EUROPEAN COMMISSION

HORIZON 2020 PROGRAMME - TOPIC H2020-LC-BAT-2019
Strongly improved, highly performant and safe all solid-state batteries for electric vehicles.

GRANT AGREEMENT No. 875189

SAFELiMOVE – Deliverable Report

<< D8.6 – Battery cell and Material Development Roadmap>>

Deliverable No.	SAFELiMOVE D8.6	
Related WP	WP8	
Deliverable Title	Battery cell and Material Development Roadmap	
Deliverable Date	2023-12-10	
Deliverable Type	REPORT	
Dissemination level	Public (PU)	
Written By	Muhammad Aleem (TUB)	2023-12-10
Checked by	Muhammad Aleem (TUB)	2023-12-20
Reviewed by (if applicable)	David Echasserieau (SAFT) Laurent Castro (TME)	2023-12-13 2023-12-20
Approved by	Maria Martinez (CICe)	2023-12-21
Status	Final	2023-12-22

Disclaimer/ Acknowledgment

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 875189. The information and views set out in this publication does not necessarily reflect the official opinion of the European Commission. Neither the European Union institutions and bodies nor any person acting on their behalf, may be held responsible for the use which may be made of the information contained therein.

Publishable summary

The SAFELiMOVE project has been integral to the research and development of SSBs, focusing on enhancing materials and manufacturing processes to cater to electric vehicles (EVs) and renewable energy storage systems. The development of lithium metal anodes, solid electrolytes/polymers, and advanced cathode materials marks the project's milestones.

Innovations in anode, solid electrolyte, and cathode materials have been pivotal. Breakthroughs in hybrid electrolytes and high-nickel cathodes demonstrate the project's success in material optimization.

The SAFELiMOVE project supports the EU's objectives for a greener economy, targeting a significant increase in SSB production capacity to 5-30 GWh by 2030. This forecast aligns with the EU's ambition to transition to sustainable energy sources and positions the project at the forefront of this transformation.

By 2030, the EU aims to commercialize SSBs with enhanced energy density, durability, and cost-effectiveness. SAFELiMOVE anticipates the integration of hybrid polymer electrolytes, establishing SSBs as a key technology in the energy sector.

In conclusion, the SAFELiMOVE project's roadmap articulates a strategic and progressive approach to SSB technology. As the project advances towards its 2030 vision, it promises to catalyze a paradigm shift, facilitating the wider adoption of SSBs in electric mobility and stationary energy storage, marking a significant step toward sustainable energy solutions.

Executive summary

The development of battery technology and materials is critical to the advancement of several sectors, including electric vehicles (EVs), renewable energy storage, and consumer electronics. The reports highlight the need for innovation in battery technology, with a focus on increasing energy density, reducing costs, and improving sustainability. Key findings include:

Technology innovation: Incremental advances in lithium-ion batteries and the introduction of next-generation battery technologies, such as solid-state batteries, are critical. These innovations aim to increase energy density, reduce greenhouse gas (GHG) emissions, and reduce environmental impact.

Sustainability and circular economy: Emphasis on sustainable practices in the battery value chain is critical. This includes responsible sourcing of materials, ensuring ethical labor practices, and implementing recycling and end-of-life strategies for batteries.

Local value creation: The importance of supporting local economies, particularly in regions where raw materials are extracted, is emphasized. This includes adhering to international principles of accountability and transparency, promoting local sourcing, and investing in community development.

Policy and regulatory frameworks: Developing a supportive regulatory environment that encourages investment and innovation in battery technology is essential. This includes adapting regulations for battery-powered renewable energy and harmonizing international rules for the transport and handling of batteries.

Market Dynamics and Forecast: The reports forecast a significant increase in demand for advanced batteries, driven by the growth of electric vehicles and renewable energy systems. This surge in demand will require a robust and sustainable supply chain.

Contents

Figures

Tables

1 Introduction

As the world moves steadily into the 21st century, the demand for advanced and efficient energy storage solutions increases, especially in an electrified and environmentally conscious global environment. This comprehensive roadmap report represents a collaborative and multidisciplinary endeavor to map out the evolution of energy storage technologies from conventional lithium-ion batteries (LIBs) to innovative solid-state batteries (SSBs). This roadmap envisions transforming SSB technology by 2030 with a focus on material development, innovative battery cell design, and pathways to large-scale production.

The impetus behind this shift is the automotive sector, which has historically driven LIB advancement. This sector is leading the shift to safer, more efficient, and environmentally friendly energy storage solutions. LIB technology has significantly advanced the automotive and energy sectors and is approaching a developmental plateau, particularly in energy density, safety, and environmental impact. SSBs are not only an alternative, but a significant advancement, promising enhanced performance across multiple parameters, including energy density, safety, and longevity.

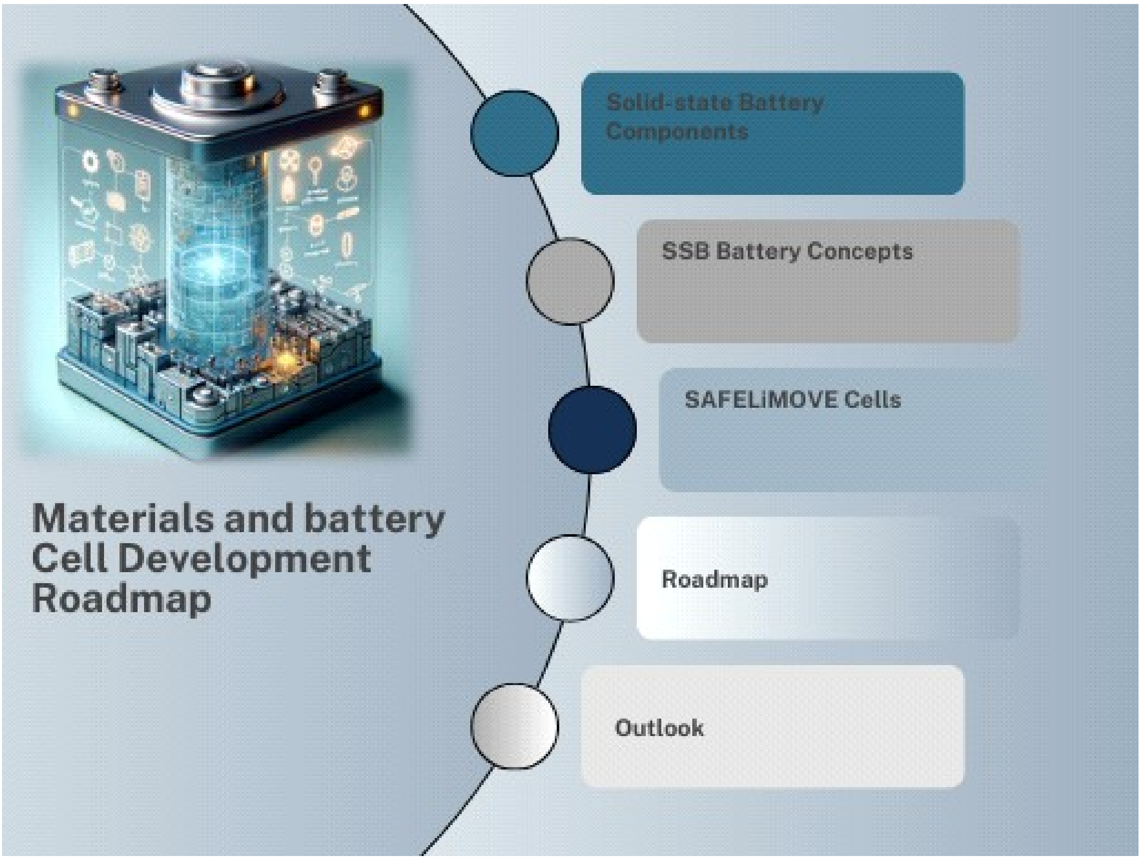
Here, we address the critical aspect of material development for SSBs. This task involves developing comprehensive and integrated roadmaps for the key components of SSBs, including anodes, cathodes, and electrolytes. The main goal of this task is to significantly cut down on production costs, which is essential for the widespread use and financial viability of SSBs. One notable initiative within this project involves HQ's efforts to boost the production of lithium anode films, which is in line with the overall objectives of the SAFELiMOVE program. This initiative is expected to introduce innovative methods for fast charging and improved performance. UMC's roadmap focuses on advancing cathode materials, particularly in reducing the reliance on cobalt in NMC materials, which is critical for cost reduction and environmental sustainability. At the same time, SCHT's research on solid electrolytes, backed by CICe's expertise in polymer and hybrid electrolytes, plays a crucial role in addressing the current limitations of SSB technology.

In conjunction with material development, this report provides a thorough overview of battery cell development, including design, scalability, and economic production. This task builds on prior research and development efforts, aiming to align different aspects of battery cell development towards an economically viable final product, aiming to optimize battery cell design to meet futuristic goals for 2030 and create a production roadmap for industrial scaling. The EU's large-scale production roadmap aims to establish a dominant presence in the global SSB market and compete effectively with established Asian and American manufacturers.

The roadmap carefully compares the KPIs of SSBs to liquid electrolyte counterparts, showcasing the advancements and potential applications of SSBs. The document presents the technical advantages of SSBs while considering the economic and environmental impacts of battery production and application. Additionally, it outlines four innovative cell concepts, providing their timelines for pilot production and market entry, and discusses the challenges and opportunities involved in scaling up production, cost estimation, and integrating new production concepts.

This roadmap is not just a strategic document but also a visionary approach to revolutionizing energy storage. It encompasses diverse perspectives, expertise, and innovative thinking all working together towards a common goal: to promote the practicality, cost-effectiveness, and environmental sustainability of SSB technology in various applications. The emphasis on the automotive industry highlights the vital importance of SSBs in shaping transportation's future. This roadmap serves as a blueprint, not simply a guide, for a future defined by efficiency, safety, and sustainability in energy storage. As such, it marks a significant stride forward towards a more electrified and eco-conscious world.

2 Solid-State-Battery (SSB)



2.1 Components of Solid-State Battery (SSB)

Solid-state batteries are at the forefront of battery technology[1]. They offer several advantages over traditional lithium-ion batteries. They use solid electrolytes instead of liquid or gel forms, which increases the energy density, which means more energy can be stored in the same amount of space, improving the compactness and duration of power. A significant safety benefit is the absence of flammable liquid electrolytes, which greatly reduces the risk of fire and explosion. These batteries also have a longer lifespan, reducing replacement frequency and environmental impact. In addition, solid-state batteries can be charged much faster than their lithium-ion counterparts can and operate effectively over a wider temperature range, benefiting various applications, including electric vehicles and consumer electronics. Despite their potential, challenges such as high manufacturing costs and scalability issues remain, but they are on the verge of revolutionizing energy storage once these hurdles are overcome.

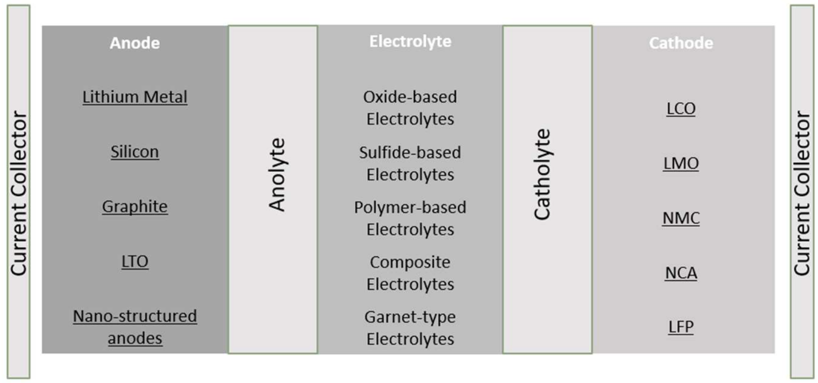


Figure 1: Components of SSB

2.1.1 Anode

Anode materials are essential to advance solid-state battery technology. Lithium metal is an ideal candidate due to its high theoretical capacity and low electrochemical potential. However, dendrite formation remains a challenge. Silicon-based materials offer a higher specific capacity compared to graphite but experience volume expansion during charging. Graphite and carbon-based materials provide greater stability and are less prone to dendrite issues despite offering lower capacity. Composite anodes, which blend materials like silicon with carbon or graphite, aim to balance high capacity with stability. Tin-based materials and titanium oxide are also considered for their high capacities and structural stability, respectively. Additionally, niobium oxide is noted for its rapid lithium-ion transport, making it suitable for fast-charging applications. Each material has distinct advantages and challenges, driving continuous research to increase performance and stability and fully exploit the potential of SSBs[1,2].

Lithium Metal: Lithium metal, often referred to as the "holy grail" of anode materials, is leading the charge in the solid-state battery (SSB) revolution. Its theoretical capacity of 3860 mAh/g surpasses traditional anode materials, offering a more efficient, compact, and lightweight energy storage solution. Its low electrochemical potential also boosts the overall cell voltage, increasing energy output. The foremost challenge for lithium metal anodes is dendrite growth, which may cause short circuits and safety hazards. To address this issue, research concentrates on creating innovative electrolytes and separators for suppressing dendrite growth, and employing surface modification techniques to stabilize the solid electrolyte interphase (SEI) layer. The future of lithium metal anodes is closely linked to the advancement of solid-state electrolytes, which have the potential to remove liquid elements and establish a more consistent setting. Innovations in nanotechnology show promise in modifying the molecular surface, yielding stronger and dendrite-resistant anodes[3]. The success of transitioning from laboratory experiments to commercial viability is critical, and endeavors are ongoing to ensure that the production of lithium metal anodes is both scalable and cost-effective. Additionally, the integration of lithium metal SSBs with renewable energy sources represents an exciting and promising frontier. This technology could be pivotal in storing energy garnered from intermittent sources such as wind and solar, ultimately paving the way and facilitating a more sustainable, resilient energy grid. With its high capacity and efficiency, lithium metal is poised to revolutionize the battery industry. Current research and technological advancements are steadily leading to practical and commercially viable solutions.

Silicon-Based Materials: Silicon anodes offer greater specific capacity compared to conventional graphite anodes, making them a promising choice for increasing the energy density of SSBs and improving battery efficiency for a given size. However, a major challenge with silicon is its high volume expansion up to 300% during lithiation, resulting in mechanical stress and decreased battery performance over time. Research focuses on nano-structuring silicon and creating silicon-carbon composites to mitigate these effects.

Graphite and Carbon-Based Materials: Graphite and other carbon-based materials are commonly used as anode materials in LIBs due to their reliable electrical conductivity and stable cycling performance resulting from minimal volume fluctuations. Despite their stability and reduced risk of dendrite formation, their lower specific capacity (around 372 mAh/g) compared to that of lithium or silicon make them a non-suitable choice for SSBs. Innovations in this field encompass improving surface modifications and developing advanced carbon materials, such as graphene, to boost performance.

Composite Anodes: Composite anodes combine high-capacity materials like silicon with more stable materials like carbon or graphite. This approach aims to leverage both advantages, offering a balance between high capacity and stability, thus improving overall battery performance. The challenge lies in optimizing the composite composition for the best performance and ensuring uniform distribution of the different materials. Research in this area focuses on advanced manufacturing techniques for scalable composite production.

Tin-Based Materials: Tin-based materials are another category of anode materials with a high theoretical capacity (994 mAh/g). They provide better structural stability than silicon but face similar challenges of significant volume expansion during charge-discharge cycles. The research is directed towards nano-structuring tin, creating alloys or composites, and applying surface coatings to improve stability and mitigate volume expansion issues.

2.1.2 Cathode

In solid-state batteries (SSBs), cathode materials are crucial for dictating performance, energy density, and safety. Lithium Cobalt Oxide (LCO) is valued for its high energy density. However, it has limitations in lifespan and safety at high temperatures, and it is often used in consumer electronics. Lithium Iron Phosphate (LFP) offers excellent thermal stability and longevity, albeit with lower energy density, making it ideal for safety-critical applications. Lithium Nickel Manganese Cobalt Oxide (NMC), particularly the NMC811 variant, strikes a balance with high energy density, reasonable safety, and cost-effectiveness, notable for its high capacity and reduced cobalt content. However, it faces challenges in thermal stability and cycling life. Lithium Nickel Cobalt Aluminum Oxide (NCA) shares similarities with NMC in high energy density. It is suited for high-power applications like electric vehicles but with potential stability issues at high temperatures. Lithium Manganese Oxide (LMO) is known for its high thermal stability and rate capability, but lower energy density and capacity fade over time. The selection of cathode material in SSBs is thus a balance of various factors, including energy density, safety, cost, and cycle life, with continuous advancements being made to meet diverse industry demands, particularly in electric vehicles and renewable energy sectors.

Lithium Nickel Manganese Cobalt Oxide (NMC811):
NMC811, a specific variant of Lithium Nickel Manganese Cobalt Oxide (NMC), is emerging as a promising cathode material for solid-state batteries (SSBs), largely due to its optimal blend of high energy density, cost-effectiveness, and reduced reliance on cobalt. Characterized by its nickel, manganese, and cobalt composition in an 8:1:1 ratio, NMC811 stands out for its significantly high nickel content, which contributes to an exceptional energy capacity, making it an ideal choice for energy-intensive applications such as electric vehicles (EVs). This high nickel composition boosts the battery's energy capacity and reduces the amount of cobalt required—a crucial factor considering the ethical and economic concerns surrounding cobalt mining. However, the increased nickel content presents challenges, particularly in thermal stability and susceptibility to degradation over numerous charging cycles. These issues can potentially affect the longevity and safety of the battery. NMC811's performance is also closely tied to the effectiveness of the solid-state electrolyte used, which needs to be highly compatible to maximize the cathode's efficiency and safety. Advances in electrolyte formulations and structural modifications of NMC811, such as coating or doping, are being extensively researched to overcome these challenges. These modifications aim to enhance the stability of the cathode material, thereby improving the battery's overall lifecycle and safety profile. The ongoing development and optimization of NMC811 reflect the dynamic nature of battery

technology research, focusing on achieving a balance between high performance and sustainability while addressing the practical concerns of cost and safety in SSB applications.

Lithium Iron Phosphate (LFP): is a cathode material used in solid-state batteries (SSBs) due to its excellent thermal and chemical stability. This enhances safety by reducing the risk of thermal runaway. LFP also has a long cycle life, making it durable over many charge-discharge cycles. Additionally, it is cost-effective due to the use of abundant, cheaper materials, unlike cobalt-based batteries. Furthermore, LFP is environmentally friendly and free from toxic elements, simplifying recycling efforts. However, LFP has a lower energy density than other lithium-ion chemistries, such as NMC. This results in larger and heavier batteries for the same energy capacity. LFP batteries feature a flat voltage discharge profile, offering consistent power output, and can operate across a wide temperature range. LFP's compatibility with various solid electrolytes, such as polymer, oxide, sulfide, and composite electrolytes, enhances its application versatility in solid-state batteries. Compatibility is crucial as it determines the efficiency, safety, and overall performance of the SSBs. Therefore, LFP is a promising option in the evolving landscape of advanced battery technologies.

Lithium Manganese Iron Phosphate (LMFP): is a cathode material that stands out for its improved safety and stability in solid-state batteries (SSBs). Its thermal and chemical robustness significantly mitigates the risk of thermal runaway. Additionally, it is more cost-effective due to the abundance and lower cost of its constituent materials compared to NMC. LMFP batteries have two flat voltage discharge profile, and compared to LFP offers a higher energy density, resulting in a smaller and lighter batteries needed for equivalent energy storage. These properties make LMFP an increasingly relevant and promising option as cathode active materials for SSBs.

2.1.3 Solid Electrolytes

Solid electrolytes are a key component of solid-state batteries (SSBs). These materials replace the liquid electrolyte found in traditional lithium-ion batteries with a solid counterpart. This solid electrolyte must have high ionic conductivity, be chemically stable, and provide a stable electrode interface.

Several types of solid electrolytes are commonly used in SSBs:

Ceramic electrolytes: These include materials such as lithium phosphorus oxynitride (LiPON), lithium lanthanum titanate (LLTO), and garnet-type electrolytes such as lithium lanthanum zirconium oxide (LLZO). Ceramic electrolytes are known for their high ionic conductivity and good chemical stability.

Glass and glass-ceramic electrolytes: These materials offer good ionic conductivity and can be engineered to have desirable properties such as a wide electrochemical window and stability against lithium metal.Both glass and glass-ceramic (LiPON, LATP,LLZO) electrolytes are at the forefront of research for solid-state batteries, as they offer paths to overcoming the limitations of traditional liquid electrolytes, such as safety concerns and limited energy density.

Sulfide solid electrolytes: are a class of solid materials with high ionic conductivity, making them promising candidates for solid-state batteries. These electrolytes typically comprise sulfur-containing compounds such as lithium sulfide (Li2S), lithium thiophosphate (Li3PS4), or argyrodite-type materials. They exhibit excellent ionic transport properties at room temperature and offer advantages like enhanced safety, wide electrochemical stability windows, and compatibility with lithium metal anodes. Sulfide solid electrolytes are being actively researched for their potential to enable high-performance and safer solid-state battery technology, particularly in applications requiring high energy density and long cycle life.

Polymer electrolytes: Made from polymers such as polyethylene oxide (PEO) with a lithium salt such as lithium bis(trifluoromethane)sulfonimide (LiTFSI), these electrolytes are flexible and easy to process. However, their ionic conductivity is typically lower than ceramic or glass electrolytes, especially at room temperature.

Hybrid Polymer electrolytes: These hybrid materials combine different types of electrolytes, such as ceramic particles dispersed in a polymer matrix. They aim to combine the advantages of each type, such as the flexibility and processability of polymers with the high conductivity and stability of ceramics.

In SSBs, the solid electrolyte must efficiently transport lithium ions between the cathode and anode while preventing electronic conduction. This is critical to the efficiency and safety of the battery. The development of solid electrolytes with improved properties is a key research area for the advancement of solid-state battery technology.

2.1.4 Compatibility between the components

2.1.4.1 Lithium Metal against Solid Electrolyte:

There are unique challenges and benefits associated with the compatibility of lithium metal with different types of solid electrolytes in solid-state batteries - sulfide, oxide and hybrid polymer. While sulfide-based electrolytes offer high ionic conductivity, they often struggle with poor interfacial stability and increased reactivity with lithium metal, which can lead to safety concerns and an increased risk of dendrite formation. On the other hand, oxide-based electrolytes have better interfacial stability and lower reactivity with lithium, making them safer, but still prone to problems related to the formation of resistive interface layers. Hybrid polymer electrolytes offer a balance with their moderate interfacial stability and safety profile. They use their flexibility to mitigate some dendrite problems. However, in terms of completely suppressing dendrite growth, they are generally less effective than oxide-based electrolytes. Each type of electrolyte interacts differently with lithium metal, affecting key aspects such as interfacial stability, dendrite formation, and overall battery longevity and safety, driving ongoing research and development to optimize these interactions.

Figure 2 : Comparison of solid electrolyte compatibility against lithium metal

2.1.4.2 NMC811 Compatibility against Solid Electrolyte

In solid-state batteries (SSBs), the compatibility of NMC811 cathode material with different types of solid electrolytes - sulfide, oxide and hybrid polymer - plays a key role in determining the performance, efficiency and safety of the battery. While sulfide-based electrolytes offer a high level of ionic conductivity, they can have problems with chemical and thermal stability when used in conjunction with NMC811, especially at higher voltages, raising potential safety concerns. Oxide-based electrolytes, on the other hand, exhibit better chemical and thermal stability with NMC811, reducing the risk of interfacial side reactions. However, they can still present problems of interfacial resistance and degradation over time. Hybrid polymer electrolytes provide a more flexible interface with NMC811, which can accommodate volume changes during cycling and improve the stability of the interface. However, their performance is affected by their intrinsic ionic conductivity and thermal properties. Each combination of cathode material and electrolyte presents a unique set of interactions with specific benefits and challenges. This underscores the need for continued advancements in materials engineering and electrolyte formulation in SSB technology.

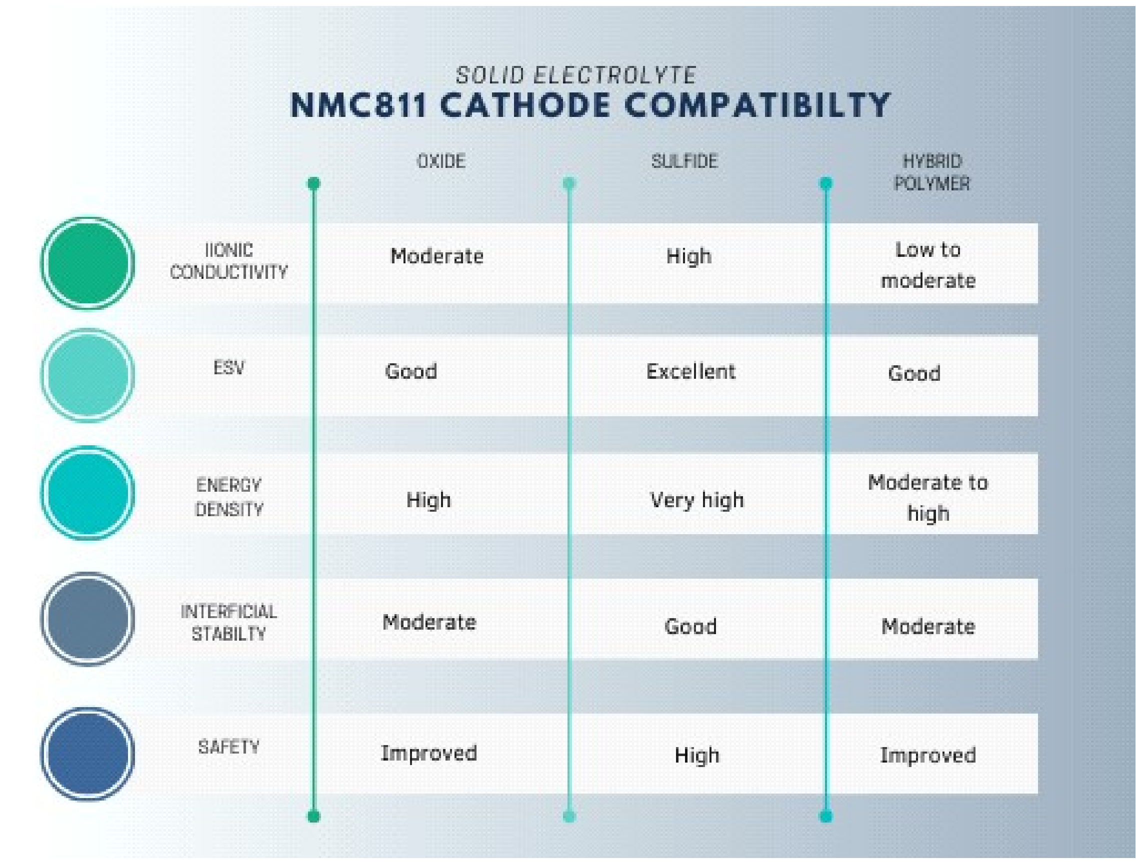


Figure 3: Comparison of Solid electrolyte compatibility against NMC811

2.2 SSB Cell Concepts

Several solid-state battery concepts have been explored in the market and scientific literature. Keep in mind that solid-state batteries are dynamic, and new concepts continue to emerge[4]. Here are some notable solid-state battery concepts:

1. Sulfide-Based Solid-State Batteries:
   - These batteries use solid electrolytes of lithium sulfide (Li2S) and related compounds.

- Sulfide-based solid-state batteries are known for their high ionic conductivity, enabling fast charge and discharge rates.

2. Oxide-Based Solid-State Batteries:
- Solid electrolytes in these batteries are typically oxide materials like lithium garnets (e.g., $Li_{6.4}La_3Zr_{1.4}Ta_{0.6}O_{12}$ or LLZO).
- Oxide-based solid-state batteries offer good stability and safety.

3. Polymer-Based Solid-State Batteries:
- Solid polymer electrolytes, such as polyethylene oxide (PEO) or poly(ethylene oxide)–poly(propylene oxide) (P(EO)n–(PO)m), are used in these batteries.
- Polymer-based solid-state batteries are known for their flexibility and potential for lower cost.

4. Glass-Based Solid-State Batteries:
- Solid electrolytes are made from glassy materials, such as sulfide or oxide-based glasses.
- Glass-based solid-state batteries offer a combination of high ionic conductivity and mechanical robustness.

5. Composite and Hybrid Solid-State Batteries:
- These batteries combine different solid electrolyte materials or use solid electrolytes with liquid or gel electrolytes.
- Composite and hybrid designs aim to leverage the strengths of multiple materials for improved performance and safety.

6. Li-Metal Solid-State Batteries:
- These batteries focus on replacing traditional lithium-ion battery anodes with lithium metal while using solid electrolytes to prevent dendrite growth.
- Li-metal solid-state batteries offer high energy density but require robust solid electrolytes to manage safety concerns.

7. Thin-Film Solid-State Batteries:
- These batteries are designed with ultrathin solid electrolyte layers, making them suitable for applications where space is limited.
- Thin-film batteries are often used in small electronic devices and microelectronics.

8. Composite Cathode Solid-State Batteries:
- In these batteries, both the anode and cathode materials are solid-state, which can improve energy density and safety.
- Composite cathode designs often use materials like lithium cobalt oxide (LiCoO2) or lithium iron phosphate (LiFePO4) as cathodes.

9. Single-Crystal Solid-State Batteries:
- Solid electrolytes and electrodes are fabricated as single crystals, which can enhance ion transport and overall battery performance.
- Single-crystal solid-state batteries aim to achieve high energy density.

10. Quantum Dot Solid-State Batteries:
- These batteries use quantum dots as building blocks for solid-state electrolytes, potentially enabling precise control over ion transport.
- Quantum dot designs are a cutting-edge research area.

It is important to note that while these concepts have been explored in research and development, their commercialization and widespread adoption may vary. Some companies were in the process of bringing solid-state battery technologies to market, but mass production and broad commercial availability were still evolving.

2.2.1 Trends for SSB Concept Cells

The energy density trend for solid-state batteries (SSB) has been on an upward trajectory, driven by advances in materials science and cell design. Historically, SSBs started with modest improvements over traditional lithium-ion batteries due to their increased safety profile and stability. However, as research into solid electrolytes and compatible electrode materials has progressed, significant gains in gravimetric and volumetric energy densities have been achieved[5].

The gravimetric energy density (measured in watt-hours per kilogram, Wh/kg) has improved as researchers developed lithium metal anodes, which offer higher capacities than traditional graphite anodes. With the advent of lithium metal anodes paired with advanced solid electrolytes, SSBs are expected to surpass the 500 Wh/kg threshold, considered a significant benchmark for the next generation of electric vehicles and portable electronics.

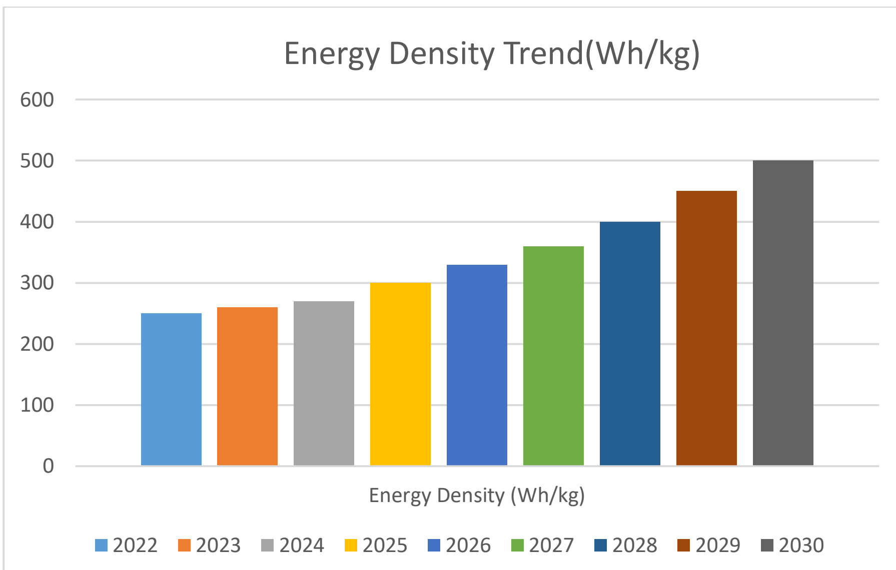


Figure 4: Energy density trend of SSB up to 2030 in Wh/kg

R & D Investment Trend," which presents data on investments in research and development (R&D) in US dollars (USD Billion) from the years 2022 to 2030. Each year is represented by a different colored bar, indicating the amount of investment in R&D. This upward trend indicates a strong and growing commitment to R&D, suggesting that SSB (presumably the entity for which the data is represented) is progressively increasing its R&D budget over the years. By 2030, the investment seems to be sustaining a level that significantly exceeds the investment at the start of the decade.

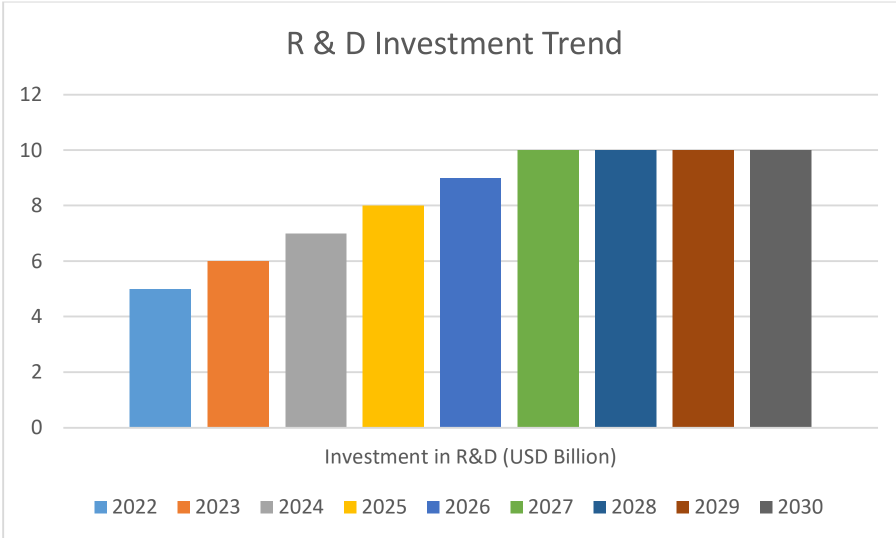


Figure 5: R&D investment in SSB tech for 2030 trend

Supply Chain Diversification shows a clear upward trajectory in SSB's diversification efforts from 2022 to 2030. Diversification levels, represented by the height of the bars for each year, start at around 15 units in 2022 and show consistent growth year over year. By 2027, there is a noticeable increase, indicating a more aggressive diversification strategy during this period. The graph peaks at nearly 35 units in 2030, suggesting that by the end of the timeline shown, SSB aims to triple its supply chain diversification efforts from 2022. This progressive increase may reflect SSB's commitment to improving the resilience of its supply chain, possibly by expanding its supplier base, entering new markets, or adopting new technologies and processes to mitigate future supply chain risks.

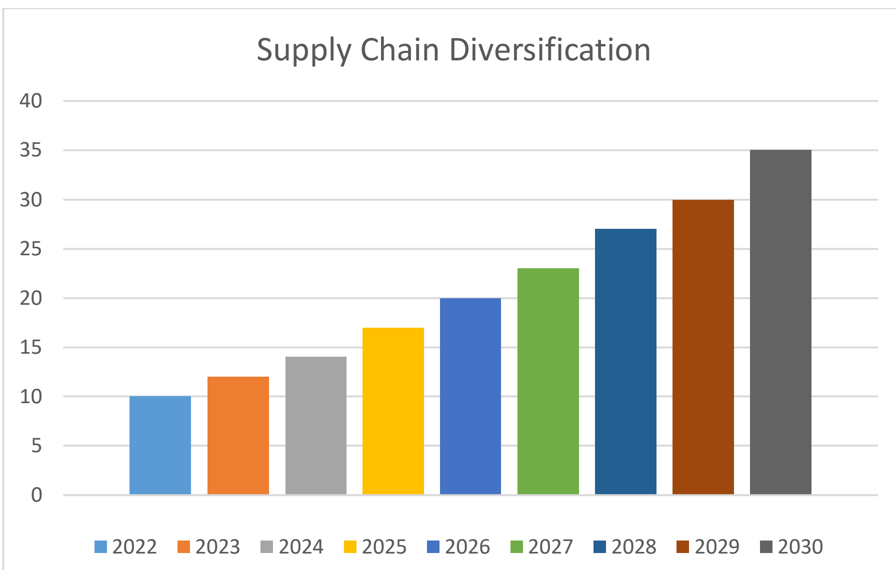


Figure 6: Supply chain diversification of SSB around the globe

The bar chart illustrates a declining cost trend in USD per kilowatt-hour from 2022 to 2030, starting at over 300 USD and decreasing steadily to just above 100 USD by 2030. This decline could signify technological advancements, a shift to more cost-effective renewable energy sources, or improved energy efficiency, which aligns with the European Union's aggressive targets for renewable energy and efficiency under its 2030 climate and energy framework and the European Green Deal. The trend suggests that SSB may benefit from or contribute to these goals, as the decreasing costs are consistent with the EU's initiative to lower emissions while making renewable energy more affordable and prevalent in the energy market by 2030.

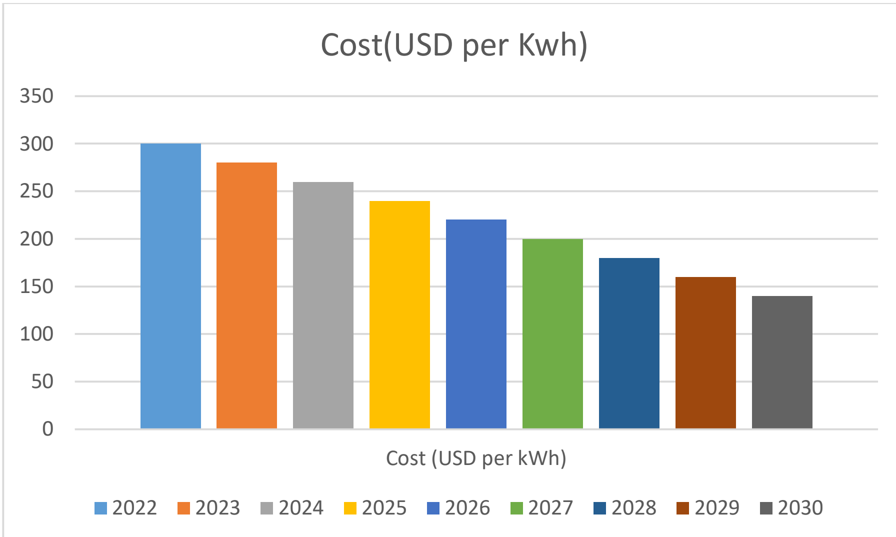


Figure 7: Cost prediction of SSB

2.3 SAFELiMOVE Cell Concept

The SAFELiMOVE project is centered on creating a new SSB cell technology that incorporates a hybrid ceramic-polymer composite electrolyte compatible with LiM anode and high-voltage cathode materials. This composite is designed to be optimized for high ionic conductivity, low interface resistance, and to prevent dendritic growth, thus enhancing the safety and performance of the cells. The project also aims to develop new electrode materials that will increase the energy density of the batteries, thus reducing the cost per stored kWh of energy.

2.3.1 State of the art vs SAFELiMOVE Technology

The SAFELiMOVE project sets out to significantly enhance the capabilities of battery technology beyond the current state-of-the-art LIBs, particularly in terms of energy density, safety, and cost. The project targets an energy density of 450 Wh/kg and 1200 Wh/L, which is substantially higher than the current highest energy density of ~300 Wh/kg provided by LIB technology[5,6].

Safety improvements are anticipated through the adoption of a solid-state design, decreasing the risk of side reactions and instabilities associated with liquid electrolytes. Material dependency is another area of advancement, with SAFELiMOVE batteries aiming to reduce reliance on critical raw materials such as cobalt.

Furthermore, the SAFELiMOVE project is developing battery cells that are expected to last over 500 cycles, offer fast charging capabilities (10 C), and reach higher voltages (up to 4.4 V) compared to the current LIB maximum of around 4.2 V. These developments are coupled with competitive costs achieved through innovative materials and efficient cell designs. In summary, SAFELiMOVE is positioning itself to offer batteries that can meet the increasing demands of EVs and other applications where higher performance and safety are paramount.

Table 1 : KPI comparison of State of the art LIB tech vs development inside SAFELiMOVE

Feature	State-of-the-Art LIB Technology (as of the report)	SAFELiMOVE Project Developments
Energy Density	~300 Wh/kg	Targeted 450 Wh/kg and 1200 Wh/L
Safety	Risks with liquid electrolytes	Solid-state concept with decreased risk of side reactions and instabilities
Material Dependency	Dependent on cobalt and other materials	Reduced dependency on critical materials like cobalt
Cycle Life	Varies, typically over 500 cycles	Targeting over 500 cycles
Charge Rates	Generally slower charging	Fast charge (10 C) capabilities by 2030
Voltage	Up to 4.2 V	Optimizing towards 4.4 V
Cost	Varies, economies of scale in play	Competitive cost with innovative material and cell design
Material Innovation	Graphite-based anode and liquid electrolyte	High capacity LiM anode, Ni-rich NMC cathode, hybrid ceramic-polymer electrolyte

2.4 SSB Production

The production of SSBs involves a sophisticated process, beginning with preparing materials like the cathode, anode, and solid electrolyte. The cathode, typically a lithium-based compound, and the anode, which can be lithium metal or other compatible materials, are prepared separately. The solid electrolyte, made from ceramics, polymers, or composites, is also synthesized and processed into a fine powder. These components are then assembled in layers, with the solid electrolyte sandwiched between the anode and cathode. This assembly occurs in a highly controlled, moisture-free environment to prevent material degradation. The assembled cell is sealed in a protective casing for stability and safety. The final steps involve a series of formation and conditioning cycles to activate the battery and ensure optimal performance. Each cell undergoes stringent testing for capacity, safety, and durability before being integrated into larger battery packs, complete with a battery management system for operational control. This complex process highlights the advanced technology and precision involved in producing solid-state batteries.

2.4.1 Lithium Metal Production:

In this section, we provide information about the process developed by Hydro-Québec for the production of lithium metal as anode materials for solid-state batteries (SSBs). Here is the detailed process based on the information provided:

Hydro-Québec (HQ) has refined a method for producing lithium metal used in the anodes of SSBs. They have surmounted technical challenges to create very thin films of lithium metal with a highly uniform surface, which is crucial for the efficient operation of the battery. The process involves:

1. Unwinding: The production begins with the unwinding of raw lithium metal material, which is typically supplied in rolls.

2. Diffusion Lamination: During this step, the lithium metal is laminated to ensure uniform thickness and consistency across the film. This lamination process likely also involves compressing the lithium to a specified density, enhancing its electrochemical properties.

3. Precision X-Ray Monitoring: To ensure the film's thickness is within the required specifications, precision X-ray monitoring is employed. This allows for real-time measurements and adjustments during the manufacturing process.

4. Rewinding: After reaching the desired thickness and uniformity, the lithium metal film is rewound. This is typically done under controlled environmental conditions to prevent any contamination or reaction of the lithium with moisture or air.

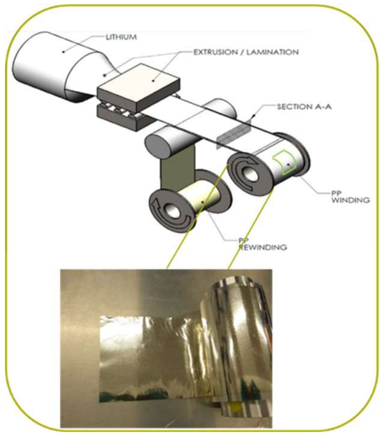


Figure 8: Production process of thin lithium metal foil developed by HQ

Hydro-Québec has specifically opted for the 40 µm (micrometer) thick lithium metal anode for the remainder of their work. In order to optimize the production process, they have paid close attention to factors like roller tensions and the rolling and feeding speeds. These factors are crucial for achieving the desired film thickness and homogeneity. Additionally, the gap openings through which the lithium metal passes are finely adjusted to attain the required thickness.

This careful optimization of production parameters ensures that the lithium metal anode produced is of high quality, with a uniform surface that is essential for the efficiency and longevity of solid-state batteries. The image also indicates that this project has received funding from the European Commission, highlighting its importance and the innovation involved in the development of advanced battery materials.

2.4.2 Hybrid Polymer Electrolyte Production:

The synthesis of the hybrid electrolyte for the SAFELiMOVE project involved several levels of development, each tailored to optimize the properties of the polymer electrolyte (PE) for use as either an electrolyte/separator or catholyte. Here are the details of the synthesis and characterization process for each level:

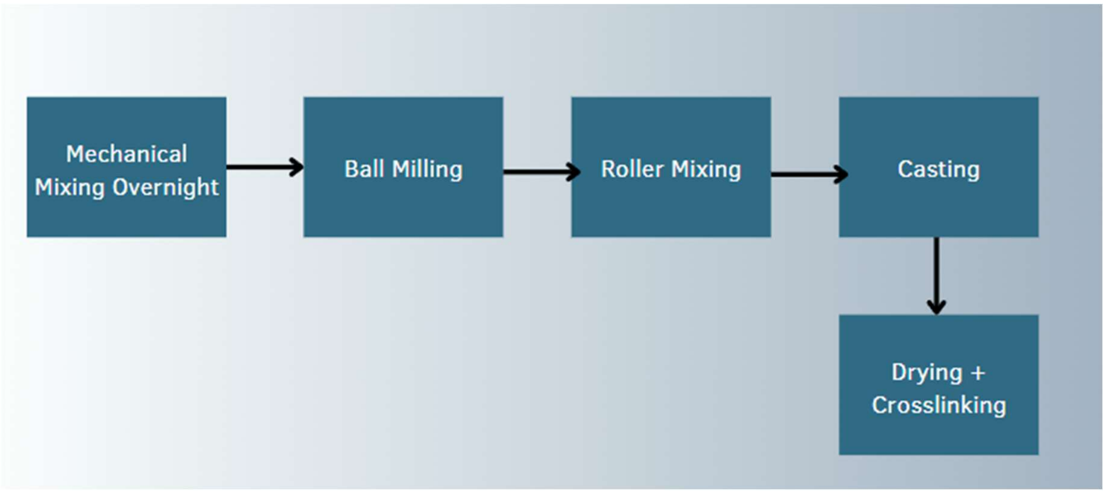


Figure 9: Process flow diagram for the production of hybrid solid electrolyte

Hybrid Ceramic Polymer Electrolyte (HCPE) Development:
The HCPE development progressed through levels as follows:

Level 1 HCPE: Used EO-PO/LiTFSI + 10 vol% LLZO. The LLZO content impacted the ionic conductivity, with lower conductivity at higher LLZO content. The HCPE showed semicrystalline behavior with a melting temperature of 31 °C and a low glass transition of -41 °C, confirming high thermal stability.

Level 2 HCPE: Incorporated 5 vol% LATP for better stability and performance, with optimized processing parameters for homogeneous dispersion of the ceramic component into the polymer matrix.

Level 3 HCPE: Addressed inhomogeneous plating and stripping issues observed with Level 2 HCPE by implementing a double-coated HCPE approach, which was easier to scale up.

Each level aimed to optimize the electrolyte's thermal and electrochemical stability, ionic conductivity, and mechanical properties while ensuring compatibility with the ceramic components and overall stability in the intended application environment. The development process was iterative, with each level building on the feedback and findings from the previous one.

2.4.3 SSB Pouch Cell Assembly:

The process involves precise cutting of anodes, solid electrolyte (SE) membranes, and cathodes, stacking them in order, wrapping, welding tabs, and housing the assembly in a pouch which is then sealed. The final step is the electrical formation of the cell. Notably, the lamination step ensures good contact between components, and compared to traditional lithium-ion batteries, the SSB process omits liquid electrolyte filling and degassing, leading to cost savings.

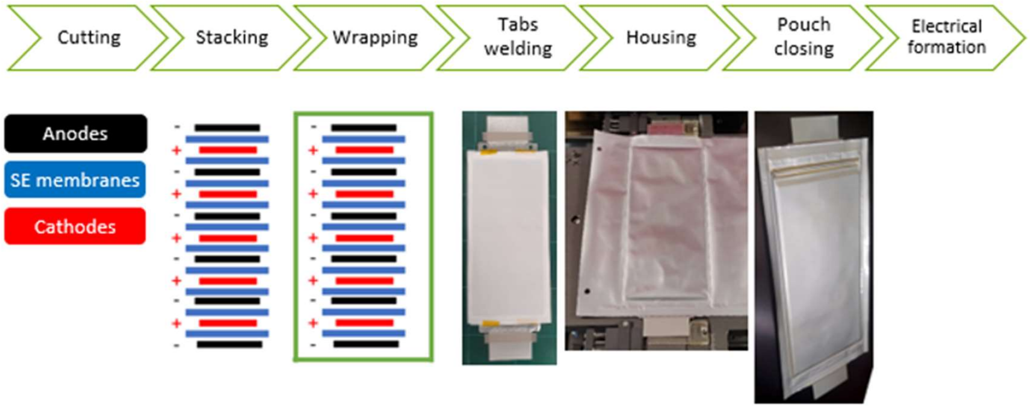


Figure 10: Pouch cell assembly flow diagram process developed by SAFT

2.5 Roadmap

The roadmap for solid-state batteries (SSBs) leading up to 2030 signifies a pivotal shift in battery technology with substantial advancements and commercialization efforts. Key industry players like Toyota are at the forefront, intending to roll out new battery technologies, including SSBs. These efforts are part of a broader strategy to deliver batteries with higher power, extended driving range, faster charging times, and reduced costs. The development of solid-state batteries is particularly promising due to their potential for greater energy density, safety, and longevity than current lithium-ion batteries.

By the end of the decade, Toyota anticipates that their SSBs will offer a 20% increase in driving range and the ability to charge from 10% to 80% in 10 minutes or less. The goal is to achieve these batteries' mass production and commercial viability by 2027/28, with initial applications likely in battery electric vehicles (BEVs).

Moreover, research initiatives like the one from the Fraunhofer Institute, under Germany's "Battery 2020" initiative, also contribute to the SSB development landscape, with roadmaps extending beyond 2030. These roadmaps direct research and development efforts and support knowledge exchange and technology transfer to ensure that SSBs reach their full potential.

The collective global efforts outlined in these roadmaps are geared towards overcoming current battery limitations and meeting the rising demand for more efficient, durable, and eco-friendly energy storage solutions. As we approach 2030, these developments are expected to play a critical role in the broader adoption of electric vehicles and the transition to renewable energy sources.

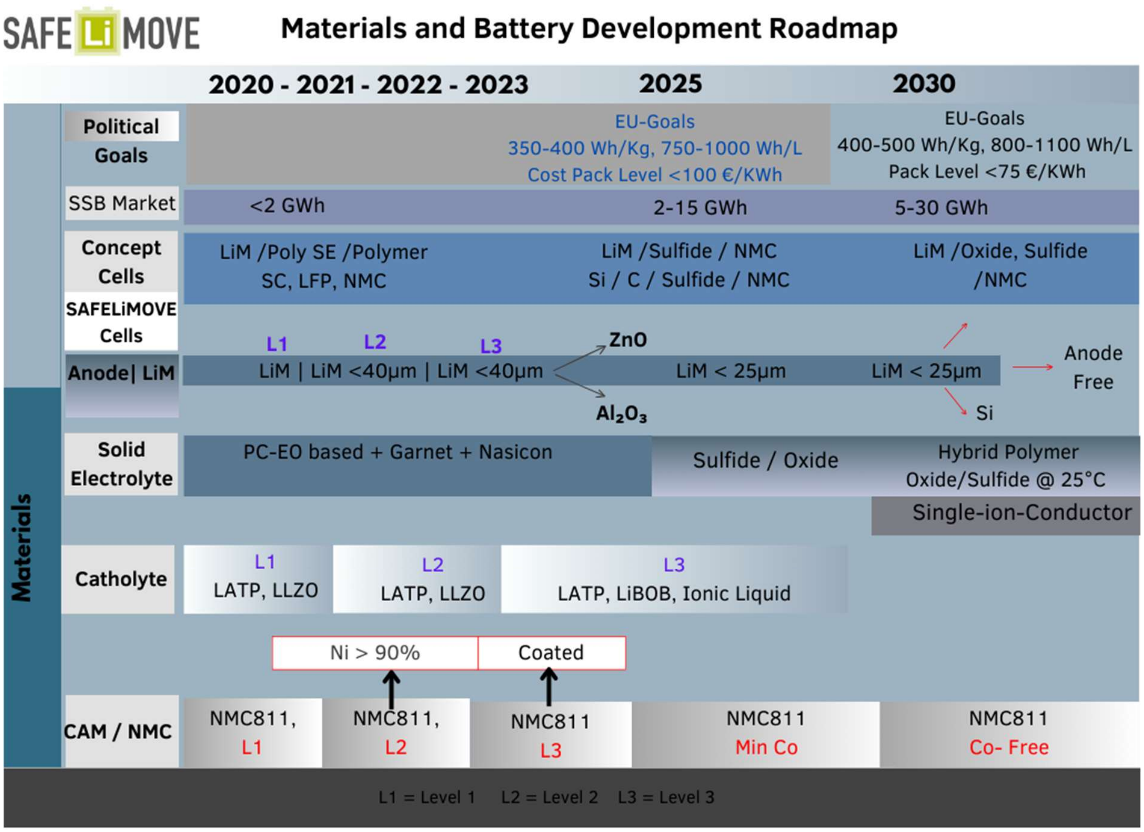


Figure 11: Battery Cell and Materials roadmap development for 2030

The roadmap outlines the material and battery development for solid-state batteries (SSBs) from 2020 to 2030, as part of the SAFELiMOVE project. Here's a summary of the roadmap details:

Political Goals and SSB Market:

2020-2023: The initial phase focuses on developing SSB concepts with an emphasis on lithium metal (LiM) anodes, hybrid/polymer electrolytes, and cathodes comprising nickel manganese cobalt (NMC).
2025: The intermediate goals include achieving specific energy targets of 350-400 Wh/kg and 750-1000 Wh/L at a pack level cost of less than €100/kWh, with a production capacity of 2-15 GWh.
2030: The long-term EU goals are more ambitious, targeting 400-500 Wh/kg, 800-1100 Wh/L, and a pack level cost below €75/kWh, with a production capacity of 5-30 GWh.

Concept Cells - SAFELiMOVE Cells:

L1 to L3 (Level 1 to Level 3): The development progresses from Level 1 through Level 3 cells, with advancements in anode materials to reduce the size of lithium anode thickness, improvements in solid electrolytes, and the integration of catholytes to promote ionic conductivity into the cathode.

Materials:

Anode: The roadmap shows a transition from thick lithium metal (LiM) towards the decrease of the LiM anode thickness and ultimately to an anode-free design by 2030.
Solid Electrolyte: The initial phases use PO-EO based electrolytes with garnet and NASICON-type materials. By 2030, the focus shifts to sulfide/oxide solid electrolytes, hybrid polymer electrolytes, and single-ion conductors.

Catholyte: The cathode materials evolve from LATP and LLZO to include lithium bis(oxalato)borate (LiBOB) and ionic liquids, with an emphasis on high nickel content (over 90% Ni) and a move toward cobalt-free cathodes.

Cathode Active Material (CAM)/Nickel Manganese Cobalt (NMC):
The NMC cathode materials evolve from NMC811, with refinements in composition across the different levels to minimize cobalt content and eventually move towards cobalt-free solutions.

The roadmap is a strategic plan designed to guide the development of SSBs with improved energy density, safety, and cost-effectiveness, in line with the political and market goals for the next decade. This development is expected to enhance the performance of electric vehicles and energy storage solutions, contributing to a greener and more sustainable energy landscape.

3 Conclusions and Recommendations

SAFELiMOVE project has approached its conclusion with a comprehensive understanding of the challenges and opportunities inherent in the development of solid-state batteries. While the project has achieved significant milestones in the design, synthesis, and characterization of advanced battery materials, ongoing vigilance in risk management remains crucial. As we recommend future directions, it is imperative to maintain a dynamic risk register, continuously updated to mitigate emerging threats. This proactive stance should be coupled with a commitment to sustainability and scalability, ensuring that the technological advancements in battery technology translate into practical, commercially viable solutions. Furthermore, the project should maintain an adaptable and responsive strategy towards regulatory changes and market demands, ensuring that the transformative potential of solid-state batteries is fully realized in a rapidly evolving energy landscape.

4 References

1. Schmaltz, T. *et al. Solid-State Battery Roadmap 2035+*. (2020).
2. Michaelis, S. *et al. Imprint Publisher VDMA Battery Production Lyoner Str. 18 60528 Frankfurt am Main*. http://battprod.vdma.org (2018).
3. Miyazaki, R. High-Capacity Anode Materials for All-Solid-State Lithium Batteries. *Frontiers in Energy Research* vol. 8 Preprint at https://doi.org/10.3389/fenrg.2020.00171 (2020).
4. Lin, D., Liu, Y. & Cui, Y. Reviving the lithium metal anode for high-energy batteries. *Nat Nanotechnol* **12**, 194–206 (2017).
5. Sun, Y. K. Promising All-Solid-State Batteries for Future Electric Vehicles. *ACS Energy Lett* **5**, 3221–3223 (2020).
6. Wu, D. & Wu, F. Toward better batteries: Solid-state battery roadmap 2035+. *eTransportation* **16**, 100224 (2023).
7. Berckmans, G. *et al.* Cost projection of state of the art lithium-ion batteries for electric vehicles up to 2030. *Energies (Basel)* **10**, (2017).
8. *Research and Innovation Roadmap on Battery Technologies Powering Europe's Green Revolution: Paving the Way to a More Resilient and Sustainable Battery Industry 2*.

Appendix A- Acknowledgement

The author(s) would like to thank the partners in the project for their valuable comments on previous drafts and for performing the review.

Project partners:

#	Partner	Partner Full Name
1	CICe	CENTRO DE INVESTIGACION COOPERATIVA DE ENERGIAS ALTERNATIVAS FUNDACION, CIC ENERGIGUNE FUNDAZIOA
2	SCHOTT	SCHOTT AG
3	UMICORE	UMICORE
4	HYDRO-QUEBEC	HYDRO-QUEBEC
5	SAFT	SAFT
6	RENAULT SAS	RENAULT SAS
7	TME	TOYOTA MOTOR EUROPE NV
8	IKERLAN	IKERLAN S. COOP
9	CEA	COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES
10	CIDETEC	FUNDACION CIDETEC
11	TUB	TECHNISCHE UNIVERSITAT BERLIN
12	RWTH AACHEN	RHEINISCH-WESTFAELISCHE TECHNISCHE HOCHSCHULE AACHEN
13	ABEE	AVESTA BATTERY & ENERGY ENGINEERING
14	LCE Srl	LIFE CYCLE ENGINEERING SRL
15	UNIRESEARCH BV	UNIRESEARCH BV