Chapter

Optimizing Energy Storage Solutions for Grid Resilience: A Comprehensive Overview

Sina Samadi Gharehveran, Kimia Shirini and Arya Abdolahi

Abstract

The evolving energy landscape, driven by increasing demands and the growing integration of renewables, necessitates a dynamic adjustment of the energy grid. To enhance the grid's resilience and accommodate the surging influx of green energy. Energy storage solutions have emerged as crucial components. Despite considerable research, there remains a notable gap in systematically assessing the suitability of different storage devices across diverse stationary applications. This review endeavors to bridge this gap by thoroughly examining the current landscape of energy storage and discerning its aptness for various grid support applications. Through an exploration of technical, economic, and environmental considerations, the study aims to elucidate the optimal storage technologies for different contexts. Among electrochemical storage options, lithium-ion batteries emerge as optimal choices for both low- and medium-scale applications, owing to their robust power and energy densities. Meanwhile, capacitors, supercapacitors, and superconductive magnetic energy storages exhibit promise for high-power demands within the electrical storage domain. Additionally, thermal energy storage presents a viable solution for seasonal and bulk energy requirements. This review suggests using a mix of technologies in hybrid solutions to better meet the unique needs of different applications.

Keywords: energy storage, renewable integration, techno-economic assessment, hybrid solutions, green energy

1. Introduction

The world continues to grapple with significant energy challenges, including the scarcity of reliable energy sources at reasonable costs and the environmental damage caused by polluting sources like coal. To address these issues, many countries are increasingly adopting various forms of renewable energy sources (RESs). It is projected that by 2050, wind and solar energy will fulfill 50% of global energy demand [1]. Additionally, the demand for electricity from electric vehicles (EVs) is expected to grow by 6%, reaching approximately 2 TWh by 2040 [2]. Based on the Bloomberg New Energy Finance (BNEF) report examining the global power generation mix, fossil fuels dominated the energy supply from 1970 to 2017, significantly outweighing renewable sources. However, since 2018, the reliance on fossil fuels such as coal and natural gas has been decreasing, with projections indicating a decline to 31% of the total energy mix by 2050. Conversely, renewable energy sources such as hydro, wind, and solar are expected to dominate, comprising over 62% of the energy mix. Specifically, solar and wind are anticipated to account for around 48% of the generation mix. This transition is propelling a significant surge in the deployment of network support and energy storage solutions globally. A recent BNEF study projects that by 2040, the market will grow to 1095 GW/2850 GWh, representing over a 120-fold increase from the 9 GW/17 GWh installed in 2018 [3].

Energy storage devices (ESDs) can be utilized across all levels of the network, including generation, transmission, distribution, and for local industrial and commercial customers. Presently, there is a growing interest not only in deploying existing ESDs for stationary applications but also in developing advanced future ESDs. This category encompasses upcoming advancements such as Li-ion, solid-state, lithium-polymer, lithium-sulfur, lithium-metal-polymer, metal-ion batteries, organic radical batteries, hybrid supercapacitors, and other emerging technologies [4, 5]. Studies [6, 7] indicate that for large-scale power management, thermal energy storage (TES) is currently a viable option, particularly for capacities exceeding several MW. Among electric and electrochemical ESDs, only flow batteries, sodium-sulfur, and lead-acid batteries are considered capable of meeting these extensive requirements. Additionally, various ESDs are suitable for integrating green energy at the distribution and transmission levels, addressing diverse multidisciplinary needs [6, 7]. Assessing the present and prospective states of electrical, electrochemical, and thermal ESDs is essential for determining their suitability for various roles and

		Integrated centralized storage and transmission framework	**The distribution system and regional storage**	**Consumer (building and residential level)**
Function	Balance between supply and demand	Large geographic disparities and variations on seasonal, weekly, daily, and hourly scales result from the intermittent nature of wind turbines (WT) and solar photovoltaics (PV), leading to fluctuating electricity generation	Daily/hourly variations Peak saving	Daily deviations
	Distribution—moving energy	Voltage and frequency regulation Increased peak generation for traditional power stations Global electricity market	Voltage and frequency control Power market	Combining small stored energy quantities to address distribution needs, including capacity issues and reducing losses
	Energy efficiency improvement	Improved productivity in the globe energy mix with time-shift	Storage and load control for improved performance in the distribution system	Enhanced energy production and utilization, along with changes in behaviors

Table 1.
Function of energy storage in the energy supply chain [8].

power applications. **Table 1** outlines the roles and significance of ESDs, their required specifications, and how they interact across various power levels.

This review distinguishes itself from prior reports [4, 7, 9] in several key aspects. It provides a comprehensive analysis of ESD using up-to-date and reliable data. In contrast to earlier reviews, this study integrates graphical analysis and compares it with effective and standardized performance evaluation criteria, encompassing economic, technical, and environmental metrics. In terms of economics, this review goes beyond capital cost to include an analysis of operating and maintenance expenses, which is often overlooked in earlier studies. Additionally, the advanced features of ESDs are evaluated. The review's contributions are as follows: It identifies the specific requirements of various ESDs for different application types, with a particular focus on the integration of RESs into the grid. Graphical analyses are conducted to determine the most suitable ESDs for specific services. Through precise identification of application needs and comprehensive assessment of the economic, technical, and environmental implications of storage devices, this review proposes that adopting a hybrid approach to ESDs offers a practical solution for integrating RES and addressing stationary application demands.

These contributions collectively aim to enhance the understanding and deployment of energy storage technologies in supporting a resilient and sustainable energy grid.

- Extensive evaluation of energy storage devices (ESDs) considering technical, economic, and environmental metrics.

- Integration of graphical analysis with evaluation criteria including capital and operational costs.

- Advocacy for hybrid energy storage solutions combining multiple technologies for optimal grid resilience.

- Emphasis on emerging technologies like solid-state batteries and hybrid supercapacitors.

- Focus on ESDs' role in integrating renewable energy sources into the grid, addressing intermittency challenges.

2. State of the art in energy storage devices

The authors conducted an extensive investigation into the requirements of diverse storage applications for grid support and identified suitable ESDs for these purposes. Energy storage plays a multifaceted role across varying power scales to bolster grid operations. At the transmission level, centralized storage systems effectively manage supply and demand fluctuations, spanning from seasonal to hourly variations, crucially stabilizing intermittent energy generation from renewable sources. Centralized storage in transmission also aids in regulating voltage and frequency while enhancing overall efficiency through time-shifting strategies. At lower power levels, such as distribution and consumption, ESDs contribute by offering lower energy densities, thereby managing daily and hourly fluctuations, facilitating peak shaving, and improving system efficiency. The study provides a concise overview of diverse ESD

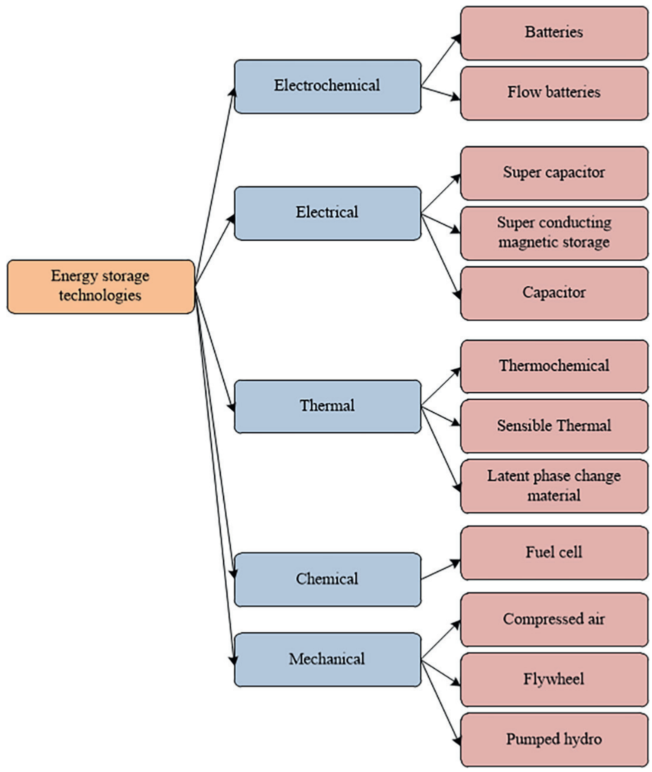

Figure 1.
Classification of various energy storage systems.

types and their respective attributes. A detailed classification of these ESD types is depicted in **Figure 1**.

2.1 Key drivers for energy grid adaptation in the modern energy landscape

The primary drivers necessitating the adjustment of the energy grid in the current energy landscape are multifaceted and interconnected. One of the foremost drivers is the integration of renewable energy sources (RESs) such as wind and solar power. These sources are inherently intermittent and variable, requiring the grid to be more flexible and resilient to manage fluctuations and maintain a reliable power supply. Additionally, the rising energy demand, particularly from electric vehicles (EVs) and other electrified sectors, necessitates a more robust and capable grid to meet the growing consumption needs. The decline in the use of fossil fuels like coal and natural gas, prompted by environmental regulations and economic factors, further underscores the need for the grid to accommodate a larger share of renewable energy sources.

To ensure a continuous and stable energy supply despite the variability of RESs, the grid must incorporate advanced energy storage solutions and other technologies to balance supply and demand effectively. Environmental concerns also play a critical role, as the urgent need to reduce carbon emissions and mitigate climate change impacts drives the shift toward cleaner energy sources and the development of a more sustainable energy grid. Technological advancements in energy storage, such as lithium-ion batteries and thermal energy storage, enable better management of energy resources and support the integration of renewable energy into the grid. Economic considerations are equally important, as the cost-effectiveness of integrating advanced energy storage devices and renewable energy technologies into the grid is crucial for long-term sustainability and efficiency. These drivers collectively necessitate significant adjustments to the energy grid to ensure it can support the evolving energy landscape characterized by increased renewable energy integration, rising energy demand, environmental sustainability, and technological advancements.

2.2 Suitability of storage devices for stationary applications

The significant gap in assessing the suitability of different storage devices for various stationary applications can be attributed to several factors. One primary reason is the diverse range of technical, economic, and environmental requirements that different applications entail. Each type of energy storage device, such as lithium-ion batteries, lead-acid batteries, and sodium-sulfur batteries, has unique characteristics that make it suitable for specific contexts but not universally optimal. For instance, while lithium-ion batteries are known for their high energy and power densities, making them suitable for transportation and some stationary uses, their cost and environmental concerns, including the availability of materials like lithium and cobalt, pose significant challenges for broader applications.

Additionally, the evolving energy landscape, driven by the integration of renewable energy sources, necessitates a dynamic adjustment of the energy grid. This complexity is compounded by the intermittent nature of renewable energy, which requires storage solutions that can manage fluctuations in supply and demand across different time scales—from hourly to seasonal variations. Furthermore, the rapid advancement of technology means that new storage solutions are continuously being developed, which adds to the challenge of systematically evaluating their suitability across all potential applications.

Another critical aspect is the varying performance metrics used to evaluate storage devices, which can differ significantly based on the application. Factors such as specific energy, power density, round-trip efficiency, service life, and self-discharge rate are crucial in determining the appropriateness of a storage technology for a particular use case.

2.3 Energy challenges and renewable integration

The projected contributions of wind and solar energy to the global energy demand by 2050 include:

- By 2050, wind and solar energy are expected to fulfill approximately 50% of the world's energy needs.

- This increase is driven by technological advancements, which make these sources more efficient and cost-effective.

- Supportive government policies worldwide are encouraging the adoption of wind and solar power.

- The growth in wind and solar energy will significantly reduce reliance on fossil fuels.

- These renewable energy sources will help decrease greenhouse gas emissions.

- Wind and solar energy will enhance global energy security by diversifying the energy mix.

The reliance on fossil fuels has seen a significant shift since 2018, with a gradual decline as the world transitions toward renewable energy sources. Here are the key points summarizing the changes and projections:

- Decline in fossil fuel usage: Since 2018, there has been a noticeable reduction in the use of fossil fuels such as coal and natural gas. This decline is driven by increasing environmental concerns, regulatory policies, and the economic viability of renewable energy sources.

- Increase in renewable energy: There has been a substantial increase in the adoption of renewable energy sources like wind and solar power. Technological advancements and decreasing costs have made these sources more attractive and feasible.

By 2050, renewable energy sources are projected to dominate the global energy mix, with wind and solar energy alone expected to fulfill approximately 50% of the world's energy needs. This significant shift toward renewables is driven by advancements in technology, decreasing costs, and increasing global efforts to reduce carbon emissions. Meanwhile, the reliance on fossil fuels is anticipated to decline considerably, with forecasts suggesting they will account for about 31% of the total energy mix by 2050. This reduction reflects a growing commitment to transitioning away from high-carbon energy sources. The remaining portion of the energy mix will be composed of contributions from nuclear power, hydroelectricity, and other emerging technologies, each playing a role in supporting a more sustainable and diversified energy portfolio. This diverse energy mix aims to enhance energy security, reduce environmental impacts, and support global economic growth.

2.4 Electrochemical technologies

Li-ion batteries dominate storage installations, comprising more than 85% of new energy storage deployments in 2016. While highly favored, achieving a decarbonized grid necessitates the adoption of diverse energy storage technologies beyond Li-ion batteries alone [5, 8, 10]. Li-ion batteries dominate the field of electrochemical energy storage due to their rapid and extensive adoption across diverse market sectors, ranging from personal electronics to electric vehicles and industrial applications. This widespread usage has led to a significant reduction in the cost of Li-ion battery packs by more than 85% over the past decade [11]. Ongoing research and recent investment trends indicate that new technologies will emerge to better meet daily energy demands with improved reliability and efficiency, potentially driving further cost reductions and increasing deployment in stationary applications. However, challenges persist in integrating batteries into energy storage systems, including the need for longer duration and environmentally friendly solutions. Alternative technologies may offer economically viable and dependable alternatives to address these challenges. Consequently, the suitability of Li-ion storage devices may vary depending on specific requirements for power output and energy density. Evaluation of electric and electrochemical energy storage devices typically considers their performance across specific application contexts [12]. Key technical characteristics of electrochemical energy storage devices are summarized below.

2.4.1 Li-ion batteries

Li-ion batteries are notable for their superior energy and power densities, making them highly suitable for both transportation and stationary uses [13–17]. These attributes are typically quantified using various performance metrics. Key technical specifications of Li-ion batteries include a specific energy range of 75–250 Wh/kg, specific power of 150–315 W/kg, round-trip efficiency between 85 and 95%, a service life spanning 5–15 years, and a self-discharge rate of 0.1–0.3% [18]. Their high specific energy and power densities contribute to their lightweight design, which is advantageous in applications where weight is a critical consideration [17, 18].

They are extensively used in personal electronics, electric vehicles, and industrial applications due to their lightweight design and decreasing costs. However, their limitations in long-duration storage and environmental concerns have led to the exploration of alternative technologies.

Table 2 provides a concise overview of the key technical characteristics and performance metrics of Li-ion batteries.

Characteristic	Description	Performance metrics
Energy density	Gravimetric Energy Density	150–250 Wh/kg
	Volumetric Energy Density	250–700 Wh/L
Efficiency	Coulombic Efficiency	>99%
	Round-Trip Efficiency	85–95%
Cycle life	Number of charge-discharge cycles before capacity significantly degrades	Several hundred to several thousand cycles
Charging and discharging rates	C-Rate: Rate at which a battery is charged or discharged relative to its capacity	0.5–5°C (varies by application)
Temperature range	Effective operating temperature range for maintaining performance and safety	−20 to 60°C
Voltage	Nominal Voltage	3.6–3.7 volts
	Voltage Range	2.5–4.2 volts
Self-discharge rate	The rate at which a battery loses charge when not in use	2–3% per month
Safety features	Mechanisms to prevent overcharging, deep discharging, and overheating	Thermal cut-offs, pressure relief valves, advanced BMS
Environmental impact	Environmental considerations and impact compared to other battery types	Fewer toxic components require careful recycling and disposal handling

Table 2.
An overview of the key technical characteristics and performance metrics of Li-ion batteries.

2.4.2 Lead-acid (Pb-acid) batteries

Lead-acid (Pb-Acid) batteries are recognized for their moderate round-trip efficiency and cost-effectiveness [13, 15, 17]. Typical technical specifications for Pb-Acid batteries include a specific energy range of 30–50 Wh/kg, specific power ranging from 75 to 300W/kg, round-trip efficiency between 70 and 80%, a service life of 5–15 years, and a self-discharge rate of 0.1–0.3% [16–18]. Despite offering comparable service life and self-discharge rates to Li-ion batteries [17, 18], their lower cost makes Pb-Acid batteries particularly suitable for stationary applications [13].

2.4.3 Sodium sulfur (NaS) batteries

Among electrochemical storage devices, Sodium-Sulfur (NaS) batteries are increasingly gaining attention as an emerging technology [12, 17]. NaS batteries are evaluated based on various technical parameters, which include a specific energy range of 150–240 Wh/kg, specific power ranging from 150 to 230 W/kg, round-trip efficiency typically between 80 and 90%, a service life averaging around 15 years, and a negligible self-discharge rate [17, 18]. Notably, NaS batteries are distinguished by their high specific energy, setting them apart from other storage technologies. This characteristic makes them particularly suitable for applications that demand high specific energy [17].

Table 3 outlines the key technical specifications and applications of lead-acid (Pb-Acid) and sodium-sulfur (NaS) batteries, highlighting the differences in energy density, cycle life, efficiency, operating conditions, environmental impact, cost, maintenance requirements, safety, and typical applications.

Specification/Characteristic	Pb-acid batteries	NaS batteries
Energy density	30–50 Wh/kg	150–240 Wh/kg
Cycle life	300–500 cycles	2500–4500 cycles
Efficiency	70–80%	85–90%
Charge/discharge rate	Moderate, typically up to 1°C	High, capable of 2–4°C
Operating temperature range	−20 to 50°C	300–350°C
Self-discharge rate	3–5% per month	<1% per day
Environmental impact	Contains toxic lead and sulfuric acid, and needs careful disposal	High operating temperatures require thermal insulation
Cost	Low initial cost	Higher initial cost
Maintenance	Requires regular maintenance (water refilling)	Low maintenance
Safety	Risk of acid spills and hydrogen gas release	High operating temperature poses safety concerns
Applications	• Automotive (starter batteries) • Uninterruptible power supplies • Emergency lighting • Grid energy storage	• Grid energy storage • Renewable energy integration • Load leveling and peak shaving

Table 3.
Key technical specifications and applications of Pb-Acid and NaS batteries.

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2.4.4 Nickel–cadmium (Ni-Cd) batteries

Nickel-cadmium (Ni–Cd) batteries are important in stationary energy storage applications, known for their relatively higher specific power despite a higher self-discharge rate [13, 14]. Key performance parameters for Ni-Cd batteries include a specific energy range of 50–75 Wh/kg, specific power ranging from 150 to 300 W/kg, round-trip efficiency of approximately 70%, a service life spanning 10–20 years, and a self-discharge rate between 0.03 and 0.6% [13–15].

Nickel-cadmium (Ni-Cd) batteries offer several advantages for stationary energy storage applications. One of their primary benefits is their long cycle life, often exceeding 1500–2000 cycles, making them highly durable and suitable for applications requiring frequent charging and discharging. Additionally, Ni-Cd batteries can deliver high discharge currents, which is beneficial for systems needing a rapid release of energy, such as backup power systems and peak shaving applications. Their ability to perform well across a wide operating temperature range, from −20 to 50°C, adds to their versatility, allowing them to be used in various environmental conditions. Moreover, these batteries are robust and resilient, able to withstand electrical abuse, including overcharging and deep discharging, as well as mechanical stress. This robustness enhances their reliability in harsh conditions. Ni-Cd batteries also require relatively low maintenance compared to lead-acid batteries, with no need for regular electrolyte refilling, adding to their convenience.

However, Ni-Cd batteries come with significant disadvantages. They contain cadmium, a toxic heavy metal that poses substantial environmental and health risks. Disposal and recycling of these batteries require careful handling to prevent contamination, making their environmental impact a major concern. Ni-Cd batteries are also susceptible to the memory effect, where the battery gradually loses its maximum energy capacity if not fully discharged and recharged regularly. This can impact their performance over time. Additionally, Ni-Cd batteries have a higher self-discharge rate compared to other battery types, losing approximately 10% of their charge per month when not in use, which affects their efficiency. The initial cost of Ni-Cd batteries is higher than that of lead-acid batteries, which can be a disadvantage for cost-sensitive applications. Furthermore, due to their cadmium content, Ni-Cd batteries face regulatory restrictions in many regions, limiting their use and availability.

The review highlights several primary electrochemical storage options and their suitable applications, which include:

1. Lithium-ion (Li-ion) batteries:

    - Electric vehicles: Li-ion batteries power a wide range of electric vehicles, from cars to busses, providing the necessary energy density for long-range travel.

    - Grid storage: They are increasingly used for grid energy storage solutions, particularly for balancing supply and demand and integrating renewable energy sources like solar and wind power.

    - Industrial applications: Used in various industrial equipment and machinery requiring reliable and efficient energy storage.

2. Lead-acid (Pb-Acid) batteries:

   - Uninterruptible power supplies: Lead-acid batteries are commonly used in UPS systems to provide backup power during outages.
   - Renewable energy storage: Suitable for storing energy generated from renewable sources, such as solar panels, especially in off-grid systems.
   - Automotive: Traditional starter batteries in internal combustion engine vehicles.

3. Sodium-sulfur (NaS) batteries:

   - Grid-scale energy storage: NaS batteries are ideal for large-scale energy storage solutions, providing high specific energy and long service life, suitable for stabilizing the grid and supporting renewable energy integration.
   - Industrial power backup: Used in industrial settings requiring reliable backup power.

4. Nickel-cadmium (Ni-Cd) batteries:

   - Emergency lighting: Ni-Cd batteries are used in emergency lighting systems due to their reliability and durability.
   - Aviation: Employed in aircraft for emergency power and starting the engines.
   - Railway systems: Used for backup power in railway signaling and control systems.
   - Renewable energy storage: Suitable for small-scale renewable energy applications where robustness and durability are essential.

2.5 Thermal energy storage (TES) technologies

Thermal Energy Storage (TES) systems, designed to store heat energy within insulated enclosures, are currently in the initial phases of commercial adoption. TES technology spans a wide temperature spectrum, from −40 to 400°C, accommodating various methods categorized into low-temperature and high-temperature TES. Low-temperature systems encompass options like auriferous and cryogenic energy storage, while high-temperature systems include sensible, latent, and concrete thermal storage techniques [18]. Cryogenic storage stands out due to its high-power capability and extended discharge durations. In sensible heat storage, the storage medium's specific heat capacity plays a crucial role, directly influencing the storage capacity of the TES system [19]. Water offers limited storage capacity, whereas higher capacities can be achieved with latent-phase change materials (PCMs), which leverage the latent heat of the PCMs [20, 21]. Thermochemical storage technology stores and releases heat or cold as required through diverse chemical reactions. Sensible heat storage is currently accessible on the market, whereas PCMs and thermochemical technologies are primarily in developmental stages. Based on various studies, the performance characteristics of TES technologies encompass power capacities ranging from a few MW to 300 MW and energy capacities between 20 and 140 MWh. These systems offer discharge times ranging from hours to several days, an unlimited cycle life, rapid response times in seconds, efficiencies of 30–60%, and energy densities of 80–250 Wh/kg. Additionally, they provide specific energies of 80–250 Wh/kg, specific powers of 10–30 W/kg, service lives spanning 10–30 years, and self-discharge rates of 0.05–1% [5, 18, 22–24].

One of the leading Thermal Energy Storage (TES) technologies utilizes molten salt for energy storage by harnessing and concentrating solar energy. Molten Salt Energy Storage (MSES) systems, which can serve as both storage media and heat transfer agents, operate at high temperatures (up to 570°C) and employ smaller storage tanks [5]. MSES is notable for its efficient heat transfer capabilities and is a commercially viable technology, unlike many other TES technologies still in early development. Despite its advantages, MSES must handle corrosive molten salts that require specific temperature maintenance to prevent freezing, and it is commonly integrated with concentrating solar power plants. The primary advantage of TES is its low self-discharge rate, making it a cost-effective system, albeit with somewhat reduced cycle efficiency [18, 23]. TES serves diverse applications such as electricity generation, heat engine cycle load shifting, and meeting peak energy demands. Moreover, TES plays a role in environmental conservation by reducing reliance on fossil fuels for heat and cold production [24]. At present, TES is predominantly deployed worldwide to facilitate energy time-shifting and enhance the reliability of renewable energy capacities, highlighting its essential function in integrating sustainable energy sources [25].

Thermal energy storage (TES) technologies are crucial for storing thermal energy for later use, helping balance supply and demand in energy systems. There are several types of TES technologies, each with specific temperature ranges and applications.

Sensible heat storage involves storing thermal energy by raising the temperature of a solid or liquid medium. The amount of energy stored depends on the specific heat capacity of the material and the temperature difference. Common media include water, sand, rocks, concrete, and molten salts. The temperature range for these media varies: water (0–100°C), sand and rocks (up to 300°C), and molten salts (150–600°C). Sensible heat storage is straightforward and cost-effective, making it widely used in applications such as domestic hot water systems, building heating and cooling, and solar thermal power plants. Water is commonly used due to its high specific heat capacity and availability, while molten salts are utilized in concentrating solar power (CSP) plants to store solar energy for electricity generation.

Latent heat storage utilizes phase change materials (PCMs) that absorb or release thermal energy during a phase change, such as from solid to liquid or liquid to gas. Common PCMs include paraffin wax, salt hydrates, fatty acids, and eutectic salts, with temperature ranges as follows: paraffin wax (0–100°C), salt hydrates (30–150°C), and eutectic salts (up to 1000°C). Latent heat storage is highly efficient as it stores large amounts of energy at a constant temperature. This technology is used in building temperature regulation, industrial waste heat recovery, and refrigerated transport. The choice of PCM depends on the application temperature range, with paraffin wax and salt hydrates being popular for moderate-temperature applications, while eutectic salts are used for high-temperature industrial processes.

Thermochemical storage involves reversible chemical reactions to store and release thermal energy, storing energy in the form of chemical bonds. Common media include metal hydrides, ammonia-based systems, silica gel, and zeolites. These media operate within different temperature ranges: metal hydrides (300–500°C), ammonia-based systems (−60 to 100°C), and silica gel/zeolites (100–300°C). Thermochemical storage has a high energy density and can store energy for long periods with minimal losses, making it suitable for seasonal storage and long-duration energy applications. For instance, metal hydrides can store hydrogen for high-temperature applications, ammonia-based systems are used for cooling and refrigeration, and silica gel and zeolites are employed in low to moderate-temperature ranges for dehumidification and industrial drying.

Cryogenic energy storage involves cooling air or other gases to cryogenic temperatures (−150 to −273°C) to store energy in the form of liquid gases, such as liquid air and liquid nitrogen. Cryogenic storage is used for large-scale energy storage solutions, particularly for balancing intermittent renewable energy sources like wind and solar. When energy is needed, the liquid gas is vaporized to drive turbines and generate electricity. This technology is advantageous for its high energy density and ability to provide long-term storage.

2.6 Electrical storage

An alternative approach to energy storage includes utilizing electrical storage technologies like Superconducting Magnetic Energy Storage (SMES), supercapacitors, capacitors, and hybrid supercapacitors.

2.6.1 Superconducting magnetic energy storage (SMES)

Superconducting Magnetic Energy Storage (SMES) systems function by converting electrical energy into a magnetic area stored within a superconducting coil during charging. This involves a cooling process to maintain the coil at low temperatures and reduce energy losses. When discharging, SMES releases the stored energy through a power converter configuration [26]. As a well-developed technology, SMES provides a robust solution characterized by high-power density and is particularly suited for short-term energy storage. It holds promise for enhancing the utility of variable renewable energy sources. SMES systems are noted for their high efficiency, exceptional power density, and low degradation rates. However, they also present several drawbacks, including high costs [27], significant self-discharge rates, environmental concerns related to magnetic effects, and sensitivity to temperature fluctuations. SMES systems typically have power capacities ranging from 0.1 to 10 kW and can store up to 100 MWh of energy. They also feature high-power densities, reaching up to 4000 W/L, specific power ratings ranging from 500 to 2000 W/kg, and service lives lasting more than 20 years [18].

2.6.2 Capacitors and supercapacitors

Capacitors: Capacitors are constructed with two or more metal foils separated by a thin insulator, commonly plastic, ceramic, or glass. In the charging process, energy is stored within the dielectric material using an electrostatic field. Capacitors are primarily used for storing small amounts of energy and are well-suited for applications needing high specific power, such as voltage correction and smoothing, owing to their quick charging ability compared to electrochemical cells. Capacitors come in a variety of capacitances and nominal voltages, and recent advancements have focused on enhancing heat dissipation and increasing power levels. Capacitors are widely used in frequency converters, traction systems, and drives. The advantages of capacitors include their quick charging time and high-power output. However, they are limited by their self-discharge losses, low energy provision, limited capacity, and significant energy dissipation, which are considered drawbacks. Capacitors generally offer power capacities ranging from 200 kW to several MW and can store energy between 0.007 kWh to a few kWh. They discharge rapidly within seconds and have a long lifespan of up to 40 years, with efficiency typically ranging from 60–70%. Capacitors exhibit an energy density of 0.07 Wh/kg, specific energy varying between 0.05 and 5 Wh/kg, and specific power ranging from 3000 to 107 W/kg.

Supercapacitors: Supercapacitors, also referred to as electrical double-layer capacitors (EDLCs) or ultracapacitors, are energy storage devices that consist of two carbon electrodes, a porous membrane separator, and an electrolyte. These capacitors can be housed in cylindrical or prismatic shapes, each affecting their energy capacity, power output, volume, and weight characteristics respectively. They can employ either aqueous or nonaqueous electrolytes and can be arranged in different configurations to meet specific application needs. Owing to their design, supercapacitors exhibit properties of both electrochemical cells and traditional capacitors. They typically offer a power capacity extending to several megawatts, energy storage of a few kilowatt-hours, a discharge duration of several minutes, a cycle life of up to 10,610^6106 cycles, and a lifespan of around 10 years at room temperature. Supercapacitors demonstrate efficiencies ranging from 95–98%, energy densities between 4 and 7 Wh/kg, specific energies from 2.5 to 15 Wh/kg, specific power levels from 500 to \ (10^4\) W/kg, and self-discharge rates between 20 and 40%.

The working principle of an SMES system involves several components: a superconducting coil, a refrigeration system, a power conditioning system, and a cryostat to maintain the low temperatures necessary for superconductivity. When energy is supplied to the system, DC flows through the superconducting coil, generating a magnetic field. The energy is stored in this magnetic field as long as the current continues to flow through the superconducting coil. When energy is needed, the system converts the magnetic field energy back into electrical energy by allowing the current to flow out of the coil through the power conditioning system, which manages the conversion and delivery of power to the grid or load.

One of the key benefits of SMES systems is their high efficiency. Since superconductors have no electrical resistance, there are minimal energy losses during the storage and retrieval processes. This efficiency, often exceeding 95%, makes SMES an attractive option for applications requiring rapid response and high-power output, such as grid stabilization, frequency regulation, and uninterruptible power supply (UPS) systems. SMES systems also have extremely fast response times, often in the milliseconds range, allowing them to quickly absorb and release energy as needed, which is crucial for maintaining grid stability and managing power quality.

However, SMES systems also have significant drawbacks. One of the primary challenges is the need for cryogenic cooling to maintain the superconducting state of the coil. This requires sophisticated and expensive refrigeration systems to keep the superconductors at temperatures close to absolute zero (below −196°C for most superconducting materials). The cost and complexity of these refrigeration systems contribute to the high initial investment and operational costs of SMES technology. Additionally, the materials used for superconducting coils, such as niobium-titanium (NbTi) or high-temperature superconductors (HTS), are expensive and require careful handling and maintenance.

Another drawback is the relatively low energy density of SMES systems compared to other energy storage technologies like batteries or pumped hydro storage. While

SMES systems excel in power density and rapid response, they are less suited for applications requiring long-term energy storage or large-scale energy capacity due to their limited storage duration and high costs. Furthermore, the need for continuous cryogenic cooling means that any interruption in the cooling process can lead to a loss of superconductivity, resulting in significant operational challenges.

2.7 Advanced energy storage technologies currently being developed

Several advanced energy storage technologies are currently being developed to enhance the efficiency, capacity, and integration of renewable energy sources into the grid. These technologies include:

1. Gravity-based energy storage: This technology involves utilizing the potential energy of heavy masses, such as large blocks or weights, that are lifted to a certain height. When energy is required, these masses are released to fall, and the potential energy is converted into electricity using generators. This system is particularly useful for grid energy storage, peak shaving, and integrating renewable energy sources, as it can store excess energy generated during low-demand periods and release it when demand is high.

2. Compressed air energy storage (CAES): CAES systems store energy by compressing air and storing it in underground caverns or large, reinforced containers. When electricity is needed, the compressed air is released, heated, and expanded to drive turbines, generating electricity. This method is effective for large-scale energy storage, ensuring grid stability, and supporting the integration of intermittent renewable energy sources like wind and solar.

3. Liquid air energy storage (LAES): LAES technology involves cooling air to a liquid state and storing it in insulated tanks. When energy demand rises, the liquid air is reheated, causing it to expand and turn into a gas that can drive turbines and generate electricity. This system is ideal for large-scale energy storage, providing backup power, and delivering grid services by balancing supply and demand.

4. Hybrid supercapacitors: Hybrid supercapacitors combine the features of supercapacitors and batteries, providing both high-power density and moderate energy density. This combination makes them suitable for applications that require quick bursts of energy as well as steady power output. They are used in grid stability, electric vehicles, and consumer electronics, benefiting from rapid charge and discharge capabilities.

5. High-temperature thermal energy storage: This technology involves storing energy in high-temperature ceramic-based systems or using phase change materials (PCMs) with high melting points. These systems can efficiently store thermal energy for industrial heat processes, concentrated solar power (CSP) plants, and district heating applications, allowing for the utilization of stored heat energy when needed.

6. Pumped thermal energy storage (PTES): PTES systems store energy by transferring heat between two thermal reservoirs, one hot and one cold. The stored

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thermal energy is then converted back into electricity using heat engines. This technology is well-suited for grid-scale energy storage, helping balance the supply and demand of renewable energy sources, and providing flexibility in energy management.

7. Iron-air batteries: Iron-air batteries use iron and air as the primary materials, making them a low-cost and environmentally friendly option for large-scale energy storage. These batteries are particularly suitable for grid energy storage, renewable energy integration, and providing backup power, offering a sustainable and cost-effective alternative to traditional batteries.

8. Phase change material (PCM) Batteries: PCM batteries use materials that change phases, such as from solid to liquid, to store and release energy efficiently. These batteries are used for thermal management in buildings, industrial heat storage, and grid energy storage, providing a reliable way to manage temperature fluctuations and store energy in various applications.

These advanced energy storage technologies are being developed to address the limitations of current systems, such as energy density, cost, efficiency, and environmental impact, thereby supporting the transition to a more sustainable and reliable energy infrastructure.

2.8 Optimal energy storage solutions for large-scale power management: key devices and applications

Table 4 highlights the key energy storage devices suitable for large-scale power management, along with their reasons for suitability and primary applications.

Energy storage device	Why suitable for large-scale power management	Applications
Lithium-ion (Li-ion) batteries	High energy density, efficiency, and scalability. Fast response times.	Grid storage, balancing supply and demand, peak shaving, renewable energy integration.
Sodium-sulfur (NaS) batteries	High energy density and long service life. Scalable for large-scale applications.	Grid stabilization, large-scale renewable energy integration.
Flow batteries	Decoupled energy storage capacity and power output. Long cycle life.	Renewable energy storage, grid applications.
Pumped hydro storage (PHS)	High capacity and efficiency for long-duration storage. Established and reliable.	Grid stability, peak load management, storing excess renewable energy.
Compressed air energy storage (CAES)	Large energy storage for extended periods. Effective for grid stability.	Grid stability, integrating intermittent renewable energy sources.
Thermal energy storage (TES)	Effective for storing large amounts of energy in the form of heat. Cost-effective.	Concentrating solar power (CSP) plants, industrial applications, and large-scale energy storage.

Table 4.
Key energy storage devices suitable for large-scale power management, along with their reasons for suitability and primary applications.

2.9 Function of energy storage in the energy supply chain

2.9.1 Crucial role of energy storage in balancing supply and demand across the energy network

Energy storage plays a crucial role in balancing supply and demand at various levels of the energy network by providing flexibility, reliability, and stability. Firstly, one of the primary functions of energy storage systems (ESS) is to enhance grid stability and reliability. ESS can respond quickly to short-term fluctuations in energy supply and demand, helping to stabilize the grid and prevent blackouts. Additionally, they can provide frequency regulation by absorbing excess energy when supply exceeds demand and releasing energy when demand exceeds supply, thus maintaining the grid's frequency within safe limits.

Renewable energy integration is another critical area where energy storage is indispensable. Renewable energy sources such as solar and wind are intermittent by nature. Energy storage systems can store excess energy generated during periods of high production and release it during periods of low production, ensuring a continuous and reliable energy supply. This capability is essential for peak shaving and load leveling, where ESS can reduce the strain on the grid during peak demand periods by discharging stored energy and storing energy during off-peak periods, leveling the load, and optimizing grid performance.

Also, energy storage can help defer infrastructure upgrades. By strategically placing ESS at congested points in the grid, utilities can defer costly infrastructure upgrades. Energy storage systems can manage local supply and demand, reducing the need for new transmission and distribution lines. Additionally, ESS can provide voltage support by absorbing or injecting reactive power, improving power quality, and reducing losses in the transmission and distribution networks.

In microgrids, energy storage plays a vital role. ESS enables island mode operation in microgrids, allowing them to operate independently of the main grid during outages and disturbances, thereby enhancing energy security and resilience. Moreover, ESS can optimize the use of distributed energy resources, such as rooftop solar panels and small wind turbines, by storing excess generation and ensuring that energy is available when needed.

Energy storage systems also facilitate energy arbitrage, which can lead to significant cost savings. ESS can be used for energy arbitrage by buying energy when prices are low (usually during off-peak hours) and selling it or using it when prices are high (during peak hours), leading to cost savings and improved economic efficiency. This practice not only benefits the energy providers but also the consumers by potentially lowering energy costs.

Lastly, ESS provides essential emergency backup power. In the event of emergencies or grid outages, energy storage systems can ensure that critical infrastructure like hospitals, data centers, and communication networks remain operational. This capability is vital for maintaining the functionality of essential services and ensuring public safety during power disruptions.

2.9.2 Role of storage systems in voltage and frequency regulation

For voltage regulation, ESS provides reactive power support, which is essential for stabilizing voltage levels across the grid. They help mitigate voltage drops and sags by supplying or absorbing reactive power, ensuring consistent voltage levels.

Additionally, ESS can manage localized voltage control, particularly in areas with significant fluctuations due to varying demand or renewable energy generation. They also address voltage sags by quickly injecting power during short-term drops and manage voltage swells by absorbing excess power during periods of high generation, preventing harmful voltage rises.

In terms of frequency regulation, ESS offers both immediate and sustained support. For primary frequency response, they can rapidly inject or absorb power to counteract deviations in grid frequency, thus balancing supply and demand in real time. For secondary frequency control, ESS provides longer-term support by continuously adjusting its output to maintain frequency stability until slower-responding resources can take over. Moreover, ESS can participate in frequency regulation markets, offering ancillary services that help grid operators maintain precise frequency control.

Modern ESS are equipped with advanced control systems that allow for real-time adjustments, enabling them to simultaneously manage both voltage and frequency. This dynamic response is particularly valuable for integrating renewable energy sources, which are inherently variable. By smoothing out the intermittency of renewables, ESS ensures that both voltage and frequency remain stable, supporting the increasing share of renewable energy in the grid.

3. Comparison results of the energy storage devices

Section 3 outlines the key performance characteristics of electrochemical, electrical, thermal, and, to some extent, mechanical energy storage technologies. This section, through figures and matrices, underscores that no single energy storage technology currently meets all the requirements for power system applications. Typically, these requirements determine the comparative criteria used for various cases discussed in the preceding sections. To illustrate, the volumetric energy and power capacity of ESDs are depicted in the graphical comparative analysis.

A comparison of thermal energy storage (TES) solutions and electrochemical storage options in terms of capacity and application suitability is presented in **Table 5**.

Table 6 provides a comprehensive overview of the criteria used to evaluate the suitability of different energy storage devices for grid applications. Each criterion is described in detail, with various storage technologies that excel in those areas, highlighting the diverse requirements and capabilities necessary to support a reliable and efficient energy grid.

3.1 Graphical result analysis and selection of ESDs

The assessment of ESDs is conducted primarily through technical, economic, and environmental lenses. To effectively assess the suitability of these ESDs for large-scale grid applications, comprehensive criteria integrating technical, economic, and environmental considerations are employed, utilizing up-to-date and credible data sources. This evaluation is supported by graphical analyses and comparisons. The tables and graphs provided herein reflect mean values obtained from the latest peer-reviewed literature, online sources, and datasheets. These comparisons highlight the diverse metrics of different ESDs. Key technical aspects considered for evaluating selected ESDs include specific energy, specific power, round-trip efficiency, discharge duration, lifetime, and daily self-discharge, detailed in **Table 7**. **Figures 2–4** depict

Aspect	Thermal energy storage (TES)	Electrochemical storage options
Storage Capacity	High	Varies by type; generally lower than TES
Energy Density	Lower	Higher (especially for lithium-ion batteries)
Efficiency	Lower round-trip efficiency due to conversion losses	Higher round-trip efficiency
Cost	Cost-effective for large-scale, long-term storage	Generally higher, though decreasing for technologies like Li-ion
Scalability	Highly scalable for large-scale applications	Scalable, but limited by cost and energy density
Response Time	Slower	Rapid response times
Durability and Lifecycle	Long-term with lower operational costs	Varies; some like lead acid has shorter lifecycles
Primary Applications	Grid stabilization, renewable energy integration, industrial thermal management	Electric vehicles, portable electronics, grid services (peak shaving, load leveling, frequency regulation)
Examples of Technologies	Molten salt storage, ice storage, phase change materials	Lithium-ion, lead-acid, sodium-sulfur, nickel-cadmium batteries
Advantages	Suitable for long-duration, bulk energy storage; lower operational costs	High energy density; efficient for quick discharge/recharge applications
Disadvantages	Lower efficiency due to energy conversion losses	Higher cost; lifecycle and disposal concerns

Table 5.
Comparison of TES solutions and electrochemical storage options in terms of capacity and application suitability.

Criteria	Description	Storage technology
Energy density	The amount of energy stored per unit volume or mass. Higher energy density means more energy can be stored in a smaller space.	Li-ion batteries, Flywheels
Power density	The rate at which energy can be delivered or absorbed per unit volume or mass. Important for applications requiring quick response.	Supercapacitors, SMES
Efficiency	The ratio of the energy output to the energy input is typically expressed as a percentage. Higher efficiency means less energy is lost during storage and retrieval.	Li-ion batteries, SMES
Response time	The time it takes for the storage device to respond to a demand for power. Critical for grid stability and frequency regulation.	Supercapacitors, SMES, Flywheels
Cycle life	The number of charge and discharge cycles a storage device can undergo before its capacity significantly degrades. Longer cycle life means longer service life and lower replacement costs.	Li-ion batteries, Flow batteries

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Criteria	Description	Storage technology
Scalability	The ability to increase storage capacity and power output to meet larger demands. Important for accommodating growing energy needs.	Pumped Hydro Storage, Compressed Air Energy Storage (CAES)
Cost	The total cost of ownership, including initial capital costs, operational and maintenance costs, and replacement costs. Lower costs improve economic feasibility.	Lead-acid batteries, Pumped Hydro Storage
Environmental impact	The environmental footprint of the storage device, including resource extraction, manufacturing, operation, and disposal. The lower impact is better for sustainability.	Flow batteries, Pumped Hydro Storage
Safety	The inherent safety risks associated with the storage device, include the potential for fires, explosions, and toxic emissions. Safer technologies are preferred for widespread use.	Lead-acid batteries, Flow batteries
Operational flexibility	The ability of the storage device to perform under various conditions and integrate with other energy systems. Flexible systems can support diverse grid applications.	Li-ion batteries, Flow batteries
Durability and reliability	The robustness of the storage device under operational stresses and its ability to perform consistently over time. Reliable systems ensure continuous power availability.	Flywheels, SMES
Discharge duration	The length of time the storage device can deliver power at its rated capacity. Longer durations are needed for applications like load shifting and backup power.	Pumped Hydro Storage, Flow batteries
Geographic constraints	The limitations imposed by the location and physical space required for the storage system. Some technologies require specific geographic features to be feasible.	Pumped Hydro Storage, CAES

Table 6.
Comprehensive overview of the criteria used to evaluate the suitability of different energy storage devices.

the technical attributes of various ESDs, utilizing average parameter values from **Table 2** for analysis.

Figure 2 illustrates that the SCES system offers the highest specific power among the various ESDs evaluated. Conversely, NaS, Li-ion, PCM, and TCS systems exhibit superior specific energy values. In contrast, PSB and other thermal storage technologies display the lowest specific power metrics. Moreover, both SCES and SMES systems demonstrate the lowest specific energy values.

It is observed that SCES, SMES, NaNiCl2, and Li-ion batteries exhibit very high round-trip efficiencies exceeding 85%. In contrast, STES and Ni-MH systems have a lower cycle efficiency. Regarding service life, TCS stands out with the longest average lifespan of approximately 35 years, whereas electrochemical energy storage devices, such as batteries, typically have shorter service lifespans ranging from 7.67 to 14 years.

Figure 4 shows the daily self-discharge characteristics of different ESDs. $NaNiCl_2$, Ni-MH, and SCES display the highest self-discharge rates, whereas PSB, VRFB, and

Category of energy storage devices	Specific energy (Wh/kg)	Specific power (W/kg)	Round trip efficiency (%)	Service life (years)	Daily self-discharge rate (%)
NaS	150–240 [28, 29] 100–175 [30]	150–230 [28, 29]	75–90 [28, 31] 77 [32]	10–15 [28] 10–20 [30]	20 [28] 0.5–20 [30]
$NaNiCl_2$	120 [31] 100–120 [28, 29] 119 [33]	150 [28, 31] 150–200 [28, 29] 169 [33]	85–90 [29] 92.5 [34]	10–14 [28, 29] >8 [35]	15 [28, 29] 11.887 [33]
Pb-Acid	30–50 [31, 36] 25–32 [37, 38] 20–35 [32, 39]	75–300 [28, 29] 180–200 [30] 25 [32] 74–415 [40]	65–80 [31] 70–90 [28] 85 [41] 72–76 [37]	5–15 [28, 30]	0.1–0.3 [28, 31] Low [32] 0–0.6 general battery [42]
Li-ion	200 [31] 56–200 [28, 29] 90–151 [37] 61–200 [30]	135–315 [28, 29] 61–200 [43] 185–351 [30] 300 [44]	95 [31] 61–90 [35] 59–88 [30] 85 [45]	5–15 [28, 29] 14–16 [30] 6–20 [40]	0.1–0.3 [28, 29] Medium [32] 0.17–0.33 [46] 0.036–0.0833 [47]
Ni-Cd	35–56 [28, 29, 31] 30–61 [30] 40–44 [32, 46]	135–300 [28, 29] 100–144 [30] 140–161 [32] 135 [46]	53 [30] 44–57 [37] 44–51 [29] 51–90 [46]	10–20 [28] 13–20 [30] 10 [40] 5–20 [29]	0.2–0.6 [28] 0–0.6 general battery [42] 0.2–0.3 [30] 0.33 [46]
Ni-MH	44–61 [32] 31–51 [40] 30.13 [48] 51 [49] 89 [50]	200 [49] 220 [32] 158 [50] 440 [44]	35–61 [32] 50 [35, 46]	5–15 [40] >3 [50]	0–0.6 general battery [42] 0.83 [50] 0.3 [50]
VRFB	10–20 [35] 20–29 [37] 20 [30] 25 [32]	150 [30] 61–135 [32]	61 [32, 45] 51–85 [46] 44–85 [29]	10–20 [30, 35] 5–15 [29]	Small [28] Very low [30] 0.2 [29]
PSB	20–29 [37] 10–15 [51]	1.31 [52]	53–83 [37] 44–56 [30] 56 [45]	15 [30, 53] 10–15 [29]	Small [28] 0 [29]
Zn Br	20–29 [37] 34.4–39 [35] 34.4 [54]	90–110 [55]	51 [35] 56 [31] 53–83 [37] 49–85 [30]	8–10 [30] 5–10 [29]	Small [28] 0.24 [29]
SCES	2.5–15 [29] 0.5–1.5 [28] 11 [56] 4 [57]	10,000 [31] 350–3500 [28, 29] 2000–3500 [30] 610–2000 [58]	95 [31, 32] 95–99 [37] 49–90 [30]	20 [28, 29] 8–17 [30]	5–40 [31] 20–40 [28, 29]
SMES	10–56 [30] 1–12 [59] 3 [59]	350–2000 [28, 29]	95 [58] 61–95 [30] 90–98 [29]	20 [30] 20–30 [29, 57]	10–15 [28, 29]
STES	61–120 [28] 10–35 [60] 61–235 [24]	10–30 [24]	35–90 [61] 44 [58] 35–90 [60] 30–44 [24]	10–20 [28] 10–30 [24]	0.5 [28] 0.05–1 [24]

Category of energy storage devices	Specific energy (Wh/kg)	Specific power (W/kg)	Round trip efficiency (%)	Service life (years)	Daily self-discharge rate (%)
PCM	135–235 [28] 61–235 [24]	10–30 [28]	56–90 [61] 35–90 [60] 40–90 [41]	20–40 [28] 30 [41]	0.5–1 [28]
TCS	235 [60] 61–235 [24]	10–30 [24]	56–100 [61] 56–100 [60] 40–90 [41] 30–44 [24]	10–30 [24] 30 [41]	0.05–1 [24]

Table 7.
Key technical characteristics of diverse energy storage technologies.

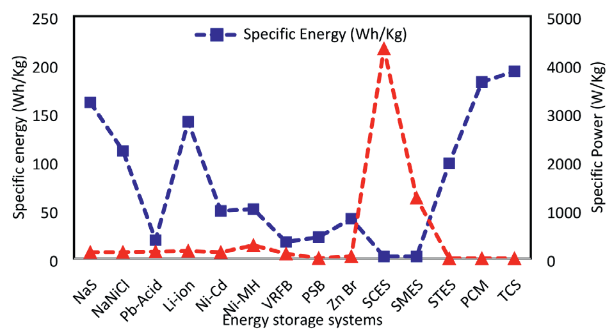

Figure 2.
*Comparison of specific energy and specific power of ESD based on the average values derived from **Table 2**.*

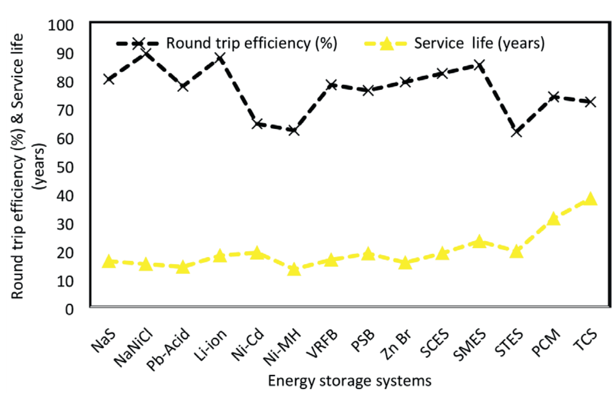

Figure 3.
*Mean cycle efficiency and operational longevity of energy storage systems as detailed in **Table 2**.*

Li-ion technologies exhibit lower self-discharge ratios. Particularly notable among electrochemical ESDs, $NaNiCl_2$ and NaS demonstrate considerable daily self-discharge rates. **Figure 5** demonstrates how the size of energy storage devices (ESDs) correlates with their power and energy densities. Higher energy and power densities result in smaller ESD volumes, shown in the top right corner of the graph. Conversely,

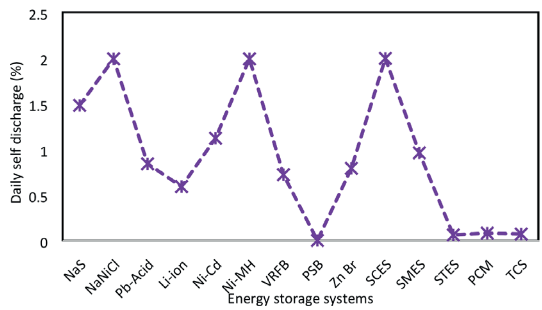

Figure 4.
Typical daily self-discharge rates of energy storage devices from data presented in ***Table 2****.*

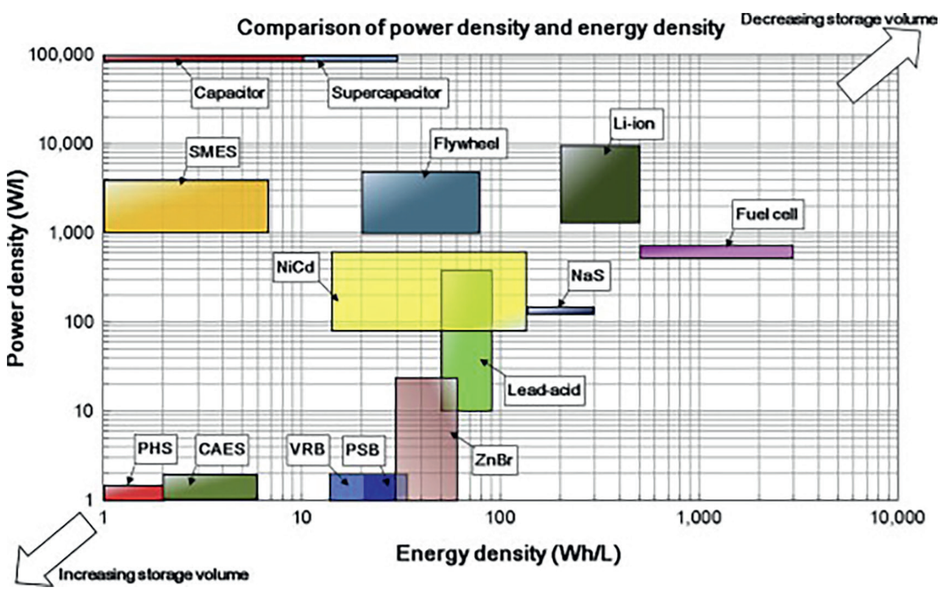

Figure 5.
Comparative analysis of power and energy densities across energy storage devices.

ESDs with lower energy and power densities occupy larger volumes, as indicated in the bottom left corner. Thermal ESDs and electrochemical ESDs like Ni-MH, Na-S, Li-ion, and $NaNiCl_2$ generally exhibit higher energy densities. In contrast, SCES, SMES, and FES show higher power densities. CAES and PHS have the lowest energy densities, while CAES, PHS, VRFB, PSB, and Zn-Br have the lowest power densities. Li-ion batteries are notable for combining high energy and power densities, resulting in compact sizes suitable for diverse applications, including portable devices, transportation, and grid-scale systems.

Figure 6, depicted as a bubble chart, compares discharge times and power ratings among various ESDs, revealing distinctive characteristics. Mechanical energy storage systems such as CAES and PHS demonstrate extended discharge durations and higher power ranges compared to other technologies. In contrast, SCES, FES, and SMES are characterized by short discharge times and lower power ranges.

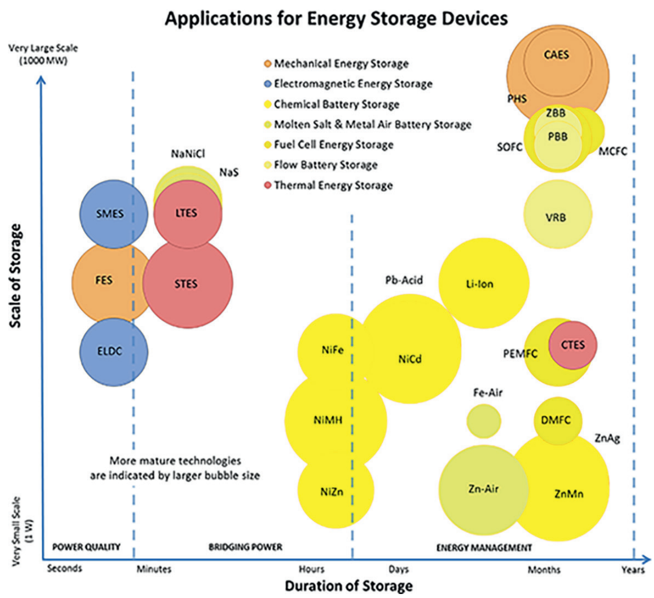

Figure 6.
Comparison of ESDs based on average discharge time and power rating.

3.2 Future outlook and hybrid solutions

The review suggests using a mix of technologies in hybrid solutions for energy storage to leverage the unique strengths of each technology while mitigating their individual limitations. Different energy storage technologies excel in various aspects, such as power density, energy density, response time, cycle life, and cost. For instance, while some technologies like supercapacitors provide high power density and quick response times, they may not offer sufficient energy density for long-duration storage. Conversely, technologies such as lithium-ion batteries or thermochemical storage provide high energy density, suitable for prolonged energy discharge but may lack the rapid discharge capabilities required for certain applications.

By integrating multiple technologies in a hybrid system, it is possible to create a more versatile and efficient energy storage solution that can handle a wide range of applications and operational conditions. For example, a hybrid system combining supercapacitors and lithium-ion batteries can provide both immediate power response and sustained energy supply, thus supporting both grid stability and long-term energy storage needs. This approach allows for optimization of the overall system performance, cost-effectiveness, and operational flexibility, making hybrid energy storage solutions particularly valuable in complex and variable energy markets. Additionally, using a mix of technologies can enhance the reliability and resilience of the energy storage system, ensuring continuous power supply even when one component experiences issues.

Hybrid energy storage solutions are designed to combine multiple energy storage technologies to address the diverse and unique requirements of different energy applications. Each energy storage technology has its own strengths and limitations; by integrating them into a hybrid system, it is possible to harness the advantages of each while compensating for their weaknesses.

1. Power and energy density needs: Some applications require high-power density (fast charge/discharge rates) while others need high energy density (long-duration storage). Supercapacitors or flywheels, which offer high-power density, can be combined with lithium-ion batteries, which provide high energy density, to cater to applications like frequency regulation (which needs quick response) and load leveling (which requires sustained energy delivery).

2. Cost and efficiency optimization: Hybrid systems can be optimized to use the most cost-effective technology for a specific function. For instance, flow batteries might be used for large-scale energy storage due to their relatively lower costs and long cycle life, while more expensive but efficient technologies like lithium-ion batteries are used for applications needing high energy density and fast response.

3. Operational flexibility and reliability: Hybrid systems can improve the overall reliability and flexibility of energy storage. By integrating different technologies, the system can continue to operate effectively even if one component fails or underperforms. This is crucial for maintaining grid stability and ensuring a continuous power supply.

4. Environmental and space considerations: Different technologies have different environmental impacts and space requirements. For instance, pumped hydro storage requires specific geographic features and large areas, while batteries can be installed in more diverse locations. Hybrid systems can optimize space use and minimize environmental impacts.

5. Application-specific requirements: Different applications, such as residential energy storage, industrial use, or renewable energy integration, have varying requirements in terms of scale, efficiency, and performance. Hybrid solutions can be tailored to meet these specific needs more precisely than a single technology might.

4. Conclusion

Energy storage plays a pivotal role in the future electricity grid, particularly in achieving the goal of generating 70% of electricity from RESs. It offers flexibility to balance supply and demand and facilitates the efficient integration of RESs. As a result, there is an anticipated increase in energy storage capacity, driving the development of a diverse array of electric and thermal power technologies tailored to meet operational and economic requirements. This comprehensive review examines the maturity, current status, and future directions of various storage technologies, with a primary focus on electrical, electrochemical, and thermal storage systems. The key findings highlight the advancements and potential of ESDs.

- Considerations of source availability, accessibility, and environmental impact are crucial for the life cycle analysis of electrochemical energy storage systems. For instance, producing 1 kWh of lithium-ion battery requires approximately 400 kWh of energy and emits 75 kg of CO_2, whereas a coal-fired plant emits 1 kg of CO_2 per kWh. This highlights the necessity for lithium-ion systems to undergo at least 400 cycles to offset their energy consumption and achieve a positive

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environmental impact over their long service life. Among electrochemical ESDs, lithium-ion batteries stand out for their higher power and energy densities, superior round-trip efficiency, minimal environmental footprint, and lightweight characteristics. Consequently, they are regarded as a promising choice for grid-scale stationary applications, particularly in integrating renewable energy sources (RESs) into the grid.

- The availability of lithium and cobalt poses challenges to the current technology of Li-ion cells in terms of cost and scalability. Additionally, electrodes often contain toxic elements such as lead, cadmium, and mercury, which raise significant health and environmental concerns. Addressing these challenges through practices like recycling, second-life utilization, and innovative concepts such as Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) can play a crucial role. These approaches are essential for mitigating environmental impacts and overcoming the limitations associated with these materials.

- Utilizing TES derived from renewable sources offers substantial potential to decrease CO_2 emissions across residential, nonresidential, and industrial sectors by conserving significant amounts of energy. However, TES encounters challenges related to costs and stability, particularly with emerging technologies such as TCS and PCMs. Similar to other energy storage solutions, designing TES systems must be tailored to meet specific application boundaries and requirements.

Author details

Sina Samadi Gharehveran[1*], Kimia Shirini[1] and Arya Abdolahi[2]

1 Faculty of Electrical and Computer Engineering, University of Tabriz, Tabriz, Iran

2 Azarbaijan Shahid Madani University, Tabriz, Iran

*Address all correspondence to: s.samadi@tabrizu.ac.ir

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