

# SOLID STATE STORAGE SYSTEMS

## ABSTRACT

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This thesis explores the development, challenges, and applications of solid-state batteries (SSBs) as a next-generation energy storage solution. Solid-state batteries offer significant advantages over conventional lithium-ion batteries, including improved safety, higher energy density, and enhanced cycle life. However, technical challenges such as interface stability, dendrite formation, and material compatibility remain critical. This research examines recent advances in materials science, manufacturing processes, and potential applications across industries, particularly in electric vehicles (EVs) and portable electronics. The findings underscore the promising future of solid-state batteries, contingent on overcoming current limitations.

## ENERGY STORAGE

Conventional energy storage systems, like lithium-ion batteries, lead-acid, and nickel-based models, have been widely used but come with limitations in sustainability, lifespan, and efficiency that are driving research towards newer alternatives. These conventional models often degrade over time, reduce capacity with each charge-discharge cycle, and, particularly in the case of lead-acid and nickel-cadmium (Ni-Cd) batteries, involve toxic materials that are harmful to the environment if not properly recycled.

New energy storage models, including electrochemical solutions like redox flow batteries, and mechanical systems like pumped hydro storage, are being explored to overcome these limitations. These newer systems promise longer life cycles and, in some cases, the ability to separate energy capacity from power output, enabling more flexibility and efficiency for grid integration. However, these systems are not without their challenges, as many still need substantial geographic and economic considerations, such as appropriate storage capacity, environmental factors, and initial installation costs, especially for options like pumped hydro storage.

The move toward sustainable and high-capacity energy storage solutions is essential, as renewable energy sources like wind and solar fluctuate in output. Enhanced storage technology enables renewable energy integration into the grid and ensures reliable power supply despite these variations, aiding in the reduction of carbon emissions and dependence on non-renewable resources.

With the rising demand to have sustainable development there is a need to replace conventional energy storage systems if we want to fully replace conventional resources. So in the following topics we talk about all of the non conventional sources of energy that we can replace it with.

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## NON CONVENTIONAL ENERGY STORAGE SYSTEMS

As the demand for renewable energy sources rises, the importance of efficient and sustainable energy storage systems has become increasingly evident. Traditional storage methods, like lithium-ion batteries, have limitations in lifespan, environmental impact, and storage capacity, especially when used in large-scale applications. This project explores alternative energy storage systems that offer potential solutions to these challenges, providing options that are more adaptable to renewable energy sources, sustainable, and, in many cases, more efficient.

### Types of Alternative Energy Storage Systems

#### 1. Pumped Hydro Storage (PHS)

**Description:** Pumped hydro storage is one of the oldest large-scale energy storage methods, involving the movement of water between two reservoirs at different elevations. During periods of low energy demand, water is pumped from the lower to the upper reservoir. When demand increases, the stored water is released, flowing back down through turbines to generate electricity. **Advantages:** High efficiency (70-85%) and long operational life, with minimal environmental impact during operation. **Limitations:** Requires specific geographic features, such as elevation differences, and significant upfront costs. **Application:** Often used for grid stabilization and storing excess energy from renewable sources like wind and solar.

#### 2. Compressed Air Energy Storage (CAES)

**Description:** CAES stores energy by compressing air and storing it in large underground or aboveground storage facilities. When energy is needed, the compressed air is released, expanding through a turbine to generate electricity. **Advantages:** CAES offers a longer life span and larger capacity compared to traditional batteries and can be used in combination with renewable sources for grid support. **Limitations:** CAES is less efficient (40-70%) than other methods and requires significant space for storage and high-pressure systems. **Application:** Suitable for grid energy management, particularly when there are large fluctuations in energy production.

#### 3. Thermal Energy Storage (TES)

**Description:** TES involves storing excess heat or cold energy in mediums like molten salts, ice, or other materials. This stored energy can then be converted back into electricity or used directly for heating or cooling purposes. **Advantages:** High energy density and efficiency, especially for applications requiring large heat storage. **Limitations:** Energy conversion can result in efficiency losses, and TES is best suited for applications where heat can be utilized directly, rather than solely for electricity generation. **Application:** Widely used in solar power plants, industrial processes, and building heating systems.

#### 4. Flywheel Energy Storage

**Description:** Flywheel systems store energy mechanically in a rotating mass. When energy input is high, the flywheel accelerates, storing kinetic energy; during low input periods, the flywheel releases this energy back to the grid by decelerating. **Advantages:** High response time, good efficiency (80-90%), and relatively long lifespan with minimal

maintenance. **Limitations:** Limited storage capacity and high initial setup costs make flywheels better suited to short-term energy storage. **Application:** Frequently used for frequency regulation, uninterruptible power supply (UPS) systems, and balancing intermittent renewable energy inputs.

## 5. **Hydrogen Storage**

**Description:** This method involves using excess electricity to split water into hydrogen and oxygen (electrolysis), storing the hydrogen for later use as a fuel. When electricity is needed, hydrogen is converted back to electricity in a fuel cell or combusted in a turbine.

**Advantages:** High energy density, suitable for long-term storage, and can serve as both a fuel and an energy storage medium. **Limitations:** Low round-trip efficiency (~30-40%) and high production costs, with safety considerations for hydrogen storage and handling.

**Application:** Utilized in long-duration energy storage, backup power systems, and as a renewable energy carrier.

These are the present technologies for energy storage systems that are going on but no energy storage system could replace Lithium based batteries . But one of the futuristic Technology termed as Solid State Batteries are a great chance to replace **Lithium based batteries**.

## **WHAT ARE SOLID STATE BATTERIES?**

Currently, liquid electrolyte batteries are widely used in most modern devices. They are advantageous primarily due to their high power density; however, they also carry significant risks, such as leakage, limited chemical stability, and high flammability. These concerns have created a demand for safer alternatives, paving the way for solid-state batteries.

The fundamental difference between liquid and solid-state batteries lies in the electrolyte's state of matter, which affects their ionic conductivity. Solid-state batteries tend to have lower ionic conductivity than liquid electrolyte batteries, which directly influences power density; higher conductivity leads to greater power density. However, the ionic conductivity of solid-state batteries is limited to only 10-15% of its theoretical potential, which restricts their use in high-energy-demand devices like laptops. Currently, these batteries are commercially viable only for smaller devices, such as pacemakers.

Large-scale manufacturing processes for solid-state batteries remain under development, with production methods primarily confined to laboratory settings. Scaling production to meet market demand requires costly equipment and advanced manufacturing techniques, which ultimately results in a high cost for the end product.

## **FUNCTIONALITY**

A solid-state battery is composed entirely of solid materials, with key components including the **anode**, **cathode**, **solid electrolyte**, and **casing**. These components must possess specific properties to ensure optimal battery performance. Energy in solid-state batteries is transported through **redox reactions**, where oxidation occurs at the anode during charging (electrons are taken up), and reduction occurs at the cathode (electrons are released). This exchange of electrons allows ions to travel through the solid electrolyte, completing the circuit and enabling the battery to store and release energy.

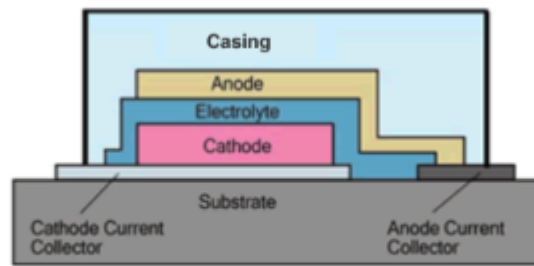


Figure 1: Generalized construction model of solid state batteries [4]

## ANODE

Lithium metal has been considered as a potential anode material due to its excellent properties: it has a low electrochemical potential, low density, and an exceptionally high specific capacity. However, lithium metal anodes have not yet been commercially implemented because of the growth of lithium dendrites during the charge/discharge cycle. These dendrites, which are needle-like structures that form on the anode, can cause battery failure by puncturing the separator, leading to short circuits, fires, and other hazards.

**Graphite** is used in most commercial lithium-ion batteries as the negative electrode, relying on an **intercalation mechanism**. In this process, lithium ions fit into interstitial spaces within the layered graphite structure, avoiding the issue of dendrite formation. This mechanism helps to prevent structural damage, making graphite-based anodes more durable. The small strains generated during the insertion and extraction of lithium ions ensure minimal irreversible volume changes, which contributes to the anode's ability to withstand numerous charge/discharge cycles, leading to good charge retention over time. However, a limitation of graphite is the **limited number of intercalation sites**, which restricts its specific capacity, making it less efficient for high-capacity applications.

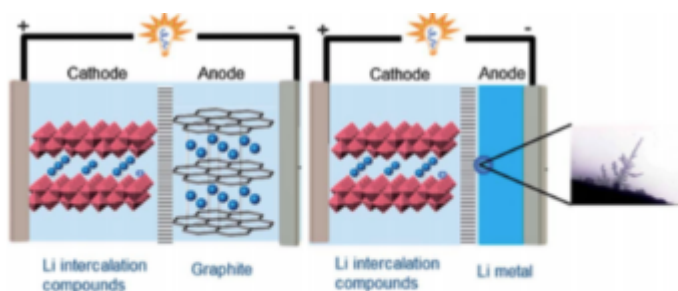


Figure 2: Comparison of lithium anode with graphite anode

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## **CATHODE**

### **SODIUM BASED SOLID STATE BATTERIES**

Sodium-ion batteries are considered a promising alternative to lithium-ion technology. Sodium, being abundant and inexpensive compared to lithium, has garnered interest for use in solid-state batteries. Sodium-based solid-state batteries operate similarly to lithium-ion batteries but use sodium ions ( $\text{Na}^+$ ) as the charge carriers instead of lithium ions ( $\text{Li}^+$ ). Although sodium-ion solid-state batteries are still under development, they are seen as a potential option for large-scale applications where cost and resource availability are more critical than the raw energy density provided by lithium-based systems.

#### **Sodium Cobalt Oxide ( $\text{NaCoO}_2$ )**

Similar to lithium cobalt oxide ( $\text{LiCoO}_2$ ) in lithium-ion batteries, **sodium cobalt oxide** is one of the most promising cathode materials for sodium-based batteries. It has a layered structure that supports the intercalation of sodium ions, which enhances the battery's performance. However, like its lithium counterpart, it faces challenges such as high cost and potential environmental concerns due to the use of cobalt. **Sodium manganese oxide** ( $\text{NaMnO}_2$ )\*\* is another cathode material widely studied for sodium-based solid-state batteries. It offers a spinel structure, which allows good ion mobility and stability. While it shows promise in terms of stability and lower cost compared to cobalt-based cathodes, the energy density of sodium manganese oxide is typically lower than that of lithium-based materials .

**Sodium iron phosphate** is a promising cathode material because of its **low cost, abundance, and sustainability**. This material features a **olivine structure**, which can effectively accommodate sodium ions, making it a good candidate for sodium-ion batteries. Its performance may not match the higher energy density of cobalt-based materials, but it offers a safer and more environmentally friendly alternative .

Similar to the mixed-metal cathodes used in lithium-ion technology, **sodium nickel manganese cobalt oxide** offers a combination of high capacity and stability. However, the cost of the cathode materials, particularly due to the use of cobalt and nickel, remains a limitation. This material is still in the research phase but has potential for high-performance sodium-based solid-state batteries .

### **Challenges and Future Directions:**

While solid-state batteries offer promising advantages, such as the abundance of sodium and lower material costs, challenges remain in finding cathode materials that combine high performance, stability, and cost-effectiveness. Researchers are focused on optimizing the structural properties of cathodes to improve energy density and cycling stability while addressing the issues of phase transitions and ion migration.

## CASING

In **solid-state batteries**, the **casing** serves as a critical component to ensure the protection, structural integrity, and safety of the battery throughout its lifecycle.

### Key Materials Used for Casings in Solid-State Batteries:

**Stainless Steel**: Commonly used due to its high strength, durability, and resistance to corrosion.

**Aluminium**: Lighter than stainless steel, aluminium casings are used for some applications where weight is a concern, such as in portable electronics.

**Polymer-Based Composites**: Some solid-state batteries use polymer-based materials for the casing to reduce weight and enhance flexibility.

**Ceramic Casing**: For batteries that use ceramic-based electrolytes, a ceramic or ceramic-coated casing may be used to match the properties of the electrolyte and prevent chemical reactions.

## ELECTROLYTE

To function effectively, the **electrolyte** in a solid-state battery must exhibit three primary characteristics: **high ionic conductivity**, **high electronic resistance**, and **low internal resistance**. These attributes ensure that ions can move freely between the anode and cathode while blocking the flow of electrons. This selective movement of ions over electrons is essential for maintaining the battery's functionality and efficiency.

## CHARGE TRANSFER MECHANISM

The **charge transfer mechanism** in sodium-ion batteries is similar to that in lithium-ion batteries, with some unique characteristics due to the differences in atomic size, ion mobility, and electrolyte interactions.

1. **Intercalation Mechanism**: In sodium-ion batteries, the **intercalation mechanism** is widely used, particularly in electrodes like **graphite** and **transition metal oxides**. During discharge, **sodium ions ( $\text{Na}^+$ )** are released from the anode, travel through the electrolyte, and intercalate into the cathode material. The reverse process happens during charging, where  $\text{Na}^+$  ions are extracted from the cathode and migrate back to the anode. Because sodium ions are larger than lithium ions, they typically have lower mobility and require specific electrode materials that can accommodate this larger ion size.

2. **Redox Reactions:** The transfer of charge between electrodes is accompanied by **redox reactions**. In the anode, oxidation occurs during discharge, releasing electrons and  $\text{Na}^+$  ions. These electrons travel through an external circuit to the cathode, where they reduce the active material, allowing  $\text{Na}^+$  ions to be stored. This process is reversible, enabling multiple charge/discharge cycles.
3. **Electrolyte Role:** The electrolyte in sodium-ion batteries must facilitate **sodium ion conduction** while blocking electron flow between the electrodes. Commonly used electrolytes include organic solvents with dissolved sodium salts (e.g., sodium perchlorate or sodium hexafluorophosphate), which provide a medium for  $\text{Na}^+$  ions to move through the battery. Advances in solid electrolytes for sodium-ion batteries are also under investigation, aiming to enhance ionic conductivity and reduce the risk of leakage and flammability. **Materials for Enhanced Charge Transfer\*\*:** Sodium-ion batteries often use **layered oxides** (such as  $\text{NaCoO}_2$  or  $\text{NaFeO}_2$ ), **polyanionic compounds** (like  $\text{Na}_3\text{V}_2(\text{PO}_4)_3$ ), or **organic materials** for the cathode, each of which provides a different structure for  $\text{Na}^+$  ion intercalation. These materials aim to balance energy density, ionic conductivity, and stability. **Hard carbon** is often used as the anode material due to its compatibility with  $\text{Na}^+$  ions and stability across charge cycles.

Overall, the charge transfer mechanism in sodium-ion batteries emphasises the design of compatible electrode materials that can handle the relatively larger  $\text{Na}^+$  ions and specific electrolyte formulations that enable efficient ion mobility without compromising stability.

## **INDUSTRIAL LEVEL APPLICATIONS**

The future of **solid-state battery (SSB)** technology is at a pivotal point where it could either revolutionize the next generation of batteries or fade without significant impact. The difference between these outcomes lies in effectively addressing the core challenges SSBs face. With an increasing number of commercial companies investing in SSB development, momentum is building to establish SSBs as a key technology of the future. The success of SSBs hinges on several factors: (i) resolving interfacial stability issues, (ii) innovating cost-effective manufacturing processes, (iii) designing battery cells and packs that incorporate solid-state materials effectively, and (iv) surpassing the performance benchmarks set by advanced lithium-ion batteries.

As the demand for electric vehicle (EV) batteries grows—driven by the need for high energy density, rapid charging, long lifespan, and low production costs—SSBs have considerable potential. The U.S. Department of Energy has set ambitious EV battery targets, including reducing costs to less than \$100/kWh, increasing vehicle range to 300 miles, and achieving 15-minute charge times. **A fully developed SSB that meets these targets within the next decade would be a substantial achievement, yet the optimal combination of anode, cathode, and electrolyte materials is still uncertain.**

**Urban air mobility** is another rapidly advancing field where SSBs could make a significant impact, especially as conventional liquid electrolyte batteries face stricter safety standards for aviation applications. In high-demand applications like electric vertical take-off and landing (eVTOL) aircraft, batteries must operate under extreme temperature variations and withstand frequent mechanical stresses. SSBs, with their superior safety and energy density, are



well-suited for these demands. To unlock SSB potential in aviation, close collaboration between industry and research institutions is needed to define performance benchmarks and address technical challenges through targeted material science and engineering innovations.

Several companies are leading the development of solid-state batteries (SSBs), focusing on safer, high-energy applications. **QuantumScape**, in partnership with Volkswagen, is advancing lithium-metal SSBs for electric vehicles. **Solid Power**, collaborating with **Ford and BMW**, is another key player, aiming to improve safety and efficiency. **Toyota** is investing heavily in solid-state research to integrate these batteries into its EV lineup, while **Samsung SDI and LG Chem** focus on high-density SSBs for consumer electronics. These companies aim to overcome current challenges, such as production costs and ionic conductivity, to make SSBs commercially viable.

## **WILL IT BE A GAMECHANGER IN ENERGY STORAGE INDUSTRY?**

**Solid-state batteries (SSBs) have the potential to be a game-changer in energy storage systems**, particularly for applications like electric vehicles (EVs), renewable energy storage, and even portable electronics. Here's a detailed look at why SSBs hold this potential and what challenges they face in realizing it:

1. **Improved Safety:** SSBs replace liquid electrolytes with solid materials, which significantly reduces the risk of leaks, combustion, and thermal runaway. Traditional lithium-ion batteries use liquid electrolytes that are flammable and reactive under high temperatures or physical damage. The enhanced safety profile of SSBs makes them particularly appealing for EVs, aviation, and other applications where battery safety is critical. This feature is expected to drive a shift to SSBs as the preferred technology in fields with stringent safety standards, such as aerospace and urban air mobility.
2. **High Energy Density and Longevity:** SSBs have the potential for higher energy density than conventional batteries, meaning they can store more energy within a smaller or lighter cell. This is particularly beneficial for EVs and renewable energy storage, where maximizing range and capacity is essential. Moreover, SSBs are believed to have longer lifespans, as their solid electrolytes suffer less degradation over time compared to liquid electrolytes. For instance, they are more resistant to the formation of dendrites (small lithium formations that can puncture battery cells), which is a leading cause of short circuits and reduced lifespan in conventional batteries.
3. **Increased Temperature Stability:** SSBs can operate effectively at higher temperatures, which reduces the need for complex cooling systems in EVs and industrial applications. In energy storage systems, especially those tied to renewable energy grids, the ability to operate at varying temperatures can help lower maintenance costs and improve efficiency, making SSBs a more robust option for large-scale storage solutions.
4. **Potential for Fast Charging:** SSBs can theoretically support faster charging times, a critical requirement for widespread EV adoption. Although current prototypes still face challenges in achieving this, advances in materials and engineering could enable fast-charging capabilities that rival or exceed lithium-ion batteries. This feature would make SSBs more suitable for consumer electronics and EVs, where convenience and reduced downtime are key to user satisfaction.



5. **Challenges in Production and Cost:** Despite these advantages, SSBs face significant barriers to becoming a mainstream technology. Manufacturing solid-state batteries at scale remains costly and complex, requiring new materials, processes, and infrastructure that differ greatly from those used for lithium-ion batteries. Furthermore, the materials needed for SSBs, such as solid electrolytes and stable cathode-anode interfaces, are still under active research, with many questions about optimal compositions and long-term performance still unanswered.
6. **Development of Suitable Materials:** Unlike lithium-ion batteries, where graphite and lithium cobalt oxide are well-established materials, SSBs require novel materials to function effectively. Research is ongoing to identify the best solid electrolytes (such as sulfides or oxides) and compatible anode materials (potentially lithium or sodium metal) that can offer high conductivity and stability. This research is critical, as incompatible materials can lead to high resistance, reduced power output, and shorter battery life.

**If solid-state batteries (SSBs) succeed, they could revolutionize energy storage by making electric vehicles (EVs) safer, faster to charge, and capable of longer ranges, thereby accelerating EV adoption. SSBs would also enhance renewable energy storage with greater longevity and stability, supporting a more resilient grid. In consumer electronics, SSBs could lead to thinner, longer-lasting devices with improved safety. In aviation, SSBs' high energy density and thermal stability could enable electric aircraft. Despite these transformative benefits, challenges like cost, scaling production, and material compatibility remain before SSBs reach their full potential in reshaping the energy landscape**

## **CONCLUSION**

**Solid-state batteries** (SSBs) offer promising potential as a safer, more sustainable alternative to lithium-based systems. These batteries utilize sodium, which is more abundant and less expensive than lithium, potentially lowering costs and easing supply chain issues. Furthermore, Na-SSBs reduce environmental concerns associated with lithium and cobalt mining, as sodium is widely available and the battery chemistries are more sustainable.

While Na-SSBs generally have lower energy density compared to lithium-ion batteries, they are highly stable and exhibit less risk of thermal runaway, which could enhance safety in large-scale applications like grid storage. However, key challenges remain, including improving ionic conductivity, addressing volumetric expansion during charge cycles, and refining scalable manufacturing processes. Research in Na-SSBs continues to focus on finding stable solid electrolytes, such as sulfides and oxides, to support reliable performance.

In conclusion, if these hurdles are overcome, sodium-ion solid-state batteries could play a critical role in the future of sustainable energy storage, particularly for grid applications where cost and resource availability are paramount.

