SUBLIME

Solid state sUlfide Based LI-MEtal batteries for EV applications

Deliverable 2.4 - Upgraded requirements and targets for 2030

Mattia Giuliano
CRF

Riccardo Rocca
CRF

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Reviewed by (if applicable)	David Echasserieau (SAFT) Alexander Tesfaye (UMICORE)	2024-09-25 2024-09-30
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Publishable summary

This document outlines the evolution of requirements for battery specifications, performance, and cost throughout the project. Initially, the targets set for energy density, specific energy, and cost were ambitious, aligning with industry expectations. As experimental testing progressed, the project successfully achieved its theoretical objectives in terms of energy parameters and production costs. Notably, production costs were significantly lower than anticipated, as detailed in Deliverable D6.6, "Cell Cost Assessment."

However, despite the theoretical success, several technical challenges arose during the practical phases of cell assembly and testing. These issues included self-discharge, short circuits, and rapid performance decay, which negatively impacted the overall performance and scalability of the batteries. These challenges limited the project to assembling smaller-scale coin and pouch cells, preventing the full realization of larger cell formats that are more suitable for automotive applications.

In summary, while the project made important strides in advancing battery technology and cost reduction, further work is needed to address these technical issues. Overcoming these challenges will be crucial for successfully scaling solid-state battery technology for automotive use, enabling longer-lasting, more efficient electric vehicles in the future.

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Abbreviations

SYMBOL	SHORTNAME
ASSB	All Solid-State Batteries
EVs	Electric Vehicles
SSBs	Solid-State Batteries

1 Introduction

In previous project deliverables, D2.1 and D2.2, the requirements for battery specifications, performance, and costs were thoroughly documented and explained. These initial targets were set to ensure that the developed battery technology would meet the demands of the automotive industry, providing competitive energy density, specific energy, and cost efficiency. As the project progressed, these requirements evolved in response to real-world testing and the experimental results that emerged from ongoing research and development efforts. The experimental findings provided valuable insights into the technological feasibility of the proposed objectives, leading to refinements in both the targets and the approach to achieving them.

Throughout the project, a systematic process of benchmarking was carried out, where initial theoretical expectations were compared against experimental outcomes. The following document presents a table that summarizes the most important parameters defined at the project's inception, alongside the actual experimental results and the calculated performances of scaled-up battery cells. This comparison highlights the significant advances made, as well as the challenges encountered in scaling the technology from small, experimental cell formats to larger, more commercially viable cells.

While the project successfully met several of its theoretical goals, such as achieving lower-than-expected production costs and reaching target-specific energy and energy density figures, there were notable technical challenges encountered during cell assembly and testing. Issues like self-discharge, short circuits, and rapid performance decay hindered the overall performance of the cells, particularly when scaling up from small coin cells to larger pouch formats. Despite these difficulties, the insights gained from this research provide a strong foundation for future development and optimization of solid-state battery technologies.

The subsequent sections of this document will delve deeper into the detailed comparison of theoretical and experimental results, outlining both the achievements and the areas that require further investigation. By reflecting on these outcomes, we can better understand the steps needed to refine the technology for broader automotive applications, ultimately guiding the path towards commercial viability.

2 Upgraded requirements

In D2.1 and D2.2 requirements for specifications, performances and cost were extensively reported and explained. During the project activities those requirements evolved based on the testing results, hereafter is reported a table that summarizes the most important requirements for batteries defined at the beginning of the project compared with the experimental results obtained.

Table 1 Parameters defined at the beginning of the project, experimental results and calculated performances.

Parameter	Defined at the beginning of the project	1 Ah Cell (Experimental)	10.2 Ah Cell (scaled-up from 1 Ah Cell)	9.56 Ah Cell (Theoretical)
Voltage (V)	2.5 – 4.4	3 – 4.3	-	-
Specific Energy (Wh/kg)	From 400 to 450	93	93	465
Energy Density (Wh/L)	From 750 to 1200	121	225	912
Cost (€/kWh)	80€ by 2025, 75€ by 2030	-	-	122.02 $

From a theoretical standpoint, the objectives of the project were fully achieved. The specific energy and energy density of the cells are in line with the targets established at the onset of the project activities. These parameters were carefully defined at the beginning to ensure alignment with the project's goals, and the outcomes matched those expectations. The calculation of the cost for the battery pack was a challenging and complex task. To approach it, the team began by referencing the cost of a battery pack based on NMC (Nickel Manganese Cobalt) technology as reported by Argonne National Laboratory[1]. According to this data, the cost of producing the cell system is approximately 110$ per kWh, with material costs accounting for around 63% of the total cost, or 69$ per kWh. When estimating the production cost of a solid-state battery, a rough approximation was made by replacing the traditional separator and liquid electrolyte with an LPSCL (Lithium Phosphorus Sulfur Chloride) solid electrolyte. The material costs for these components were analysed individually. For instance, the cost of the separator, which makes up 10% of the total material cost, was noted to increase from 1$ per square meter to 2$ per square meter when switching to solid-state technology. Similarly, the cost of the electrolyte—also comprising 9% of the material cost—was found to increase more significantly. While the liquid electrolyte in conventional systems starts at 15$ per square meter, the cost rises to 85$ per Liter when using LPSCL, based on an LPSCL price of 50$ per kilogram. When replacing conventional materials with solid-state alternatives, particularly the solid-state separator and electrolyte, the overall material cost was recalculated. Using the LPSCL electrolyte separator, the new material cost came to approximately 107.94 $ per kWh. Considering the production cost is reported to be 22% of the total cost, the costs related to the cell production covers the 12.8% that gives 14.08 $/kWh. In the end the production cost of a solid-state battery, considering replacing the liquid electrolyte and the separator with a solid electrolyte and considering the same production cost as "conventional" batteries is 122.02 $ per kWh against the 124.08 $/kWh for the "conventional" batteries. This analysis indicated that the transition to solid-state technology results in only a modest reduction in material costs when compared to traditional battery systems. While the shift to solid-state components does offer some potential for cost savings, the reduction achieved at this point is not particularly significant. However, it is important to note that there remains considerable opportunity for further cost reductions as the technology advances and production processes become more efficient. With ongoing research and development, as well as economies of scale, it is likely that solid-state battery costs will decrease more substantially in the future, making the technology more competitive and economically viable.

However, while the theoretical aspects of the project were a success, several technical challenges emerged during the practical phases of cell assembly and testing. These challenges included issues such as self-discharges, short-circuits, and a very fast decay in performance over time. These phenomena significantly impacted the cells' overall performance, limiting their efficiency and long-term reliability. Self-discharge refers to the loss of charge when the battery is idle, which reduces its available energy capacity. The occurrence of short circuits, which can arise from flaws during assembly or internal defects, further degraded the battery's performance and safety. Additionally, the fast performance decay was a major concern, as it indicates a rapid deterioration of the battery's ability to retain energy and deliver consistent power over repeated cycles.

As a result of these technical difficulties, the project was constrained in terms of the types of cells that could be assembled and tested. Specifically, the team was limited to producing coin cells and small pouch cells, rather than larger-scale batteries. These smaller cell formats allowed for testing in controlled environments but do not reflect the full range of potential applications, particularly for automotive or large-scale energy storage systems. The reduced scale of these cells makes it challenging to evaluate the technology's performance under conditions that would more closely mimic real-world applications. Nonetheless, the insights gained from the assembly and testing of these smaller cells provide valuable information that will guide further development efforts.

In conclusion, while the project achieved its theoretical goals in terms of energy parameters and cost efficiency, the technical hurdles encountered during the practical phases will require further investigation and optimization. Addressing these issues will be critical to ensuring that the technology can be scaled up for broader applications, and future work should focus on overcoming these assembly and testing difficulties to unlock the full potential of the technology developed within the SUBLIME project.

3 Targets for 2030

Battery market is in continuous evolution: automotive companies, battery producers and research centres are pushing forward the capabilities and forecasts of Lithium-ion batteries. All Solid-State Batteries (ASSB) are one the most promising, but at an early stage, technology to completely revolutionize the market. Targets are challenging and in continuous evolution.

The automotive industry is undergoing a transformative shift toward electrification, with electric vehicles (EVs) at the forefront of global efforts to decarbonize transportation. As governments set ambitious targets for reducing greenhouse gas emissions and phasing out internal combustion engine vehicles, the need for advancements in battery technology has never been more urgent. Solid-state batteries (SSBs) represent a potential breakthrough in the automotive sector, promising significant improvements in energy density, safety, charging speed, and lifespan compared to the current industry standard, lithium-ion (Li-ion) batteries. By 2030, solid-state batteries are expected to reach commercial viability and widespread application, enabling a new era of electric vehicles with longer ranges, faster charging times, and lower costs. This chapter delves into the future targets for solid-state batteries in the automotive field by 2030, exploring the technological advancements, commercialization timelines, and the potential challenges and opportunities that lie ahead.

One of the most crucial factors for the success of electric vehicles is the energy density, which determines how much energy a battery can store relative to its weight. Higher energy density translates directly into longer driving ranges, a critical factor in overcoming consumer "range anxiety" and making EVs more competitive with gasoline-powered vehicles. Conventional lithium-ion batteries offer energy densities in the range of 200-300 Wh/kg. While this is sufficient for many modern EVs, it limits the driving range to around 200-300 miles on a single charge for most mass-market vehicles. By 2030, solid-state batteries are expected to achieve energy densities between 600 and 800 Wh/kg [2,3,4], with some projections suggesting that more could be attainable. Higher energy density will be a game-changer for electric vehicles, particularly in the luxury and long-range segments. Electric trucks, SUVs, and high-performance vehicles will especially benefit, as these categories typically require more energy to power larger and heavier models. A higher energy density also allows for more compact battery packs, freeing up space for other vehicle components and enhancing vehicle design flexibility.

Safety has always been a critical concern in the design of electric vehicles, with thermal runaway being one of the primary risks associated with current lithium-ion batteries. Solid-state batteries promise to greatly enhance the safety of EVs. Commercially available Lithium-ion batteries use liquid electrolytes, which are flammable and prone to leakage, leading to potential fire hazards in the event of damage or manufacturing defects. EV manufacturers have implemented numerous safety mechanisms, but the risk remains. By 2030, solid-state batteries are expected to be fully commercialized, with the solid electrolytes replacing flammable liquid ones. Solid electrolytes are inherently more stable and less reactive at high temperatures, which drastically reduces the risk of thermal runaway. This enhanced safety could eliminate the need for complex cooling systems in EVs, simplifying battery design and reducing vehicle costs. In conventional batteries, thermal runaway can occur when the temperature rises due to internal short circuits or mechanical damage, causing a chain reaction that leads to the battery catching fire. Solid-state electrolytes are more thermally stable, meaning they can withstand higher temperatures without breaking down or creating hazardous conditions. This greatly reduces the likelihood of thermal runaway. Solid-state batteries typically have a wider operating temperature range. They can perform safely and efficiently in higher temperatures without significant degradation, which is a key improvement in their thermal stability. This ability to operate under a broader range of temperatures improves safety and makes them suitable for more demanding applications. Solid-state batteries can achieve higher energy densities than traditional lithium-ion batteries. Despite this increase in energy storage, the solid electrolyte's superior ion transport properties often result in less heat generation during charging and discharging cycles. This further enhances thermal stability and reduces overheating risks. Improved safety will not only benefit consumers by reducing the risk of catastrophic battery failures, but it will also lower insurance costs for EV manufacturers and drivers. Furthermore, the enhanced safety of solid-state batteries could unlock new applications, such as in aerospace or high-speed electric vehicles, where safety and weight are paramount concerns.

Charging speed remains one of the most significant barriers to widespread EV adoption. Today's EVs typically take 30-60 minutes to charge to 80% capacity using a fast charger, which is still slower than the time it takes to refuel a gasoline vehicle. Solid-state batteries are poised to offer a solution to this issue by enabling much faster charging. Conventional Lithium-ion batteries are limited in charging speed due to the risk of lithium plating (the formation of metal deposits on the anode, which can degrade the battery over time) and the generation of excess heat during fast charging. Solid-state batteries are expected to support charging times as low as 10-15 minutes for an 80% charge, achieving parity with the refuelling time of internal combustion engine vehicles. This will be possible due to the increased thermal stability of solid electrolytes, which can handle higher charge rates without degrading the battery's performance or lifespan. Faster charging will significantly improve the convenience of EV ownership, particularly for long-distance travellers and fleet operators. The development of ultra-fast charging infrastructure in parallel with solid-state batteries will be key to achieving widespread adoption. Additionally, reduced charging times could lead to smaller battery packs for certain vehicles, lowering costs and vehicle weight while maintaining consumer convenience.

Battery cycle life is another critical performance metric for electric vehicles. A longer cycle life means fewer battery replacements over the vehicle's lifetime, reducing both the environmental impact and the cost of ownership. Current lithium-ion batteries typically last for 1,000 to 3,000 cycles, after which their capacity degrades significantly. This translates to a battery lifespan of around 8-10 years for most EVs, after which performance may decline to a point where the battery needs replacement. Solid-state batteries are expected to achieve a cycle life of 5,000 to 10,000 cycles, effectively doubling or tripling the lifespan of current lithium-ion batteries. This would extend the life of an EV's battery to over 15 years in most cases, aligning it more closely with the overall lifespan of the vehicle. Improved cycle life will greatly enhance the durability and sustainability of electric vehicles, reducing the need for costly battery replacements. This will also reduce the environmental impact of battery production, as fewer batteries will need to be manufactured and disposed of. EVs with long-lasting solid-state batteries will be especially attractive to fleet operators and businesses that require vehicles with high utilization rates and long service lives.

Cost is one of the most significant barriers to EV adoption, particularly in the mass-market segment. While the cost of lithium-ion batteries has been falling steadily over the past decade, solid-state batteries could provide an even more dramatic reduction in costs over the long term. The cost of lithium-ion batteries in 2015 was around 400 € per kWh, while in 2023 was near 170 €/kWh, with projections suggesting that costs could fall below $100 per kWh by 2025. However, the cost of producing solid-state batteries is currently much higher due to challenges in materials and manufacturing processes. Advancements in manufacturing techniques and economies of scale are expected to bring the cost of solid-state batteries down to below $69 per kWh in average by 2030 [5], making them competitive with or even cheaper than conventional lithium-ion batteries. This will be achieved through innovations in solid electrolyte materials, improved automated production processes, and the reduction of rare or expensive materials in battery construction. Lower battery costs will translate directly into lower vehicle costs, making electric vehicles more affordable for the average consumer. As battery prices drop, we can expect to see price parity between EVs and internal combustion engine vehicles by the end of the decade. This will help drive mass adoption of electric vehicles, particularly in emerging markets where cost sensitivity is a major factor in vehicle purchasing decisions.

While solid-state battery technology has shown significant promise in laboratory settings and small-scale prototypes, scaling up to mass production and widespread deployment is one of the greatest challenges the industry faces. Several companies, including Toyota, QuantumScape, Solid Power, and Samsung, have made substantial progress in solid-state battery development. However, most of these efforts are still in the prototype stage, and large-scale production remains several years away. By 2030, solid-state batteries are expected to enter full-scale commercial production. Major automakers like Toyota and BMW have announced plans to launch solid-state battery-powered vehicles by the mid-

2020s, with mass-market vehicles expected by the end of the decade. The deployment of gigafactories specifically designed to produce solid-state batteries will be key to achieving cost reductions and meeting global demand. The successful commercialization of solid-state batteries will mark a turning point for the electric vehicle industry, enabling a new generation of EVs that are safer, more efficient, and more affordable. Automakers that can successfully integrate solid-state batteries into their vehicle platforms will have a significant competitive advantage in the increasingly crowded EV market.

The road to 2030 will be a critical period for the development and deployment of solid-state batteries in the automotive sector. By achieving breakthroughs in energy density, safety, charging speed, cycle life, and cost reduction, solid-state batteries will play a pivotal role in the mass adoption of electric vehicles. These advancements will not only make EVs more practical and affordable for consumers but will also contribute to global efforts to reduce carbon emissions and combat climate change. While challenges remain, particularly in terms of manufacturing scalability and commercialization timelines, the next decade holds immense promise for solid-state batteries. As research continues and investment pours into the field, the automotive landscape is set to be transformed by the widespread adoption of this revolutionary technology, heralding a new era of cleaner, safer, and more efficient transportation by 2030.

Stellantis/CRF have forecasted the key automotive requirements for all-solid-state batteries for the years 2028 and 2030, with detailed performance parameters outlined in the table below. These requirements represent their vision for the future of solid-state battery technology in the automotive sector, taking into account the expected advancements in battery chemistry, manufacturing, and the overall evolution of electric vehicles in the coming decade.

Table 2 Stellantis and CRF automotive requirements for 2028 and 2030

		2028	**2030**
Usable Energy Density @BOL 90%SOC	Wh/L	>900	>1000
Usable Specific Energy @BOL 90%SOC	Wh/kg	>360	>400
Charge Time (20-80%SOC)	min	15	10

It is important to note that the projections made by Stellantis and CRF are slightly more conservative compared to other studies and forecasts from various research groups, institutions, and industry players. While other sources often predict highly ambitious targets for the performance of solid-state batteries, Stellantis and CRF have defined a set of objectives that, while still reflecting significant progress, are not as aggressive as some of the more optimistic projections in the field.

Specifically, the energy density, specific energy, and cycle life goals laid out by Stellantis and CRF are positioned slightly below the expectations set by other studies. Many other forecasts within the battery research and development community have projected that by 2030, solid-state batteries will achieve ultra-high energy densities well beyond 500 Wh/kg, offering EVs substantially extended driving ranges. In contrast, Stellantis and CRF have opted for more measured targets, focusing not only on energy density but also on the practicality of scaling the technology for mass automotive production.

Similarly, while other studies propose highly accelerated charging times and exceptional durability metrics, Stellantis and CRF's forecast is more in line with the current pace of technological progress. Their objectives consider the real-world challenges associated with large-scale manufacturing, safety regulations, and cost-effectiveness—factors that are often underestimated in more optimistic predictions. This cautious approach reflects an understanding of the complexities involved in transitioning from laboratory-scale breakthroughs to the deployment of ASSBs in mass-market EVs.

Moreover, their forecast also places an emphasis on cost efficiency, reliability, and safety standards, recognizing that while reaching extremely high energy densities and fast-charging capabilities are desirable, the real challenge lies in creating a commercially viable product that can be mass-produced at competitive costs. This focus on balanced objectives suggests that Stellantis and CRF are prioritizing a holistic approach, ensuring that the advancements in ASSB technology can be integrated into their future vehicle lineup without compromising safety or affordability.

An example of near-commercially available vehicles adopting solid state batteries is Welion. Welion has entered into a notable collaboration with Chinese electric vehicle (EV) manufacturer NIO to develop and integrate a 150-kWh semi-solid-state battery into NIO's high-end EVs. This partnership is aimed at enhancing vehicle range, safety, and energy density. The semi-solid-state battery, developed by Welion, offers a significant improvement in energy storage capacity, allowing NIO’s vehicles, such as the flagship ET7 sedan, to achieve ranges of up to 930 kilometers on a single charge. This battery combines traditional lithium-ion technology with solid-state components, offering increased thermal stability and safety compared to conventional liquid electrolytes. The partnership represents a breakthrough in EV battery technology, as NIO aims to differentiate itself with cutting-edge energy solutions that enable longer driving ranges without compromising safety. Although these batteries are currently expensive, NIO has planned to initially offer the battery packs for rental, with the option for customers to purchase them later. Welion’s ongoing advancements in solid-state technology, combined with NIO’s leadership in EV design, could drive significant innovations in the automotive industry.

In summary, while the objectives set by Stellantis and CRF for 2028 and 2030 may seem less ambitious than those presented by other studies, they represent a realistic and achievable roadmap for the near-term future of all-solid-state batteries in the automotive industry. Their cautious but strategic outlook takes into account both the technological hurdles that remain to be overcome and the industrial scaling challenges that will need to be addressed to ensure that solid-state battery technology can be successfully deployed in EVs at a commercial level.

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Project partners

#	PARTICIPANT SHORT NAME	PARTNER ORGANISATION NAME	COUNTRY
1	FEV	FEV Europe GmbH	Germany
2	ABEE	AVESTA BATTERY & ENERGY ENGINEERING	Belgium
3	CICE	CENTRO DE INVESTIGACION COOPERATIVA DE ENERGIAS ALTERNATIVAS FUNDACION, CIC ENERGIGUNE FUNDAZIOA	Spain
4	FORD	FORD OTOMOTIV SANAYI ANONIM SIRKETI	Turkey
5	CRF	CENTRO RICERCHE FIAT SCPA	Italy
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