

Energy Storage Systems - a Way of Increasing Operational Time of WSN Devices

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Abstract—The increasing demand for sustainable and efficient energy solutions have led to significant advancements in energy storage systems. This paper provides a comprehensive overview of various energy storage technologies, including thermal energy storage (TES), mechanical energy storage (MES), chemical energy storage (CES), battery energy storage (BES), and electrical energy storage (EES). We explore specific methods such as molten salt, aquifer, and thermochemical systems for TES; pumped hydro, gravity, compressed air, and flywheel systems for MES; hydrogen, synthetic natural gas, and solar fuels for CES; and a range of battery types, including lithium-ion, lead-acid, nickel-cadmium, sodium sulfur, sodium ion, and metal-air. Additionally, we examine emerging technologies like paper batteries, advanced capacitors, and supercapacitors for EES. The paper concludes with a comparative analysis of this storage systems and discusses the most promising directions for the future energy storage solutions.

Keywords—Energy storage systems, Thermal energy storage, Mechanical energy storage, Chemical energy storage, Electrochemical energy storage, Electrical energy storage

I. INTRODUCTION

The rapid increase in global energy consumption, driven by industrialization, technological advancements, and economic growth, particularly in developing countries, has intensified the need for efficient and sustainable energy solutions. According to the International Energy Agency (IEA), global energy demand surged by 4.5% in 2021, significantly contributing to the rise in CO₂ emissions. To combat this environmental challenge, renewable energy sources are being deployed at an unprecedented rate, aiming to reduce greenhouse gas emissions. Renewable energy, notably from photovoltaic cells, wind turbines, and hydropower plants, reached record levels in 2021, accounting for a significant portion of the global energy generation. [1]

However, the inherent intermittency of renewable energy sources, such as the variability of solar and wind power, poses challenges in maintaining a consistent energy supply. Energy storage systems (ESSs) have emerged as a crucial technology to address these challenges by storing excess energy and ensuring a reliable energy supply when renewable sources are insufficient.

ESSs encompass a diverse range of technologies, each with unique applications and benefits. These systems include thermal, mechanical, chemical, battery, and electrical storage methods, all designed to optimize energy management and mitigate energy spillage. Despite the extensive research on ESSs, reviews often focus on specific types, leaving a gap in comprehensive studies covering all major storage technologies.

This paper aims to provide an in-depth review of the various energy storage systems, highlighting their evolution, classifications, current status, characteristics, and applications. By assembling comprehensive information on ESSs, this review seeks to offer valuable insights for researchers and industry professionals, guiding future developments in the field of energy storage. [2]

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II. THERMAL ENERGY STORAGE (TES) SYSTEM

Thermal energy storage (TES) systems are engineered to store heat energy by processes such as cooling, heating, melting, condensing, or vaporizing a substance. Depending on the temperature range, these materials are stored at either high or low temperatures in insulated containers. The stored energy can later be recovered for various applications, including residential and industrial uses like space heating or cooling, hot water production, or electricity generation.

TES systems are employed for diverse purposes, ranging from industrial cooling below -18°C , building cooling between 0 and 12°C , heating buildings between 25 and 50°C , to industrial heat storage over 175°C . TES technologies are broadly categorized into low-temperature energy storage (LTES) and high-temperature energy storage (HTES), based on the operating temperature of the storage material relative to the ambient temperature. [3]

LTES systems include aquifer thermal energy storage (ATES) and cryogenic energy storage. In ATES, water is cooled or frozen during periods of low energy demand and later used to meet cooling requirements during peak demand periods. Cryogenic energy storage involves the use of cryogenics, such as liquid nitrogen or liquid air, which are boiled using ambient heat and subsequently used to generate electricity through a cryogenic heat engine. LTES is well-suited for high-power density applications, such as load shaving, industrial cooling, and future grid power management.

HTES systems often involve the use of materials like molten salts, which can store and release substantial amounts of thermal energy at high temperatures, making them ideal for electricity generation and industrial processes.

This section will explore different types of TES systems, focussing on molten salt thermal energy storage (HTES), aquifer thermal energy storage (ATES), and thermochemical energy storage (TCES) systems, highlighting their principles, advantages, and applications.

A. Molten salt thermal energy storage system

Molten salts are highly effective for storing sensible heat at temperatures exceeding 100°C . These salts are liquids formed by melting inorganic salts, and they offer several advantages, including high boiling points, low viscosity, low vapour pressure, and high volumetric heat capacities. The low vapour pressure allows for storage solutions that do not require pressurized vessels, and the high volumetric heat capacity reduces the required storage tank space.

Molten salts are widely used in concentrated solar power (CSP) plants, which utilize parabolic troughs or heliostats to concentrate sunlight. Due to the high demand for molten salts in the CSP industry, extensive research has been conducted to identify suitable molten salt mixtures for both heat transfer fluids (HTFs) and thermal energy storage (TES) materials. The market for molten salt thermal energy storage is expected to expand significantly during the coming years.

Common molten salt fluids include solar salts, Hitec, and Hitec XL. These mixtures are frequently used due to their optimal properties for thermal storage. Molten salt energy storage systems are typically configured in two ways: two-tank direct and two-tank indirect systems. In a direct storage system, molten salt functions as both the heat transfer fluid, absorbing heat from the reactor or heat exchanger, and the storage medium. In contrast, an indirect system uses a separate medium to store heat, with molten salt acting only as the HTF.

These systems employ two tanks: one for cold storage and one for hot storage. The cold tank typically operates at temperatures between 280°C and 290°C , while the hot tank operates between 380°C and 550°C .

In this system, the heater converts renewable energy into heat. In the hot tank is stored the heated molten salt that is heated by the circulation of cooled molten salt from the cold tank

through the heater. When we want to release the energy stored in the hot tank, we circulate the heated molten salt from the hot tank through the steam generator. The steam from this generator can be directly used to heat buildings or power steam turbines inside electricity generators. The cooled molten salt from the stem generator is returned to the cold tank for later use.

The size and number of tanks depend on the storage capacity, with commercial operations commonly using tanks with heights of 12–14 meters and diameters exceeding 35 meters.

B. Aquifer thermal energy storage (ATES) system

Aquifer thermal energy storage (ATES) involves the use of permeable rock layers, or aquifers, to store and convey groundwater for heating and cooling purposes. ATES is a form of sensible seasonal storage, where groundwater is extracted and injected through at least two hydraulically connected wells and a heat pump. One well stores warm water (approximately 14–16°C) and the other stores cold water (approximately 5–10°C). These wells can be arranged horizontally (doublet) or vertically within a single borehole (monowell). The critical distance between the wells is determined by factors such as well production rates, aquifer thickness, and the hydraulic and thermal properties governing the storage volume.

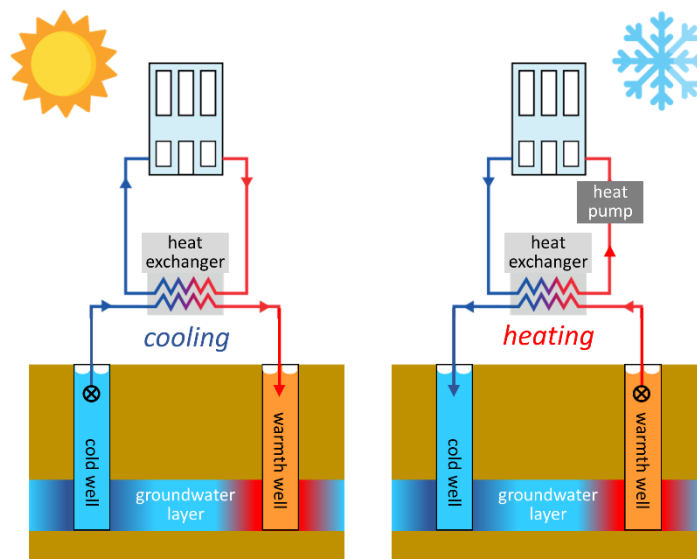


Figure 1 - Schematic ATES system

In a large-scale ATES system, multiple wells are used in a multi-well configuration. During the summer, groundwater from the cold well is used for cooling, and the resulting warm water is fed back into the warm well. In winter, the process is reversed: groundwater from the warm well is heated further to around 40–50°C for heating purposes, and the cooled water is returned to the cold well. Both wells are often equipped with heat pumps to facilitate the bidirectional flow of water. The efficiency of energy storage with ATES is highly dependent on the geological characteristics of the site.

C. Thermochemical energy storage (TCES) system

Thermochemical energy storage (TCES) systems store heat energy indirectly through reversible chemical reactions, unlike sensible heat storage (SHS) or latent heat storage (LHS). In TCES, heat is absorbed and released during the dissociation and association of molecular bonds in an endothermic and exothermic reaction, respectively. The stored heat energy is determined by the type and quantity of the storage material, the enthalpy of the reaction, and the degree of conversion of the reactants.

During an endothermic reaction, heat is stored as reactive components dissociate into

individual components. This stored energy is later released in an exothermic reaction when the components recombine. Key parameters for selecting thermochemical materials include energy density and reaction temperature, which are crucial for practical applications. Promising thermochemical storage materials and their respective properties, such as energy density and reaction temperature, are listed in relevant research tables.

Various review articles have assessed the potential applications of TCES and identified challenges impeding its maturity. For instance, research has evaluated the technical properties of cobalt, manganese, and copper oxide-based TCES systems in terms of energy density and cycle life. These studies aim to advance the development and deployment of TCES technologies.

III. MECHANICAL ENERGY STORAGE (MES) SYSTEM

Mechanical energy storage (MES) systems store energy by converting electrical energy into mechanical energy, which can be stored in the form of potential or kinetic energy. When energy demand is low during off-peak hours, the electrical energy from the grid is transformed and stored as mechanical energy. During peak hours, this mechanical energy is converted back into electrical energy to meet the increased demand. MES systems are categorized into four main types: pumped hydroelectric energy storage (PHES), gravity energy storage (GES), compressed air energy storage (CAES), and flywheel energy storage (FES). PHES, GES, and CAES store energy as potential energy, while FES stores it as kinetic energy. One of the main advantages of MES systems is their ability to quickly convert and release stored mechanical energy. [5]

A. Pumped hydroelectric energy storage (PHES) system

The pumped hydroelectric energy storage (PHES) system is the most widely used mechanical energy storage system due to its large energy capacity, long storage duration, and high efficiency. A typical PHES system consists of two large water reservoirs situated at different elevations, a pump to move water from the lower reservoir to the upper reservoir, and a turbine to generate electricity as water flows back down. During off-peak hours, electrical energy is used to pump water to the higher reservoir, storing energy as gravitational potential energy. During peak demand, the stored water is released back to the lower reservoir, passing through turbines to generate electricity. The energy storage capacity of a PHES system is determined by the volume of water reservoirs and the height difference between the reservoirs.

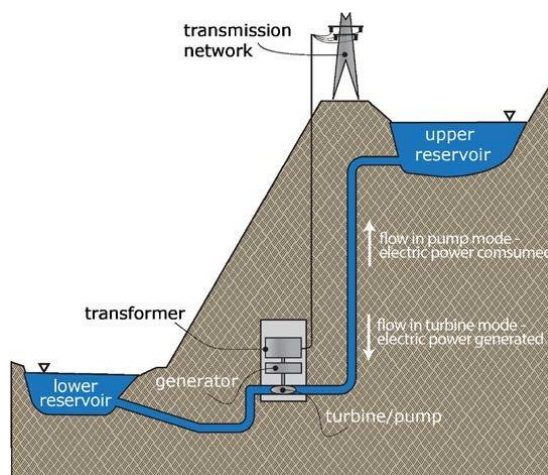


Figure 2 - Schematic of pumped storage hydropower system [6]

Innovations in PHEs technology include underground PHEs (UPHEs) and seawater PHEs (SPHEs). UPHEs uses abandoned quarries or mines as lower reservoirs, while SPHEs uses the sea as lower reservoirs, reducing construction costs and environmental impact. Additionally, variable-speed PHEs, employing asynchronous motor generators, allows for better control of the pump/turbine speed, enhancing energy absorption during the pumping cycle. These advancements aim to improve the efficiency and feasibility of PHEs systems.

B. Gravity energy storage (GES) system

Gravity energy storage (GES) systems have emerged as an alternative to PHEs, particularly in regions with geological limitations and water scarcity. GES systems store energy by using gravitational potential energy. The basic concept involves lifting a heavy object, such as a piston, using excess electrical energy during off-peak hours. When energy is needed, the object is allowed to fall, driving a generator to produce electricity.

A typical GES system comprises a large piston in a water-filled shaft, connected to a powerhouse with a pump, turbine, and motor/generator. During charging, the pump lifts the piston by moving water into the shaft. During discharging, the falling piston forces water through the turbine, generating electricity. The storage capacity of GES systems depends on the mass of the piston and the height of the shaft. This technology aims to provide power in the range of 40 MW to 1.6 GW, offering a flexible and scalable energy storage solution.

C. Compressed air energy storage (CAES) system

Compressed air energy storage (CAES) systems store energy by compressing air and storing it in underground caverns or reservoirs. The amount of energy stored depends on the volume, pressure, and temperature of the compressed air. CAES systems offer a reliable and economically feasible alternative to PHEs, with lower environmental impacts.

A typical CAES system includes a motor-driven compressor, a multi-stage compressor, a storage cavern, high- and low-pressure turbines, and a generator. During off-peak hours, surplus electricity drives the compressor, which compresses air and stores it in the cavern. During peak demand, the compressed air is released, driving the turbines to generate electricity. CAES systems can store large amounts of energy and provide grid stability, making them an important component of modern energy storage infrastructure.

D. Flywheel energy storage (FES) system

Flywheel energy storage (FES) systems store energy in the form of kinetic energy, utilizing the rotational energy of a massive rotating cylinder. A modern FES system consists of a flywheel, magnetic bearings, an electrical motor/generator, a power conditioning unit, and a vacuum chamber. The motor/generator is reversible, acting as a motor to spin the flywheel during charging and as a generator to convert kinetic energy back into electrical energy during discharging.

FES systems are classified into low-speed and high-speed categories. Low-speed FES systems use steel flywheels rotating at speeds below 6,000 rpm, while high-speed FES systems use advanced composite materials for flywheels that rotate at speeds up to 100,000 rpm. FES systems offer rapid response times, high power density, and long cycle life, making them suitable for applications requiring frequent and rapid energy storage and retrieval.

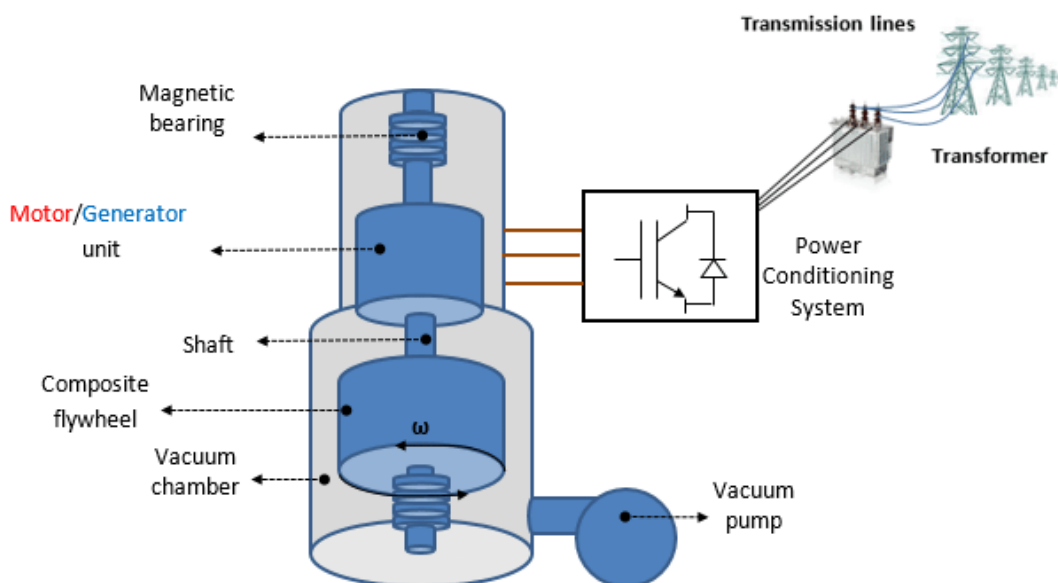


Figure 3 - Schematic of flywheel energy storage system [7]

IV. CHEMICAL ENERGY STORAGE (CES) SYSTEM

Chemical energy storage (CES) systems are particularly effective for long-term energy storage. These systems store energy in the chemical bonds between atoms and molecules, releasing this stored energy through chemical reactions. During this process, the materials' composition changes as original chemical bonds break and new ones form. Chemical fuels play a significant role in both electricity generation and the transportation industry worldwide. Common chemical fuels include coal, petrol, diesel fuel, natural gas, liquefied petroleum gas (LPG), propane, butane, ethanol, and hydrogen. These fuels are first converted into mechanical energy and subsequently into electrical energy, which is then used for power generation. CES systems mainly encompass hydrogen, synthetic natural gas (SNG), and solar fuel storage systems.

A. Hydrogen energy storage system

Hydrogen is considered an ideal energy carrier due to its clean and carbon-free nature, making it a zero-emission chemical energy carrier. Hydrogen can be produced from water via electrolysis or directly from sunlight through photocatalytic water splitting. A typical hydrogen energy system includes three main components: a hydrogen generation unit (such as an electrolyser) to convert electrical energy into hydrogen, a hydrogen storage system, and a hydrogen energy conversion unit (such as a fuel cell) to convert the stored chemical energy in hydrogen back into electrical energy. This versatile approach to energy storage offers significant potential for clean and sustainable energy solutions.

B. Synthetic natural gas (SNG)

Natural gas is a widely used and relatively clean energy source among fossil fuels. The conversion of coal to synthetic natural gas (SNG) has been established as a viable alternative for energy production. Biomass can also be used to produce SNG, presenting a carbon-neutral option. The methanation process, initially used in the 1960s and 1970s, converts coal into SNG. Recent advancements have developed new thermal gasification processes to produce SNG from coal and dry biomass, involving multiple conversion steps such as drying, gasification, gas cleaning, and methanation of producer gas. SNG can be stored in pressurized tanks,

underground caverns, or fed directly into the gas grid. An example of this technology in practice is the Great Plains Synfuels Plant (GPSP) in North Dakota, USA, which has been producing approximately 4.1 million m³/day of SNG from lignite coal since 1984.

C. *Solar fuels*

Solar fuels aim to capture the sun's abundant energy, convert it into usable forms, store it in chemical bonds, and utilize it as needed. There are three main approaches to producing solar fuels: natural photosynthesis, artificial photosynthesis, and thermochemical production.

Natural photosynthesis is the process by which plants, algae, and some bacteria convert solar energy into fuel, storing it in carbohydrates. These carbohydrates act as fuels that support plant growth and maintenance. Artificial photosynthesis mimics this natural process, capturing sunlight and using it to chemically convert water and carbon dioxide into fuels, resulting in solar fuels. The term "artificial leaf" refers to this process, which aims to produce fuels using solar energy. Thermochemical production involves using sunlight to heat materials to very high temperatures, where they react with steam or CO₂ to produce hydrogen or carbon monoxide, which can then be used as fuels.

V. BATTERY ENERGY STORAGE (BES) SYSTEM

Batteries are electrochemical devices that convert chemical energy into electrical energy. They consist of multiple cells, each with three primary components: an anode, a cathode, and an electrolyte. Batteries are broadly categorized into two types: primary and secondary. Primary batteries are single-use and cannot be recharged once their chemical energy is depleted. Secondary batteries, however, are rechargeable. Depending on the materials used for the electrodes and electrolyte, secondary batteries are classified into various types, including lead-acid (LA), lithium-ion (Li-ion), nickel-cadmium (Ni-Cd), sodium-sulphur (NaS), sodium-ion (Na-ion), and metal-air batteries. Each type has its own specific characteristics and applications. [8]

A. *Lithium-ion (Li-ion) batteries*

Li-ion batteries are widely used in electronics and the transportation industry, particularly in power grid applications and plug-in hybrid electric vehicles, due to their high charge density. These rechargeable batteries have a lithium metal oxide cathode, a graphitic carbon anode, and an electrolyte containing dissolved lithium salts. During charging, lithium ions move from the cathode to the anode, where they are stored. During discharge, the process reverses, releasing energy.

B. *Lead-acid (LA) batteries*

Lead-acid batteries are among the oldest and most established types of rechargeable batteries. They consist of lead dioxide as the cathode, sponge lead as the anode and sulphuric acid as the electrolyte. They are commonly used in automotive starters and backup power systems due to their reliability and low cost.

C. *Nickel-cadmium (Ni-Cd) batteries*

Nickel-cadmium batteries have a nickel oxide hydroxide cathode, a cadmium anode, and an alkaline electrolyte. They are known for their robustness and long life cycle. These batteries are used in various applications, including emergency lighting and portable power tools.

D. *Sodium sulphur (NaS) batteries*

Sodium-sulphur batteries consist of a liquid sodium anode and a liquid sulphur cathode, separated by a solid ceramic electrolyte. These batteries operate at high temperatures and are used for grid energy storage due to their high energy density and efficiency.

E. Sodium-ion (Na-ion) batteries

Sodium-ion batteries use sodium ions as charge carriers, with a sodium metal oxide cathode, a hard carbon anode, and an electrolyte containing sodium salts. They are considered a potential alternative to Li-ion batteries due to the abundance and low cost of sodium.

F. Metal-air batteries

Metal-air batteries generate electricity through the oxidation of a metal (such as zinc or aluminium) with oxygen from the air. They have a high energy density and are used in applications requiring long-term energy storage and high energy output.

VI. PAPER BATTERIES

Paper batteries are innovative energy storage devices made primarily of paper or cellulose and carbon nanotubes. They are ultra-thin, flexible, non-corrosive, and require minimal housing. Their flexibility allows them to be bent, twisted, or wrapped around objects, making them ideal for fitting into tight spaces and reducing overall system size and weight.

A typical paper battery consists of a sheet of paper coated with an ionic solution and smeared with carbon nanotube ink as the cathode. On the other side, a thin layer of lithium serves as the anode, and aluminium rods on each side carry the current.

Various types of paper batteries have been developed for different applications. For example, coating cellulose paper with materials of opposite electrochemical potentials generates voltage, with a simple Cu/paper/Al combination producing 0.5 V. Recent advancements include water-activated paper batteries using activated carbon as the anode, where power output is proportional to the carbon load.

Recent research highlights breakthroughs in paper-based electrodes and their use in flexible energy storage devices. Studies also explore the potential of paper batteries in point-of-care testing, environmental monitoring, and food safety.

Overall, paper batteries offer a flexible, lightweight, and environmentally friendly alternative to traditional batteries.

VII. ELECTRICAL ENERGY STORAGE (EES) SYSTEM

Electrical energy storage (EES) systems store energy in an electric field without converting it into other forms of energy. They are broadly classified into two types: electrostatic energy storage systems and magnetic energy storage systems. Capacitors and supercapacitors fall under electrostatic energy storage systems, while superconducting magnetic energy storage (SMES) represents magnetic energy storage systems.

A. Capacitors

Capacitors are fundamental components in EES systems, known for their ability to store electrical energy using an electrostatic field. A typical capacitor comprises two conductive metal plates separated by a dielectric material (an insulating layer), as illustrated in Fig. 48. When a voltage is applied across the plates, an electric field develops in the dielectric, causing one plate to accumulate positive charge and the other plate to accumulate negative charge. This arrangement allows the capacitor to store energy in the electrostatic field between the plates.

Capacitors are characterized by their rapid charge and discharge capabilities, making them ideal for applications requiring short bursts of energy. However, they have a relatively low energy density compared to other storage technologies, limiting their use to applications such as power conditioning, signal processing, and coupling/decoupling in electronic circuits.

B. Supercapacitors

Supercapacitors, also known as electric double-layer capacitors (EDLCs) or ultracapacitors,

represent a significant advancement in capacitor technology. They consist of two electrodes, typically made of activated carbon, an electrolyte, and a separator. The electrodes are porous, providing a large surface area for charge storage, which significantly enhances the energy density compared to conventional capacitors.

In supercapacitors, energy is stored in the form of an electrostatic field created by the separation of charges at the interface between the electrode material and the electrolyte. When a voltage is applied, ions in the electrolyte move towards the electrode of opposite charge, forming a double layer of charge. This mechanism allows supercapacitors to achieve much higher capacitance values.

Supercapacitors are particularly useful in applications requiring rapid energy delivery and high power density. They are used in hybrid electric vehicles (HEVs), renewable energy systems, and various high-power applications such as backup power supplies and power stabilization.

The development of supercapacitors has been driven by advances in materials science, particularly in the use of carbon-based materials with high specific surface areas and novel electrolytes. These materials allow for the fabrication of supercapacitors with enhanced performance characteristics, such as higher energy density, better cycle life, and improved thermal stability.

Supercapacitors bridge the gap between traditional capacitors and batteries. They offer higher energy densities than conventional capacitors and can deliver more power than batteries, albeit with lower overall energy storage capacity. This makes them ideal for applications where both high power and rapid charge/discharge cycles are required.

C. *Superconducting Magnetic Energy Storage (SMES) System*

Superconducting magnetic energy storage (SMES) systems store energy in the magnetic field generated by a direct current (DC) flowing through a superconducting coil. The superconductivity principle, discovered in 1911, enables these systems to operate with zero electrical resistance, allowing highly efficient energy storage. The first SMES concept was proposed by Ferrier in 1969 for large-scale energy storage, and practical research began in 1971 at the University of Wisconsin. The first commercial SMES application in a power grid was implemented in 1981 along the 500 kV Pacific Intertie in the United States.

An SMES system comprises three primary components: a superconducting coil, a control and power conditioning system, and a cryogenically cooled refrigeration system.

Superconducting Coil: The coil is made from superconducting materials, such as niobium-titanium (Nb-Ti) or high-temperature superconductors (HTS). To maintain superconductivity, the coil must be cooled to cryogenic temperatures using liquid helium or other cooling techniques. The superconducting state allows the coil to conduct electricity without resistance, minimizing energy loss.

Control and Power Conditioning System: This system manages the charging and discharging cycles of the SMES. It regulates the flow of current to and from the superconducting coil, ensuring that the system operates efficiently. It also includes power conversion equipment to switch between alternating current (AC) and direct current (DC) as needed.

Cryogenic Cooling System: The superconducting coil is maintained at cryogenic temperatures to ensure it remains in a superconducting state. This is achieved using a refrigeration system that continuously cools the coil, typically with liquid helium for low-temperature superconductors or liquid nitrogen for HTS.

During the charging phase, a DC current is passed through the superconducting coil, generating a magnetic field and storing energy. When energy is needed, the current is decreased, and the magnetic field collapses, releasing the stored energy back into the electrical grid. The

energy stored in an SMES system is proportional to the square of the current and the inductance of the coil.

SMES systems are characterized by their rapid response times (in milliseconds), high power output (multi-megawatts), and high efficiency (near 100%). These attributes make SMES particularly suitable for applications in power systems that require fast and reliable energy delivery, such as grid stabilization, frequency regulation, and load leveling.

VIII. COMPARISON AMONG THE ENERGY STORAGE SYSTEMS

In this section, we present a comparative review of various energy storage systems (ESS) that have been discussed in the preceding sections. Energy storage systems play a crucial role in modern energy management, providing solutions for balancing supply and demand, enhancing grid stability, and supporting the integration of renewable energy sources. Each storage technology has distinct characteristics, making it suitable for specific applications.

The comparison is based on several key parameters, including energy density, response time, cost, and typical applications. Energy density refers to the amount of energy stored per unit volume or mass, which affects the capacity and size of the storage system. Response time measures how quickly the storage system can release or absorb energy, which is critical for applications requiring immediate power. The cost encompasses both the initial investment and operational expenses, influencing the economic feasibility of the storage technology. Typical applications highlight the common uses and scenarios where each technology excels.

The following table provides a summarized comparison of the various energy storage systems, allowing for an easy understanding of their strengths and weaknesses in different contexts.

Table 1 - Comparison of energy storage systems

Storage system	Energy density	Response time	Cost	Typical applications
Molten salt TES	High	Slow	Medium	Solar thermal power plants
ATES	Medium	Slow	Low	Seasonal storage, building heating
TCES	High	Slow	Medium	Industrial processes
PHES	High	Medium	High	Grid storage, load leveling
GES	Medium	Medium	Medium	Grid storage (future potential)
CAES	Medium	Medium	Medium	Large-scale energy management
FES	Low	Fast	High	Grid stabilization, short-term storage
Hydrogen	High	Slow	High	Energy storage, fuel for transport

SNG	Medium	Slow	High	Energy production, grid storage
Solar fuels	High	Slow	High	Sustainable energy (future potential)
Li-ion batteries	High	Fast	High	Electronics, electric vehicles
Lead-acid batteries	Low	Medium	Low	Automotive, backup power
Ni-Cd batteries	Medium	Medium	Medium	Industrial applications
NaS batteries		Medium	Medium	Grid storage
Na-ion batteries	Medium	Medium	Medium	(Developing technology)
Metal-air batteries	High	Medium	Medium	(Experimental, future potential)
Paper batteries	Low	Medium	Low	Flexible electronics (developing)
Capacitors	Low	Very Fast	Low	Short-term power demands
Super-capacitors	Medium	Very Fast	Medium	Regenerative braking, power smoothing
SMES	Medium	Very Fast	High	Grid stabilization, power quality

IX. PROMISING WAY TO STORE ENERGY

The evolution of energy storage technologies is critical to meeting the demands of a world increasingly reliant on renewable energy sources. Each energy storage system (ESS) has its unique advantages, and the Technology Readiness Level (TRL) framework helps gauge their development stages and commercialization readiness.

As we evaluate promising energy storage solutions, it's essential to understand their current status and potential. Technologies like lead-acid, lithium-ion, and nickel-cadmium batteries have reached high levels of maturity and are widely deployed in various applications due to their reliability and established performance. Pumped hydro energy storage (PHES) and low-speed flywheel energy storage systems are also well-established, demonstrating their effectiveness in large-scale and grid stabilization applications.

Emerging technologies such as electric double-layer capacitors (EDLC) and advanced compressed air energy storage (CAES) systems are progressing rapidly. These technologies are promising due to their potential for improved performance and scalability. Additionally, hydrogen storage systems, despite their high costs, offer significant future potential due to their

versatility and ability to support sustainable energy solutions.

Thermal energy storage methods, including molten salt, aquifer, and thermochemical storage, are gaining attention for their ability to store and dispatch energy effectively over long periods. These methods are particularly suitable for balancing energy supply with demand in renewable energy applications.

As the energy landscape evolves, ongoing research and development will likely drive advancements in these technologies. The focus will continue to be on enhancing efficiency, reducing costs, and expanding the range of applications. By advancing these promising storage solutions, we can better address the challenges of integrating intermittent renewable energy sources and support a more sustainable energy future.

X. CONCLUSION

The transition to renewable energy sources presents significant challenges due to their intermittent nature. Effective energy storage systems (ESS) are crucial for ensuring a stable and reliable energy supply, addressing the gaps between energy production and consumption.

This review has explored a range of ESS technologies, each with its specific characteristics and applications. For large-scale energy management, technologies like pumped hydro storage and thermal energy storage are highly effective. Battery technologies, including lithium-ion and lead-acid batteries, offer robust solutions for various power needs, from electronics to electric vehicles. Supercapacitors, SMES, and flywheel systems excel in applications requiring rapid response and short-duration energy storage.

While hydrogen and synthetic natural gas (SNG) present exciting future possibilities, they currently face challenges related to efficiency and cost. However, their potential for large-scale energy storage remains significant. As research progresses, these technologies may become more viable and cost-effective.

In summary, the advancement and deployment of diverse energy storage technologies are essential for optimizing energy systems and supporting the shift towards renewable energy. Continued innovation and development in these areas will play a pivotal role in meeting future energy needs and achieving sustainability goals.

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