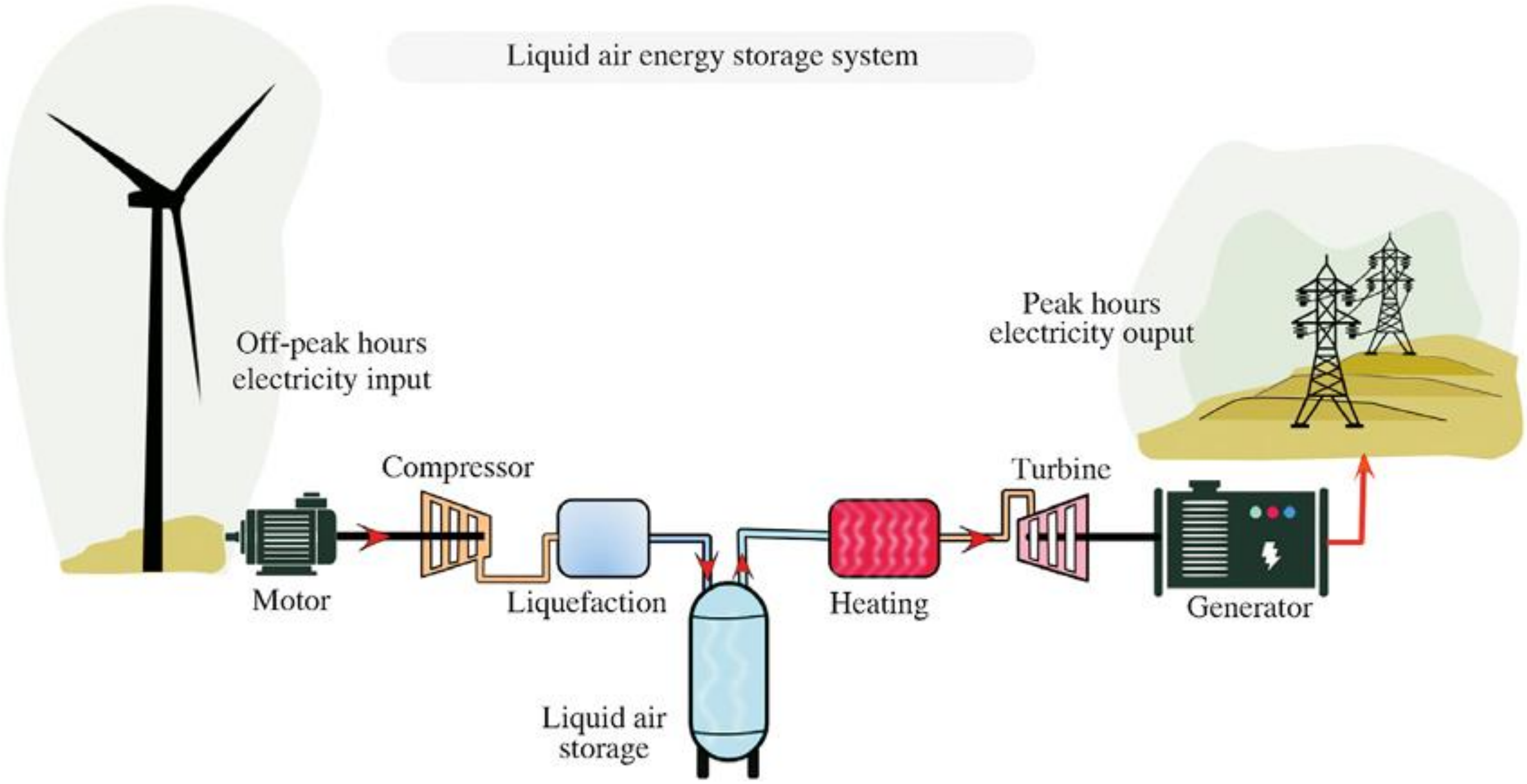
SCHEMATIC DIAGRAM OF ADIABATIC COMPRESSED AIR ENERGY STORAGE (A-CAES) SYSTEM.



During the **charging cycle, excess electrical energy from the grid is used to power the motor, which generates mechanical energy and drives the multi-stage compressor**. The compressed atmospheric air is stored in the underground cavern, while the heat released during the compression stage is stored in a heat storage.

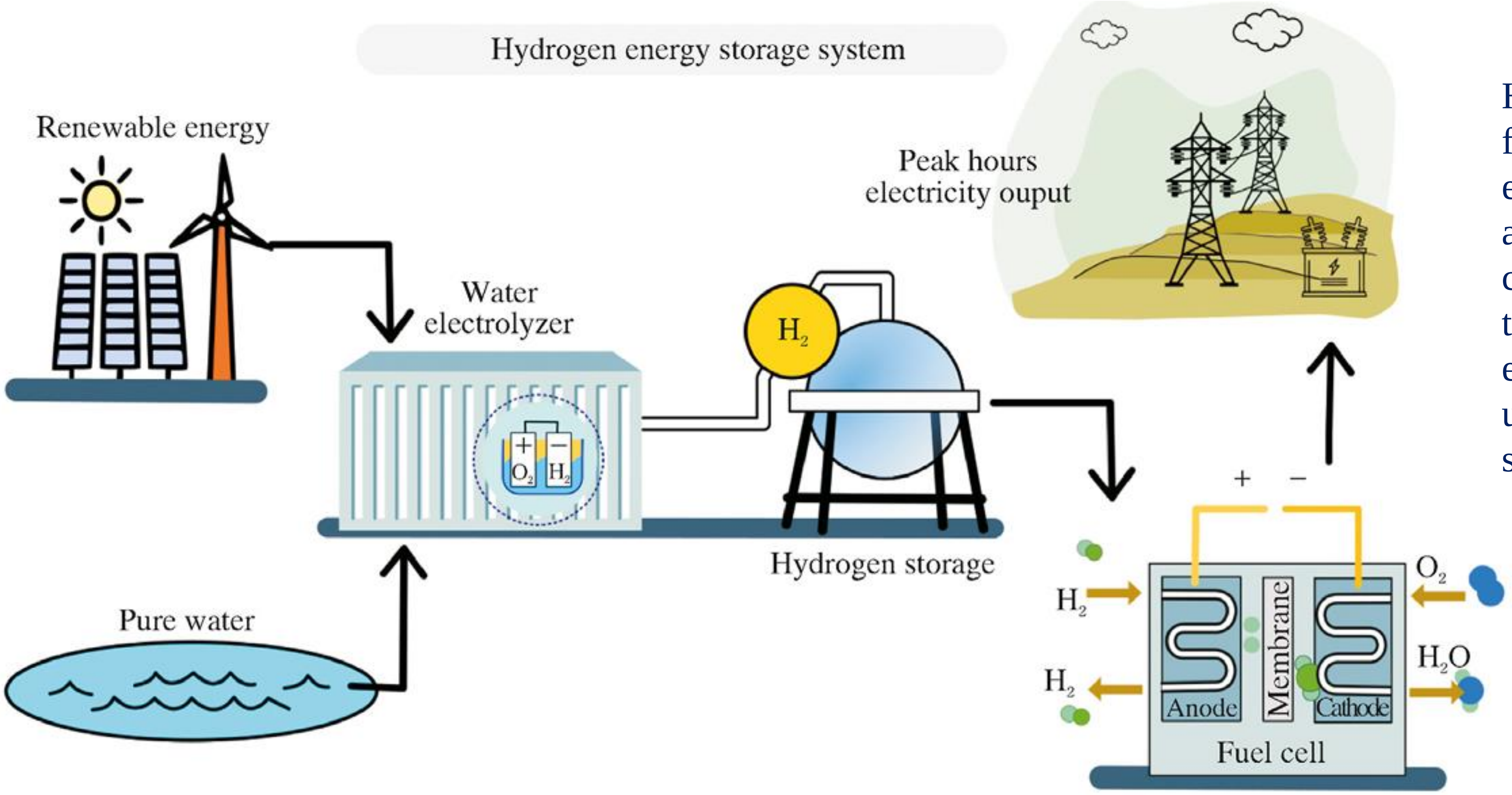
During the **discharging cycle, the stored compressed air is heated by utilizing the surplus heat and then expanded to release the required energy.**

SCHEMATIC DIAGRAM OF LIQUID AIR ENERGY STORAGE (LAES) SYSTEM



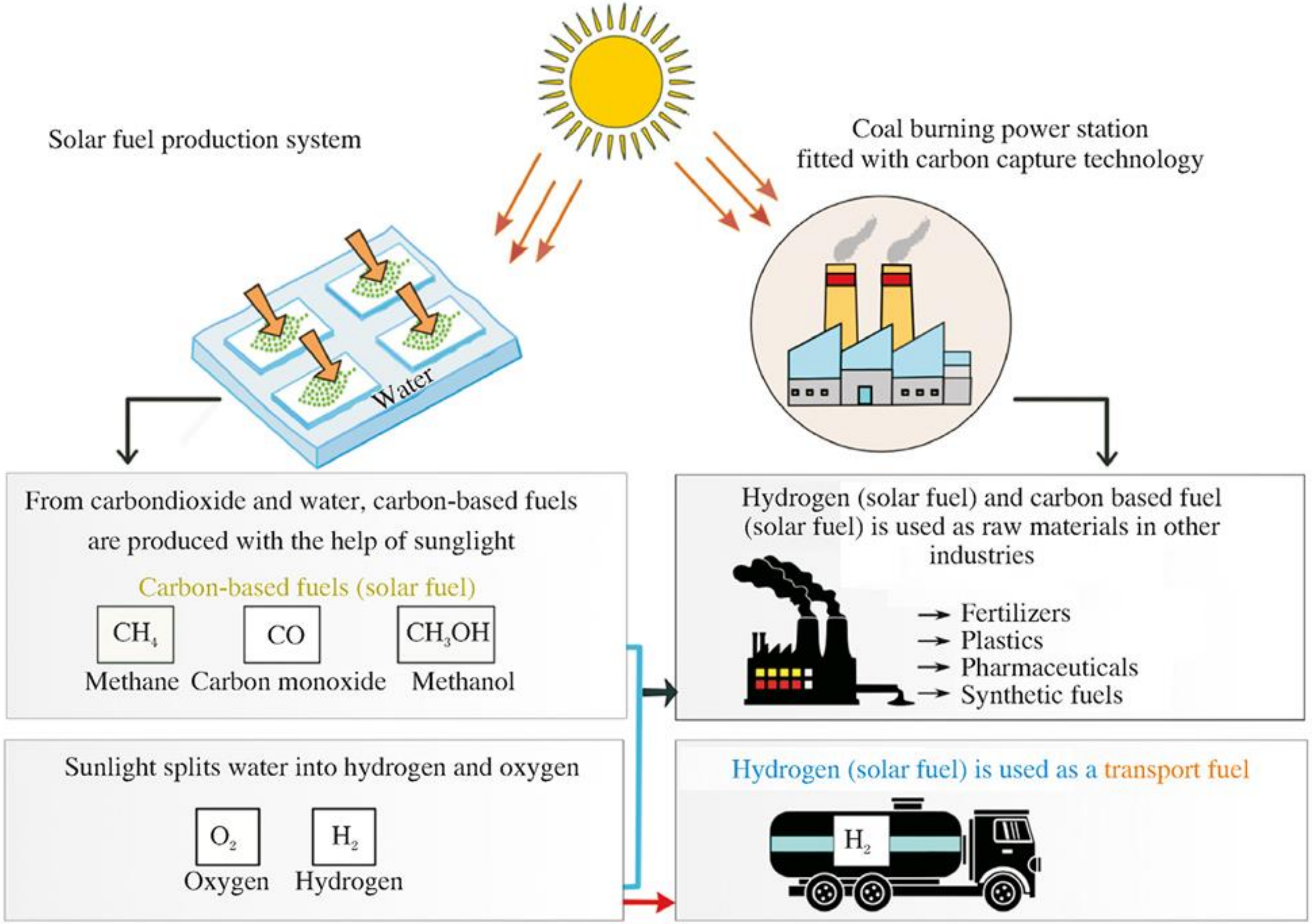
During the **charging cycle, excess electricity from the grid is used to power the motor which generates mechanical energy and drives the multi-stage compressor.**
The compressed atmospheric air is stored in liquefied form at low temperature in the liquid air storage.
The **stored liquified compressed air is then expanded into gaseous form at high temperature during the discharging cycle to extract the required energy.**

SCHEMATIC DIAGRAM OF HYDROGEN ENERGY STORAGE SYSTEM



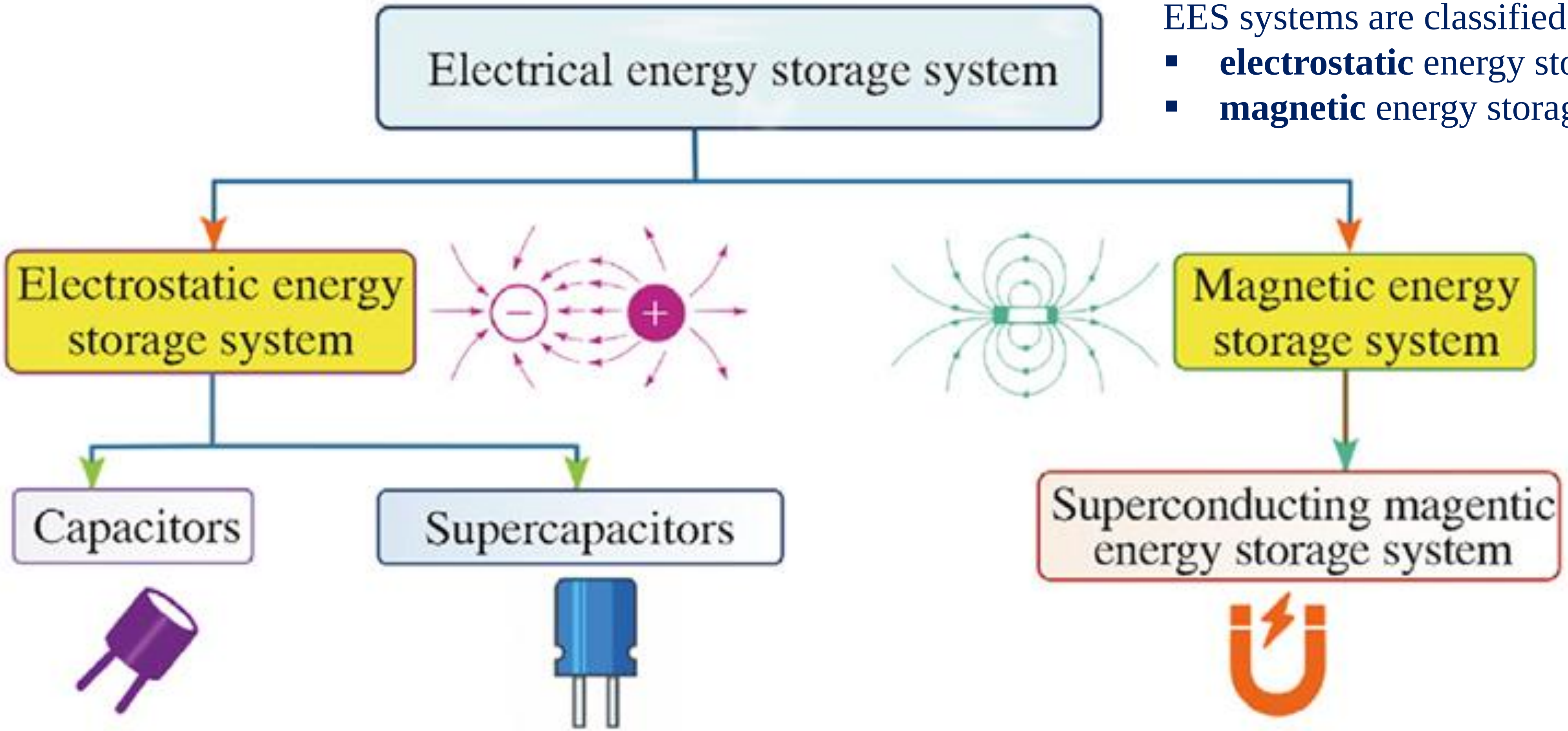
Hydrogen is produced from water via electrolysis and stored in a storage tank during the charging cycle. During the discharging cycle, electricity is generated using a fuel cell from the stored hydrogen.

SOLAR FUELS



Energy Storage and Saving 1 (2022) 166–216

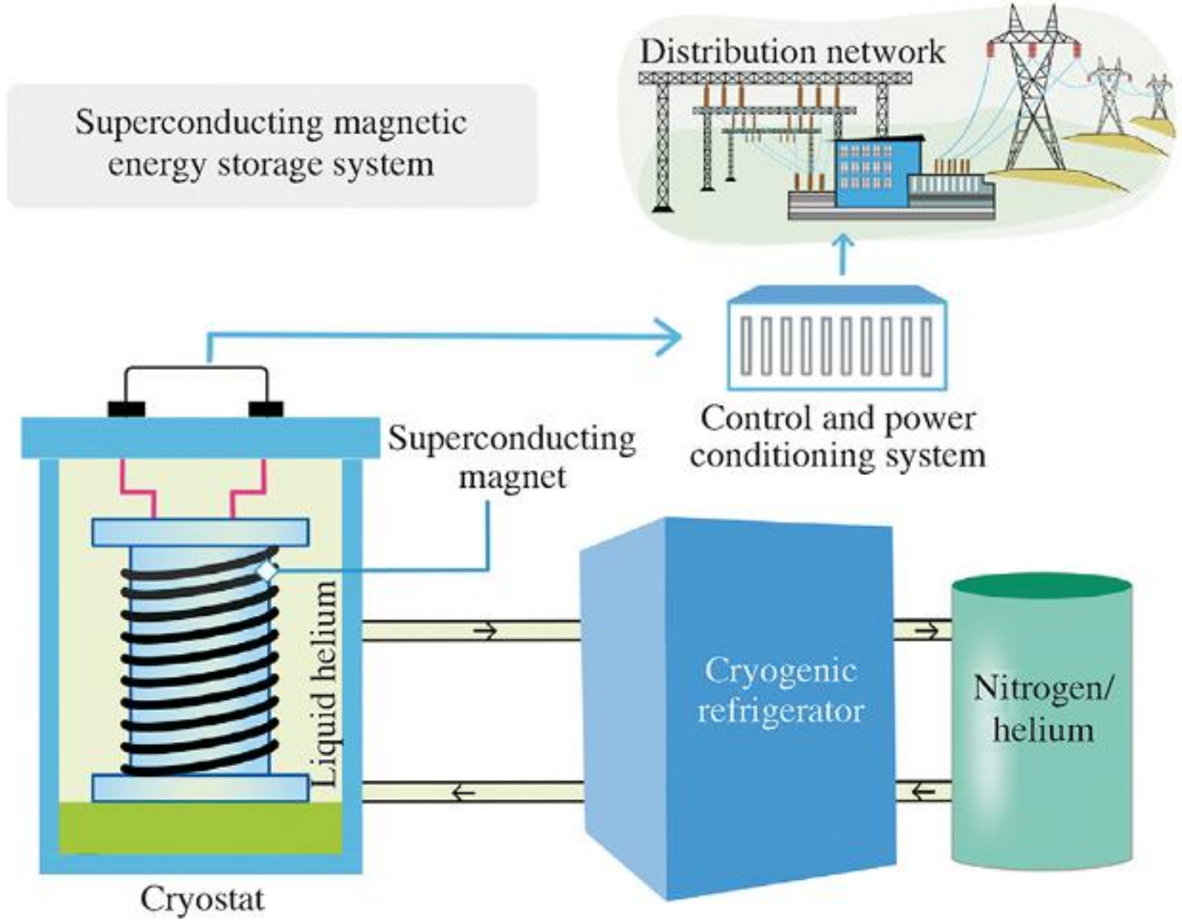
CLASSIFICATION OF ELECTRICAL ENERGY STORAGE SYSTEMS



EES systems are classified into two types
- **electrostatic** energy storage systems
- **magnetic** energy storage systems

The capacitors and supercapacitors are electrostatic energy storage systems.
The superconducting magnetic energy storage (SMES) is a magnetic energy storage system.

SUPERCONDUCTING MAGNETIC ENERGY STORAGE (SMES) SYSTEM



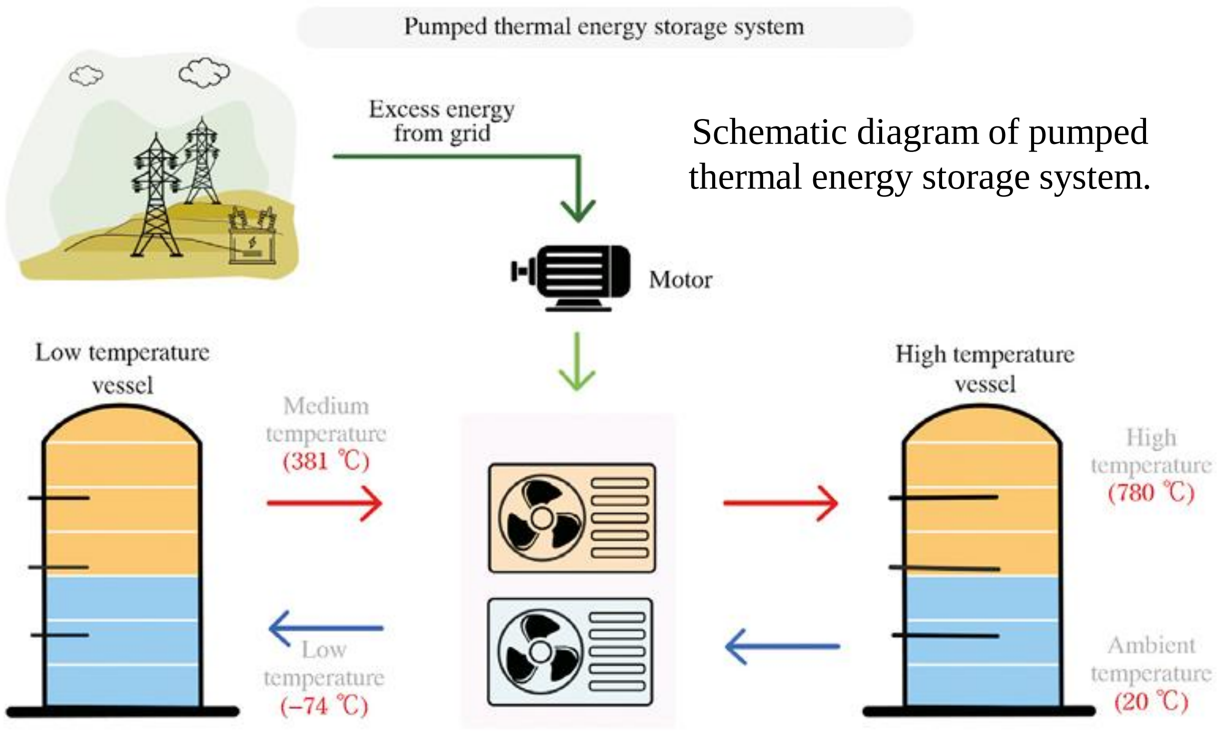
Schematic diagram of superconducting magnetic energy storage (SMES) system. It **stores energy in the form of a magnetic field** generated by the flow of direct current (DC) through a superconducting coil which is cryogenically cooled. The stored energy is released back to the network by discharging the coil.

SMES is made up of three major components: a superconducting coil, a control and power conditioning system and a cryogenically cooled re- frigerator (Fig. 50). To retain its superconducting condition, the super- conducting coil is cryogenically chilled to a very low temperature using a refrigeration system. During the charging phase, the flow of current increases in the superconducting coil while decreasing during the dis- charging cycle. The control and power conditioning system regulates the electrical energy of the SMES system during the charging and discharging cycle according to the output power requirements and also converts AC into DC and vice versa as per requirement

Summary of superconducting magnetic energy storage (SMES) system applications to power systems

Summary	Description
Improving power quality	• Balancing fluctuating load • Offering spinning reserve • Offering load levelling • Defending critical loads • Offering backup power supply • Balancing voltage and current asymmetries • Enhancing FACTS performance
Improving power system stability	• Improving voltage stability • Reduction of system oscillation

PUMPED THERMAL ENERGY STORAGE (PTES) SYSTEM



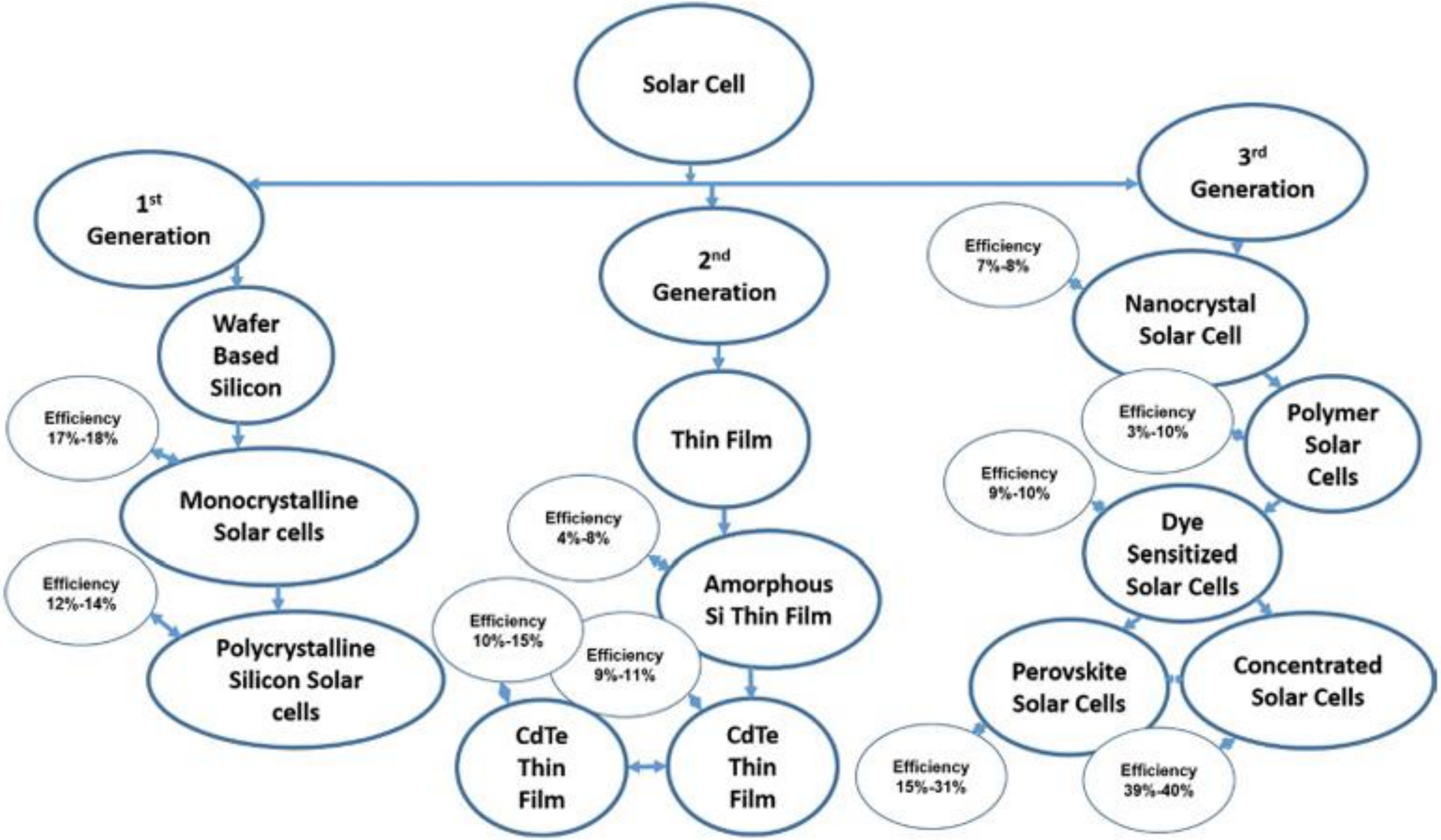
Schematic diagram of pumped thermal energy storage system.

Working principle: During the charging cycle, excess electrical energy from the grid is utilised to pump heat from the low temperature vessel to the high temperature vessel.
This is achieved by propagating a cold thermal front through the low temperature vessel and a hot thermal front through the high temperature vessel.
The working fluid flows in a clockwise direction during the charging cycle, following an energy consuming Brayton heat pump cycle. During the discharging cycle, a warm front propagates through the low temperature vessel and a cool front through the low temperature vessel. The temperature difference between the two storage vessels is used to generate required energy.

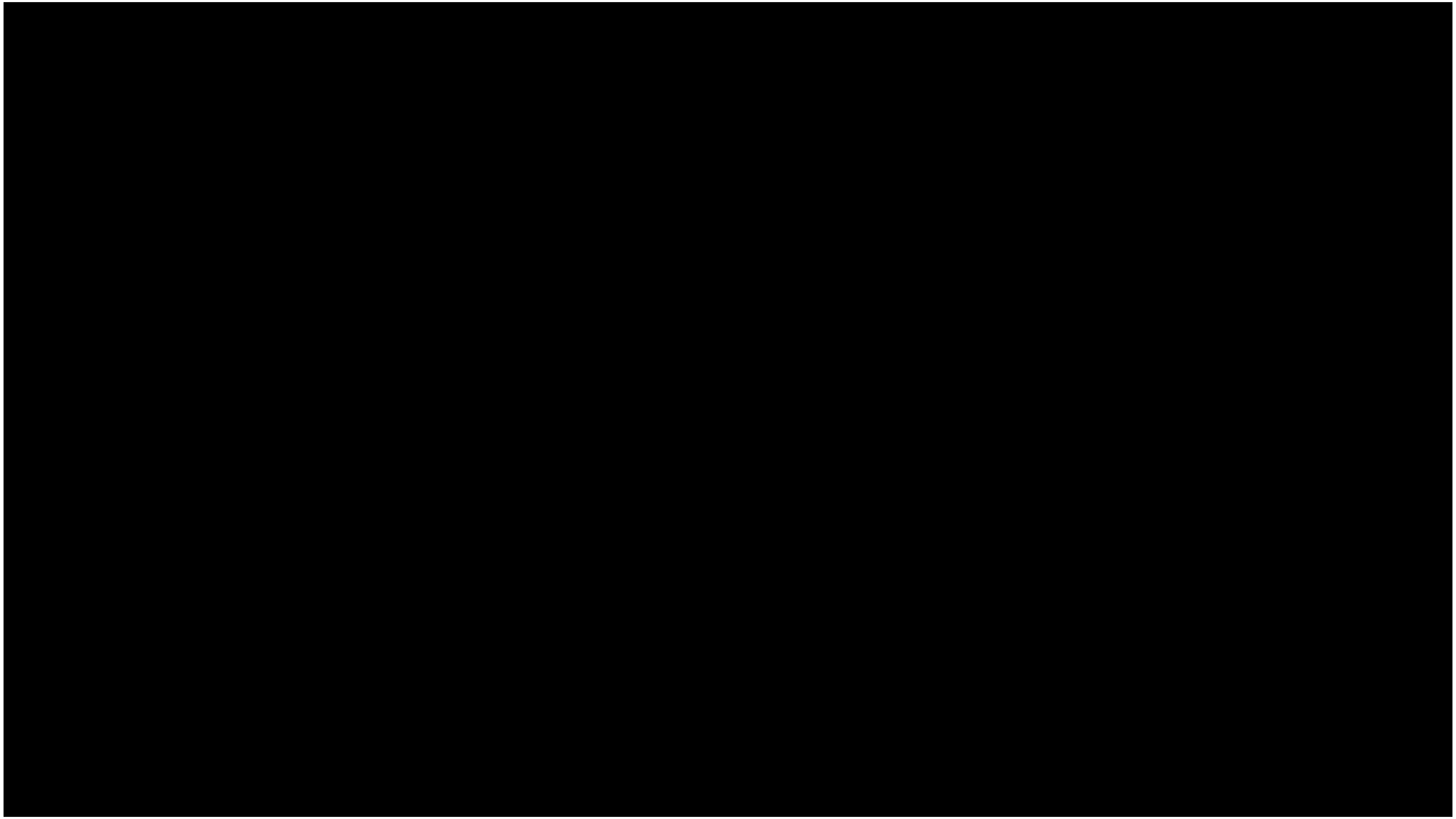
Technical characteristics of various pumped thermal energy storage (PTES) systems

Variant	Discharge power range (MW)	Charge power range (MW)	Discharge time (h)	Charge time (h)	Power density (kW/m^3)	Energy density (kWh/m^3)	Efficiency (%)	Lifetime (years)
Brayton PTES	10–150	10–150	6–20	6–72	1–15	20–50	50–75	30
Transcritical Rankine PTES	10–100	10–100	2–5	3–10	2–8	10–15	50–65	>25
Compressed heat energy storage (CHEST)	10–100	10–150	6–72	6–72	0.5–17	40–100	60–70	30

RECENT ADVANCES IN SOLAR PHOTOVOLTAIC MATERIALS AND SYSTEMS FOR ENERGY STORAGE APPLICATIONS

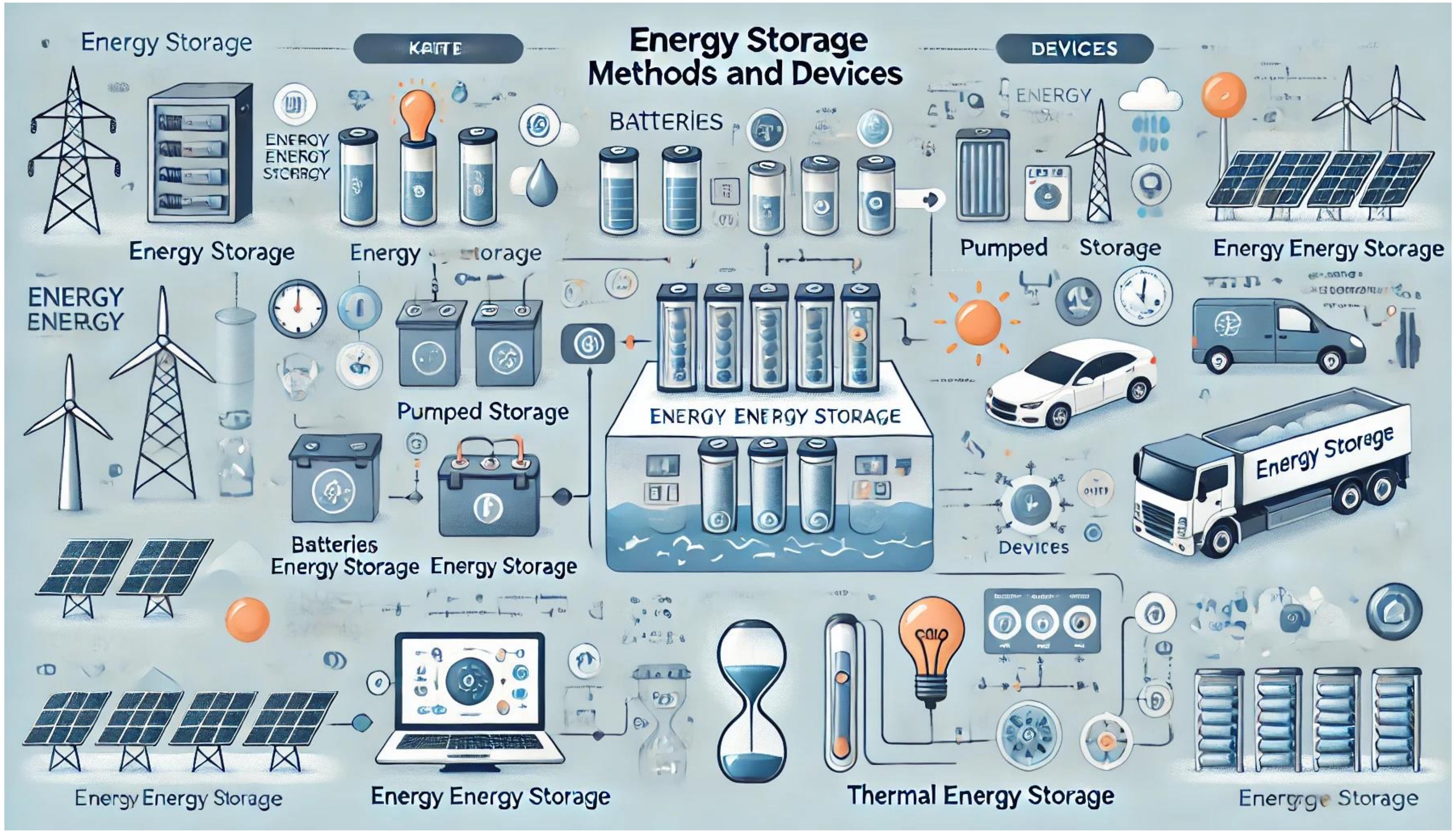


HOW DOES IT WORK?



CONCLUSION

1.The selection of the best energy storage method depends on a combination of factors such as cost, efficiency, and environmental impact.
2.The success of energy storage technologies will determine the widespread adoption of renewable energy systems globally.
3.Efficient energy storage solutions will allow for the smooth integration of renewable energy sources into national power grids.
4.Energy storage methods can help stabilize electricity grids by compensating for fluctuations in energy demand and supply.
5.Innovations in energy storage will contribute to the creation of a sustainable, reliable, and efficient energy system.



Thank you very much for your attention!

Dilshod KODIROV
Professor, Doctor of Science
Head of the Department of
Power Supply and Renewable Energy Sources
“TIIAME” National Research University

kodirov.dilshod@gmail.com
d.kodirov@tiiame.uz