RECENT DEVELOPMENTS IN ELECTRICAL ENERGY STORAGE AND THEIR APPLICATIONS IN POWER SYSTEMS

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Abstract

This study offers a comprehensive review and comparison of various Energy Storage Systems (ESS), analyzing their characteristics, performance metrics, and potential applications. The systems discussed include lead-acid, lithium-ion, sodium-sulfur, flywheel, and pumped hydro, each demonstrating distinct advantages in areas such as energy efficiency, density, power output, cycle life, and self-discharge rates. Lithium-ion and sodium-sulfur technologies show considerable promise for high-density energy applications, while flywheels and electrochemical double-layer capacitors (EDLCs) excel in power density and cycle longevity. The study highlights the growing importance of hybrid energy storage devices (HESDs), which combine the benefits of multiple ESS technologies to meet diverse energy demands. However, it also acknowledges the limitations, such as the exclusion of emerging technologies and reliance on secondary data, mainly for large-scale applications. Future advancements should focus on reducing costs, enhancing efficiency, and improving the lifespan of ESS technologies, offering valuable insights for their optimization in renewable energy, grid support, and electric vehicles.

Keywords: *Energy Storage Systems (ESS), lithium-ion batteries, sodium-sulfur batteries, lead-acid batteries, flywheels.*

1. Introduction

Energy Storage Systems (ESS) are pivotal in addressing the growing global demand for efficient and sustainable energy solutions [1]. As energy consumption rises and renewable energy sources become more prevalent, the need for advanced ESS technologies has intensified to ensure energy reliability, grid stability, and enhanced performance across various applications. This study provides a comprehensive review of leading ESS technologies, including lead-acid, lithium-ion, sodium-sulfur, flywheel, and pumped hydro systems. Each of these systems is evaluated based on key performance metrics such as energy efficiency, energy density, power output, cycle life, and self-discharge rates, highlighting their strengths and limitations. Lithium-ion and sodium-sulfur technologies emerge as strong contenders for high-density energy applications, while flywheels and electrochemical double-layer capacitors (EDLCs) excel in power density and extended cycle life [2]. The study underscores the growing significance of hybrid energy storage devices (HESDs), which integrate the advantages of multiple ESS technologies to cater to diverse energy demands. Despite the advancements, the research identifies challenges, including high costs, limited lifespan, and the exclusion of emerging technologies. The findings aim to guide future research and practical implementations, focusing on cost reduction, efficiency improvements, and lifespan extension, offering critical insights for renewable energy integration, grid support, and electric vehicle applications.

2. Literature Review

Electrical energy storage (EES) systems play a pivotal role in modern power systems, addressing challenges in renewable energy integration, grid stability, and energy efficiency. Recent advancements in EES technologies, including lithium-ion, sodium-sulfur batteries, and flywheels, have significantly enhanced performance in terms of energy density, power output, and cycle life. The growing demand for sustainable energy solutions has driven innovations such as hybrid energy storage systems (HESS) that combine multiple technologies. This review explores the latest developments in E

Summary of Literature Review

Author's	Work Done	Findings
Chen & Li (2023)	Investigated lithium-ion battery innovations and their grid impact.	Innovations improve grid efficiency and energy density, reducing integration challenges.
Allen (2022)	Analyzed electrochemical storage systems for decentralized power applications.	Found ESS crucial for localized power solutions, with potential for decentralized grids.
Singh (2022)	Studied sodium-sulfur batteries in grid-scale storage.	Identified high energy density and durability as key advantages for large-scale applications.
Patel (2021)	Reviewed flywheel energy storage systems in smart grids.	Highlighted long cycle life and high power density as ideal for smart grid applications.
Lopez (2020)	Explored recent innovations in pumped hydro energy storage.	Innovations improve efficiency and scalability, making it a preferred option for bulk storage.
Wang (2020)	Evaluated challenges of integrating EDLCs into hybrid energy systems.	Found EDLCs effective for power density but faced integration and cost-efficiency hurdles.
Brown (2019)	Assessed the role of advanced ESS in renewable energy penetration.	ESS advancements promote higher renewable penetration and system reliability.
Davis (2018)	Studied the evolution of lead-acid batteries in modern power systems.	Improved lead-acid batteries remain viable for cost-sensitive applications.
Rodriguez (2018)	Examined ESS roles in addressing power fluctuation challenges.	ESS significantly mitigates power fluctuations in renewable-based systems.
Lim (2017)	Conducted an economic analysis of lithium-ion batteries for utility-scale storage.	Lithium-ion systems offer economic and operational benefits for large-scale storage.
Wilson (2017)	Investigated design and optimization of hybrid ESS.	Found optimized HESDs effective for dynamic energy demands and grid reliability.

Research Gap

This study identifies several research gaps in the field of Energy Storage Systems (ESS). While the analysis provides valuable insights into established systems like lead-acid, lithium-ion, and sodium-sulfur, it excludes emerging technologies such as solid-state batteries and flow batteries, limiting a comprehensive evaluation. Additionally, the reliance on secondary data restricts the exploration of real-world performance variations across applications. The focus on large-scale applications leaves gaps in understanding ESS suitability for small-scale or decentralized energy systems, emphasizing the need for more targeted, empirical studies.

3. Problem Statement

The study aims to address the need for optimized Energy Storage Systems (ESS) by comparing various technologies, identifying their strengths and limitations. It explores solutions to enhance cost-effectiveness, efficiency, and lifespan, offering insights into their application in renewable energy and electric vehicles.

4. Methodology

The methodology for this study on Energy Storage Systems (ESS) involves a comprehensive review and comparison of different energy storage technologies based on key performance indicators. The review is structured to analyze the characteristics, efficiency, energy density, cycle life, and self-discharge rates of various ESSs. A systematic literature survey was conducted to collect data from primary sources, including research papers, technical reports, and industry publications, to evaluate the operational capabilities and limitations of these technologies. For each ESS type, such as lead-acid, lithium-ion, sodium-sulfur, flywheel, and pumped hydro, performance metrics like energy efficiency, energy density (Wh/kg), power density (W/kg), and cycle life (number of cycles) were examined. Additionally, the self-discharge rates, as well as the potential for scalability and applicability in different industries (e.g., electric vehicles, grid support, and renewable energy storage), were considered. A comparative analysis of hybrid energy storage devices (HESDs) was also carried out, highlighting potential combinations of ESSs that could provide optimal solutions based on energy and power density needs. This analysis also explored the future prospects of these technologies by focusing on emerging advancements, including cost reduction, efficiency improvement, and enhanced lifespan. The research outcomes provide insights into the practical applications and future directions of energy storage technologies in real-world scenarios.

5. Result & Discussion

Review of Energy Storage Technologies

Energy Storage Systems (ESSs) convert electrical energy into a form that can be stored and released when required [3]. The selection of an appropriate energy storage system for a specific application depends on factors such as power and energy ratings, response time, weight, volume, and operating temperature. Table I presents a summary of the key characteristics of various energy storage technologies.

A. Batteries: The use of lead-acid batteries for energy storage dates back to the mid-1800s. A lead-acid battery cell consists of spongy lead as the negative active material, lead dioxide as the positive active material, and a diluted sulfuric acid electrolyte, with lead acting as the current collector. Despite their low energy density and limited cycle life, lead-acid batteries remain common in cost-sensitive applications where ruggedness and tolerance to abuse are crucial. These include automotive starting, lighting, and ignition (SLI) systems, as well as battery-powered uninterruptible power supplies (UPS). SLI applications typically utilize flat plate grid designs for current collectors, whereas more advanced batteries employ tubular designs [4]. Recent advancements focus on replacing lead with lighter materials such as carbon to improve both power and energy density. Lithium-ion (Li-ion) batteries operate by moving lithium ions between the anode and cathode to generate a current flow. These batteries are known for their high energy-to-weight ratios, absence of memory effect, and low self-discharge rates. Li-ion batteries are widely used in portable devices, laptops, cameras, mobile phones, and power tools. Due to their high energy density, Li-ion technology is also emerging as a leading option for plug-in hybrid and electric vehicles. However, the relatively high cost of Li-ion batteries remains a barrier for many applications. Nickel-cadmium (NiCd) batteries were the preferred choice for high-performance applications from the 1970s to the 1990s.

However, they have since been largely replaced by Li-ion and nickel-metal hydride (NiMH) batteries. NiCd batteries have several drawbacks compared to NiMH batteries, including: (1) shorter lifecycle, (2) more significant "memory effect," (3) toxicity of cadmium, which requires complex recycling, (4) lower energy density, and (5) a flat discharge curve and negative temperature coefficient that may cause thermal runaway in voltage-controlled charging. As a result, NiMH batteries have become more widely adopted in recent years. NiMH batteries were favored for electric vehicle (EV) and hybrid electric vehicle (HEV) applications during the 1990s and 2000s, owing to their relatively high power density, proven safety, good abuse tolerance, and long life in partial charge states [5]. One disadvantage of NiMH batteries is their relatively high self-discharge rate, although the introduction of new separators has helped mitigate this issue. When overcharged, NiMH batteries use excess energy to split and recombine water, making them maintenance-free. However, excessive charging rates can cause hydrogen buildup, which may lead to cell rupture. In cases of over-discharge, the cell may become reverse-polarized, resulting in a loss of capacity.

Table 1 Energy storage systems

Type	Energy Efficiency (%)	Energy Density (Wh/kg)	Power Density (W/kg)	Cycle Life (cycles)	Self Discharge
Pb-Acid	70–80	20–35	25	200–2000	Low
Ni-Cd	60–90	40–60	140–180	500–2000	Low
Ni-MH	50–80	60–80	220	< 3000	High
Li-Ion	70–85	100–200	360	500–2000	Medium
Li-Polymer	70	200	250–1000	> 1200	Medium
NaS	70	120	120	2000	–
VRB	80	25	80–150	> 16000	Negligible
EDLC	95	< 50	4000	> 50000	Very High
Pumped Hydro	65–80	0.3 –	–	> 20 years	Negligible
CAES	40–50	10–30	–	> 20 years	–
Flywheel (Steel)	95	5–30	1000	> 20000	Very High
Flywheel (Composite)	95	> 50	5000	> 20000	Very High

Sodium sulfur (NaS) batteries feature molten sulfur at the positive electrode and molten sodium at the negative electrode, separated by a solid beta alumina ceramic electrolyte. These batteries offer impressive power and energy density, exceeding four times that of lead-acid batteries, along with high coulombic efficiency, excellent temperature stability, long cycle life, low cost, and strong safety [6]. NaS batteries are ideal for applications such as load leveling, emergency power supply, and uninterruptible power supply (UPS), serving various markets, including industrial, commercial, and wind power generation sectors. Flow batteries (FB) present an innovative technology that separates the total stored energy from the rated power. The rated power is determined by the size of the reactor, while the stored capacity depends on the volume of the auxiliary tank. This flexibility makes FBs highly suitable for providing the large power and energy demands of electrical utilities. FBs operate similarly to hydrogen fuel cells, using two electrolytes stored in separate tanks, with no self-discharge, and a microporous membrane that separates the electrolytes while allowing ions to pass through, generating an electrical current. The key advantages of FB technology include: (1) high power and energy capacity, (2) rapid recharge by replacing the depleted electrolyte, (3) extended lifespan enabled by easy electrolyte replacement, (4) full discharge capability, (5) use of non-toxic materials, and (6) operation in low temperatures [7]. A significant drawback of the system is the need for moving mechanical components, such as pumps, which hinder system miniaturization. As a result, commercial adoption has been limited to date.

B. Electrochemical Double-Layer Capacitors (EDLCs): Electrochemical double-layer capacitors (EDLCs) operate similarly to conventional capacitors, as they do not involve ionic or electronic transfer that leads to a chemical reaction. Energy is stored in EDLCs through simple charge separation. These capacitors are designed with an extremely high electrode surface area and employ high-permittivity dielectrics. The surface area is maximized by using porous carbon as the current collector, which allows a significant amount of energy to be stored on the surface. As a result, EDLCs achieve much higher capacitance values (measured in kilo-Farads) compared to conventional capacitors (which are measured in milli- and micro-Farads) [8]. The two electrodes are separated by a very thin, porous separator and are immersed in an electrolyte, such as propylene carbonate. Due to the high permeability and close proximity of the electrodes, EDLCs have a low voltage withstand capability (typically 2V-3V). They also feature long cycle lives because, in normal operation, no chemical changes occur on the electrodes. EDLCs excel in terms of efficiency and power density, as energy is physically stored on the electrodes. However, their energy density is relatively low since the charges are not bound by chemical reactions.

C. Regenerative Fuel Cells (FCs): Fuel cells (FCs) are electrochemical devices that use hydrogen and oxygen to produce water and electricity. Regenerative fuel cells (RFCs) combine the functions of both a fuel cell and an electrolyzer, enabling the storage of hydrogen as a gaseous fuel for future electricity generation. While all fuel cells can theoretically function as regenerative fuel cells, they are typically optimized for one function—either electricity production or hydrogen production. By combining both functions, RFCs reduce the system size for applications that require both energy storage (hydrogen production) and energy production (electricity generation) [9]. Current research focuses on utilizing polymer electrolyte membrane (PEM) fuel cells with hydrogen or methanol as the primary fuel. However, the challenge remains to design a system that efficiently produces both hydrogen and electricity. Existing FC designs are less efficient in hydrogen production compared to conventional electrolysis methods. Regenerative fuel cells are particularly suited for aerospace applications, where high energy density is crucial and cost sensitivity is less of an issue. Like conventional fuel cells, RFCs experience degradation over time in dynamic applications. As a result, they are often paired with EDLCs or other energy storage systems (ESS) to mitigate fluctuations and enhance their performance.

D. Compressed Air Energy Storage (CAES): Compressed air energy storage (CAES) technology stores energy as compressed air for later use. Energy is extracted using a standard gas turbine, where the air compression stage of the turbine is replaced by the CAES system, eliminating the need for natural gas to fuel the compression process. The system design is complex due to the fact that air compression and expansion are exothermic and endothermic processes, respectively. CAES has been proposed for various applications, especially for electric grid support and load leveling [10]. In these systems, energy is stored during periods of low electricity demand and is later converted back into electricity when demand is high. Installed commercial CAES system capacities range from 35 MW to 300 MW.

E. Flywheel Energy Storage Systems (FESS): Flywheel energy storage systems (FESS) store energy in a rotating mass, a concept historically used to stabilize voltage output in synchronous generators. Recent advancements in power electronics and material engineering have made this technology appealing for a variety of applications, including transportation and power quality improvement. Flywheel systems are capable of delivering very high peak power, with the input/output peak power being primarily limited by the power converter. FESS have both high power and energy densities, along with the ability to undergo virtually an unlimited number of charge-discharge cycles. As a result, they are commonly employed in transportation and power quality applications that demand frequent charge-discharge cycles. Moreover, FESS enable straightforward state monitoring, as the "state-of-charge" can be determined by easily measurable parameters like flywheel inertia and speed. The key design factor for FESS is the maximum rotational speed of the flywheel, which classifies systems into low-speed and high-speed categories, typically with the dividing line at around 10,000 rpm. The rotational speed impacts the choice of materials, geometry, and the length of the flywheel, as well as the type of electrical machine and bearing [11]. High-speed systems are more complex due to the technological requirements but provide higher energy density, as the total energy stored in the flywheel is proportional to the square of the rotational speed. Other design considerations include system performance, safety, and reliability.

F. Superconductive Magnetic Energy Storage (SMES): Superconductive magnetic energy storage (SMES) involves storing energy in the magnetic field generated by a direct current flowing through a superconducting coil. The coil is maintained at a temperature below its superconducting critical temperature via cryogenic cooling. The system is typically designed as a solenoid or a series of solenoids arranged to cancel out the surrounding magnetic field. The first SMES system was introduced in [27]. SMES offers one of the highest energy densities among power storage methods, with its key advantage being storage efficiency exceeding 90% (excluding the refrigeration system, which consumes about 1.5 kW continuously per

MWh of storage capacity). Another benefit of SMES is its high dynamic response, enabling rapid response times in the millisecond range.

G. Thermo-Electric Energy Storage (TEES): Thermo-electric energy storage (TEES) for solar thermal power plants involves storing energy in the form of heat using synthetic oils or molten salts [12]. This heat is collected by solar thermal plants to ensure smooth power output during cloudy periods and extend power production for 1-10 hours after sunset. Additionally, TEES can store electricity from off-peak periods using materials such as hot or cold storage in underground aquifers, water or ice tanks, or other storage media. This stored energy is then used to reduce electricity consumption in building heating or air conditioning systems during peak demand periods.

Hybrid Energy Storage Devices (HESD)

Certain applications require a combination of energy, power density, cost, and life cycle specifications that cannot be met by a single energy storage device. To address this need, hybrid energy storage devices (HESDs) have been proposed. HESDs combine the power output of two or more devices with complementary characteristics, merging high-power devices (with fast response times) and high-energy devices (with slower response times). These hybrid systems have been suggested for use in propulsion applications and grid support.

Examples of proposed HESDs include the following pairings, with the energy-supplying device listed first and the power-supplying device second:

- Battery and EDLC
- Fuel Cell and Battery or EDLC
- CAES and Battery or EDLC
- Battery and Flywheel
- Battery and SMES

To combine multiple energy storage devices into a unified power source, more complex conditioning circuitry is required. Various topologies have been suggested to achieve this, ranging from simple configurations to highly flexible ones [13]. Generally, these topologies fall into three categories:

1. Direct parallel connection of two energy storage devices
2. Insertion of an additional converter between the two power sources
3. Connection of each power source to a dedicated power converter, with the converters then connected to a common output bus.

Applications of Energy Storage Systems (ESS)

Energy Storage Systems (ESS) significantly enhance the performance of a wide range of applications. They are particularly well-suited for both transportation and utility-scale applications, and in some cases, they are a key factor determining the adoption of certain technologies, such as electric vehicles. The operational range of various energy storage technologies in terms of time and power is illustrated in Figure 1. This figure highlights the suitability of different ESS for both transport and utility applications. In transportation, the time and power ranges span from seconds to hundreds of minutes and from tens of kW to tens of MW, while in utility-scale applications, they range from tens of minutes to hours and from MW to GW. For utility or renewable energy integration, key performance indicators include energy storage capacity, power output, and life cycle [14]. The need for long life cycles has driven the use of storage technologies based on reversible physical processes, such as Compressed Air Energy Storage (CAES) and pumped hydro systems, as alternatives to electrochemical batteries, which face challenges like aging and recycling difficulties. In transportation, portability, scalability, and energy and power density are the primary performance criteria. Despite challenges such as limited lifespan, batteries remain the most viable solution for transport applications due to their modularity and portability.

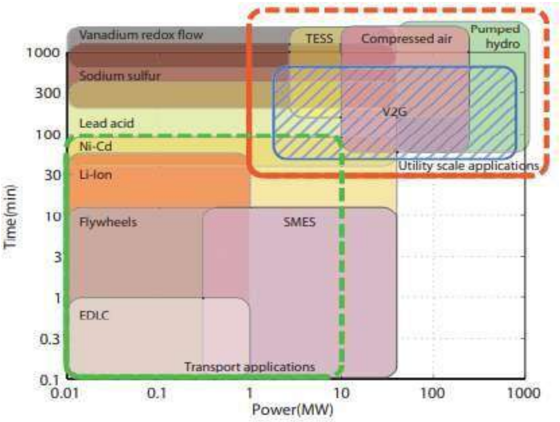

Figure 1 Storage technology.

6. Conclusion

In conclusion, this study provides an in-depth comparison and review of various Energy Storage Systems (ESS), highlighting their characteristics, performance metrics, and potential applications. The systems examined, including lead-acid, lithium-ion, sodium-sulfur, flywheel, and pumped hydro, each demonstrate unique advantages in energy efficiency, energy density, power density, cycle life, and self-discharge rates. Technologies like lithium-ion and sodium-sulfur show strong potential for high-density energy applications, while flywheels and electrochemical double-layer capacitors (EDLCs) excel in power density and cycle life. The study also emphasizes the role of hybrid energy storage devices (HESDs) that combine the strengths of multiple ESSs to meet specific energy demands. Despite the promising advancements, the study acknowledges limitations such as the exclusion of emerging technologies, reliance on secondary data, and the focus on large-scale applications. Future research and development are expected to focus on reducing costs, improving efficiency, and extending the lifespan of ESS technologies to further enhance their viability in real-world applications. The findings provide valuable insights for selecting and optimizing ESS solutions across various sectors, including renewable energy integration, grid support, and electric vehicles.

Future Scope

- Explore emerging ESS technologies like solid-state batteries and graphene-based supercapacitors.
- Improve energy conversion efficiency and retention capabilities for better performance.
- Extend ESS lifespan and durability for long-term viability in harsh environments.
- Develop hybrid ESS that combine strengths to optimize energy density, power density, and cycle life.

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