The Impact of Solid-State Batteries on the Revolution of Mobility

Instituto Superior Técnico
Project in Energy Engineering and Management 2

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January 17, 2025

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1 Abstract

This project investigates the potential of solid-state batteries (SSBs) in the energy storage landscape, with a particular focus on their application in electric vehicles (EVs). SSBs represent a shift from traditional lithium-ion batteries (LIBs) by replacing liquid electrolytes with solid counterparts, offering enhanced safety, higher energy density, extended lifespan, and faster charging capabilities. These advancements align with global efforts to transition towards sustainable energy solutions and combat climate change.

The study begins with an overview of the global EV and battery markets, highlighting the growing demand for more efficient and sustainable energy storage systems. The state-of-the-art of SSB technology is explored, examining its components, manufacturing methods, recycling potential, and current market dynamics. A comparison is made between SSBs and LIBs, underscoring the technological and economic advantages of the former while addressing existing challenges such as manufacturing complexity and scalability.

Furthermore, the project identifies key industry players driving innovation in SSBs, with a particular emphasis on Toyota's significant contributions to advancing this technology. Finally, the future outlook of SSBs is discussed, emphasizing the need for continued research and development, investment in manufacturing infrastructure, and strategic collaborations to overcome barriers and accelerate commercialization.

By providing a comprehensive analysis of SSB technology and its potential to redefine energy storage for EVs, this work contributes to the broader discourse on sustainable energy solutions and highlights the critical role of SSBs in the transition to a cleaner and more efficient energy future.

2 Introduction

2.1 Objectives and Motivation

The increasing global demand for sustainable energy solutions and the rapid growth of the electric vehicle (EV) market have placed batteries at the center of modern technological advancements. As lithium-ion batteries (LIBs) dominate the current energy storage landscape, their limitations—such as safety concerns, energy density constraints, and environmental impact—underscore the necessity for alternative solutions. This has driven interest in solid-state batteries (SSBs), which promise higher energy densities, improved safety, and greater durability.

This project seeks to address the question: **"Can solid-state batteries redefine the future of electric vehicles and accelerate the transition to sustainable energy?"** By exploring the fundamental components of SSBs, their manufacturing processes, and their economic and market potential, this work aims to explain the major aspects regarding SSBs and trying to evaluate whether SSBs can overcome the limitations of traditional LIBs and facilitate the transition to more sustainable energy solutions. There isn't a particular case study present because the information found is mostly basic and scarce.

The motivation behind this project lies in understanding more about this topic and also to adress the urgent need for cleaner energy technologies to combat the climate crisis and reduce greenhouse gas emissions. Solid-state batteries have the potential to revolutionize the EV market by addressing consumer concerns such as range, charging time, and safety, while also contributing to broader global sustainability goals. Through a detailed analysis of SSB technologies and their potential applications, this project aspires to shed light on their role as a transformative force in the energy sector.

2.2 Organization of the Document

This project is organized as follows:

Chapter 2 outlines the primary objectives and motivations driving this work. It provides an overview of how the document is structured and introduces the topic within its broader context. This introduction draws upon existing literature, notably the Global EV Outlook 2024 [2] from the International Energy Agency (IEA), which offers insights into recent developments in electric mobility worldwide and situates the relevance of solid-state batteries within the current landscape.

Chapter 3 delves into the state of the art of solid-state batteries (SSBs). It provides a comprehensive explanation of their operating principles, detailing the key components, including solid electrolytes and electrodes. Additionally, this chapter explores the potential manufacturing processes, recycling methods, and current market dynamics of SSBs. It concludes by discussing the key performance indicators (KPIs) that define their potential impact.

Chapter 4 focuses on a comparative analysis between SSBs and traditional lithium-ion batteries (LIBs). This comparison highlights the advantages, disadvantages, and trade-offs associated with transitioning from LIBs to SSBs, providing a clear perspective on how these technologies differ and complement each other.

Chapter 5 presents an overview of the leading players in the SSB landscape, emphasizing the efforts of Toyota as a pivotal driver of innovation in this field. This chapter explores Toyota's technological advancements, patent activities, and collaborative initiatives, which have positioned the company at the forefront of SSB research and development.

Chapter 6 examines the future outlook for solid-state batteries, discussing the potential directions for their development, commercialization, and integration into the global energy and mobility sectors. This chapter highlights the opportunities and challenges that lie ahead for SSBs and their capacity to redefine energy storage solutions.

Chapter 7 concludes the project by synthesizing the insights gained throughout the work. It revisits the key question posed at the outset: "Can solid-state batteries redefine the future of electric vehicles and accelerate the transition to sustainable energy?" By reflecting on the findings from previous chapters, this section provides a final perspective on the transformative potential of SSBs and their role in shaping the future of energy storage and mobility.

2.3 General Context

The global shift towards electric vehicles (EVs) has gained momentum as nations, companies, and individuals recognize the urgent need to address climate change and reduce greenhouse gas (GHG) emissions.

Road transportation is the second largest producer of CO2 emissions worldwide, coming in right after electricity and heating as shown in Figure 1. The sector accounts for nearly 15% of global energy-related emissions [3].

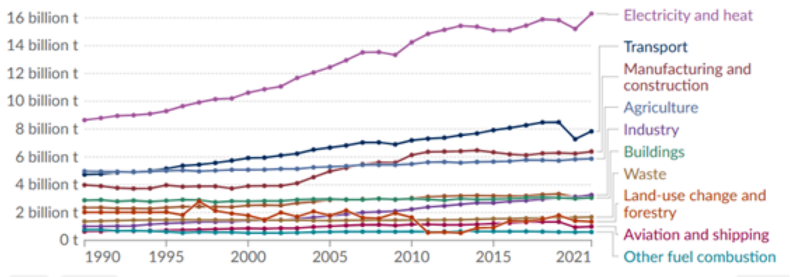

Figure 1: Greenhouse gas emissions by sector [1]

The dependency on fossil fuels not only accelerates climate change but also brings significant public health risks. In urban areas, air pollution—largely contributed by ICE vehicles—has become a pressing health concern, impacting respiratory and cardiovascular health [9]. As a result, the reduction in ICE vehicle dependency and the accelerated adoption of EVs have become vital components of global decarbonization efforts.

2.3.1 EV Sales

Reflecting this shift, EV sales have surged, nearly reaching 14 million units in 2023, with China, Europe, and the United States representing 95% of these sales and bringing the total number of EVs on roads worldwide to over 40 million. This marked a substantial increase of 3.5 million units compared to 2022, translating to a 35% year-over-year growth. To illustrate the scale of this expansion, weekly new registrations in 2023 surpassed 250,000, which, only a decade ago, would have represented an entire year's worth. Battery electric vehicles (BEVs) alone accounted for about 70% of the total electric car stock in 2023, and EVs collectively made up 18% of all new car sales globally, up from just 2% in 2018. These trends underscore the rapid expansion and maturation of the EV market over recent years (Figure 2) [2].

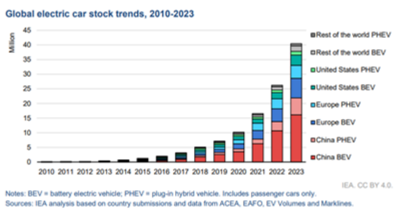

Figure 2: Global electric car stock trends [2]

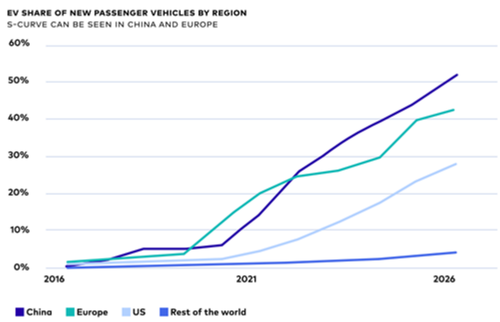

Figure 3: EV share of new passenger vehicles by region [3]

Although EV adoption is progressing globally, it remains highly concentrated in a few major markets. In 2023, China alone was responsible for nearly 60% of global EV registrations, followed by Europe with just under 25% and the United States with around 10% [2]. Together, these regions accounted for close to 95% of total EV sales, illustrating the pivotal role of policy support in driving regional adoption rates. In these markets, EVs hold a significant share of new car registrations, with one in three cars sold in China, over one in five in Europe, and one in ten in the United States being electric as represented in Figure 3.

However, in other parts of the world, including key automotive markets like Japan and India, EV penetration remains relatively low. Given that China, Europe, and the United States together represent approximately two-thirds of global car sales, the accelerated adoption of EVs in these regions will likely be influential on a global scale [2].

2.3.2 Charging Infrastructure

One crucial factor driving this shift is the simultaneous development of EV charging infrastructure. In North America, for instance, the United States has made notable advancements in expanding its charging network, supported by federal programs and private sector investments. Despite these developments, accessibility challenges remain, particularly between rural and urban areas, and more efforts are needed to standardize charging infrastructure to ensure interoperability. In Asia, China's rapid increase in EV adoption is paired with significant infrastructure investments, though charging accessibility continues to be an issue in some less-developed regions.

Europe has set the pace in terms of expanding its EV charging network (Figure 4), creating a model that other regions are working to replicate. As EV adoption accelerates globally, cross-regional collaboration and knowledge sharing are expected to play key roles in building an interconnected global EV charging network [3].

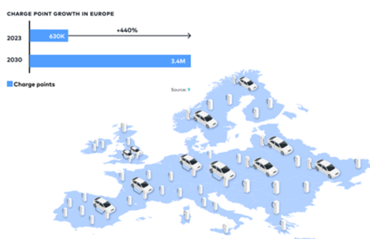

Figure 4: Charge Point Growth in Europe [3]

2.3.3 Battery Demand

EV adoption and the development of charging infrastructure have also fueled a substantial rise in the demand for batteries, a critical component of EVs.

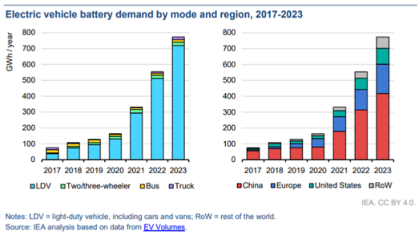

Figure 5: Electric vehicle battery demand by mode and region [2]

In 2023, the demand for EV batteries exceeded 750 GWh, marking a 40% increase compared to 2022. Among the major EV markets, the United States and Europe saw the highest year-on-year growth in battery demand, each exceeding 40%, followed closely by China at approximately 35%, as can be seen in the Figure 5 above. Still, the United States remains the smallest of these markets, with a battery demand of roughly 100 GWh in 2023, compared to 185 GWh in Europe and 415 GWh in China [2].

In other regions, battery demand surged by over 70% in 2023 compared to 2022, driven by rising EV sales.

2.3.4 Battery materials

In consequence, battery production growth has also prompted demand for essential battery minerals, particularly lithium, cobalt, and nickel (Figure 6), which are vital for battery manufacturing.

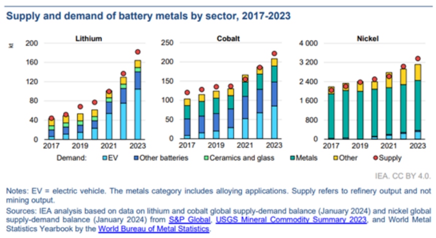

Figure 6: Supply and demand of battery by sector [2]

Battery-related demand for lithium reached around 140 kilotonnes in 2023, accounting for 85% of total lithium demand and marking a 30% increase over 2022. Similarly, demand for cobalt rose by 15% to 150 kilotonnes, while battery demand for nickel grew by nearly 30%, reaching close to 370 kilotonnes. The expansion in battery production has driven significant investments in mining and refining, which have collectively helped ensure that current supply levels meet the rising demand. In 2023, the supply of cobalt and nickel exceeded demand by 6.5% and 8%, and supply of lithium by over 10%, thereby bringing down critical mineral prices and battery costs [2].

2.3.5 Battery Production

Battery production capabilities, however, are not evenly distributed globally.

China leads the global supply chain, holding over 90% of the capacity for cathode active materials and more than 97% for anode materials, partly due to its vertically integrated battery production structure.

By contrast, Europe and the United States rely on imports for over 20% and 30% of their EV battery needs, respectively. Within Europe, Poland is the leading battery producer, followed by Hungary and Germany. The United States remains at a disadvantage in terms of battery production costs, with a manufacturing cost nearly 20% higher than in China, driven by less streamlined supply chains and higher regional material costs[2].

The global supply chain for lithium-ion batteries is represented in Figure 7.

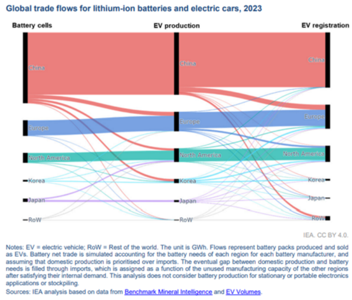

Figure 7: Global trade flows for lithium-ion batteries and electric cars [2]

2.3.6 Battery Costs

Battery costs have shown a downward trend, supported by innovations in battery chemistries and efficiencies in production processes.

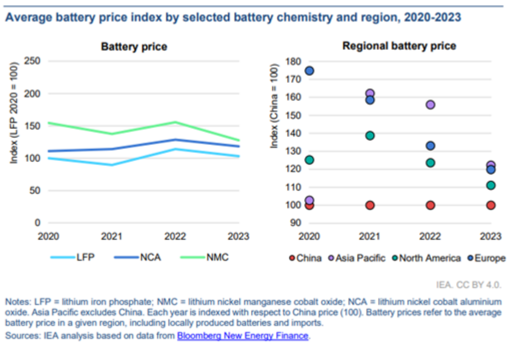

Figure 8: Average battery price index by selected battery chemistry and region [2]

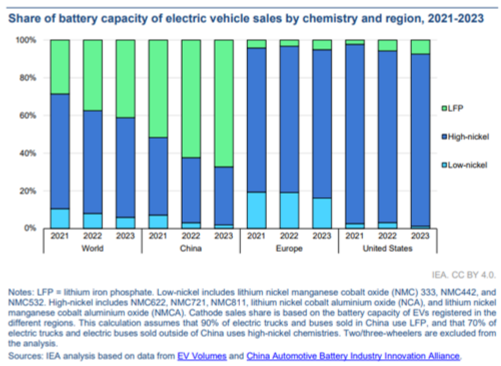

Figure 9: Share of battery capacity of EV sales by chemistry and region [2]

Figure 8 shows that in 2023 battery prices declined, resulting in a 14% reduction in lithium-ion battery pack costs from the previous year. Its also visible that in this year battery prices came close to the ones practiced in China.

This reduction was also influenced by the rising adoption of lithium iron phosphate (LFP) batteries, particularly within China, where they accounted for more than 40% of EV demand by capacity. In fact, over the past five years, lithium iron phosphate (LFP) has evolved from a minor player to a prominent choice in the battery sector, meeting over 40% of global EV demand by capacity in 2023—more than double its share in 2020.

LFP production and usage are heavily concentrated in China, where this chemistry powered two-thirds of EV sales in 2023. In contrast, the share of LFP batteries in EV sales in Europe and the United States remains below

10%, with high-nickel chemistries still dominating these regions as can be seen in Figure 9.

2.3.7 Venture Capital Investments in Alternative Battery Chemistries

Venture capital investments in alternative battery chemistries have increased, with emerging technologies like metal-hydrogen qnd redox-flow capturing over 25% of total investment by 2023 (Figure 10).

Among these new technologies there are the **solid-state batteries**, the topic in discussion for this project.

These developments indicate a broader diversification within the battery market and signal potential cost reductions in the coming years.

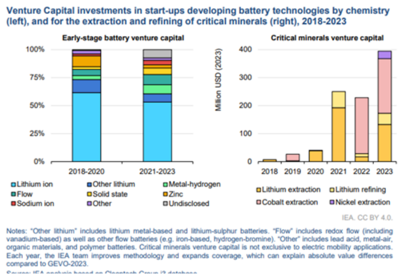

Figure 10: VC investments in developing battery technologies [2]

Its also visible in Figure 10 the investment made in 2023 for lithium extraction, wich explains the current battery technology used in EVs.

2.3.8 Current Battery Technologies for EVs

Currently, the dominant battery energy storage technology for electric vehicles (EVs) is the lithium-ion (Li-ion) battery. It offers the highest specific power and energy density, along with a notably low self-discharge rate. However, its higher cell voltage, while advantageous, also necessitates a specially designed charging system due to its limited overcharge tolerance [10].

These batteries function as energy storage systems based on insertion reactions at both electrodes, with lithium ions serving as the charge carriers. This broad definition encompasses a variety of cell chemistries within the Li-ion battery family. Typically, the negative electrode is made from carbon-based materials like graphite or lithium titanate ($Li_4Ti_5O_{12}$), with emerging alternatives such as lithium metal and lithium-silicon (Li(Si)) alloys under development. The electrolyte composition depends on electrode materials but usually includes lithium salts (e.g., $LiPF_6$) and organic solvents (e.g., diethyl carbonate) to facilitate ion transfer. A separating membrane ensures ion passage between electrodes while preventing short circuits [4].

The choice of materials for electrodes, electrolyte, and separator is driven by their functional requirements. The electrolyte must support optimal lithium-ion transport across a wide temperature range, from extreme cold (e.g., -30°C in winter) to high heat (e.g., +60°C from combined environmental and charging conditions). Similarly, the separator must maintain high ionic conductivity under these conditions while enabling rapid thermal shutdown to prevent thermal runaway [4].

A successful Li-ion battery design requires a cost-effective combination of high-capacity electrode materials. Various options and their electrochemical potentials relative to a $\mathrm{Li}/\mathrm{Li}^+$ reference are illustrated in Figure 11.

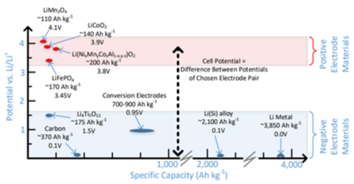

Figure 11: Summary of some present and future electrode chemistry options for Li-ion batteries [4]

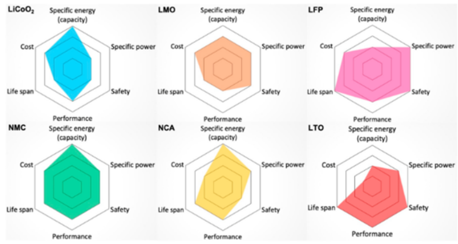

Figure 12: Comparisons of different types of Li-ion batteries used in EVs [4]

Despite their limitations, Li-ion batteries remain a strong contender for EV applications. Figure 12 compares different Li-ion battery chemistries used in EVs highlighting specific energy (capacity), specific power, safety, performance, life span, and cost.

As demand for cleaner and more efficient transportation grows, and electric vehicles (EVs) transition from early-adopters to the mainstream, the limitations of traditional lithium-ion batteries (LIBs) have become increasingly apparent.

Although LIBs continue to make incremental improvements to energy density, charging rate, and low-temperature performance, signifcant challenges remain. Further improvements are needed to make EVs a viable/attractive option for an ever-wider range of customers and use-cases, particularly those in cold climates, rural areas, or requiring hauling/towing heavy loads [11].

2.4 The Emergence of Solid-State Batteries

Like stated above, among the most promising upcoming battery technologies is the solid-state battery (SSB), a novel innovation that could shape the direction of energy storage. This transition is driven by two main factors: recognizing the limitations of traditional energy storage systems, particularly those using liquid electrolytes like in lithium-ion batteries (LE-LIBs), and significant advancements in materials science, introducing new materials and fabrication techniques critical to solid-state energy storage systems [12].

These two factors are pushing and will continue to push the development of SSBs, redefining new boundaries for energy storage, needed for this type of technology to penetrate the market of EVs.

3 State of the Art of Solid-State Batteries (SSBs)

3.1 Definition and Basic Operation

Solid-state batteries (SSBs) can represent a significant advancement in energy storage technology, particularly for electric vehicles (EVs). Unlike traditional lithium-ion batteries, which use a liquid or gel electrolyte to facilitate the movement of ions between the anode and cathode, SSBs replace this liquid with a solid electrolyte.

The operation of SSBs is similar to that of lithium-ion batteries in principle but differs in key aspects due to the solid electrolyte. During the charging process, lithium ions migrate from the cathode to the anode through the solid electrolyte. During discharge, this movement is reversed, releasing stored energy to power the device or vehicle. The solid electrolyte not only serves as a medium for ion transfer but also acts as a separator between the anode and cathode, reducing the risk of short circuits and thermal runaway.

This transition from liquid to solid-state electrolytes (SSEs) fundamentally alters the battery's architecture and performance characteristics. Solid electrolytes are non-volatile, resistant to high temperatures and corrosion, and less reactive with lithium metal, offering the potential for safer, higher-energy-density solutions suitable for the automotive industry [5].

3.2 Solid-State Electrolyte (SSE)

As mentioned above, the electrolyte plays an important role in the battery.

Solid-state electrolytes (SSEs) used in rechargeable batteries are generally categorized into three types based on their chemical composition: inorganic solid ceramic electrolytes (ISEs), organic solid polymer electrolytes (OSPEs), and composite solid electrolytes (CSEs), also referred to as hybrid SSEs, which combine the characteristics of the first two classes of materials. These categories are shown in the Figure 13 below, which illustrates their structural differences and key properties [13].

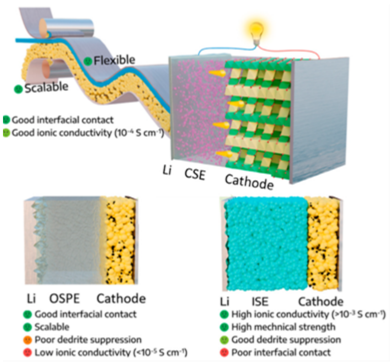

Figure 13: Comparison of the structure and properties of inorganic solid electrolytes (ISEs), organic solid polymer electrolytes (OSPEs), and composite solid electrolytes (CSEs) [5]

Inorganic Solid Electrolytes (ISEs) are primarily composed of lithium ceramics, such as lithium aluminum titanium phosphate (LATP). These materials are characterized by their high ionic conductivity and excellent thermal stability. However, they tend to be fragile, which can pose challenges in manufacturing and integration [5].

Organic Solid Polymer Electrolytes (OSPEs) are derived from polymers like polyethylene oxide (PEO) or polyvinylidene fluoride (PVDF). These materials offer superior mechanical flexibility and ease of processing but exhibit lower ionic conductivity compared to their inorganic counterparts [5].

Composite Solid Electrolytes (CSEs) integrate inorganic ceramic materials with organic polymers to achieve a balance of high ionic conductivity and good mechanical properties. By varying the composition and structure of the materials, CSEs can be designed to meet specific application requirements[13].

For solid-state batteries (SSBs) to succeed, the selection of optimal SSEs is crucial. Ideal SSEs should have extremely low electronic conductivity ($< 10^{-10}\,\mathrm{S\,cm^{-1}}$) — which refers to the movement of electrons within the material and must be minimized to prevent energy losses and maintain battery efficiency. Additionally, they should exhibit high lithium-ion (Li^+) conductivity ($> 10^{-3}\,\mathrm{S\,cm^{-1}}$) — which is the material's ability to facilitate the rapid movement of lithium ions, essential for efficient energy transfer during charge and discharge cycles.

Furthermore, they should possess strong chemical compatibility with electrodes, a wide electrochemical stability window, and remarkable thermal stability [5].

3.2.1 Inorganic Solid Electrolytes (ISEs)

ISEs can be classified into three main groups based on their anion chemistry: oxide-based, sulfide-based, and halide-based materials. These groups are further subdivided into additional material classes, each with distinct properties, as illustrated in Figure 14.

Figure 14: Schematic representation of inorganic solid electrolyte material classes [5]

Oxide-Based

Oxide-based ISEs represent a key subclass of ceramic materials within the broader category of solid electrolytes. They are further divided into three main types: **garnet-type**, **perovskite-type**, and **NASICON-type**, each with unique properties and applications in solid-state batteries (SSBs) [5].

1. Garnet-Type Oxides

Garnet-type oxides, such as lithium lanthanum zirconate (LLZO) and lithium aluminum titanium phosphate (LATP), are key oxide-based solid electrolytes due to their high ionic conductivity and stability, making them suitable for solid-state batteries (SSBs).

LLZO ($Li_6 \cdot 4\,La_3Zr_1 \cdot 4\,Ta_0 \cdot 6\,O_{12}$) exhibits a cubic garnet structure with lithium-ion channels, achieving ionic conductivities of approximately 1e-3S/cm at room temperature. It offers excellent chemical and thermal stability, a wide electrochemical stability window exceeding 6V, and low electronic conductivity (1e-8S/cm). However, its production involves high-temperature sintering, increasing costs and complicating material consistency [14], [15].

LATP ($Li_{1+x}Al_xTi_{2-x}(PO_4)_3$) features a three-dimensional framework supporting lithium-ion transport, with good ionic conductivity and mechanical robustness. However, LATP is more moisture-sensitive than LLZO, degrading under ambient conditions, and exhibits slightly lower ionic conductivity, which may limit its ultra-fast charging applications [16].

LLZO outperforms LATP in conductivity and direct lithium metal compatibility, while LATP benefits from simpler, cost-effective synthesis methods. Despite their potential, both materials face challenges such as high costs, scalability issues, and electrode interface compatibility. Research continues to address these limitations through advanced synthesis techniques and composite designs, aiming to unlock their full potential for SSB applications [5], [17].

2. Perovskite-Type Oxides

Perovskite-type oxides, such as lithium lanthanum titanium oxide (LLTO, $La_{2/3-x}Li_{3x}TiO_3$), are notable for their high ionic conductivity and robust structural properties. These oxides have a cubic crystal structure (ABO_3), where lithium (Li) and lanthanum (La) ions partially occupy the A-sites, and titanium (Ti) ions occupy the B-sites, forming channels that facilitate lithium-ion transport.

LLTO achieves ionic conductivities of 1e-3S/cm to 1e-4S/cm at room temperature and exhibits excellent chemical and thermal stability, with a wide electrochemical stability window of up to 8V. These attributes make LLTO suitable for high-voltage cathodes and advanced battery designs [17], [5].

Challenges include grain boundary resistance, instability with lithium metal anodes below 1.8V, and brittleness, which can lead to delamination during cycling. Addressing these limitations is critical for LLTO's adoption in solid-state batteries [17].

3. NASICON-Type Oxides

NASICON-type oxides, such as $LiZr_{2-x}Ti_x(PO_4)_3$, are distinguished by their high ionic conductivity and structural adaptability. These materials, derived from $Na_3Zr_2Si_2PO_{12}$, replace sodium (Na^+) with lithium (Li^+), creating a three-dimensional framework that enables efficient lithium-ion transport. They offer excellent chemical and thermal stability, along with compatibility with various cathode materials and lithium metal anodes [5].

Unlike other oxide-based electrolytes, NASICON oxides resist degradation in humid environments, making them stable under ambient conditions. However, challenges such as interfacial instability with electrodes and the need for precise control of stoichiometry remain obstacles. Research efforts are focused on advanced synthesis techniques and interface engineering to address these issues and unlock their potential for solid-state batteries [18], [5].

Sulfide-Based

Sulfide-based solid electrolytes are a subclass of inorganic solid electrolytes (ISEs) characterized by the substitution of oxygen atoms with sulfur, leading to exceptional lithium-ion conductivities often exceeding $10^{-4}\,\mathrm{S/cm}$. This surpasses or matches the performance of organic liquid electrolytes. Their mechanical softness enhances electrode contact, crucial for interface stability in solid-state batteries (SSBs).

These electrolytes are classified into three types:

- **Glass sulfides:** Represented by lithium thiophosphate (LPS), they exhibit high ionic conductivity (up to $10^{-2}\,\mathrm{S/cm}$ at room temperature) and stability with lithium metal but face challenges such as moisture sensitivity and high manufacturing costs.

- **Glass–ceramic sulfides:** Systems like Li_2S-P_2S_5 combine improved ionic conductivity with tunable properties through composition adjustments.

- **Crystalline sulfides:** Materials like lithium germanium phosphorus sulfide (LGPS) and $Li_{9.54}Si_{1.74}P_{1.44}S_{11.7}Cl_{0.3}$ achieve exceptional conductivities and compatibility with lithium metal but are hygroscopic and require complex synthesis methods.

While sulfide-based solid electrolytes offer high conductivity and excellent electrode compatibility, their sensitivity to moisture, synthesis costs, and interface stability challenges hinder widespread adoption. Research efforts focus on addressing these issues to unlock their full potential in safer, high-performance SSBs [19], [5].

Halide-Based

Halide-based solid electrolytes are an emerging class of inorganic solid electrolytes (ISEs) incorporating halide ions (e.g., fluoride, chloride, bromide, iodide). They offer high ionic conductivity, a wide electrochemical stability window, and improved moisture resistance compared to sulfide electrolytes, making them promising for solid-state batteries (SSBs).

These electrolytes are categorized into three types: Group 3 halides (e.g., Li_3YCl_6, Li_3ScCl_6) with high conductivity and stability; group 13 halides (e.g., aluminum, indium-based) known for conductivity and electrochemical stability; halides with divalent metals (e.g., titanium, zirconium) that allow property customization.

Examples like Li_3YCl_6 and Li_3YBr_6 showcase compatibility with lithium metal and balanced performance. However, challenges include sensitivity to moisture, high synthesis costs, and limited scalability. Research efforts focus on improving synthesis and interface engineering to unlock their full potential for next-generation SSBs [20], [5].

3.2.2 Organic Solid Polymer Electrolytes (OSPEs)

Organic solid polymer electrolytes (OSPEs) are considered a promising alternative to traditional inorganic solid electrolytes (ISEs), offering unique properties such as high ionic conductivity, thermal stability, and mechanical flexibility. These features enhance battery performance by reducing interface resistance and enabling scalable, cost-effective manufacturing. However, limitations such as lower ionic conductivity, restricted chemical stability, and inadequate mechanical strength necessitate ongoing research to optimize their properties and expand their applicability [5].

Key Polymer Electrolytes

Polyvinylidene Fluoride (PVDF): PVDF is a fluoropolymer often combined with lithium salts like LiTFSI to create polymer electrolytes with high ionic conductivity and good mechanical properties. It is typically processed into films using gel formation methods with solvents such as acetonitrile. While PVDF demonstrates excellent compatibility with various chemistries and strong mechanical stability, it faces challenges like limited electrochemical stability and sensitivity to ambient conditions [21], [5].

Polyethylene Oxide (PEO): PEO is widely used in combination with lithium salts, offering compatibility with lithium metal anodes and relatively high ionic conductivity. It is cost-effective and scalable, and it reduces dendrite formation, making it suitable for a range of applications. However, PEO is prone to degradation in the presence of moisture, is sensitive to temperature fluctuations, and has a limited voltage stability range [21], [5].

Polyacrylonitrile (PAN): PAN-based polymer electrolytes are created by mixing PAN with lithium salts and plasticizers. These electrolytes exhibit high ionic conductivity and elasticity, which can be further enhanced through methods like solution casting or electrospinning. While PAN offers advantages such as scalability, high conductivity, and mechanical flexibility, its cycling stability and composition require further optimization for improved performance [21], [5].

Efforts to advance polymer electrolyte systems focus on enhancing mechanical durability and improving interface compatibility with electrodes. By addressing these challenges, OSPEs could become a cornerstone in the development of next-generation solid-state battery technologies.

3.2.3 Composite Solid Electrolytes (CSEs)

While many studies have focused on either inorganic solid ceramic electrolytes or organic solid polymer electrolytes, increasing attention is being directed toward composite solid electrolytes (CSEs). These materials combine the advantages of both inorganic and organic electrolytes while addressing their respective limitations. In CSEs, inorganic ceramic electrolytes primarily serve as fillers, enhancing mechanical strength and boosting ionic conductivity [22].

Figure 15 represents some examples of these fillers and the overall advantages of CSEs.

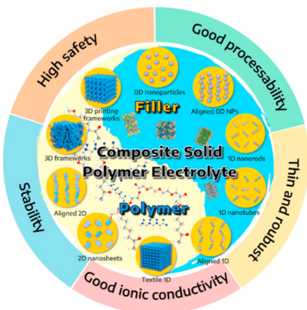

Figure 15: Representation of the structure of fillers and template polymers used in developing CSEs [5]

Inorganic fillers are incorporated into polymer matrices to enhance mechanical strength, ionic conductivity, and stability. Recent research includes the investigation of various morphologies such as 0D nanoparticles, 1D nanowires, 2D nanosheets, and 3D frameworks. Depending on the Li ion conductivity, these fillers are classified into two types: **passive** and **active**, based on their role in ion conduction [22].

Passive Fillers

Passive fillers, such as Al_2O_3, SiO_2, and TiO_2, improve the mechanical and thermal properties of polymer electrolytes without directly contributing to ion conduction. For instance, SiO_2 nanoparticles enhance the ionic conductivity of PEO/LiTFSI electrolytes, increasing it from 6.13×10^{-8} S/cm to 4.35×10^{-4} S/cm at 30 °C. These fillers also improve interfacial contact and resistance to cracking, making composite electrolytes more durable in demanding applications [5].

Active Fillers

Active fillers, such as LLZO, LATP, and NASICON, contain lithium ions and actively participate in ion conduction, providing pathways for Li^+ transport. Incorporating LLZO (30 wt.%) into a polymer matrix significantly increases ionic conductivity to 2.2×10^{-4} S/cm at room temperature. LATP frameworks suppress dendrite growth and enhance conductivity, achieving 7.47×10^{-4} S/cm at 60 °C. NASICON-based fillers, optimized at 20 wt.%, yield a high conductivity of 1.44×10^{-3} S/cm and improved mechanical properties, suitable for high-temperature applications[5].

While passive fillers primarily enhance structural stability, active fillers offer superior improvements in ionic conductivity due to their high intrinsic conductivity. Combining these fillers in polymer SSEs provides a balance of mechanical strength, thermal stability, and enhanced performance, making them ideal for next-generation batteries.

3.2.4 Progress, Challenges, and Prospects in Solid Electrolytes

Like it has been explained in the previous subsections, the development of solid electrolytes has advanced significantly due to innovations in materials and fabrication techniques. Researchers have focused on ceramics, polymers, and composites for solid-state batteries (SSBs), offering improved stability and safety compared to liquid electrolytes. Techniques like thin-film deposition, sintering, and lithography have enabled the production of solid electrolytes with enhanced structural and electrochemical properties.

Among solid electrolytes, oxide-based materials provide broad electrochemical stability windows, making them suitable for high-voltage cathodes and enabling batteries with higher energy and power densities. However, they face challenges such as brittleness, limited compatibility with cathodes, and high densities that reduce gravimetric energy density. To overcome these issues, oxide electrolytes are fabricated as thin ion-conducting layers or ceramic separators in SSBs.

Thin-film batteries (TFBs) are constrained by limited electrode volume, which restricts their energy storage capacity. Traditional designs allow for increased electrode thickness to boost capacity, but this is not feasible in TFBs due to kinetic limitations. A promising solution is to deposit battery components onto 3D-structured substrates, increasing the surface area available for energy storage. This design relies on two key factors: the area enhancement factor (AEF), which increases capacity per footprint area, and the open volume of the 3D substrate, balancing capacity and structural efficiency [6]. This concept is specified in Figure 16.

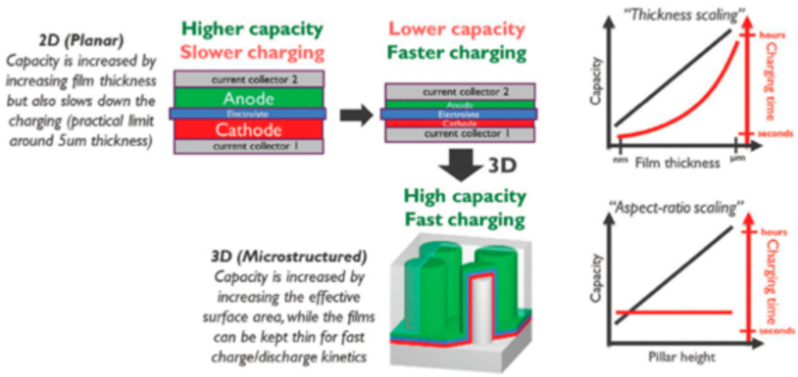

Figure 16: TFBs (planar) and 3D TFBs properties [6]

3.3 Electrode for SSBs

3.3.1 Anode

3.3.1.1 The importance of the Anode

The anode in solid-state batteries (SSBs) plays a vital role in determining important performance parameters, like the energy density, safety, lifespan, and the ability to support fast-charging cycles.

For solid-state batteries (SSBs), the ideal anode must offer a high theoretical capacity to maximize energy storage per unit of mass. It should also possess a low electrochemical potential relative to lithium, enabling a high cell voltage and greater energy output. Excellent electronic conductivity is essential for efficient electron transfer, enhancing the battery's rate capability. Additionally, the anode material requires robust structural stability to endure volume changes during lithium intercalation and deintercalation without degradation, which could otherwise reduce the battery's lifespan [23].

Current research focuses on materials like silicon, tin, and various alloys, which show high capacity and compatibility with solid electrolytes. However, challenges such as significant volume expansion and the formation of an unstable solid electrolyte interphase (SEI) remain. Developing a stable SEI is particularly critical in SSBs, as it can prevent dendrite growth, improve safety, and facilitate the use of lithium-metal anodes.

Transitioning from liquid-electrolyte-based lithium-ion batteries (LIBs) to SSBs with advanced anode materials requires overcoming interface challenges. The anode–solid electrolyte interface must remain stable and conductive throughout the battery's lifespan to maintain ion transport properties essential for efficient operation. Therefore, careful material selection and optimization are vital to ensuring compatibility with solid electrolytes and achieving a durable and reliable interface [6], [23].

3.3.1.2 Anode Material Selection for SSBs

In SSBs, the commonly used anode materials include lithium (Li) metal, lithium titanium oxide (LTO, $Li_4Ti_5O_{12}$), and lithium silicon (LiSi), chosen for their high energy densities and stability [6].

1. Lithium Metal Anodes

Li metal anodes offer unparalleled theoretical capacity, low electrochemical potential, and lightweight properties, enhancing energy density by up to 1.5 times compared to graphite. However, Li metal is prone to challenges such as dendrite formation, high reactivity, and oxidation, posing safety risks. Solid-state electrolytes (SSEs) mitigate these issues by preventing dendrite penetration and enhancing battery stability. Despite these benefits, Li dendrites can still form in certain SSEs, leading to ongoing research into alternatives such as silicon, sulfur, metallic alloys, and carbon-based materials [6].

2. Lithium Titanate (LTO) Anodes

LTO is a safer and more stable option compared to Li metal, with excellent cycle life and minimal risk of dendrite formation. However, it has lower energy density. Composite anodes combining Li metal and LTO have been proposed to reduce interface resistance with garnet-structured SSEs [6].

Silicon Anodes

Silicon is a promising candidate for next-generation SSBs due to its high theoretical capacity, low cost, and environmental stability. It addresses limitations in energy storage and driving range for EVs. However, significant volume expansion during lithiation cycles leads to mechanical degradation, reduced cycling stability, and limited electrical conductivity. Advanced engineering, such as material modifications and innovative electrode designs, aims to harness silicon's full potential [6].

3. Alloy and Composite Anodes

Metallic alloys like lithium-aluminum (Li-Al) and lithium-tin (Li-Sn) strike a balance between capacity and stability, offering mechanical advantages and reducing safety risks; Li-Sn alloys, reinforced with polyacrylonitrile (PAN) fibers, extend cycle lifespan by forming stable passivation layers [6].

Silver-carbon composite interlayers have also demonstrated potential for Li-free cycling, leveraging Li-Ag alloy formation to suppress dendrite growth and improve cycling performance.

4. Other Potential Anode Materials

Lithium silicides (Li-Si alloys) and sulfur-based materials are being explored for their high energy densities. Techniques like heteroatom doping (e.g., sulfur or phosphorus doping) enhance ionic conductivity and structural properties, further optimizing performance [6].

3.3.1.3 Overcoming Anode Challenges

Prevention of Dendritic Lithium Formation

Dendritic lithium formation is a major challenge for improving the performance and safety of all-solid-state batteries (ASSBs). Materials like Ag, Al, Sn, and the antiperovskite conductor $Li_3S(BF_4)_{0.5}Cl_{0.5}$ are described as effective in stabilizing electrodeposition and mitigating dendrite growth [6].

Additionally, strategies like active stack pressure control and hot pressing of binder-inclusive anodes, can enhance discharge capacity and maintain mechanical contact during cycling, paving the way for commercial ASSB applications [6].

Enhancement of Anode/Electrolyte Contact

Improving anode–electrolyte contact remains a key challenge in solid-state batteries. [6] introduced a gradient composite polymer solid electrolyte (GCPE) synthesized via UV-curing polymerization. The GCPE features a high-LLZTO-content side for enhanced oxidation resistance and an LLZTO-deficient side for improved interfacial contact with Li-metal anodes. This design promotes uniform Li deposition, low-voltage hysteresis, and extended cycle life in symmetric Li//Li cells.

[6] investigated the stability of anode–electrolyte interfaces in sodium all-solid-state batteries, analyzing chloride, sulfide, and borohydride electrolytes. Their results, obtained via advanced techniques like FIB–SEM imaging and XPS, showed that interface stability depends on the solid electrolyte's intrinsic electrochemical properties and the passivating nature of interfacial products.

[6] also proposed a conductive carbon felt elastic layer for anode-free solid-state lithium-metal batteries (ASLMBs). This layer autonomously adjusts pressure on the anode side, enhancing lithium–solid electrolyte contact. The approach improved Coulombic efficiency and cycling stability, offering a practical solution to lithium stripping inefficiencies.

Augmentation of the Anode Lifecycle and Efficiency

Recent advancements in anode development for solid-state batteries (SSBs) have significantly improved their lifecycle and efficiency. [6] tackled challenges in anode-free Li-metal batteries (AFLBs), such as Li dendrite accumulation and dead Li, by introducing electrolyte additives like $LiAsF_6$ and FEC. These additives stabilized Li deposition and solid electrolyte interphase (SEI) formation, achieving 75% capacity retention after 50 cycles and an average Coulombic efficiency of 98.3% over 100 cycles.

Other researchers addressed the chemical instability between $Li_{10}GeP_2S_{12}$ (LGPS) and Li metal by developing a LiH_2PO_4 protective layer on the Li anode. This layer enhanced stability, maintaining polarization voltage over 950 hours at 0.1 mA cm^2 and achieving a reversible discharge capacity of 113.7 mAh g^1 after 500 cycles under 0.1 C [6].

3.3.1.4 Anode Enhancement Techniques

Surface Modification and Coating

Integrating lithiophilic layers has shown promise in enhancing anodes for solid-state batteries. [6] demonstrated that a 1 µm Li_2Te lithiophilic layer on a Cu collector improved lithium deposition, achieving a cycling Coulombic efficiency above 99%.It also highlighted surface modifications of Cu foils with composite layers (e.g., Ag, Sn, Zn) to enhance Li plating/stripping reversibility.

Nanoengineering for Improved Performance

Nanoengineering techniques, such as incorporating carbon nanotubes (CNTs) into lithium-metal anodes, have improved lithium transport and discharge capacity without external pressure. Similarly, nanoparticle-decorated porous carbon structures have optimized interfaces in molten sodium batteries, enabling nearly 6000 cycles [6].

Formation of Protective Layers

Protective layers play a critical role in enhancing anode performance. The development in situ ion-conducting layers using spin-coating techniques improved lithium deposition and interface stability. Also showcased mechanically prelithiated aluminum foil anodes, achieving superior cycling stability [6].

3.3.2 Cathode

The cathode, as the battery's positive electrode, accepts electrons during discharge and is typically made of lithium-containing materials such as lithium cobalt oxide ($LiCoO_2$), lithium iron phosphate ($LiFePO_4$), or nickel-rich materials like $LiNiMnCoO_2$ (NMC). These materials offer high energy densities and stability but are sensitive to electrolyte chemistry. Solid-state electrolytes (SSEs) provide a more stable interface, reducing side reactions and enhancing cycle life and safety, particularly for high-voltage and oxygen-reactive cathodes like Li-air or Na-air systems [5].

The selection of cathode materials is critical for determining battery energy density. Efficient Li^+ transport at the solid-solid interface requires optimized connections between SSEs and cathodes. For instance, single-crystalline cathodes with enhanced mechanical strength and density show promise in addressing issues like particle cracking and loss of ion transport pathways, common in SSBs with Ni-rich cathodes [5].

Advancements in Cathode Design

- **Interface Optimization:** Coating oxide cathodes with Li ionic conductors, such as $LiNbO_3$, reduces interfacial resistance and improves charge-discharge capacity. Core-shell architectures in Ni-rich oxides further enhance stability by balancing high capacity from the core and stable interactions from the shell.

- **Organic Cathodes:** Organic materials like hexaazatriphenylene (HATN) offer potential when combined with gel polymer electrolytes, showing improved electrochemical performance.

- **Composite Cathodes:** Zhang et al. demonstrated superior performance using NCM523-based composite cathodes paired with ceramic-based SSEs, highlighting their potential in SSB applications.

Despite these advancements, challenges remain in reducing interfacial resistance, ensuring compositional alignment between cathodes and electrolytes, and enhancing cycle performance without compromising energy density. Continued research into structural modifications and novel materials is essential for optimizing cathodes in SSBs [5].

3.4 Manufacturing approaches for Solid-State Batteries

3.4.1 SSB Manufacturing Processes

After explaining the major components of a battery, in specific a solid-state one, it is important to clarify the possible options available for producing this type of batteries, considering the materials that were discussed in the previous points.

It is clear that the material selection and the processing approach for the different components will dictate strategies for manufacturing large- format solid-state batteries.

Current solid-state batteries (SSBs) are predominantly thin-film designs with nominal capacities below 1 mAh. These batteries often rely on vacuum deposition methods, which pose scalability challenges for electric vehicle (EV) applications. Additionally, many SSB materials are sensitive to air and moisture, necessitating inert environments during processing—key factors for engineering low-cost solid-state batteries [24].

Recent advancements include roll-to-roll manufacturing techniques capable of producing multi-layered SSBs with 20 Ah cell capacities. However, three critical challenges remain in scaling up SSB production: (1) defect-free thin solid electrolyte processing, (2) dense composite cathode fabrication, and (3) thin lithium metal processing. Various approaches are under investigation to address these issues, including tape casting, screen printing, extrusion, and aerosol deposition. Tape casting and screen printing, widely explored for solid electrolytes and composite cathodes, enable scalable, high-throughput production but may require additional steps like calendaring to improve part density [24].

Extrusion and melt processing are being explored for lithium metal and alloys, but contamination and the effects of shear and stress during processing pose significant challenges [24].

In addition to these techniques, additive manufacturing, commonly known as 3D printing, has emerged as a promising approach for producing SSBs on a commercial scale. Researchers and engineers have explored various 3D printing techniques to enhance efficiency, energy density, and overall performance. The versatility of 3D printing offers several advantages, including intricate design possibilities, improved manufacturing precision, and the ability to create complex internal structures that optimize battery architecture. Techniques such as selective laser sintering, stereolithography (SLA), and roll-to-roll printing have been investigated for fabricating solid electrolyte structures and improving battery performance.

For electrode materials, conventional fabrication methods like sol-gel, electron beam evaporation, and chemical vapor deposition are complex and expensive, often leading to side reactions that reduce efficiency. Inkjet printing presents a simpler alternative.

3D printing has also been employed for fabricating solid-state electrolytes (SSEs).

The integration of 3D printing in SSB manufacturing offers a pathway to streamlined production, reducing costs and enhancing scalability. As research advances, further breakthroughs in 3D printing techniques and their application to SSBs are anticipated, paving the way for next-generation energy storage technologies [5].

Overall, this transition from laboratory-scale synthesis to large-scale production necessitates the careful consideration of factors such as cost, efficiency, and quality control to enable the widespread adoption of ASSB technology [11].

3.4.2 Material Availability and Sustainability

The production of solid-state batteries (SSBs) faces challenges similar to conventional lithium-ion batteries (LIBs) in terms of raw material extraction, material production, and cell manufacturing. Addressing these issues is essential to improve the sustainability of these technologies, especially for applications like electric mobility.

From a resource perspective, SSBs share many components with LIBs, including transition metal-based cathode materials, carbon additives, copper, aluminum or nickel current collectors, and cell housings. However, significant differences arise from the choice of solid electrolytes (SEs) and anode materials. Several SEs under investigation incorporate metals not commonly found in LIBs, such as lanthanum, germanium, zirconium, and tin [25].

- Zirconium is relatively abundant, with global production around 1 megaton per year, used mainly in alloys.
- Lanthanum, a more common rare earth metal, is produced as a by-product in metallurgy, with annual usage near 50 kilotons. Increased use in SSBs could significantly raise demand.
- Germanium is scarce and extracted as a by-product of zinc production. Its high cost (900 EUR/kg) limits its feasibility for mass application.

Lithium demand is expected to rise significantly with the transition to SSBs, driven by the specific requirements of SE materials. In liquid electrolytes, lithium accounts for approximately 3 g/kWh at the cell level. Polymer SEs, such as Li salts in PEO, require similar amounts, but inorganic SEs like LLTO, LATP, and sulfides demand much higher lithium concentrations, ranging from 10 to 15 wt.%. This corresponds to an additional 10–20 g/kWh at the cell level. While this is small compared to the ˜100 g/kWh needed for NMC811 cathode materials, it could still place additional pressure on lithium supplies.

The adoption of lithium metal anodes further increases demand. For example, a 5 µm-thick lithium layer in an electrode configuration with a cathode loading of 6 mAh/cm^2 requires approximately 15 g/kWh of lithium. These shifts highlight the need for careful resource planning to sustain the growing demand for SSB technologies [25].

3.5 Recycling of Solid-State Batteries

Another important aspect to take into account for this possible change in the battery market is the environmental impact and the sustainability aspects.

Similar to conventional lithium-ion batteries (LIBs), solid-state batteries (SSBs) can adapt established recycling processes to recover their primary components. The metallic constituents of solid electrolytes and cathodes are recoverable via pyro- or hydrometallurgical techniques. The higher lithium content in inorganic solid-state cells enhances the incentive to recover lithium during recycling.

Different types of solid electrolytes require tailored recycling approaches. Oxide-based electrolytes are suited for pyrometallurgical treatment, while sulfides often necessitate complex hydrometallurgical processes. Polymer-based electrolytes may be thermally utilized, with salts and fillers being recoverable. Direct recovery processes for solid electrolytes could bypass energy-intensive recycling methods, as their chemical stability during battery cycling allows reprocessing and reuse without breakdown into precursors. However, dismantling individual components is challenging due to the solid and partially 3D interfaces between layers [25].

Although promising, the separation of structurally similar catholytes and active cathode materials remains complex. SSBs also eliminate the flammability risks associated with liquid electrolytes during mechanical crushing but introduce challenges due to reactive lithium metal.

From an industrial perspective, it is unlikely that entirely separate recycling processes will be developed for LIBs and SSBs due to the need for additional pre-sorting, which could delay economic efficiencies. Significant returns of used SSBs are not expected before 2040, giving time to adapt current recycling processes for compatibility with SSBs.

The potential for second-life applications of SSBs remains unclear. While solid electrolytes, particularly oxides and sulfides, are stable over time, material fatigue, such as cracks or fractures, can increase contact resistance. If contact detachment drives the end of the battery's first life, second-life applications may result in performance losses or failures [25].

3.6 Solid-State Battery Market

3.6.1 Market Overview

The global battery market is projected to experience exponential growth, increasing from a capacity of approximately 330 GWh in 2018 to around 2.6 TWh by 2030—a 14-fold expansion driven primarily by the electric vehicle (EV) mobility sector. Material costs dominate battery production, with cathode costs comprising nearly half of these expenses where cell assembly costs hover around 17 €/kWh. Key applications driving this market include EVs, portable consumer electronics, and energy storage systems. Regulations for emission control, increasing renewable energy generation, and storage capacity needs further stimulate market growth, positioning solid-state batteries (SSBs) as a future competitor to lithium-ion batteries (LIBs).

Consumer concerns about EV limitations, including short driving ranges and lengthy charging times, highlight the need for advanced battery technologies. SSBs have gained prominence on the roadmaps of battery producers and OEMs due to their suitability for EV applications. The mass commercialization of SSBs will depend on EV manufacturers, who play a decisive role in shaping the supply chain and establishing strategic market direction [5],

[25].

3.6.2 Market Size

The solid-state battery (SSB) market is still in its early stages, with current applications limited to low-volume electric vehicles (EVs) and smaller portable devices like sensors and medical equipment. Most existing SSB products are polymer-based or microbatteries with oxide thin-film electrolytes. Examples include ultra-thin ceramic SSBs from STMicroelectronics and batteries for medical devices by companies like Ilika. However, the technology for small-scale applications differs significantly from that required for large-scale EV installations, making economic comparisons challenging.

Global SSB production capacity is estimated to be below 2 GWh, representing less than 0.5% of lithium-ion battery (LIB) capacities. Assuming major technological barriers are overcome, SSB demand for EVs is projected to grow from 200 MWh in 2022 to 2 GWh by 2025, representing a compound annual growth rate (CAGR) of 118%. Industrial-scale production is expected to begin around 2025, with oxide- and sulfide-based SSBs entering the market by 2030. Projections suggest total SSB capacity could reach 15–40 GWh by 2030 and 55–120 GWh by 2035, still a fraction of the LIB market, which is estimated to exceed 2 TWh by 2035 [5], [25].

Revenue forecasts for SSBs remain uncertain, but estimates suggest the market could grow significantly. IdTechEx Research predicts the solid-state electrolyte (SSE) industry will reach 25 billion euros by 2029, while Lux Research anticipates the SSB market to reach 42 billion euros by 2035. Patent activity, primarily dominated by Japanese companies like Toyota, which holds over 1300 patents, further underscores the potential for rapid innovation and technological advancement. Recent years have seen an explosive increase in Chinese patent filings, signaling a highly competitive landscape. This dynamic environment is expected to drive significant progress in SSB development, aligning market forecasts with ongoing R&D investments by leading battery and automotive manufacturers [5].

3.6.3 Economics of Solid-State Batteries (SSBs)

The cost structure of solid-state batteries (SSBs) remains uncertain due to limited commercial deployment. Current SSB prices are estimated between 400 and 800 €/kWh, with some optimistic exceptions, such as Ampcera's announcement of a 75 €/kWh SSB. While initial costs are high, parallels can be drawn to the dramatic price reductions in lithium-ion battery (LIB) technology, which dropped from over 1200 €/kWh in 2010 to as low as 90 €/kWh today. Economies of scale and advancements in manufacturing are expected to similarly drive down SSB costs [25].

Economic feasibility is focused on addressing key factors such as material costs, processing efficiencies, and scalable production methods. While cathode costs for SSBs are comparable to those of LIBs, the costs of solid electrolytes (SEs) remain higher due to the use of materials like titanium, lanthanum, and zirconium. Metal-based SEs range from 6–13 €/kg, with final costs heavily influenced by purity levels and additional processing requirements.

Sulfide-based SEs, however, lack a robust supply chain, complicating cost projections. Notably, the cost of SE materials alone (3–6 €/kWh) is already comparable to or higher than the total electrolyte cost in LIBs (3–8 €/kWh).

Manufacturing SSBs presents unique challenges. Processes such as high-temperature sintering for oxide SEs and electrode coating are more expensive than those for LIBs. Coating speeds, essential for reducing costs, often shift the burden towards higher capital expenditures (CAPEX). Additionally, scaling up production requires innovative equipment, as no standardized manufacturing solutions currently exist. While fewer process steps in SSB production could lower costs, new steps like sintering and specialized assembly might offset these savings [25].

Investments in SSB production are expected to reach billions of euros globally. To justify these expenditures, manufacturing synergies with existing LIB facilities could be crucial, as shared infrastructure may help reduce CAPEX and production costs. Borrowing techniques from solid oxide fuel cell manufacturing could also optimize processes. Despite these hurdles, economies of scale and continued innovation are key to making SSBs a commercially viable alternative to LIBs [5].

3.7 Key Performance Indicators (KPI) of Solid-State Batteries

After describing the parameters and major characteristics of SSBs it's relevant to summarize the major aspects that make this batteries a possible viable solution.

Research and development in solid-state batteries (SSBs) is primarily focused on enhancing several key performance indicators (KPIs), including energy density, safety, fast charging capability, cost, and lifetime. Compared to conventional liquid electrolyte batteries, SSBs hold significant potential for improvement across these areas. However, the specific optimization of these KPIs often requires tailored approaches to cell concepts. In most applications, multiple KPIs need to be improved simultaneously to meet the demands of modern energy storage systems [25].

3.7.1 Safety

Safety is a critical consideration in the transition from liquid electrolyte lithium-ion batteries (LIBs) to solid-state batteries (SSBs). Public concerns about the safety of electric vehicles (EVs) often focus on their potential to ignite and the challenges associated with extinguishing battery fires. By replacing the flammable liquid electrolyte with a non-flammable solid electrolyte, SSBs significantly reduce the risk of fire. Additionally, the absence of liquid components eliminates the possibility of leakage, minimizing contamination and environmental hazards. A more stable separator further lowers the likelihood of short circuits.

However, SSBs are not without safety challenges. The use of a lithium metal anode introduces specific risks, as lithium is highly flammable and prone to dendrite formation during cycling. These dendrites can cause short circuits, potentially leading to thermal runaway. To mitigate this issue, mechanically stable separators are essential, and research is ongoing to minimize excess lithium, such as through the adoption of in-situ anode designs. It is important to note that the potential harm from battery malfunctions increases with energy density.

Regarding the choice of solid electrolytes, oxides are generally considered the safest option due to their lower reactivity and mechanical stability. In contrast, sulfide electrolytes present additional safety concerns, as they can react with water to produce hydrogen sulfide (H_2S), a toxic and flammable gas [25].

3.7.2 Energy Density

Energy density is one of the most critical properties of a battery, representing the amount of energy stored relative to its mass (gravimetric energy density) or volume (volumetric energy density). For electric vehicles (EVs), increasing energy density is essential to extend driving ranges, addressing a key limitation of current battery technologies.

The adoption of lithium metal anodes is a primary strategy for enhancing energy density during the transition from conventional lithium-ion batteries (LIBs) to solid-state batteries (SSBs). This requires solid electrolytes that are chemically compatible with lithium metal and resistant to dendrite formation. On the cathode side, transitioning from lithium iron phosphate (LFP) to nickel-rich lithium nickel manganese cobalt oxides (NMC) can further optimize energy density.

Maximizing the share of active materials is another approach to improve energy density. This can be achieved by manufacturing thinner inactive material components, replacing them with alternatives, or increasing the layer thickness of anodes and cathodes. Additionally, reducing system-level requirements, such as lowering the operating temperature of solid polymer electrolytes, can enable smaller and lighter thermal management systems, further enhancing the gravimetric and volumetric energy densities of the battery.

While these strategies aim to improve both gravimetric and volumetric energy densities, focusing on just one parameter may allow for additional optimizations, such as tailoring components to specific densities for targeted applications [25].

3.7.3 Fast Charging Ability

Reducing charging times is a key objective for advancing battery technologies, particularly to make electric vehicles (EVs) more competitive with internal combustion engine vehicles, where refueling is significantly faster. Fast charging in solid-state batteries (SSBs) depends on achieving high ionic conductivity and ensuring effective charge transfer.

A significant challenge lies in the electronic and ionic pathways of SSBs. Unlike liquid electrolyte systems, SSBs have limited surface areas of active material particles contributing to ionic conduction due to the multitude of particle interfaces. Polymer electrolytes, while flexible and capable of forming good interfaces, often suffer from low ionic conductivity and low cationic transference numbers, which hinder their ability to support fast charging. In contrast, inorganic solid electrolytes, particularly sulfides, exhibit higher ionic conductivity, making them better suited for high charging rates. However, oxide electrolytes are typically more limited in ionic conductivity, posing challenges for fast charging in high-energy cell designs with thick active layers.

Fast charging also induces rapid volume changes, placing stress on both the solid electrolyte and the overall cell structure. To address these issues, the cell must be engineered to withstand such mechanical stresses. Additionally, the use of lithium metal anodes during fast charging increases the risk of dendrite formation, which compromises both the safety and the lifespan of the battery [25].

3.7.4 Long-Term Stability and Lifetime

A long battery lifetime is critical for reducing the total cost of ownership and is particularly valuable in applications where battery replacement is complex or costly.

Conventional liquid electrolyte batteries face significant degradation mechanisms, including SEI layer growth, lithium plating, cathode decomposition, and particle fractures at the electrodes. While similar degradation processes can impact solid-state batteries (SSBs), these systems have the potential for a longer lifespan. The absence of liquid electrolytes reduces degradation during rest periods, thereby improving the calendric lifetime of the battery.

However, SSBs face challenges related to the stability of solid interfaces. The limited flexibility of inorganic solid materials can lead to contact deterioration at the interfaces during volume changes that occur throughout cycling. This issue poses a significant challenge for maintaining long-term performance.

Polymer-based solid electrolytes (SEs), with their inherent flexibility, can better accommodate the mechanical stresses induced by electrode volume changes, offering an advantage over inorganic SEs. Conversely, sulfide-based SEs often require electrode coatings to prevent slow decomposition reactions that can compromise the battery's stability.

Overall, enhancing the interface stability and accommodating volume changes are key to extending the lifetime of SSBs and making them competitive with traditional liquid electrolyte batteries [25].

3.7.5 Price

The cost of the battery is one of the most critical factors in determining the overall price of a battery electric vehicle (BEV), accounting for approximately one-third of the vehicle's total cost. This makes the battery price a key economic driver in the adoption of electric vehicles.

The cathode materials represent the largest cost share in a battery, primarily due to the use of expensive raw materials such as cobalt and nickel. Promising low-cost alternatives, like lithium iron phosphate (LFP) cathodes, have gained attention for their potential to reduce overall costs.

The solid electrolytes (SEs) in solid-state batteries (SSBs) are not yet produced on a large scale, making their full impact on battery costs uncertain. Among the different SE categories, polymer-based SEs hold a cost advantage due to their lower lithium content and relatively straightforward, cost-effective manufacturing processes. However, all SE categories require processing in controlled environments, such as dry rooms, to maintain material integrity.

Inorganic SEs, such as sulfides and oxides, face additional cost challenges. Sulfide SEs often necessitate processing in argon atmospheres, which significantly increases costs due to the high price of argon. Oxide SEs, on the other hand, require energy-intensive sintering processes, further contributing to their production expenses.

Ultimately, the cost of SE production and the associated manufacturing processes will play a decisive role in determining the economic viability of SSBs in large-scale applications [25].

4 Comparison Between Lithium-Ion and Solid-State Batteries

After describing the majority of aspects regarding solid-state batteries, including the key performance indicators, it can be interesting to compare this type of batteries with the ones that are currently dominating the market.

However, there isn't much information for a direct comparison between these two types of batteries.

Nonetheless, Table 1 shows the differences for the several KPI described before.

Table 1: Comparison between Traditional Lithium-Ion and All-Solid-State Lithium-Ion Batteries [11]

Feature	**Traditional Lithium-Ion**	**All-Solid-State Lithium-Ion**
Energy Density	Moderate to high	Potentially higher
Safety	Risk of leakage, flammability	More stable, less risk of leakage
Charging Speed	Moderate	Potentially faster with advancement
Temperature Range	Limited, can degrade at high temperatures	Wider, more stable at high temperatures
Lifecycle	Moderate (500–1500 cycles)	Longer (Potentially 2–10× Li-Ion)
Manufacturing Complexity	Mature technology, well-established	Emerging, still under development
Cost	Relatively lower	Higher, but expected to decrease
Form Factor	Limited flexibility	More design flexibility
Commercial Availability	Widely available	Limited, mostly in development

While Table 1 outlines the differences in key performance indicators, further analysis is required to highlight the unique strengths and weaknesses of each type of battery. Below, the advantages, challenges, and environmental considerations of solid-state and lithium-ion batteries are discussed in more detail.

Advantages

Solid-state batteries (SSBs) offer several attractive advantages. Their higher energy density stems from the use of solid electrolytes, which enable more active materials and higher energy storage per unit volume or weight. Plus, the solid-state design also improves safety by reducing the risk of electrolyte leakage, thermal runaway, and fire hazards. Furthermore, SSBs have a longer lifespan due to the enhanced chemical stability of solid electrolytes, and they demonstrate better efficiency across a wider range of temperatures and operating conditions. Additionally, the solid-state architecture has the potential for faster charging, as it allows for more efficient ion transport compared to LIBs.

Lithium-ion batteries, on the other hand, benefit from established manufacturing processes and a mature infrastructure for large-scale production. They also feature well-developed recycling methods, which support their economic and environmental sustainability [7].

Challenges

Despite their advantages, SSBs face significant challenges. Interface dynamics remain a critical issue, as precise engineering is required to maintain stable interfaces between solid electrolytes and electrodes. Continued material science innovation is also necessary to optimize performance, cost, and scalability. Moreover, the environmental impact of extracting raw materials like lithium, cobalt, and nickel for solid electrolytes, as well as the energy-intensive processes involved in their manufacture, raises concerns about sustainability.

For LIBs, the primary challenges include their lower energy density compared to SSBs and the inherent safety risks associated with liquid electrolytes, which are prone to leakage and fire hazards. Additionally, LIBs may experience lower efficiency and performance variability across a range of operating conditions [7].

Environmental Impact

Both technologies face environmental challenges, but in different ways. For SSBs, the extraction of materials like lithium, cobalt, and nickel can result in habitat disruption, water pollution, and significant carbon emissions. The high-temperature sintering processes required for manufacturing solid electrolytes also contribute to their carbon footprint. Effective recycling methods for SSBs are crucial to minimize waste and recover valuable materials, as their complex composition complicates recycling.

In contrast, LIBs benefit from an established recycling infrastructure, though challenges remain in efficiently recovering materials and reducing waste at the end of their lifecycle. The production processes for LIBs are also energy-intensive, contributing to their environmental impact [7].

5 SSB Players

The global SSB market is strongly dominated by R&D activities. Important players can generally be divided regarding their respective SSB technology type (e.g., polymer-/oxide-/sulfide-based). The Figure 17 on the left shows an overview of the key market players, representing the leading companies in SSB technology, with a distinct concentration in Asia (notably Japan, the Republic of Korea, and China) due to the regional aggregation of the battery sector [7].

The polymer-based SSB market is advancing through several collaborations and innovations. **Bollore's** BlueSolutions introduced lithium-metal polymer (LMP) batteries in the BlueCar in 2011 and expanded to buses with Mercedes-Benz in 2020. **WeLion**, in partnership with NIO, launched a lithium metal-polymer battery in 2022 and is building a 20 GWh production facility with plans to scale to 100 GWh. **Factorial Energy**, backed by Hyundai-Kia, Mercedes-Benz, and Stellantis, aims to launch automotive-grade SSBs by 2026, featuring solid separators and lithium metal anodes. **Solid Energy Systems** is targeting 2030 for market readiness, developing hybrid cells with GM and Hyundai. **Hydro-Quebec** plans production between 2025 and 2027, transitioning from polymer to composite ceramic electrolytes for improved performance. Lastly, **Ionic Materials** is collaborating with Renault-Nissan-Mitsubishi to develop lithium metal-polymer batteries, supported by A123 Systems LLC. These efforts underline the growing momentum of polymer-based SSB technologies [25], [5].

On the other side, the oxide-based SSB sector has witnessed significant advancements. **QuantumScape**, in partnership with Volkswagen, aims to deliver market-ready batteries by 2025, with an initial production capacity of 1 GWh in 2024, scaling to 20 GWh by 2026. QuantumScape's ceramic electrolyte and lithium anode designs highlight its potential in the automotive sector. **ProLogium**, collaborating with VinFast, Mercedes-Benz, and Gogoro, demonstrated a ceramic separator-based 2.5 kWh battery in 2022 and plans to bring SSBs to commercial vehicles and prototypes by 2023. China's **Ganfeng Lithium**, a leading battery producer, began constructing a 10 GWh SSB facility in 2022, with plans for an additional 10 GWh plant featuring batteries achieving 360 Wh/kg. Similarly, **Qing Tao Energy**, alongside Ampcera, focuses on solid oxide electrolytes, reporting a 1 GWh production capacity in 2020 and plans for a 10 GWh facility. **Ilika**, known for its Stereax mm-scale SSBs targeting medical implants and IoT devices, is scaling up production for EV batteries, supported by BMW [25], [5].

Finally, the sulfide-based SSB segment is driven by industry players pursuing innovative solutions and strategic partnerships. **Samsung SDI** introduced a prototype cell featuring an in situ lithium-metal anode in 2020, with pilot production facilities under construction since 2022, targeting market entry by 2027. Similarly, **CATL** aims to pioneer sulfide SSBs, planning their market debut by 2025, as outlined in their roadmap. **LG Energy Solutions (LGES)** anticipates its SSBs will reach market readiness after 2030. **PowerSolid**, in collaboration with BMW, Ford, and Hyundai, is focused on delivering SSBs for passenger vehicles. The company plans to release a 100 Ah cell with a silicon anode by 2026 and another with a lithium-metal anode by 2028. Toyota and Panasonic, under their joint venture **Prime Planet Energy**, showcased a prototype car equipped with a sulfide-based SSB in 2021, aiming for commercial availability in 2025 [25], [5].

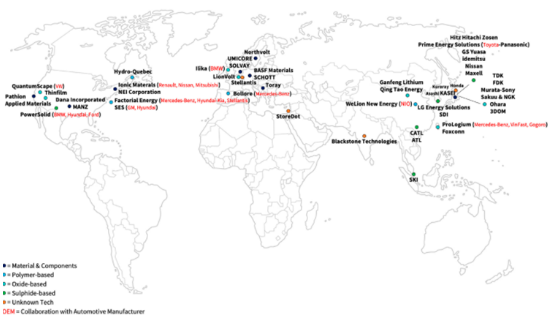

Figure 17: Overview of current key SSB market players [5]

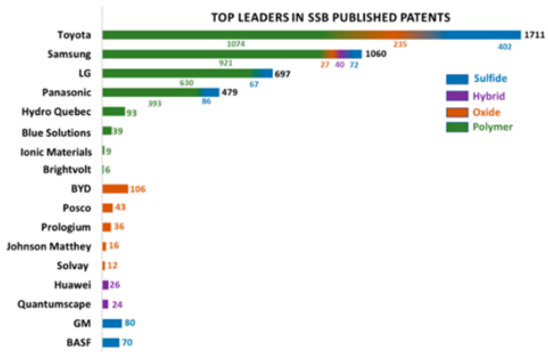

Figure 18: Patent activity related to solid-state batteries [7]

On the right side, Figure 18 represents the leaders of SSB patents across the world. In Japan, Toyota holds a dominant position in SSB patents, with over 1,700 registered innovations. Among these, a notable patent [26] introduced the use of the halide solid electrolyte Li_3YCl_6 in the positive electrode layer. This composition minimizes oxidative decomposition reactions, significantly enhancing the battery's voltage endurance. The dual application of Li_3YCl_6 as both a component of the solid electrolyte and within the positive electrode further improves voltage withstand capacity [7].

Another interesting development by Toyota Motor Corp. [27] explores the concept of a negative electrode-free battery, where lithium metal is not initially present during cell assembly but forms during the battery's charge–discharge cycles. This approach, as outlined in their patent, aims to address dendrite formation by utilizing precise formulations and concentrations of the solid electrolyte. By reducing lithium usage, this innovation highlights the importance of sustainable resource management and addresses concerns surrounding lithium's scarcity [7].

Additionally, Toyota Motor Corp. has introduced a solid electrolyte specifically engineered to address the issue of hydrogen sulfide formation, which often arises when solid electrolytes come into contact with moisture. This breakthrough involves substituting lithium with sodium to create the compound $Li_{5.1}Na_{0.3}PS_{4.4}Cl_{1.6}$. This innovative composition not only prevents water-induced reactions but also effectively inhibits sodium from substituting protons, enhancing the electrolyte's stability and safety [7].

In its pursuit of sustainability, Toyota Motor Corp. has prioritized initiatives aimed at enhancing the durability and lifespan of battery components to reduce waste. Central to these efforts is the "Battery 3R" initiative [28], which stands for "Reduce, Reuse, and Recycle." This comprehensive environmental strategy operates across multiple global markets, including Japan, the USA, Europe, China, and other Asian countries.

A notable example of the initiative's success is Toyota's collaboration with JERA Co., Inc., which resulted in the development of a large-capacity energy storage system utilizing repurposed EV batteries for non-automotive applications [29]. Also, Toyota partnered with the Tokyo Electric Power Company (TEPCO) to create a stationary storage battery system, currently under testing at the Eurus Tashirohira Wind Farm [30].

On the recycling front, Toyota has expanded its partnership with Redwood Materials to scale up battery collection and recycling efforts globally, further reinforcing its commitment to a circular economy and sustainable resource management [7].

Regarding all of the aspects described previously, it is possible to conclude that Toyota is pushing and trying to input these new technologies into the front row of electric mobility. Its actively advancing solid-state battery (SSB) technology, aiming to revolutionize electric vehicles (EVs) with enhanced performance and sustainability. The company plans to start SSB production by 2026, with mass production targeted for 2030 [31]. Figure 19 illustrates Toyota's EV battery roadmap, highlighting the transition from conventional lithium-ion batteries to advanced solid-state solutions. This progression underscores Toyota's dedication to leading the EV market by integrating new technology with sustainable practices.

	TODAY	NEXT-GENERATION		FURTHER EVOLUTION		
	2023	2026	2026-2027	2027-2028	2027-2028	TBD
	Battery for bZ4X	Performance	Popularisation	High-Performance	Solid-State 1	Solid-State 2
	Monopolar		Bipolar		N/A	N/A
Electrolyte type	Liquid				Solid	
Chemistry	Li-Ion		LiFePO*1	Li-Ion		
Driving range (WLTP)	500km	> 800km	> 600km	> 1,000km	> 1,000km	> 1,200km
Cost	-	-20% vs bZ4X	-40% vs Bz4x	-10% vs NG performance version	TBD	TBD
Fast charge time*2	~30 min.	~20 min.	~30 min.	~20 min.	~10 min.	TBD

*1 Lithium iron phosphate *2 SoC = 10-80% NOTE: Established driving range includes aerodynamic and vehicle weight improvements

Figure 19: Toyota's Battery Technology Roadmap [8]

6 Future Outlook

Solid-state batteries (SSBs) are set to play a transformative role in the future of energy storage, addressing key challenges associated with conventional lithium-ion batteries (LIBs). By replacing liquid electrolytes with solid counterparts, SSBs offer enhanced safety, higher energy density, longer lifespan, and faster charging capabilities. These improvements make them a highly attractive solution for applications ranging from electric vehicles (EVs) to clean energy storage systems, areas of critical importance in combating the climate crisis [32].

The technological progress of SSBs hinges on advancements in solid electrolyte and electrode materials. Both inorganic electrolytes like LLZO and organic alternatives such as PEO exhibit strengths and limitations. The emergence of composite solid electrolytes (CSEs), which integrate organic flexibility with inorganic stability, demonstrates significant potential to overcome these challenges. Similarly, innovations in anode and cathode materials are integral to enhancing battery performance and ensuring safety, with ongoing research exploring materials like lithium metal, silicon, and nickel-rich cathodes to optimize energy density and operational stability [5].

Despite the promising advantages, SSBs face some hurdles. Manufacturing complexities, high initial costs and challenges in scaling production remain critical barriers to widespread adoption. Achieving economies of scale and reducing material and processing costs are essential for SSBs to achieve price parity with LIBs. Encouragingly, technological synergies with existing LIB manufacturing processes could help accelerate SSB commercialization and adoption [5].

Although current market penetration is limited, the global battery market's exponential growth, driven by EV demand, creates a favorable environment for SSBs. Analysts project that with sufficient investment in R&D and manufacturing infrastructure, SSBs could secure a significant share of the energy storage market, potentially addressing key consumer concerns such as EV range and charging times. These advancements signal a promising future for SSBs as a cornerstone technology in the transition to sustainable energy systems [5], [32].

7 Conclusions

This project has extensively explored the transformative potential of solid-state batteries (SSBs) in revolutionizing energy storage systems, particularly in the context of electric vehicles (EVs). Guided by the central question, Can solid-state batteries redefine the future of electric vehicles and accelerate the transition to sustainable energy?, this work aimed to provide a descriptive analysis of how SSBs address key challenges faced by traditional lithium-ion batteries (LIBs).

By replacing liquid electrolytes with solid-state counterparts, SSBs tackle critical limitations of LIBs, such as safety concerns, limited energy density, and suboptimal charging capabilities. The research highlighted the technological advancements in SSB materials, including solid electrolytes and innovative electrode designs. Inorganic solid electrolytes like LLZO offer superior ionic conductivity and stability, while composite solid electrolytes (CSEs) demonstrate the ability to blend flexibility with performance. Similarly, improvements in anode and cathode materials, from lithium metal to nickel-rich NMC cathodes, underscore the ongoing efforts to enhance energy density and operational stability.

While SSBs show tremendous promise, this work also underscored the challenges they face. Manufacturing complexities, high costs, and difficulties in scaling production remain significant barriers. However, synergies with existing LIB manufacturing infrastructure and continued R&D investments are forging the way for broader adoption. The exponential growth of the global battery market, driven by EV demand, creates a favorable landscape for SSB integration into mainstream applications.

Through the analysis provided, this work tried to elucidate how SSBs could redefine the EV market and play a crucial role in accelerating the transition to sustainable energy. The descriptive approach highlighted that SSBs are more than just a technological advancement—they represent a critical step toward achieving global sustainability goals. By offering safer, more efficient, and higher-performing energy storage solutions, SSBs align with the urgent need for decarbonization and the shift toward renewable energy systems.

The insights gained from this work provide a foundation for further research and development in SSB technologies, highlighting their potential to drive innovation in the energy sector and beyond. Future research should focus on overcoming production challenges, reducing costs, and enhancing recycling methods to ensure the long-term sustainability of SSB technology. With continued investment and innovation, SSBs are well-positioned to become a cornerstone in the future of energy storage, enabling a cleaner, greener, and more sustainable future.

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