

# A Review on Technological Advancement in Charge Storage Technologies for Renewable Energy Applications.

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## ABSTRACT

The intermittent nature of solar and wind power necessitates reliable energy storage to stabilize electrical grids and enable high renewable penetration. This review provides a systematic assessment of charge storage technologies for renewable energy applications, with emphasis on both conventional systems and emerging post lithium solutions. A structured literature search was conducted across Scopus, Web of Science, Google Scholar, ScienceDirect, and IEEE Xplore for the period January 2013 to March 2026, yielding 101 peer reviewed sources after screening. Technologies are analyzed according to their operating mechanisms including electrochemical, electrostatic, mechanical, chemical, and thermal, as well as performance metrics such as energy density, power density, cycle life, and efficiency, and application suitability including grid scale systems, transport, and portable electronics. Key findings include the following: sodium ion batteries have emerged as compelling alternatives to lithium ion batteries for stationary storage due to sodium abundance and manufacturing compatibility, though energy density remains lower; solid state batteries offer intrinsic safety and high volumetric energy but face persistent electrode electrolyte interface challenges; advanced nanostructured materials particularly graphene, MXenes, and silicon based anodes enable hybrid systems that bridge the energy power gap between batteries and supercapacitors; no single technology satisfies all grid requirements, instead portfolios combining fast response supercapacitors for power quality, batteries for hourly shifting, hydrogen for seasonal storage, and thermal storage for concentrated solar power plants are necessary. Limitations of this review include the lack of quantitative meta analysis due to heterogeneous reporting standards. Future research priorities should focus on earth abundant materials, durable solid state interfaces, scalable recycling processes, and hybrid system integration. Charge storage technologies remain a fundamental prerequisite for a renewable powered future.

**Keywords:** Energy storage; lithium ion batteries; sodium ion batteries; solid state batteries; supercapacitors; renewable energy integration; grid storage; advanced materials.

## INTRODUCTION

To maintain a stable and reliable electrical grid, power supply must be stabilized through reliable storage systems. These systems act as a critical buffer. They absorb excess energy when generation exceeds demand. For example, during a sunny midday when solar panels operate at peak output. They discharge stored energy back into the grid during periods of high demand or low generation, such as evening hours when people return home and use appliances and lights. Without such storage, grid operators would rely on quick-start "peaker" plants to fill gaps. These plants typically run on natural gas, operate less efficiently, and emit more pollutants. Therefore, the advancement and deployment of efficient, large-scale energy storage, whether in the form of advanced batteries, pumped hydro, or other innovative technologies, is not just an enhancement but a fundamental prerequisite for a future powered predominantly by renewable energy, ensuring that clean power is available whenever it is needed, not just whenever the sun shines or the wind blows.

Electrochemical energy storage has become a cornerstone of modern energy infrastructure due to its high efficiency and scalability. This category of storage, which converts chemical energy into electrical energy through reversible reactions, offers distinct advantages over mechanical methods like pumped hydro, faster response times, modularity, and the ability to be deployed in a wide range of environments, from residential buildings to large-scale grid substations. (Ferreira-Martínez et.al, 2024). Among the available electrochemical technologies, lithium-ion batteries dominate current energy storage applications due to their high energy density and long life cycle (Goodenough & Park, 2017). Their superior performance has made them the technology of choice for the portable electronics revolution, the electrification of transportation in electric vehicles (EVs), and the majority of new grid-scale battery projects, driving down costs through massive manufacturing scale.

However, the very success of lithium-ion technology has brought its limitations into sharp focus. Concerns about lithium resource availability and safety have encouraged the development of alternative storage technologies. The geographical concentration of lithium reserves and the environmental impact of extraction raise questions about long-term supply chain sustainability and geopolitical stability. Furthermore, the use of flammable organic electrolytes in conventional lithium-ion cells presents safety risks, particularly as the industry pushes for higher energy densities. These factors, combined with the need for even lower costs for long duration grid storage, have spurred intense research and development into "post-lithium" technologies. Promising alternatives include sodium-ion batteries, which leverage far more abundant and cheaper materials; solid-state batteries, which aim to replace the flammable liquid electrolyte with a solid one for enhanced safety and energy density; and flow batteries, which offer the potential for independently scalable power and energy capacity, making them ideally suited for long-duration stationary storage applications (Shi et al., 2024).

In recent years, sodium-ion batteries have emerged as promising alternatives to lithium-ion systems, primarily driven by the natural abundance and consequent low cost of sodium resources. Unlike lithium, which is geographically concentrated and faces supply chain vulnerabilities, sodium is ubiquitously available, from common places like seawater and soda ash, offering a path toward more geopolitically stable and sustainable material sourcing for large scale energy storage. Researchers have demonstrated that sodium-ion batteries operate through mechanisms highly similar to lithium-ion batteries, a "rocking-chair" mechanism where ions move between the cathode and anode during charge and discharge. This fundamental similarity allows researchers and manufacturers to leverage existing lithium-ion battery production infrastructure, potentially accelerating commercialization. This technical parallelism, combined with the use of materials like aluminum rather than copper, which is relatively expensive to aluminum, for the anode current collector, making sodium-ion technology a compelling alternative for grid scale storage where energy density is less critical than cost and longevity. (Shi et al., 2024)

Technological advances in materials science and nanotechnology have also enabled the development of high-performance supercapacitors and hybrid storage systems capable of delivering both high energy and power densities. This progress addresses the fundamental trade-off that has long existed between batteries, which store large amounts of energy (high energy density) but release it slowly, and traditional capacitors, which release energy very quickly (high power density) but store very little. By engineering materials at the nanoscale, such as using graphene which was first isolated in 2004 by Andre Geim and Konstantin Novoselov at the University of Manchester, is a single, extremely thin layer of carbon atoms arranged in a two-dimensional honeycomb lattice that is considered the thinnest yet one of the strongest and most conductive materials known, carbon nanotubes, or metal oxide frameworks to create electrodes with immense surface areas and extremely short ion diffusion paths. Scientists have dramatically increased the energy storage capacity of supercapacitors without sacrificing their rapid charge-discharge capability.

These innovations are particularly important for grid scale storage and renewable energy integration. The electrical grid requires a diverse set of tools to remain stable. While lithium-ion batteries are excellent for smoothing power over hours, supercapacitors and hybrid systems are uniquely suited for handling transient fluctuations and power quality events. They can react in fractions of a second to absorb or release surges of power, effectively protecting the grid from the momentary dips and spikes caused by a cloud passing over a solar farm or a sudden change in wind speed. In a hybrid energy storage system, supercapacitors can act as a

shock absorber, handling the rapid, high-power pulses and thereby reducing stress on the main battery banks, prolonging their operational life and improving the overall efficiency and resilience of the renewable energy infrastructure. In addition, mechanical energy storage systems store electrical energy by converting it into potential or kinetic mechanical energy. Chemical energy storage systems utilize chemical reactions to store and release energy through molecular bond transformations. Thermal energy storage systems capture and store heat energy that can later be converted into electricity or used directly for heating applications (Koochi Fayegh & Rosen, 2020).

These conventional technologies form the foundation of modern energy storage infrastructure and continue to support numerous applications including grid stabilization, transportation, renewable energy integration, portable electronics, and industrial power systems.

## REVIEW METHODOLOGY

This review was conducted following a systematic literature search strategy to ensure transparency, reproducibility, and scientific rigor. The following electronic databases were searched: Scopus, Web of Science, Google Scholar, ScienceDirect, and IEEE Xplore. The search period covered January 2013 to March 2026, capturing both foundational works and recent advances.

**Search terms** were organized into four thematic groups and combined using Boolean operators:

- i. Energy storage types: "energy storage," "charge storage," "battery," "supercapacitor," "flywheel," "pumped hydro," "thermal storage," "hydrogen storage"
- ii. Technological focus: "lithium-ion," "sodium-ion," "solid-state battery," "redox flow battery," "hybrid energy storage," "electrochemical capacitor"
- iii. Materials: "nanostructured materials," "graphene," "MXene," "carbon nanotubes," "advanced electrodes"
- iv. Applications: "renewable energy integration," "grid storage," "electric vehicles," "power quality"

**Inclusion criteria:** Peer-reviewed journal articles, conference proceedings, and authoritative technical reports (e.g., International Energy Agency, U.S. Department of Energy) published in English. Studies were included if they presented original experimental data, comprehensive reviews, or techno-economic analyses relevant to charge storage for renewable energy.

**Exclusion criteria:** Non-peer-reviewed sources (including Wikipedia, LinkedIn, general news websites, company blogs, and commercial product announcements without technical validation), opinion pieces, and articles not directly addressing charge storage mechanisms or renewable energy applications.

**Screening process:** The initial search yielded 487 records after deduplication. Titles and abstracts were screened independently by two authors, removing 363 records that did not meet inclusion criteria. Full-text assessment of the remaining 124 articles resulted in 89 included studies. An additional 12 relevant papers were identified through citation chaining (snowball sampling) of key references, bringing the final corpus to 101 sources.

**Data extraction and synthesis:** Key information was extracted into a standardized form: (i) storage technology category, (ii) materials/composition, (iii) reported performance metrics (energy density, power density, cycle life, efficiency), (iv) application context, and (v) limitations identified by authors. Findings were synthesized thematically, organized by technology class (electrochemical, electrostatic, mechanical, chemical, thermal) and by developmental stage (conventional vs. emerging). Discrepancies in reported performance values were noted and attributed to differences in measurement conditions or cell configurations.

**Limitations of this review:** Quantitative meta-analysis was not attempted due to heterogeneity in experimental conditions, cell formats, and performance reporting standards across the literature. The review

focuses on technological and materials advances rather than economic or policy dimensions, though cost considerations are discussed where available in source literature.

## Fundamentals of Charge Storage Technology

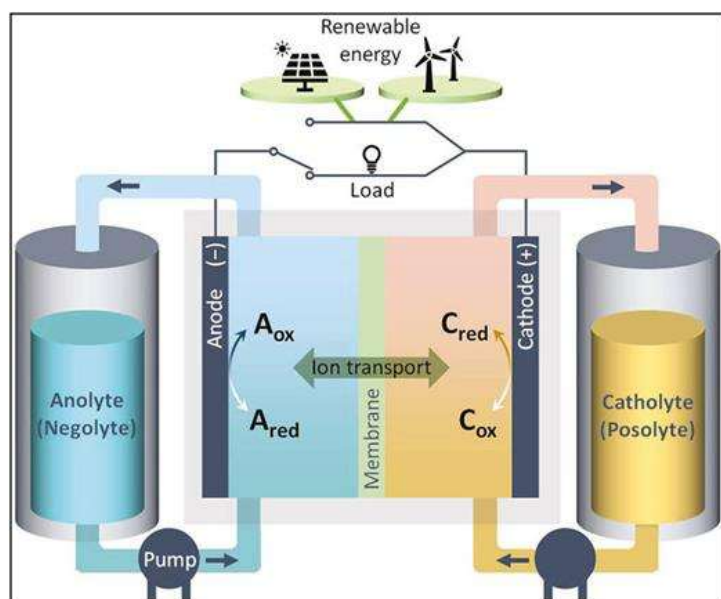
Charge storage technology refers to the methods and materials used to store electrical energy for later use, enabling electricity generated at one time to be utilized at another in applications such as renewable energy systems, electric vehicles, grid storage, and portable electronics (Aneke & Wang, 2016; Koochi Fayegh & Rosen, 2020; Mitali et al., 2022). The fundamental principle involves electron and ion movement within a storage medium. In electrostatic systems such as capacitors, stored charge follows the relationship  $Q = CV$ , where  $Q$  is charge,  $C$  is capacitance, and  $V$  is voltage, while stored energy is expressed as  $E = 1/2CV^2$ .

Electrostatic storage involves the accumulation of charges on conductive plates separated by a dielectric material, allowing rapid charging and discharging, whereas electrochemical storage in batteries involves reversible chemical reactions, including oxidation at the anode, reduction at the cathode, and ion transport through an electrolyte (Goodenough & Park, 2017; Liu et al., 2022). Based on these mechanisms, energy storage technologies are broadly classified into batteries, capacitors, and supercapacitors, with supercapacitors combining both electrostatic and electrochemical charge storage processes (Chen, 2017; Simon & Gogotsi, 2020). The performance of these systems is evaluated using parameters such as energy density, power density, cycle life, and charge–discharge efficiency (Nadeem et al., 2019; Zhao & Burke, 2021). Advanced materials including activated carbon, carbon nanotubes, graphene, metal oxides, and conducting polymers significantly enhance conductivity, surface area, and stability (Liu et al., 2019; Wang et al., 2019).

Despite their importance, challenges such as limited energy density, high material costs, environmental concerns related to battery disposal, and safety risks like thermal runaway remain (Dunn et al., 2016; Krishan & Suhag, 2019). These issues have driven research into next-generation technologies such as solid-state batteries, graphene-based supercapacitors, flow batteries, and hybrid energy storage systems (Deysheer et al., 2022; Singh et al., 2023; Wang et al., 2025).

## Electrochemical Energy Storage (EES)

Electrochemical energy storage (EES) relies on Faradaic electron-transfer reactions that convert electrical energy into chemical changes in electrode or electrolyte species and back during discharge. Key manifestations are redox at surfaces, ion insertion (intercalation) into host lattices, and multi-electron conversion reactions that define battery chemistries and their voltage and capacities (Goodenough & Park, 2017; Liu et al., 2022).



**Figure 1: Electrochemical Energy Storage system (adapted from Okazawa et al., 2023).**

**2.1.1 Faradaic redox reactions** occur when electrons are transferred between electrode and redox-active species, producing chemical state changes that store charge as chemical energy (Srividhya & Ponpandian, 2023).

**2.1.2 Ion Intercalation** involves reversible insertion/removal of ions into solid host structures (for example layered or tunneled electrodes); charge storage is coupled to lattice occupation rather than simple surface adsorption (Rudra et al., 2024)

**2.1.3 Battery Chemistry types** include intercalation-type electrodes (high reversibility and cycle life) and conversion-type electrodes (often higher capacity but larger structural change); these chemistries determine thermodynamic cell voltage, specific capacity, and rate behavior. (Srividhya & Ponpandian, 2023).

Faradaic EES performance is commonly limited by ion diffusion in solids and by phase-change kinetics, which typically make high-rate operation harder than purely electrostatic storage (Rudra et al., 2024).

Rudra et al. (2024) noted that Faradaic EES performance is typically limited by ion diffusion in solids and phase-change kinetics. These factors make high-rate operation more difficult compared to purely electrostatic storage.

**2.2 Electrostatic mechanisms**

Electrostatic storage places charge without net chemical transformation, either by forming an electrochemical double layer at electrode electrolyte interfaces or through dielectric polarization in insulating materials. These processes are inherently non-Faradaic because charge is stored through field-driven separation rather than redox reactions (Volfkovich, 2024; Rahmawati et al., 2025)

Electrical double layer capacitors store charge through the adsorption of ions at the interface between high surface area electrodes and the electrolyte, and the capacitance is largely determined by the accessible electrode surface area and the structure of the electrical double layer described in classical electrochemistry (Wei et al., 2026; Oladele et al., 2025)

Dielectric capacitors store energy by polarizing an insulating dielectric between electrodes; energy is stored in the electric field and does not involve ionic motion or chemical change (Chan, 2017)

Fleischmann et al. (2022) postulated that Non-Faradaic process means no net electron transfer chemical reactions occur at the electrode during charge/discharge. This yields very fast response and excellent cycle life compared with Faradaic devices.

In representative performance commercial electrochemical capacitors (EDLCs and related devices) can reach gravimetric energy on the order of a few Wh·kg<sup>-1</sup> and usable power densities in the kW·kg<sup>-1</sup> range, reflecting the high-rate, non-Faradaic character of EDLCs (Chan, 2017).

**Performance comparison**

The dominant differences between EES and electrostatic storage appear in energy density, power density, and the governing charge/discharge mechanisms; the table summarizes these contrasts.

**Table 1 Comparison between EES and electrostatic storage**

Device class	Energy Density	Power Density	Charge and Discharge mechanisms
Batteries	Generally higher energy per mass due to storage in chemical	Typically lower peak power than EDLCs because rates are	Charge/discharge via Faradaic electron-transfer reactions and



<b>Intercalation/conversion</b>	bonds and bulk insertion; exact values vary by chemistry and are not provided in the supplied sources (insufficient evidence)	limited by solid-state diffusion and phase transformations (Rudra et al., 2024).	ion transport into/out of host phases; kinetics often diffusion-limited (Srividhya & Ponpandian, 2023).
<b>EDLCs Electrostatic double layer</b>	Lower energy than batteries, often a few Wh·kg <sup>-1</sup> in commercial electrochemical capacitors (Chen, 2017).	Very high power, up to kW·kg <sup>-1</sup> levels in practice due to rapid ion rearrangement and non-Faradaic charge storage (Chen, 2017).	Non-Faradaic ion adsorption/desorption at the electrode/electrolyte interface; very fast charge transfer and minimal chemical change (Fleischmann et al., 2022)
<b>Dielectric capacitors</b>	Very low energy density compared with electrochemical devices (insufficient evidence for quantitative numbers in supplied sources)	Extremely high power and very fast response because energy is stored electrostatically in a dielectric medium (Chen, 2017).	Polarization and depolarization of a dielectric under applied field; no ionic motion or redox chemistry (Chen, 2017).

Electrostatic devices (EDLCs, dielectric capacitors) excel at high-power, high-cycle-life applications because they avoid bulk chemical transformation, while Faradaic EES (batteries) deliver higher stored energy but require slower, diffusion-limited ion transport and undergo chemical state changes during cycling (Srividhya & Ponpandian, 2023).

### 2.3 Hybrid Mechanism

Pseudocapacitance and hybrid energy storage devices connect electrostatic capacitive storage with Faradaic battery behavior by combining rapid surface or near surface redox reactions with capacitive responses. This results in devices with mixed characteristics whose performance may resemble either capacitors or batteries depending on electrode materials and structural confinement. Wang et al. (2025) noted that hybrid supercapacitors integrate electric double layer capacitance with Faradaic redox processes, thereby bridging the gap between conventional capacitors and batteries. Surface pseudocapacitance involves fast, reversible Faradaic reactions at electrode surfaces, producing a near-linear voltage–charge relationship unlike battery plateaus (Dunn et al., 2022; Brousse et al., 2017). Intercalation pseudocapacitance enables rapid ion insertion without phase change, supporting continuous potential variation and high-rate charge storage (Dunn et al., 2022; Fleischmann et al., 2022).

Hybrid supercapacitors and supercapatteries intentionally combine EDLC-type electrodes with Faradaic battery-type or pseudocapacitive electrodes to improve energy density while preserving much of the power and cycle-life advantages of capacitive components. According to Brousse et al. (2017), recent work emphasizes that charge storage can span a continuum from purely non-Faradaic to strongly Faradaic behavior (e.g., nanoconfined electrolytes or surface redox can blur categories), so device behavior depends on materials, confinement, and electrode architectures. Materials design such as nanoscale electrodes, conductive scaffolds,

and ion-confining architectures can tune the balance between Faradaic and non-Faradaic contributions and enable fast, high-capacitance behavior (Choudhary et al., 2023).

## CONVENTIONAL ENERGY STORAGE SYSTEMS

The continuous growth in global energy demand has intensified the need for reliable and efficient energy storage technologies capable of supporting modern power systems. Rapid industrialization, increasing population, and expanding digital infrastructure have significantly increased electricity consumption worldwide. At the same time, concerns regarding the environmental consequences of fossil fuel dependence have accelerated the transition toward renewable energy resources such as solar and wind power. Despite their environmental advantages, renewable energy systems suffer from inherent intermittency and variability in power generation. Solar energy production depends on sunlight availability, while wind energy output fluctuates according to atmospheric conditions. Consequently, effective energy storage systems are required to balance power supply and demand, stabilize electrical grids, and ensure continuous energy availability (Koochi Fayegh & Rosen, 2020; Mitali et al., 2022).

Energy storage systems function by capturing excess energy produced during periods of low demand and storing it for later use during periods of higher demand or insufficient generation. These systems enable the integration of renewable energy resources into the power grid while improving power quality, grid stability, and reliability. Moreover, energy storage technologies enhance energy efficiency by minimizing losses associated with energy transmission and distribution. Since electrical energy cannot be stored directly in alternating current form for long periods, it is typically converted into other energy forms such as mechanical, chemical, thermal, electrostatic, or electromagnetic energy for storage purposes (Guney & Tepe, 2017).

Conventional energy storage technologies have therefore been developed to store energy in various physical and chemical forms. These technologies differ in their operating principles, energy densities, efficiencies, response times, and suitability for specific applications (Aneke & Wang, 2016; Koochi Fayegh & Rosen, 2020).

### 3.1 Classification of Conventional Energy Storage Systems

Energy storage technologies can be categorized based on the form of energy stored, the technology employed, and the scale of application. In general, conventional energy storage systems are grouped into five main categories: mechanical energy storage, chemical energy storage, electrochemical energy storage, electrostatic and electromagnetic energy storage, and thermal energy storage. These classifications provide a systematic framework for understanding the different mechanisms used to store energy and facilitate the evaluation of their performance characteristics such as energy density, power density, efficiency, response time, lifespan, and cost effectiveness (Krishan & Suhag, 2019).

Mechanical energy storage systems store electrical energy by converting it into potential or kinetic mechanical energy. Chemical energy storage systems utilize chemical reactions to store and release energy through molecular bond transformations. Electrochemical storage systems rely on reversible redox reactions occurring within electrochemical cells. Electrostatic and electromagnetic systems store energy directly as electric or magnetic fields without conversion into other forms. Thermal energy storage systems capture and store heat energy that can later be converted into electricity or used directly for heating applications (Koochi Fayegh & Rosen, 2020).

These conventional technologies form the foundation of modern energy storage infrastructure and continue to support numerous applications including grid stabilization, transportation, renewable energy integration, portable electronics, and industrial power systems.

#### 3.1.1 Mechanical Energy Storage Systems

Mechanical energy storage systems represent some of the most widely implemented energy storage technologies due to their reliability, scalability, and relatively long operational lifetimes. These systems store energy by converting electrical energy into mechanical energy in the form of potential or kinetic energy and

subsequently reconvert it into electricity when required. Mechanical storage technologies are particularly valuable for large scale grid applications where rapid energy delivery and long cycle lifetimes are essential (Mahmoud et al., 2020).

The primary forms of mechanical energy storage include pumped hydroelectric energy storage, compressed air energy storage, flywheel energy storage, and gravity energy storage.

### **Pumped Hydroelectric Energy Storage**

Pumped hydroelectric energy storage is the most mature and widely deployed large scale energy storage technology worldwide. The system operates by transferring water between two reservoirs located at different elevations. During periods of low electricity demand or surplus energy generation from renewable sources, electrical energy is used to pump water from the lower reservoir to the upper reservoir. This process converts electrical energy into gravitational potential energy stored in the elevated water body.

When electricity demand increases, the stored water is released from the upper reservoir and allowed to flow downward through hydraulic turbines. The kinetic energy of the moving water rotates the turbine blades, which drive generators that produce electricity. This electricity is then supplied back to the power grid to meet demand requirements. Pumped hydroelectric systems typically exhibit high efficiency, long lifespans exceeding several decades, and large storage capacities, making them suitable for grid scale energy management (Aneke & Wang, 2016).

### **Compressed Air Energy Storage**

Compressed air energy storage stores electrical energy by compressing air and storing it in underground caverns or specially designed containers. During periods of excess electricity generation, electric compressors are used to compress air and store it at high pressure. The stored compressed air represents potential energy.

When electricity is needed, the compressed air is released and expanded through turbines that drive electrical generators. This expansion process converts the stored mechanical energy back into electrical energy. Compressed air energy storage systems are capable of providing large scale storage capacities reaching hundreds of megawatts. Variants of this technology include diabatic, adiabatic, and isothermal compressed air systems depending on how heat generated during compression is managed (Rabi et al., 2023).

### **Flywheel Energy Storage**

Flywheel energy storage systems store energy in the form of rotational kinetic energy. The system consists of a rotating mass typically in the form of a disc or cylinder connected to a motor generator assembly. During the charging phase, electrical energy is converted into mechanical energy by accelerating the flywheel to high rotational speeds using an electric motor.

When energy is required, the rotating flywheel drives the generator, converting the stored kinetic energy back into electrical energy. Flywheel systems are characterized by high power density, rapid response times, and long operational lifetimes. They are particularly useful for short duration energy storage applications such as frequency regulation, power quality improvement, and backup power supply systems (Amiryar & Pullen, 2017).

### **Gravity Energy Storage**

Gravity energy storage systems operate on principles similar to pumped hydroelectric storage but use solid masses instead of water. Excess electricity is used to lift heavy masses to higher elevations using mechanical lifting systems such as cranes or motors. The stored gravitational potential energy is later converted into electricity when the mass is allowed to descend and drive electrical generators.

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Although gravity energy storage technology is still under development, it has gained interest due to its potential scalability, long lifespan, and minimal environmental impact (Tong et al., 2022).

### 3.1.2 Chemical Energy Storage Systems

Chemical energy storage involves storing energy in the chemical bonds of molecules. Energy is released when chemical reactions occur that transform these molecules into new compounds. Chemical fuels such as coal, natural gas, gasoline, and hydrogen are traditional examples of chemical energy carriers used for electricity generation and transportation.

Modern chemical energy storage technologies aim to utilize renewable energy sources to produce clean fuels such as hydrogen and synthetic natural gas. These fuels can store energy for extended periods and can be transported and utilized in various sectors including transportation and industrial processes (Revankar, 2019).

#### Hydrogen Energy Storage

Hydrogen energy storage is considered one of the most promising solutions for long term renewable energy storage. Excess electricity generated from renewable sources can be used to split water molecules into hydrogen and oxygen through electrolysis. The produced hydrogen is then stored in compressed tanks, liquefied form, or underground reservoirs.

When electricity is needed, hydrogen can be converted back into electricity through fuel cells. Fuel cells generate electricity through electrochemical reactions between hydrogen and oxygen, producing water and heat as byproducts. Various fuel cell technologies exist including proton exchange membrane fuel cells, alkaline fuel cells, phosphoric acid fuel cells, molten carbonate fuel cells, and solid oxide fuel cells (Aminudin et al., 2023).

#### Synthetic Natural Gas Energy Storage

Synthetic natural gas storage converts electrical energy into methane through chemical reactions involving hydrogen and carbon dioxide. The resulting methane can be stored using existing natural gas infrastructure and later utilized as a fuel for power generation or heating applications (Bolt et al., 2020).

#### Solar Fuel Storage

Solar fuel technologies aim to convert solar energy into chemical fuels through processes such as artificial photosynthesis and thermochemical reactions. Artificial photosynthesis mimics natural photosynthesis by using sunlight to split water molecules and reduce carbon dioxide to produce fuels such as methane or methanol. Thermochemical processes use high temperature reactions to generate hydrogen or synthetic hydrocarbons from solar heat energy (Dogutan & Nocera, 2019).

### 3.1.3 Electrochemical Energy Storage Systems

Electrochemical energy storage systems store electrical energy through reversible electrochemical reactions occurring within batteries. Batteries consist of three primary components including an anode, a cathode, and an electrolyte that facilitates ionic transport between the electrodes.

Electrochemical storage technologies are classified into primary and secondary batteries. Primary batteries are non-rechargeable and operate through irreversible chemical reactions. Secondary batteries are rechargeable and capable of undergoing multiple charge and discharge cycles (Liu et al., 2022).

Common electrochemical storage technologies include lead acid batteries, nickel cadmium batteries, sodium sulfur batteries, lithium ion batteries, and redox flow batteries.

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## Lithium Ion Batteries

Lithium ion batteries are currently the most widely used electrochemical energy storage systems due to their high energy density, high efficiency, and lightweight design. These batteries operate by reversible intercalation of lithium ions between the cathode and anode materials during charging and discharging processes. Lithium ion batteries typically deliver energy densities between 100 and 200 Wh kg<sup>-1</sup> and power densities up to 2000 W kg<sup>-1</sup>, making them suitable for applications ranging from portable electronics to electric vehicles (Liu et al., 2022).

## Redox Flow Batteries

Flow batteries store energy in liquid electrolytes containing dissolved electroactive species. The electrolytes are stored in external tanks and pumped through electrochemical cells during operation. This configuration allows independent scaling of power and energy capacity, making flow batteries suitable for large scale grid storage applications (Soloveichik, 2015).

Vanadium redox flow batteries represent one of the most developed flow battery technologies due to their long cycle life and high reliability.

Redox flow batteries (RFBs) are electrochemical energy storage systems in which energy is stored in liquid electrolytes containing dissolved redox-active species that circulate through an electrochemical cell during operation. Unlike conventional batteries, RFBs separate energy storage from power generation: energy capacity is determined by the volume of electrolyte stored in external tanks, while power output depends on the size of the cell stack (Soloveichik, 2015; Dunn et al., 2016). During operation, oxidation and reduction reactions occur at the electrodes, enabling reversible energy conversion with high efficiency and long cycle life.

A major advantage of RFBs is their scalability and flexibility, making them suitable for large-scale and grid-level energy storage applications, particularly for integrating intermittent renewable energy sources such as solar and wind (Nadeem et al., 2019; Koohi-Fayegh & Rosen, 2020). Additionally, their design allows deep discharge, improved safety due to aqueous electrolytes, and reduced degradation compared to solid-state batteries (Aneke & Wang, 2016).

However, RFBs are limited by relatively low energy density, high system complexity, and material costs, especially for vanadium-based systems (Soloveichik, 2015). Despite these challenges, ongoing research focuses on improving electrolyte chemistry and system efficiency, positioning RFBs as a promising solution for long-duration energy storage in modern power systems (Mitali et al., 2022).

### 3.1.4 Electrostatic and Electromagnetic Energy Storage

Electrostatic and electromagnetic storage systems store electrical energy directly in electric or magnetic fields without converting it into chemical or mechanical forms. Examples include capacitors, supercapacitors, and superconducting magnetic energy storage systems.

Supercapacitors store energy through electrostatic charge accumulation at the electrode electrolyte interface. Their energy density can be expressed as

$$E = \frac{1}{2} C V^2$$

where  $C$  represents capacitance and  $V$  represents applied voltage. Supercapacitors exhibit extremely high power density and long cycle lifetimes exceeding one million cycles, making them suitable for applications requiring rapid energy delivery (Zhao & Burke, 2021).

Superconducting magnetic energy storage systems store energy in magnetic fields generated by superconducting coils maintained at cryogenic temperatures. These systems offer extremely fast response times and high efficiency but are limited by high installation and cooling costs (Mukherjee & Rao, 2019).

### 3.1.5 Thermal Energy Storage Systems

Thermal energy storage systems store heat energy that can later be converted into electricity or used directly for heating applications. Thermal storage technologies are categorized into sensible heat storage, latent heat storage, and thermochemical storage systems (Alva et al., 2018).

Sensible heat storage involves raising the temperature of a material such as water, rock, or molten salts to store thermal energy. Latent heat storage utilizes phase change materials that absorb or release heat during phase transitions such as melting or solidification. Thermochemical storage systems store energy through reversible chemical reactions that break and reform molecular bonds.

These systems play an important role in solar thermal power plants, district heating networks, and industrial heat recovery applications.

Conventional energy storage systems form the backbone of modern energy infrastructure and are essential for ensuring reliable electricity supply in the evolving global energy landscape. These systems encompass a wide range of technologies including mechanical, chemical, electrochemical, electrostatic, electromagnetic, and thermal storage solutions. Each technology offers distinct advantages and limitations in terms of energy density, response time, efficiency, lifespan, and cost.

Mechanical energy storage technologies such as pumped hydroelectric and compressed air storage provide large scale grid support, while electrochemical batteries dominate portable and transportation applications. Chemical energy storage systems such as hydrogen offer promising solutions for long duration energy storage, whereas electrostatic and electromagnetic systems provide rapid response capabilities for power quality management. Thermal energy storage technologies contribute to efficient heat management and renewable energy integration.

Despite significant advancements, ongoing research is required to improve the efficiency, safety, sustainability, and economic feasibility of these technologies. The continued development and integration of advanced energy storage systems will play a critical role in enabling the widespread adoption of renewable energy sources and achieving global energy sustainability goals.

## EMERGING CHARGE STORAGE TECHNOLOGIES (ALL-SOILD-STATE BATTERIES)

All-Solid-State Batteries are considered a next-generation energy storage solution particularly for applications requiring compact size, high safety, and high energy density, such as electric vehicles, portable electronics, and stationary storage. Their development demands multidisciplinary engineering skills (materials science, mechanical design, electrochemistry, thermal management, and manufacturing engineering (Deysner et al., 2022))

### Advantages of All-Solid-State Lithium-Ion Batteries

All-solid-state lithium-ion batteries are considered as one of the most promising battery systems and higher volumetric energy density than the currently available lithium-ion batteries are expected. Deysner et al., (2022) Further explained that All-solid-state batteries can highly enhance the capability of cell design by allowing in-series stacking and bipolar structures, greatly improving the packaging efficiency of the battery. Therefore, high energy density can be achieved by the reduction of the dead space between single cells of the conventional lithium-ion batteries, as shown in Figure 4.1.

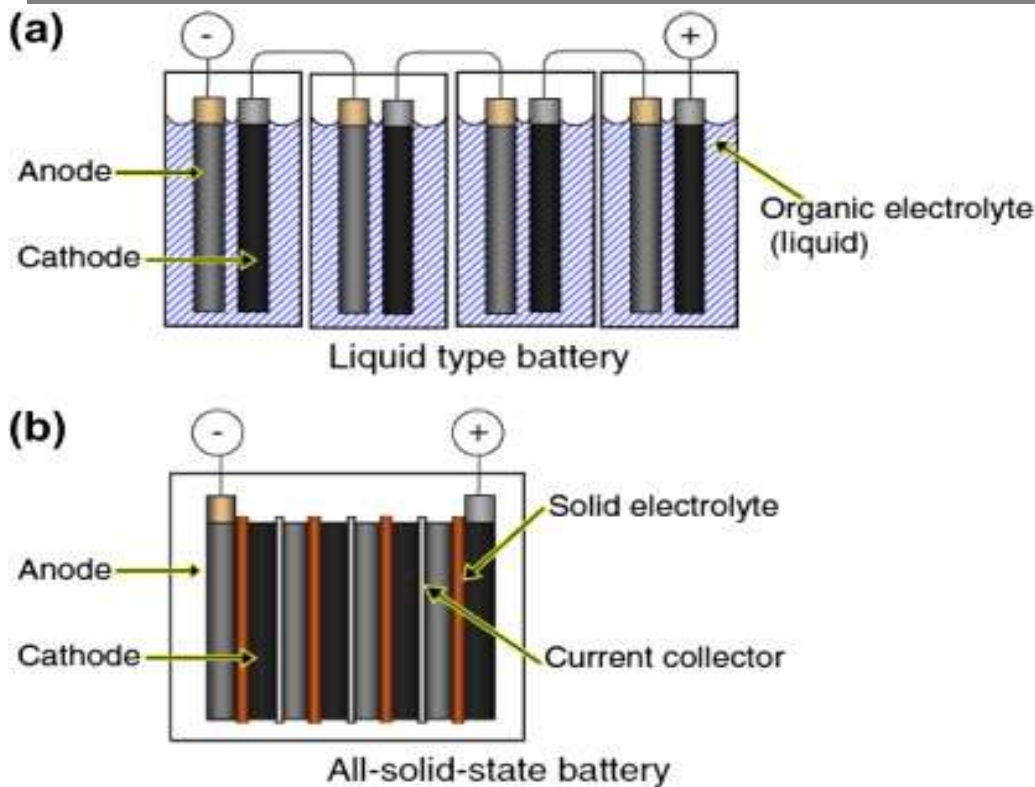


Figure 2 All-Solid-State Batteries (Deysher et al., 2022)

#### 4.1 Solid-State Batteries

Solid-state electrolytes have advanced across oxide, sulfide, polymer and composite classes but electrode electrolyte interfaces remain the dominant barrier to practical SSBs. Sodium-ion cathode chemistry and scalable electrode fabrication show strong cost-performance promise, while silicon anodes, high-nickel cathodes, and recycling are leading next-generation LIB trends.

Hou et al. (2024) stated that Oxide electrolytes offers high chemical and electrochemical stability but are mechanically brittle and suffer from poor interfacial resistance with electrodes, while Sulfide Electrolytes can reach high ionic conductivities at room temperature but pose challenges in electrochemical stability windows and sensitivity to moisture, complicating electrode compatibility (Li et al., 2024). Similarly Polymer electrolytes provide good conformal contact and flexibility, yet intrinsic ionic conductivity at room temperature is often lower; recent in-situ polymerization approaches have demonstrated markedly improved interface formation and long cycle life in high-voltage Li metal cell (Siddique et al., 2025).

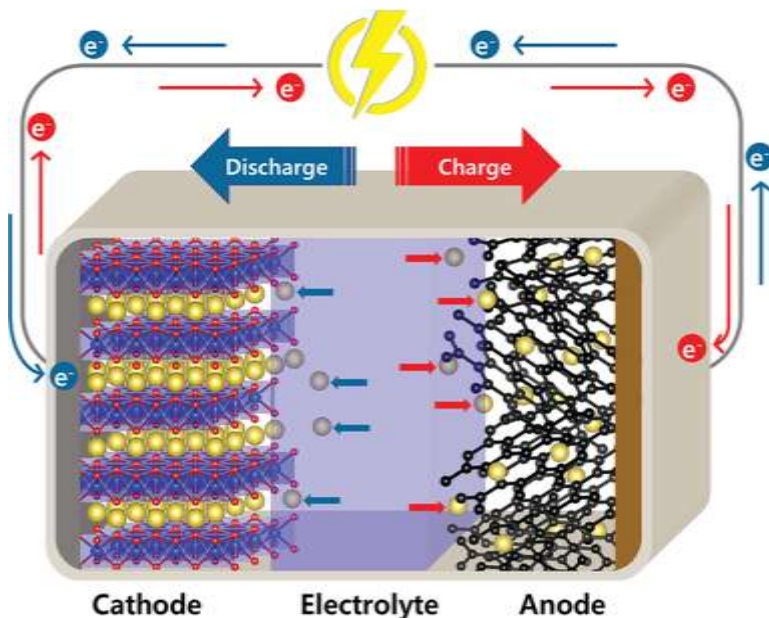
Researchers are developing three main types of solid electrolytes: inorganic-inorganic composites (combining two solid inorganic materials to enhance ionic transport), polymer-polymer blends (improving flexibility and ion conduction), and inorganic-polymer hybrids (combining high conductivity of inorganics with mechanical flexibility of polymers). Polymer-polymer, two polymers are blended to improve flexibility and ion conduction and inorganic-polymer composites, which is a hybrid of inorganic and polymer materials combines the high conductivity of inorganics with the mechanical flexibility of polymers to achieve a combination of high ionic conductivity, mechanical flexibility, and better compatibility with electrodes. Vedhanarayanan and Seetha Lakshmi (2024) discussed emerging next-generation battery technologies, including solid-state, lithium-sulfur, sodium, and multivalent metal batteries, highlighting their potential to overcome the limitations of conventional lithium-ion systems.

Interfacial stability remains a critical challenge for solid state batteries, as reactions between electrodes and solid state electrolytes can form resistive interphases or consume active species, limiting cycle life and the usable voltage window (Li et al., 2024). Mechanical contact loss at solid interfaces further increases impedance during cycling, which can be mitigated using soft polymer components or compliant interlayers

(Vedhanarayanan et al., 2024). Engineering solutions such as interface coatings, tailored interlayer chemistries, and in situ polymerization to form conformal SEI or CEI films have demonstrated improved performance for instance, in situ polymerized solid polymer electrolyte cells achieved over 1000 hours of Li cycling and approximately 86.8% capacity retention in NCM SPE Li cells after 1000 cycles (Siddique et al., 2025). Emerging electrolyte chemistries, including hydridoborate based sodium solid electrolytes, provide favorable ionic conductivity and electrode compatibility, representing promising alternatives for sodium metal solid state batteries (Yu, 2024). Overall, solid state batteries offer intrinsic safety and the potential for high energy density with metal anodes, but practical success depends on durable, low impedance electrode electrolyte interfaces achieved through integrated materials and interface engineering rather than single component improvements (Hou et al. 2024; Li et al., 2024).

## 4.2. Sodium-ion Batteries

Sodium-ion batteries (SIBs) are advancing rapidly in cathode chemistry and electrode fabrication, targeting grid and large-scale applications where raw-material cost and resource abundance are decisive. Recent reviews and experimental work report improved layered oxides, Prussian blue analogues, and polyanionic cathodes alongside scalable electrode manufacturing that narrows the performance gap with LIBs.



**Figure 3** Schematic of the working principle of a sodium-ion (Singh et al., 2023).

### 4.2.1 Cathode Materials Progress and Tradeoff.

Layered oxides provide relatively high specific capacity and voltage, but they require careful composition and surface control to improve cycling stability and rate performance. Prussian blue analogues offer open framework structures that enable fast  $\text{Na}^+$  diffusion at low cost, making them attractive for large-scale applications; however, structural water content and vacancies must be controlled to achieve long cycle life (Lv et al., 2024). Also Polyanionic compounds like  $\text{Na}_2\text{V}_3(\text{PO}_4)_3$  and related phosphates) deliver good structural stability, safety, and thermal robustness; recent fabrication advances have dramatically increased areal loading while preserving energy and power performance (Ouyang et al., 2024).

### 4.2.2 Manufacturing and Scale Indicators

High areal loading electrodes were produced using a combined electrospinning and electrospraying technique for  $\text{Na}_2\text{V}_3(\text{PO}_4)_3$  cathodes, achieving  $296 \text{ mg cm}^2$  areal loading and pouch cell validated energy and power densities of approximately  $231.6 \text{ Wh kg}^{-1}$  and  $7152.6 \text{ W kg}^{-1}$ , indicating practical pathways toward industry relevant electrode architectures (Ouyang et al., 2024).

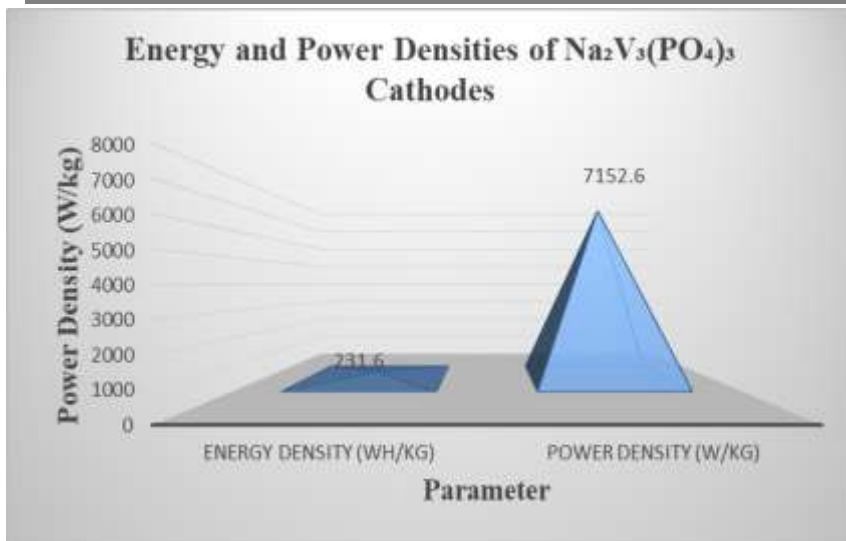


Figure 4. Energy density (Wh/kg) and power density (W/kg) of high areal loading  $\text{Na}_2\text{V}_3(\text{PO}_4)_3$  cathodes (Ouyang et al., 2024)

In terms of cost versus performance, sodium ion batteries benefit from abundant sodium resources and lower raw material costs compared with lithium systems, which supports competitiveness in grid and stationary storage; however, energy density remains lower than lithium ion batteries, so sodium ion batteries are most compelling where cost and raw material supply dominate system requirements (Lv et al., 2024).

#### 4.2.3 Deployment Considerations

Deployment considerations include the benefit of reduced material cost and resource availability aligned with large scale storage needs (Lv et al., 2024). Challenges include closing the energy density gap while ensuring long calendar life and developing compatible, scalable electrolytes and electrode fabrication methods. Integration with solid state electrolyte advances could further enhance safety but requires parallel progress in SSE conductivity and interfaces (Hou et al., 2024).

#### 4.3 Next Generation Lithium-ion

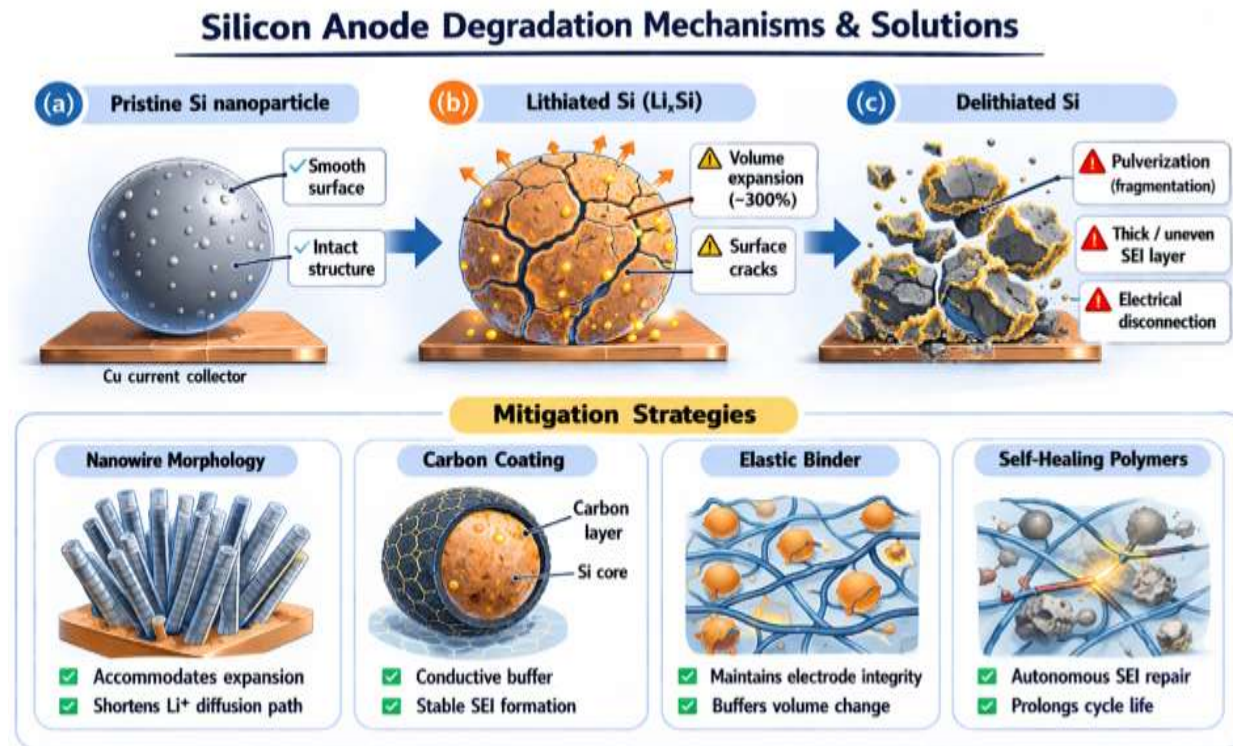
Next-generation lithium-ion development focuses on electrode materials that raise energy and/or reduce cost, plus lifecycle considerations such as recycling. Research trajectories emphasize silicon-based anodes, high-nickel cathodes, and system-level circularity. Materials-level innovations and nanostructuring are central to mitigating degradation mechanisms while enabling greater specific capacity.



Figure 5 Schematic showing the components of a next-generation lithium-ion battery with silicon-composite anode and high-nickel cathode. Annotate with key challenges.

### 4.3.1 Silicon Anodes and Related Engineering

Lee et al. (2025) discussed silicon anodes and related engineering focus on high capacity, as silicon offers very large specific capacity compared with graphite, motivating numerous nanoscale and composite strategies to accommodate drastic volume changes. Primary challenges include mechanical pulverization, unstable SEI formation, and first cycle irreversible loss. Nanoscaling, binder and architectural design, and protective coatings remain the leading mitigation routes reported in recent nanomaterials focused reviews (Lee et al., 2025)



**Figure 6** Illustration of silicon anode failure mechanisms and solutions. Show three stages: (a) pristine Si particle, (b) after lithiation (expansion and cracking), (c) after delithiation (pulverization and unstable SEI). Below, show mitigation strategies.

### 4.3.2 High-nickel Cathodes and Limits

Energy gain comes from increasing nickel content, which raises the specific energy of layered cathodes but exacerbates thermal instability, oxygen release, and surface reactivity toward the electrolyte, requiring advanced surface coatings and electrolyte stabilization strategies (Lee et al., 2025). Interface control is critical, as achieving long life with high nickel compositions depends on coupled cathode and electrolyte interface engineering, an area highlighted across next generation materials reviews (Vedhanarayanan et al., 2024).

### 4.3.3 Recycling and Lifecycle Perspective

Strategic importance arises from the environmental and economic implications of expanding battery deployment, motivating stronger emphasis on reuse and recycling in recent perspectives on post LIB futures (Lü et al., 2024). Evidence limitations include that the supplied literature highlights recycling as a priority and discusses environmental and economic contexts, but detailed, standardized process metrics and large scale recycling performance data are not provided in the available corpus, indicating insufficient evidence.

### 4.3.4 Net assessment

Benefits include that silicon anodes and high nickel cathodes promise step changes in specific energy and range for electric vehicles and portable systems when coupled with compatible electrolytes and interface

solutions (Lee et al., 2025). Challenges involve material degradation mechanisms, both mechanical and interfacial, cell safety at higher energy, and the need for economically viable recycling, which remain the central hurdles to commercialization (Lee et al., 2025; Siddique et al., 2025; Lü et al., 2024).

## ADVANCED MATERIALS FOR ENERGY STORAGE

The rapid growth of renewable energy systems and modern electronic technologies has intensified the demand for efficient and high-performance energy storage solutions. Central to this advancement is the development of advanced materials, which significantly influence the capacity, efficiency, lifespan, and safety of energy storage devices. These materials have transformed conventional storage technologies by enabling higher energy densities, faster charge–discharge rates, and improved durability.

### 5.1 Role of Advanced Materials in Energy Storage

Advanced materials form the backbone of modern energy storage technologies, especially batteries and supercapacitors. Their unique structural, electrical, and electrochemical properties determine system performance. Nanostructured and multifunctional materials are increasingly replacing traditional counterparts because they offer higher surface area, improved conductivity, and superior electrochemical stability (Arico, A. S. et al., 2020; Liu et al., 2019).

Nanostructured materials, in particular, have revolutionized energy storage by enabling efficient ion transport and electron mobility. These materials reduce diffusion distances and increase electrode-electrolyte interaction, thereby improving charge storage capacity and cycling stability (Arico et al., 2020). As a result, they are widely applied in next-generation batteries and electrochemical capacitors.

**Table 2: Nanostructured materials**

Material	Specific surface area (m <sup>2</sup> /g)	Electrical conductivity	Relative cost	Key advantage for storage
Graphene	~2630 (theoretical)	Very high (~10 <sup>6</sup> S/m)	Moderate	High surface area + conductivity
Carbon nanotubes (CNT)	200–1300	Very high (~10 <sup>5</sup> S/m)	Moderate	Mechanical strength + 1D pathways
MXenes (e.g., Ti <sub>3</sub> C <sub>2</sub> T <sub>x</sub> )	Up to ~100	High (up to 10 <sup>4</sup> S/m)	Moderate (synthesis dependent)	Tunable surface chemistry + metallic conductivity
Activated carbon	1000–3000	Low (10–100 S/m)	Low	Low cost, commercial availability
Metal oxides (e.g., MnO <sub>2</sub> , RuO <sub>2</sub> )	100–500	Low to moderate	High to very high (Ru)	High pseudocapacitance

Table 2 Comparison of nanostructured materials for energy storage applications. Specific surface area and conductivity values are representative ranges from literature; actual values depend on synthesis method and morphology.

### 5.2 Nanostructured Materials and Their Applications

Nanostructured materials, including nanoparticles, nanowires, and nanosheets, are widely used in energy storage devices due to their superior physical and chemical properties. Their high surface-to-volume ratio enhances electrochemical reactions, leading to improved energy and power densities.

For instance, nanostructured electrode materials have been successfully applied in lithium-ion batteries, where they improve charge transport and reduce degradation over time (Goodenough & Park, 2017). Similarly, in supercapacitors, nanostructured carbon materials provide high capacitance and rapid charge–discharge capabilities (Wang et al., 2019).

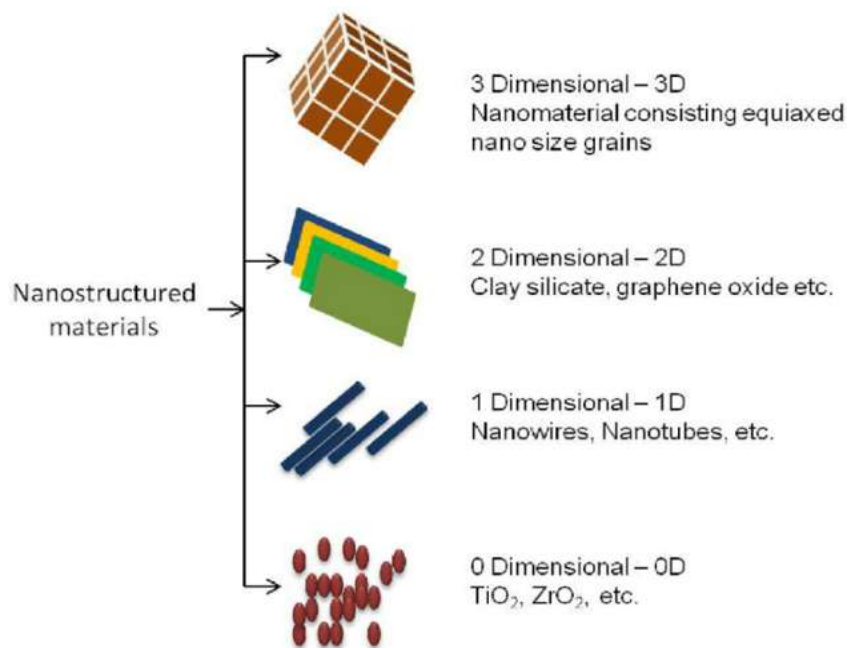


Figure 7: Nanostructured Materials (Saeed et al., 2023)

The integration of nanotechnology into energy storage systems has also enabled the development of hybrid devices, combining the advantages of batteries and capacitors. These hybrid systems offer both high energy density and high power density, making them suitable for applications such as electric vehicles and grid stabilization (Lukatskaya et al., 2018).

### 5.3 Carbon-Based Materials

Carbon-based materials remain one of the most widely studied and utilized classes of advanced materials in energy storage. These include graphene, carbon nanotubes, activated carbon, and porous carbon structures. Their popularity stems from their excellent electrical conductivity, chemical stability, and large surface area.

Graphene, in particular, has attracted significant attention due to its exceptional electrical and mechanical properties. It enables the development of high-performance supercapacitors with improved energy density and flexibility (Zhang et al., 2021). Carbon nanotubes and porous carbon materials also enhance charge storage by providing efficient pathways for electron transport and ion diffusion (Zhang et al., 2020).

Furthermore, carbon-based materials are widely used in commercial supercapacitors, where they contribute to long cycle life and high power output. Their versatility allows them to be tailored for various applications, including portable electronics and renewable energy systems (Simon & Gogotsi, 2020).

### 5.4 MXenes and Two-Dimensional Materials

The discovery of **MXenes**, a family of two-dimensional transition metal carbides and nitrides, has opened new possibilities in energy storage research. These materials exhibit excellent electrical conductivity and high capacitance, making them suitable for use in supercapacitors and batteries (Naguib et al., 2017).

MXenes also offer tunable surface chemistry, which enhances their interaction with electrolytes and improves charge storage performance. Their layered structure facilitates rapid ion transport, making them ideal for high-power applications (Lukatskaya et al., 2018).

In addition to MXenes, other two-dimensional materials such as transition metal dichalcogenides are being explored for their potential in energy storage systems. These materials contribute to the development of flexible and wearable energy storage devices.

### 5.5 Advanced Materials for Supercapacitors

Supercapacitors have benefited significantly from advancements in material science. The development of novel electrode materials has led to improved energy density, bridging the gap between conventional capacitors and batteries.

Recent studies highlight the use of nanostructured metal oxides, conductive polymers, and carbon composites in supercapacitor design. These materials enhance capacitance, energy density, and cycling stability (Wang et al., 2019; Zhang et al., 2021). Additionally, asymmetric supercapacitors, which use different materials for positive and negative electrodes, have shown improved performance compared to symmetric designs (Wang et al., 2021).

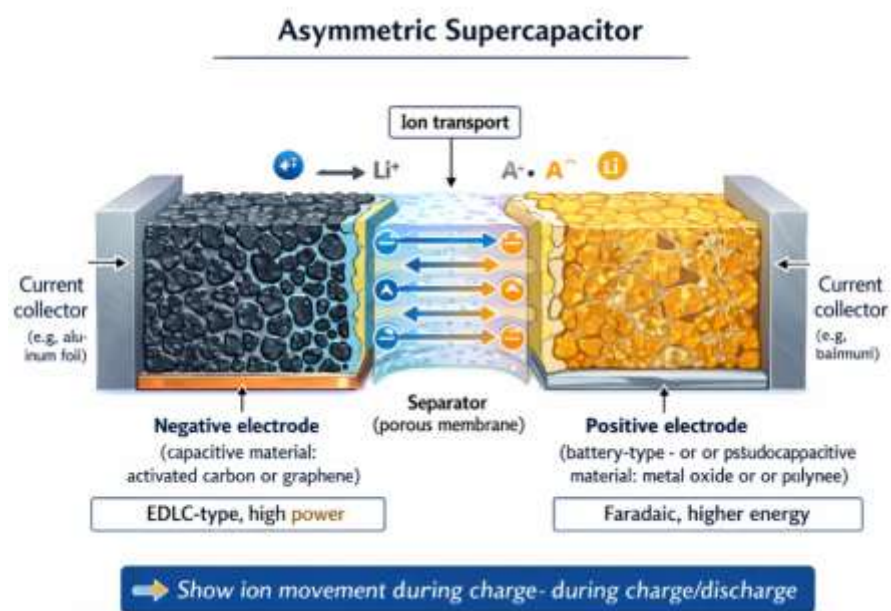


Figure 8: Asymmetric supercapacitor schematic (Cross-section of an asymmetric supercapacitor with two different electrode materials.)

The continuous innovation in material design has also enabled the development of flexible and miniaturized supercapacitors for use in wearable electronics and portable devices.

### 5.6 Materials for Advanced Battery Technologies

Battery technology has evolved significantly with the introduction of advanced materials. Lithium-ion batteries, for example, rely on high-performance electrode materials to achieve high energy density and long cycle life. Research efforts are focused on developing alternative materials such as silicon anodes, solid electrolytes, and lithium-sulfur systems (Armand & Tarascon, 2018).

These materials address key limitations of conventional batteries, including capacity fading, safety concerns, and limited energy density. For instance, silicon-based anodes offer significantly higher capacity than traditional graphite anodes, although challenges related to volume expansion remain (Goodenough & Park, 2017).

Advanced materials also enable the development of solid-state batteries, which offer improved safety and energy density compared to liquid electrolyte systems. These batteries are expected to play a crucial role in future energy storage applications, particularly in electric vehicles and grid systems.

## 5.7 Challenges and Future Directions

Despite significant progress, the development of advanced materials for energy storage faces several challenges. These include high production costs, scalability issues, and material degradation over time. Additionally, environmental concerns related to material extraction and disposal must be addressed.

Future research is focused on:

- Developing low-cost and sustainable materials
- Improving material stability and lifespan
- Enhancing energy and power density simultaneously
- Integrating advanced materials into hybrid energy storage systems.

Advanced materials have become a cornerstone of modern energy storage technologies, significantly enhancing the performance of batteries, supercapacitors, and hybrid systems. From nanostructured materials to emerging two-dimensional materials such as MXenes, these innovations have expanded the capabilities of energy storage devices. As research continues to address existing challenges, advanced materials will play a pivotal role in supporting the global transition toward sustainable and renewable energy systems.

## APPLICATION OF CHARGE STORAGE TECHNOLOGIES IN RENEWABLE ENERGY SYSTEMS

Renewable energy systems, particularly solar and wind, are inherently intermittent due to their dependence on environmental conditions. This variability introduces challenges in ensuring a stable and reliable electricity supply. Charge storage technologies play a crucial role in mitigating these challenges by storing excess energy during peak generation periods and releasing it when demand exceeds supply. As a result, they enhance energy reliability, improve grid stability, and enable deeper penetration of renewable energy into modern power systems (Adeyemo et al., 2024; Sahu et al., 2021).

### 6.1 Battery Energy Storage Systems (BESS)

Battery energy storage systems represent the most widely deployed charge storage technology in renewable energy applications. These systems store electrical energy in electrochemical form and discharge it when required.

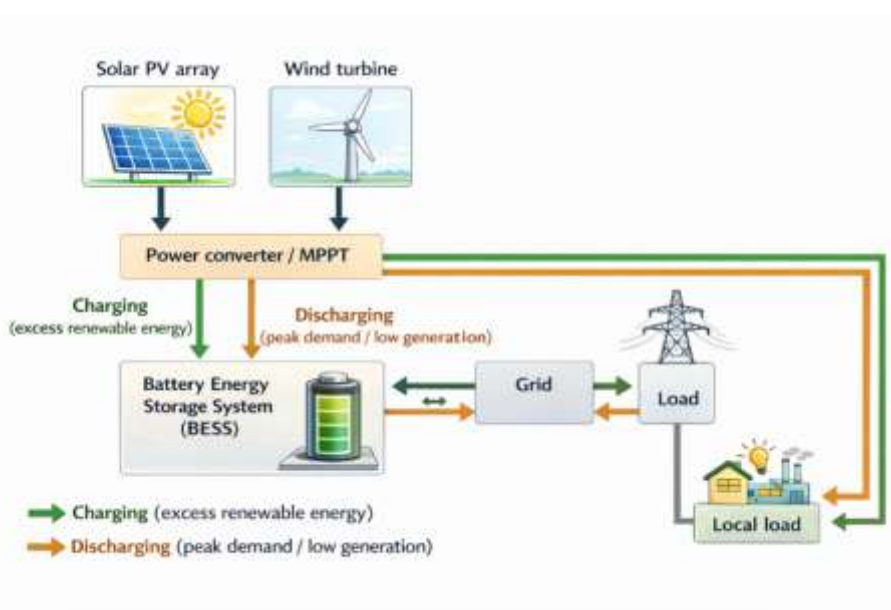


Figure 9 Simple block diagram showing solar PV and wind turbine feeding into a battery energy storage system (BESS) connected to grid and load

### 6.1.1 Application in Solar Photovoltaic Systems

In solar photovoltaic (PV) systems, batteries are used to store surplus energy generated during periods of high solar irradiance for use during nighttime or low sunlight conditions. This application is common in both residential and utility-scale solar installations, where batteries facilitate load shifting and ensure uninterrupted power supply (Adeyemo et al., 2024).

### 6.1.2 Application in Wind Energy Systems

Wind energy systems experience fluctuations due to variable wind speeds. Batteries help smooth these fluctuations by storing excess energy during high wind periods and releasing it during low wind conditions. This improves system reliability and contributes to voltage and frequency regulation within the grid (Sahu et al., 2021).

### 6.1.3 Application in Hybrid Renewable Systems

In hybrid systems combining solar, wind, and conventional generators, batteries act as a central energy buffer. They optimize energy utilization, reduce fuel consumption, and improve overall system efficiency, particularly in remote and off-grid applications (Adeyemo et al., 2024).

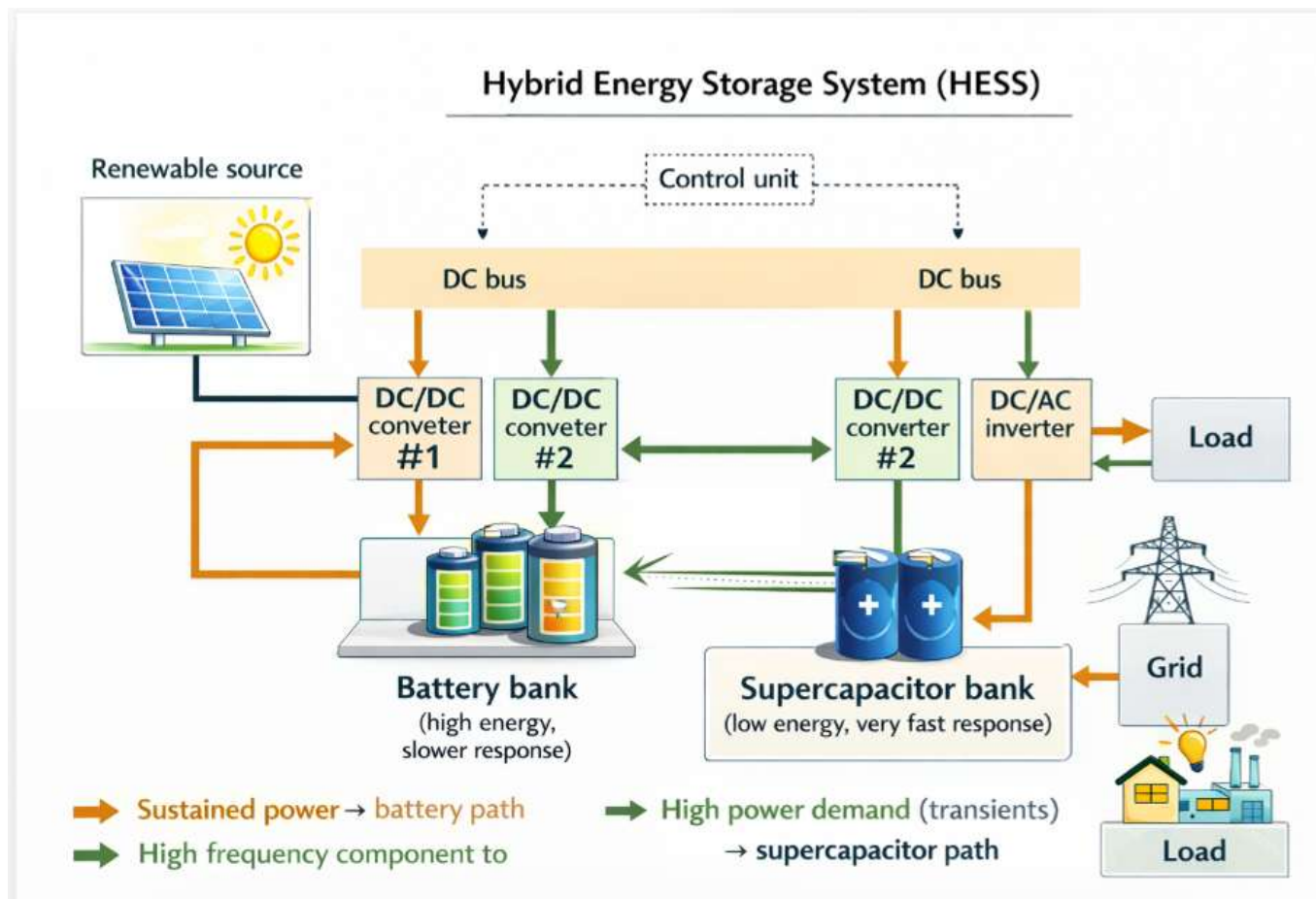


Figure 10: Hybrid energy storage system HESS (Configuration showing supercapacitor and battery connected in parallel to a common DC bus with power management)

### 6.1.4 Application in Electric Vehicles Integrated with Renewables

Battery technologies are also central to electric vehicles powered by renewable energy. In vehicle-to-grid configurations, electric vehicle batteries can store renewable energy and feed it back into the grid, enhancing energy flexibility and resilience (Danzi et al., 2021).

## 6.2 Supercapacitors in Renewable Energy Systems

Supercapacitors, also known as ultracapacitors, store energy through electrostatic charge accumulation and are characterized by high power density and rapid charge-discharge cycles.

### HYBRID ENERGY STORAGE SYSTEM (HESS): MAXIMIZING EFFICIENCY AND LIFESPAN

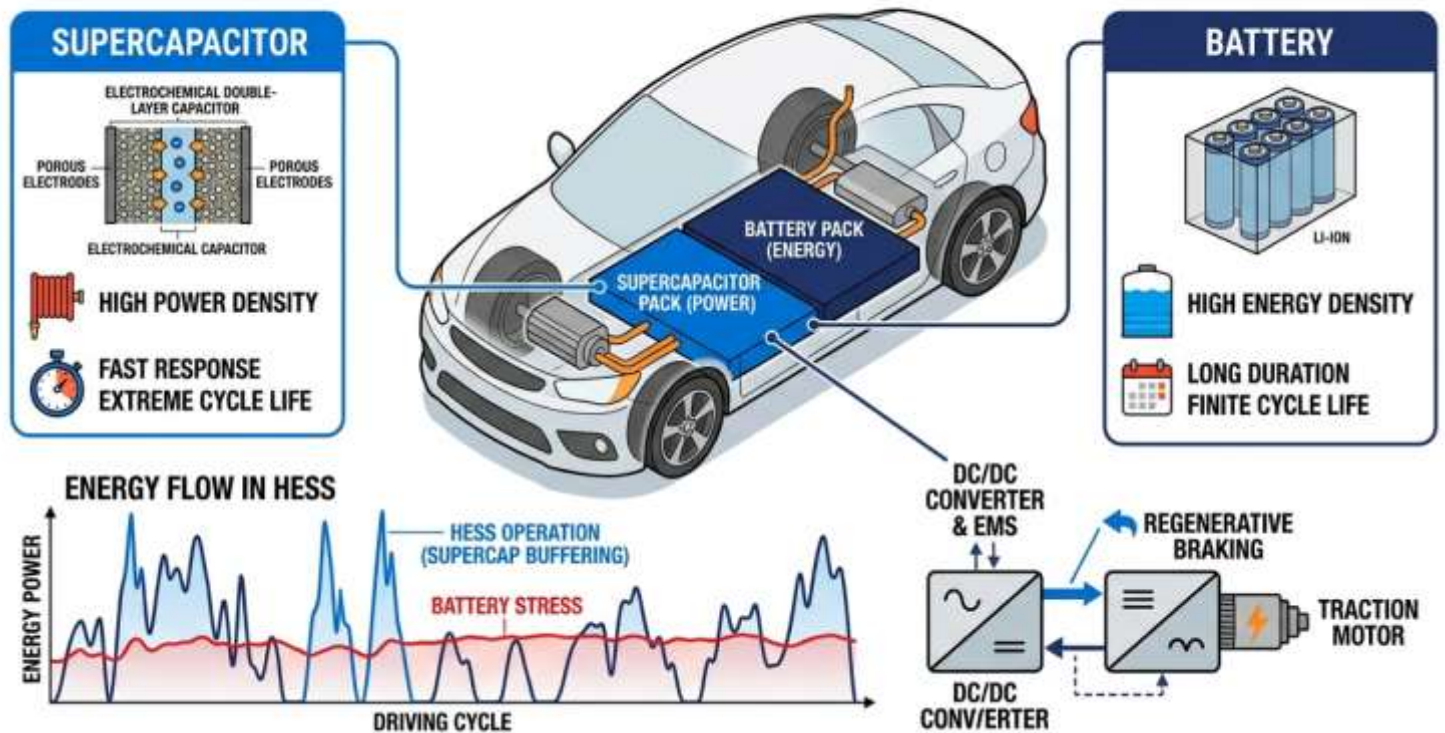


Figure 11: Supercapacitors and their use in Hybrid Energy Storage System

#### 6.2.1 Power Smoothing Applications

Supercapacitors are widely used alongside batteries to manage short-term fluctuations in renewable energy output. Their rapid response capability handles transient variations (milliseconds to seconds), whereas batteries manage longer-term energy storage (minutes to hours) Zhao & Burke (2021)

#### 6.2.2 Grid Stabilization and Power Quality

In renewable-integrated grids, supercapacitors contribute to voltage stabilization and power quality improvement by compensating for sudden disturbances and maintaining system stability (Adeyemo et al., 2024).

#### 6.2.3 Applications in Renewable-Powered Transport Systems

Supercapacitors are used in electric buses, cranes, and rail systems powered by renewable energy. They enable regenerative braking and rapid energy delivery, improving overall system efficiency (Zhao & Burke 2021)

## 6.3 Flywheel Energy Storage Systems

Flywheel energy storage systems store energy in the form of rotational kinetic energy and are suitable for high-power, short-duration applications.

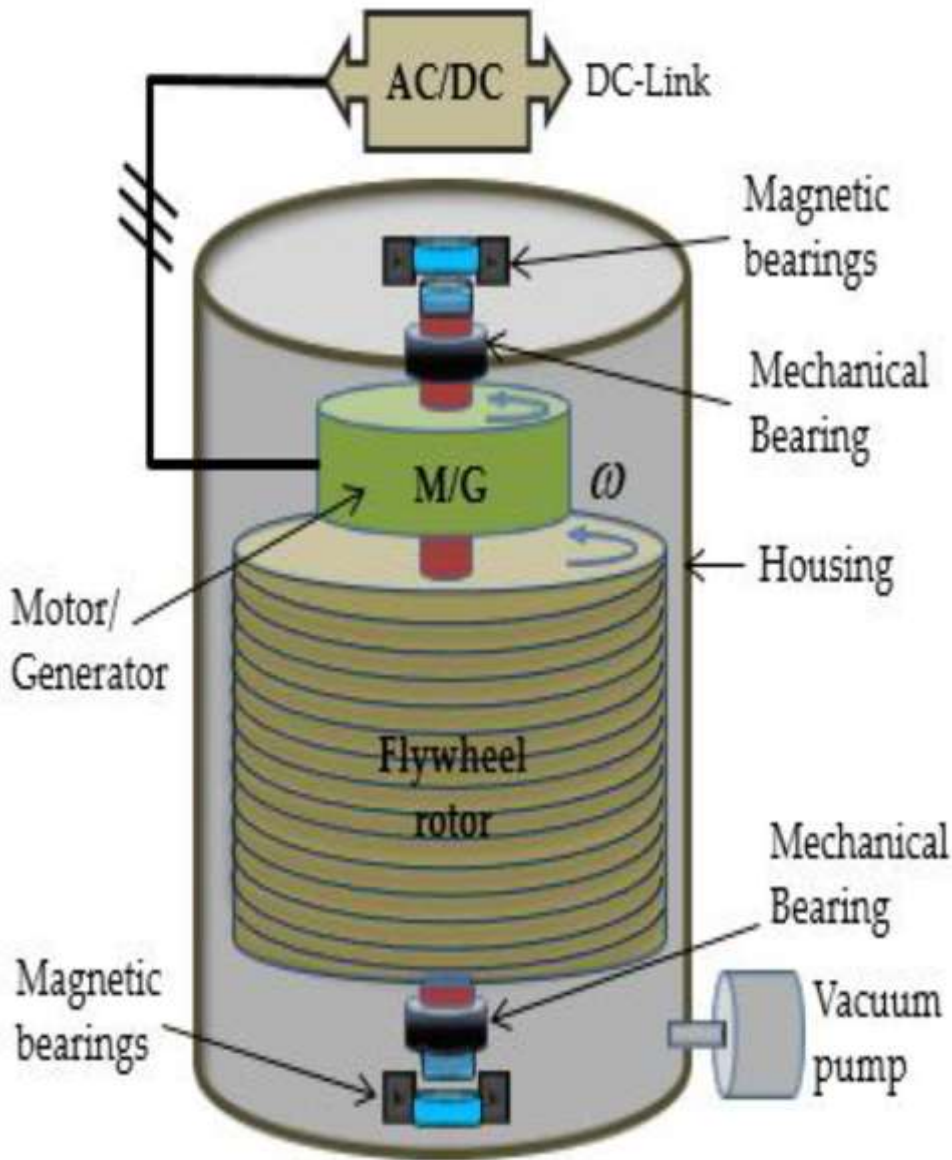


Figure 12: Flywheel Energy Storage System (Amiryar & Pullen, 2020)

### 6.3.1 Frequency Regulation in Renewable Grids

Flywheels provide rapid frequency response in grids with high renewable penetration. They stabilize frequency deviations caused by sudden changes in generation or load (Adeyemo et al., 2024).

### 6.3.2 Applications in Wind Power Systems

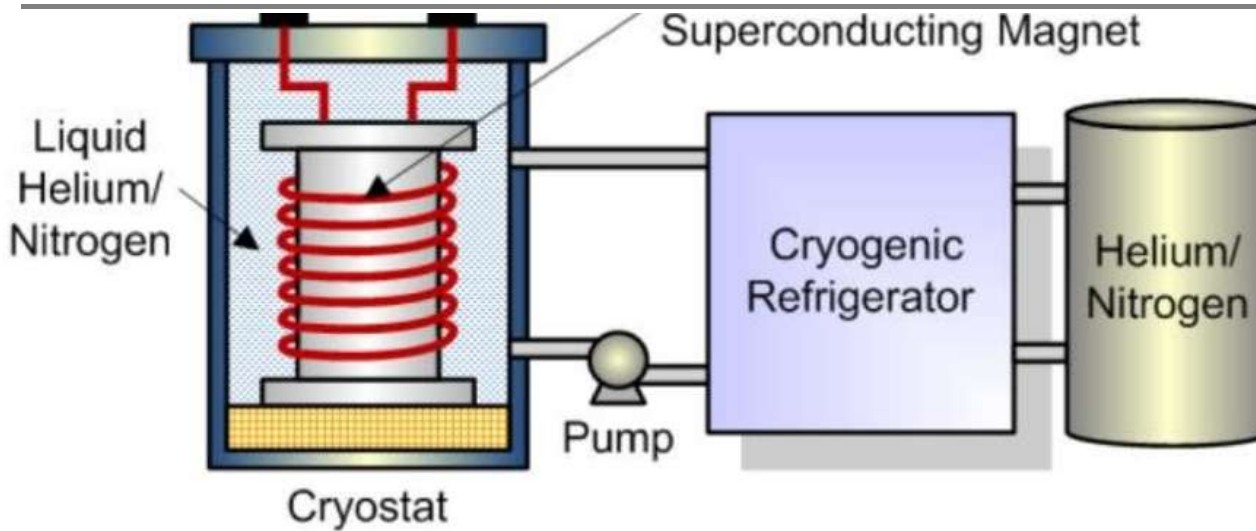
In wind energy systems, flywheels smooth output variations caused by fluctuating wind speeds, ensuring a more consistent power supply (Sahu et al., 2021).

### 6.3.3 Transportation Applications

Flywheel systems have been applied in electric transport systems such as buses, where they store and release energy efficiently during operation cycles (miryar & Pullen 2017).

### 6.4 Superconducting Magnetic Energy Storage (SMES)

SMES systems store energy in the magnetic field generated by a superconducting coil, offering near-instantaneous response and high efficiency.



Super magnetic energy storage (SMES) system design [66].

**Figure 13:** Superconducting Magnetic Energy Storage (SMES) (Nadeem et al., 2019)

#### 6.4.1 Power Quality Enhancement

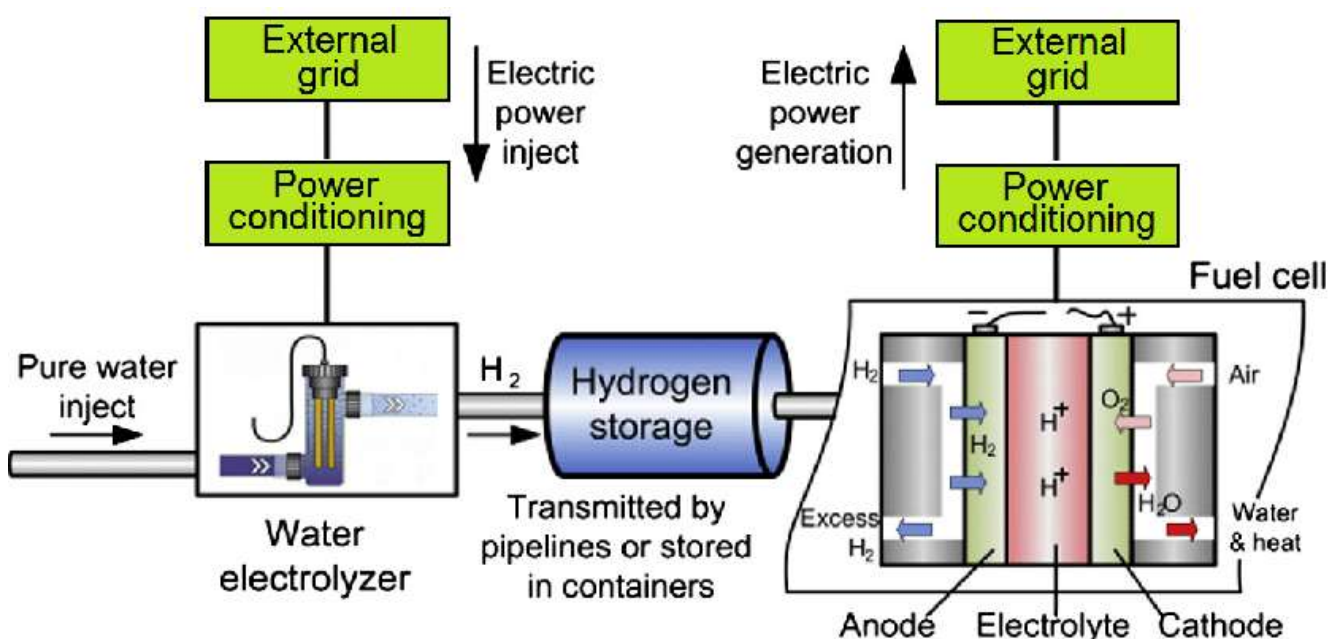
SMES systems are used to mitigate power disturbances such as voltage sags and interruptions in renewable energy systems, thereby improving power quality (Adeyemo et al., 2024).

#### 6.4.2 Grid Stability Applications

Due to their rapid response, SMES systems are suitable for stabilizing grids with high levels of renewable energy integration (Adeyemo et al., 2024).

#### 6.4.3 Hydrogen Energy Storage Systems

Hydrogen energy storage involves converting electrical energy into hydrogen through electrolysis and storing it for later use.



**Figure 14:** Hydro Energy Storage System (Kleperis et al., 2016)

## 6.5 Long-Term Energy Storage

Hydrogen storage systems are particularly suitable for long-term and seasonal energy storage, addressing limitations associated with battery storage duration (Sahu et al., 2021).

### 6.5.1 Power-to-Gas Applications

Excess renewable energy can be converted into hydrogen and integrated into gas networks or used in fuel cells to generate electricity when needed (Aminudin et al. (2023).

### 6.5.2 Industrial and Transportation Applications

Hydrogen produced from renewable energy is increasingly used in fuel cell vehicles and industrial processes, contributing to decarbonization efforts (Bolt et al. 2020).

### 6.5.3 Thermal Energy Storage Systems

Thermal energy storage systems store energy in the form of heat and are commonly used in solar thermal applications.

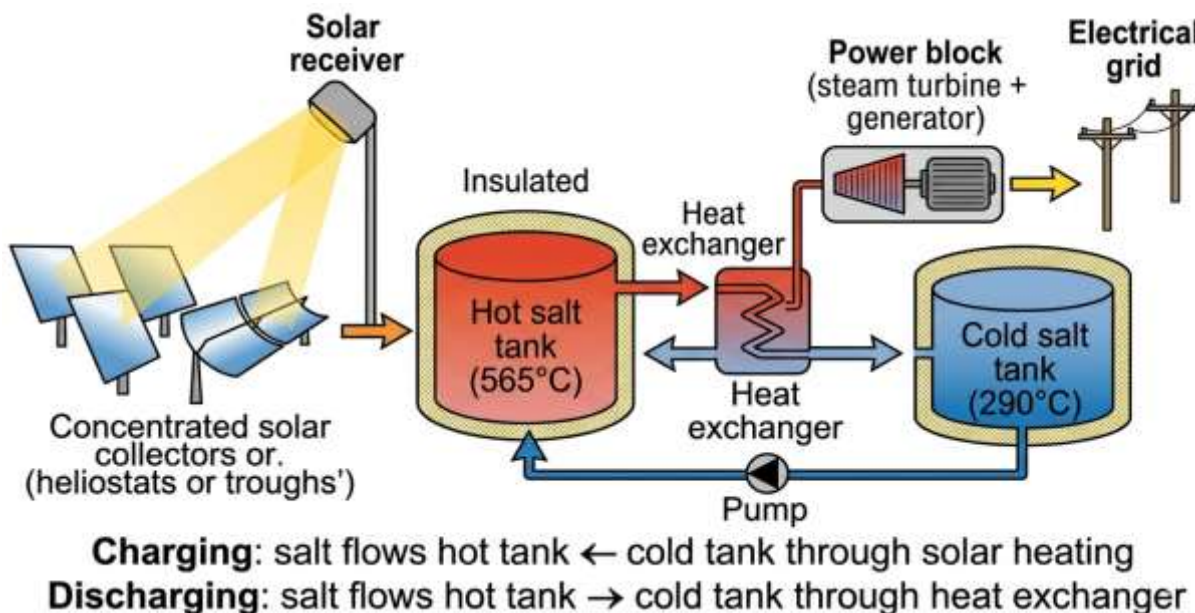


Figure 15 Thermal energy storage for CSP (Two-tank molten salt thermal storage system for concentrated solar power).

### 6.5.4 Concentrated Solar Power (CSP) Plants

As depicted in Figure 15, in CSP plants, thermal storage enables electricity generation even in the absence of sunlight, thereby improving system reliability and dispatchability (Sahu et al., 2021).

### 6.5.5 Building Energy Systems

Thermal storage systems are also applied in renewable-powered buildings to regulate temperature and reduce overall energy consumption (Alva et al. 2018).

## PUMPED HYDRO ENERGY STORAGE (PHES)

Pumped hydro energy storage is one of the most established large-scale energy storage technologies (Bellani et al. 2019).

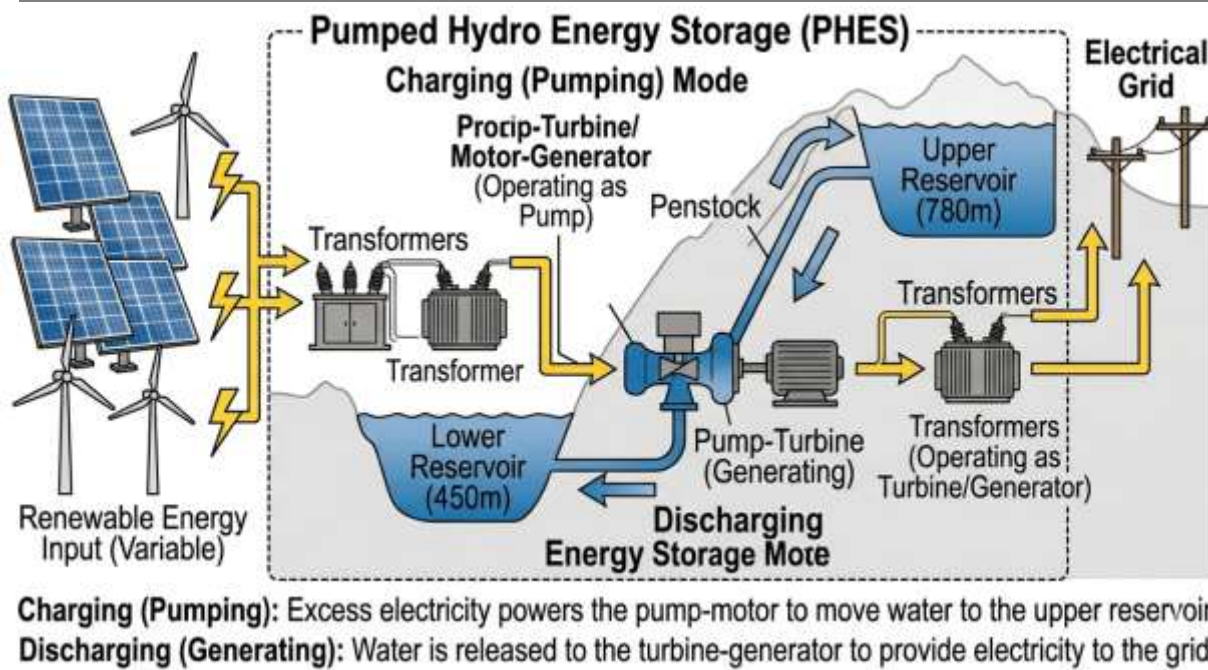


Figure 16: Schematic Diagram of a Pumped Hydro Energy Storage (PHES) System

This figure illustrates the operational framework of a Pumped Hydro Energy Storage (PHES) system, detailing the integration of variable renewable energy sources with the electrical grid through two distinct operational modes.

## EMERGING APPLICATIONS OF ADVANCED STORAGE TECHNOLOGIES

Recent advancements in materials science have led to the development of innovative storage technologies.

**Graphene-based supercapacitors** are being used in flexible electronics and wearable devices (Bellani et al., 2019).

**3D-printed energy storage devices** enable customized applications in electronics and biomedical systems (Gulzar et al., 2019; Egorov et al., 2019).

**Structural batteries** are integrated into electric vehicles and aerospace systems, serving both structural and energy storage functions (Danzi et al., 2021).

These emerging technologies expand the scope of charge storage applications beyond traditional power systems. Charge storage technologies are indispensable in renewable energy systems, providing solutions to intermittency, enhancing grid stability, and enabling efficient energy utilization. Their applications span residential, industrial, transportation, and grid-scale systems. As technological advancements continue, these storage systems will play an increasingly vital role in achieving sustainable and resilient energy systems globally.

## CONCLUSION

Charge storage technologies are an essential part of contemporary energy systems, especially for facilitating the widespread use of renewable energy sources. This review shows that traditional technologies like lithium-ion batteries, pumped hydro storage, and thermal systems are still commonly used, but they are increasingly being supplemented by new technologies aimed at overcoming their limitations. Electrochemical storage systems remain the leading choice because of their effectiveness and flexibility. However, issues concerning energy density, safety, cost, and environmental effects require ongoing improvements. New technologies like sodium-ion batteries, solid-state batteries, and redox flow batteries offer practical options, especially for large-scale and long-term energy storage. Furthermore, electrostatic systems like supercapacitors provide high power

density and quick response times, which makes them effective for managing transient energy. Advanced materials, particularly nanostructured and carbon-based materials, are seen as essential for improving the performance of future storage devices. Hybrid energy storage systems enhance the connection between energy and power density, which increases the efficiency and longevity of the overall system. In summary, the future of energy storage depends on combining various technologies, along with advancements in materials and overall system improvements, to create a dependable, efficient, and sustainable energy infrastructure.

### Future focus

There should be more focus on developing nanostructured, carbon-based, and composite materials to improve the energy density, conductivity, and lifespan of storage devices. Research and commercialization of alternatives like sodium-ion, solid-state, and redox flow batteries should be expedited to decrease reliance on lithium resources and enhance sustainability. Encouraging the combination of batteries with supercapacitors or other storage technologies can enhance both energy and power performance in renewable energy systems. Efforts should concentrate on lowering manufacturing costs, optimizing system design, and increasing efficiency to make energy storage technologies more financially feasible. Improving safety and environmental sustainability should focus on the development of non-flammable electrolytes, recyclable materials, and eco-friendly disposal methods. Governments and relevant parties should encourage policies that facilitate the widespread use of energy storage systems to integrate renewable energy and maintain grid stability. Emphasis should be placed on advancing long-duration energy storage technologies, including hydrogen storage, redox flow batteries, and thermal storage systems, to meet the requirements for extended and seasonal energy storage.

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