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EXPERIMENTAL RESEARCH AND DESIGN OF SOLID STATE BATTERY

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Abstract: Battery development is essential to satisfy the green technology trend that requires electric-based technology. Lithium-ion battery (LIB) is the most popular battery that has been used in various electric technology. However, LIB has a concern on the safety aspect by using liquid electrolyte which is prone to thermal failure that leads to flame or explosion. Solid- state battery (SSB) recent development could handle such thermal problems due to the non-flammable characteristic of the solid electrolyte. SSB also has potential for future main battery candidates due to high energy & power density. Although there are many advantages, SSB also has several problems in recent development. Interfacial stability, low ionic conductivity on room temperature, mechanical properties, etc. need to be studied further to make an adjustment for further development. This review would give information regarding recent progress on SSB development from various types of electrolyte and failure mechanisms. Market research companies expect that EVs will replace ICEVs(internal combustion engine vehicles), and become the mainstream in the auto industry. And to become the unarguable leader in the industry, EV should have the similar level of mileage as the current ICEV, and it is important to increase the battery capacity of an EV battery to do so. There are two ways to increase capacity. First is increasing the number of batteries. But in this case, the battery price goes up and batteries take up so much space in the vehicle. A solid-state battery has higher energy density than a Li-ion battery that uses liquid electrolyte solution. It doesn't have a risk of explosion or fire, so there is no need to have components for safety, thus saving more space. Then we have more space to put more active materials which increase battery capacity in the battery. A solid-state battery can increase energy density per unit area since only a small number of batteries are needed. For that reason, a solid-state battery is perfect to make an EV battery system of module and pack, which needs high capacity.

CHAPTER 1
INTRODUCTION

This chapter introduces the background of the study, along with the problem identification. Furthermore, the primary purpose of the project and the investigated research questions are defined. Lastly, the scope of the work with the limitations is discussed.

1.1 Background

The growing demand for the batteries from the automobile sector and renewable energy systems as a whole is speeding up the developments related to battery production. With new battery manufacturing technologies and assembly facilities, the Li-ion battery manufacturing industry needs to look sharp and adaptable to the change in requirements from the market to maintain an edge over other potential competitors in the market. Since the battery market is expected to expand in the coming few years, innovative designs which ensure low-cost, fast-charging battery technology that can support long-range use is set to play a significant role in controlling the market for battery systems. Backed by the claim of being safe to use and having a higher energy density when compared to Li-ion batteries, the solid-state batteries can evolve as a potential game-changer among the available battery chemistries. This research is done in collaboration with Northvolt AB, a battery manufacturing company in the startup phase and building battery production facilities with 32 GWh capacity in Skellefteå, Sweden. Northvolt was established in 2017 with a view to develop the world's greenest battery cell and to establish one of Europe's largest battery factories. Northvolt focuses mainly on the production of Li-ion battery cells with various form factors. The main aim of the research work is to provide the company with a perspective on the dynamic changes happening in the battery market and on the technologies that are emerging as a potential replacement for the Li-ion battery technology, the technology in which the company is deeply invested at present.

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1.2 Problem Identification

The Li-ion battery industry is on a boom with a consistent increase in demand from different customer segments. However, conventional Li-ion batteries pose a series of challenges when it comes to performance and safety. Hence, the market is on a constant exploration for advanced battery technologies with better performance and safety. Moreover, the advancements related to the field of Li-ion technology is expected to reach a stagnation point soon, and hence the technology is expected to slowly make way for new technologies like that of solid-state batteries, which assures improved safety and performance. Even though an economic scaled production of the next-generation battery technologies is yet to be realized, the battery production industry needs to be prepared for a possible shift in current Li-ion battery technology. Also, it is essential for any organization working in the battery manufacturing industry to have a clear perspective on the future roadmap towards the successful inception of the advanced battery technologies for scaled production. With the coming decade identified to witness a visible shift in technology, it is required to identify the general trend in conceiving different future battery technologies to be able to pinpoint the technology that shall be of increased demand during the coming decade. Furthermore, for easy integration of the next-generation battery technologies into existing facilities for scaled production and faster introduction into the market, these technologies must have a flexible manufacturing model.

1.3 Scope and Delimitation

Specific delimitation had to be defined to narrow down the scope of the project and to make the methodology reasonable to execute. The principal aim of the project will be to answer the research questions posed concerning the presented problematization and thereby to provide the commissioning organization a detailed overview on the discussed topic. However, considering the extensive scope of the topic being studied; precise boundaries needed to be defined to maintain the focus on answering the research question. Moreover, understanding and mapping out all the technologies being developed as a potential replacement for conventional Li-ion technologies and discussing a manufacturing strategy for the same, will not be a feasible approach to be followed in the limited time frame and hence the primary focus was given to the technologies that are widely acknowledged as the potential competition to the current Li- ion technology. Besides, when evaluating the battery market, as the commissioning organization is focused on the European battery market, the market study is mainly pivoted around European battery market. However, the status of other battery markets is comprehensively discussed. Furthermore, evaluation of the key requirements from different customer segments was done only on the markets in which the commissioning organization is involved.

Furthermore, the research is performed with a focus on the coming decade to develop a technology roadmap for the commissioning organization. Having recognized the growing importance of solid-state batteries, which is identified as the alternative technology for Li-ion battery technology, further research on the technologies like Lithium-sulfur battery technology, which is expected to have a considerable market penetration along with the solid-state batteries in the coming decade is excluded in order to limit the focus of the research and to narrow down the scope of the project. Hence, the latter half of the research is confined to developing a manufacturing model and defining a production infrastructure for the scaled production of solid-state batteries, with the scope narrowed down to particular solid-state battery chemistry, the production process chain of which closely aligns with the existing process sequence for the scaled production of conventional Li-ion batteries.

1.4 Batteries in EV

EV motors react swiftly with high torque and are more efficient against ICE vehicles. We see various commercially successful EV models Today, be it a sports model or an economical model. The design of the battery pack is closely related to the performance of an EV. So we all know how batteries are used in almost all the appliances we use in our daily lives and our vehicles as well. Energy is converted to electricity with the chemical energy stored in a battery.

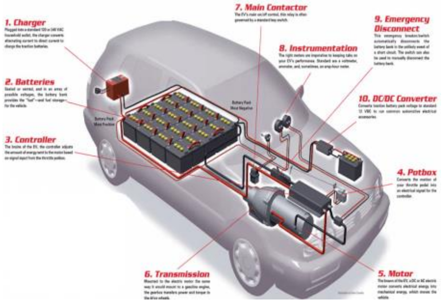

Fig 1.0 How Batteries work in Electric Car

The battery consists of a cell called the negative electrode, which has a surplus of electrons that are negatively charged subatomic particles. Electrons flow from the negative to the positive when the two are connected by an electrical cable. Companies today have come up with a way to use The energy created by these moving electrons to run a motor. Since the vehicle's engine is powered by it, it must deliver enough current to the motor over some time. If you're wondering when and if this battery dies, yes it does. This happens when the numbers of electrons on the positive & negative side are the same in number and thus no longer skilled in producing an electric flow.

1.4.1 Conventional Lithium-Ion Batteries

We start with a quick review of how conventional lithium-ion batteries work. As shown in the figure below, a lithium-ion battery consists of three main layers: A cathode, or positive electrode, consisting of a lithium containing mixed-metal oxide material; an anode, or negative electrode, consisting of carbon or a mix of carbon and silicon; a separator, an electrical insulator made of a porous polymer material; and an electrolyte, the medium through which lithium ions move through the battery, typically consisting of a hydrocarbon solvent and dissolved lithium salt. (In this document, we will use "carbon anode" to mean either a pure carbon anode or a hybrid carbon-silicon anode.)

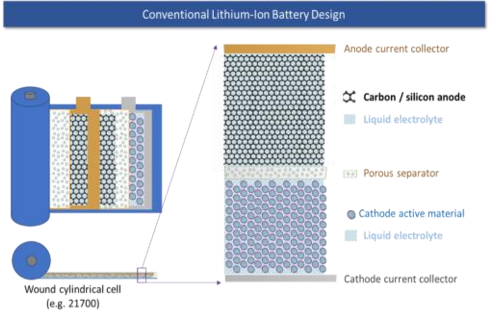

Fig 1.1 Conventional Li-Ion Battery

A battery may be envisioned as the electrochemical equivalent of rolling a ball uphill, which requires work to be put into the system, increasing potential energy in the system during the process, and letting it roll back downhill on its own, to release stored energy and do useful work. In a fully-discharged cell, the lithium in the cell resides in the cathode, the "downhill" state. When the cell is charged, work is put into the system to drive lithium ions from the cathode to the anode, where they diffuse into the carbon particles that make up the anode. In the fully charged state the lithium ions sit in the anode, like balls that have been rolled uphill, waiting until they can be freed to roll back downhill again. When the battery is discharged, these lithium ions are allowed to move back from the anode to the cathode, and in the process, energy can be extracted from the system, just like the ball rolling downhill can release its stored energy in the form of useful work.

Fig 1.2 Li batteries in electric vehicle

1.4.2 The Lithium-Metal Battery

A next generation battery may include next generation cathode material or next generation anode material (or both). The chart below, a paper published by a group from BMW, shows a dozen different next generation cathode materials and three different anode materials. What this chart makes clear is that the energy density gains from using next-generation cathode materials are limited, unless lithium metal is used as the anode. The principal reason for this limitation is that higher capacity cathodes need correspondingly thicker anodes to hold the increased amount of lithium, drowning out some of the benefits of the cathode improvement

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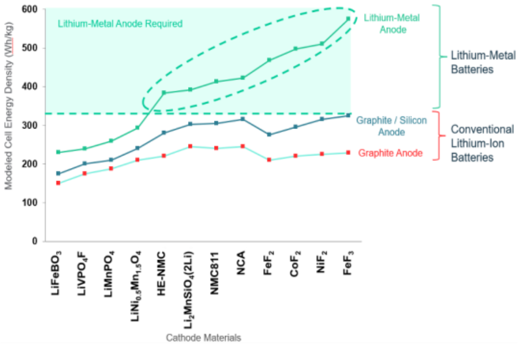

Fig 1.3 Comparison between Li-Ion Vs Li-Metal Battery

Traditional lithium-ion cells use a hosted anode in which the host material, such as carbon or silicon, provides a structure to hold the lithium. For example, in the case of carbon, it takes six carbon atoms to hold one lithium atom. The potential increase in energy density for a lithium-metal anode battery has been known since the mid-1970s. However, it has also been known that lithium-metal anodes do not work with conventional liquid electrolytes due to the twin issues of dendrite formation when a battery is being charged and rapid impedance growth from a chemical side-reaction between the liquid electrolyte and the lithium metal. Dendrites are needle-like formations of lithium metal which can grow across the separator and short-circuit the cell. Impedance refers to the internal resistance of the cell; growth in this resistance reduces the energy capacity of the cell as well as its ability to work at high rates of power. Thus, it is widely believed that to make a lithium-metal anode battery, one need a solid-state separator which is roughly as conductive as a liquid but resists dendrite formation and does not react with metallic lithium. For 40+ years, the industry has been searching for such a material.

1.4.3 Solid-State Lithium-Metal Battery

Market research companies expect that EVs will replace ICEVs (internal combustion engine vehicles), and become the mainstream in the auto industry. And to become the unarguable leader in the industry, EV should have the similar level of mileage as the current ICEV, and it is important to increase the battery capacity of an EV battery to do so. There are two ways to increase capacity. First is increasing the number of batteries. But in this case, the battery price goes up and batteries take up so much space in the vehicle. A solid-state battery has higher energy density than a Li-ion battery that uses liquid electrolyte solution. It doesn't have a risk of explosion or fire, so there is no need to have components for safety, thus saving more space. Then we have more space to put more active materials which increase battery capacity in the battery. A solid-state battery can increase energy density per unit area since only a small number of batteries are needed. For that reason, a solid-state battery is perfect to make an EV battery system of module and pack, which needs high capacity.

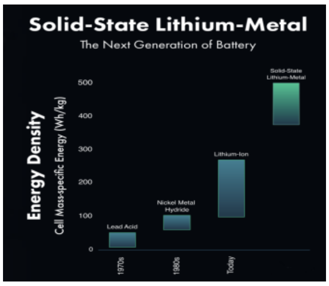

Fig 1.4 Solid-State Lithium-Metal Battery

1.4.4 The Nickel-Metal Hydride Battery

These came into commercial use a little earlier in the late 1980s. NiMH batteries have superior specific energy to lead-acid ones. They hold a value of 68 Wh/kg and a range of 60 to 120 Wh/kg.

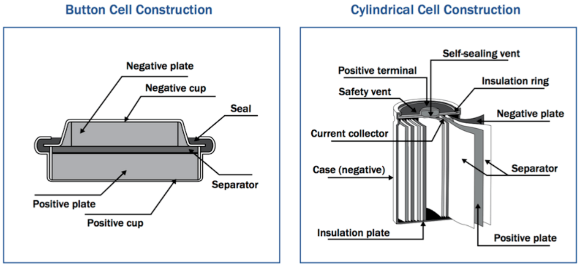

Fig 1.5 Nickel-Metal Hydride Battery Working

With a theoretical voltage of 1.2V, the Nickel-metal hydride (NiMH) batteries indicate the quantity of energy stored in the battery. Although it is remarkably lower compared to the Li-Ion batteries and is recyclable.

Fig 1.6 Nickel-Metal Hydride Battery Used in Electric Car

These batteries are proven well to use in EVs. You can expect your car to run over 100,000 miles with these batteries and an average of 5-7 years of battery life. Regarding their use in EVs, their disadvantages include:

- Low charging efficiency
- Self-discharge up to 12.5% per day at room temperature
- The heat generation rate during fast charging & discharging.

1.4.5 Lead Acid Battery

These are the oldest type of battery, formulated in 1859 and still being used. They are recyclable. They hold a mild solution of sulfuric acid and are a kind of wet cell battery. Lead-Acid batteries come with the advantage of being priced at a cheaper rate and have been in use for years. Lead-acid battery technology is considered old-fashioned but is still definitive & full-grown. This battery type comes with a short life span of 3 years and requires inspection of electrolyte levels.

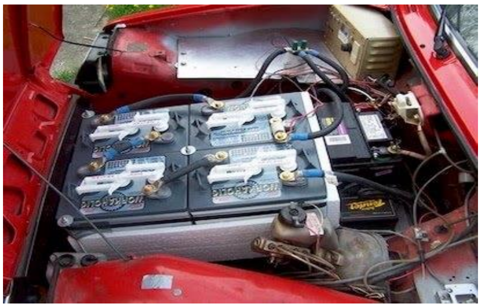

Fig 1.7 Lead Acid Battery in Electric Car

Considering it is made from lead they are heavy. They provide sufficient energy of 25-50% of the vehicle's total mass.

1.5 Roadmap for Future Batteries

According to the European commission SET plan, the top priority for the coming decade is on the development of Li-ion battery technology to develop high voltage (4.5 to 5V) systems or high capacity systems, or all solid configuration preferentially combined with high voltage and high specific capacity. The next-generation batteries will have to wait until 2030 to get a significant market share and projects that by 2030, all solid-state batteries will win $3 billion in transportation and $2 billion in electronics along with Lithium-sulfur batteries which are expected to get a small market share irrespective of its more modest growth.

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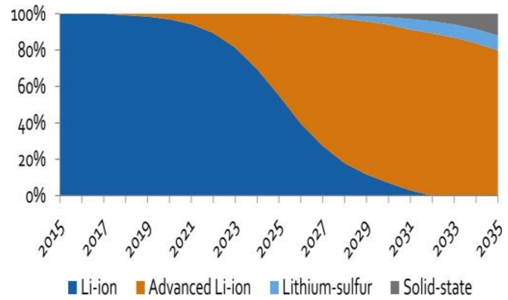

Fig 1.8 Projected Battery Market in Transportation

Massive investments in the development and procurement of facilities that are involved in the development of the next generation of batteries have officially started a transition of the market towards future batteries. The investment made by the automotive supplier Bosch on SEEO, a California based developer of polymer solid-state batteries and the procurement of Sakti3, a developer of solid-state batteries, with additional investment to scale up the mass production by Dyson are considered as some of the landmark acquisitions. C. Laslau, et al. in forecasts Lithium-sulfur and solid-state batteries to reach 4% and 2% market penetration by 2030 in the EV market and probably rising to 8% and 12% by 2035, with the solid-state batteries picking up the pace with the implementation of simpler manufacturing models, lower costs and advanced features. In the present market for Li-ion battery cells, optimized Li-ion cells of generation 1and 2a represent the core technology employed for EVs and energy storage. Moreover, considering the lead time from R&D to the commercialization of advanced technologies, the present Li-ion technology is expected to prevail during the coming decade. There is a strong drive from the market for generation 2b and 3a batteries, which exhibit increased energy density due to the improved uppercut voltage.

The transition onto generation 4 and 5 is pretty much unclear as the technology needs to be more evident and has to overcome the more obvious limitations. Also, a proper commercialization strategy has to be developed. Considering these challenges, from today's perspective, the development and efforts for commercialization of next-generation batteries would be most likely pivoted around solid-state batteries in which solid electrolytes replace the liquid electrolyte and the separators. From a European market perspective, having identified the role of Li-ion batteries in the coming decade and considering the capability of the Asian countries, especially China, in manufacturing Li-ion battery chemistries up to generation 2a, it would be ideal to focus on the development and commercialization of Li-ion batteries of generation 2b and beyond. Moreover, rapid deployment of new cell generation requires a simultaneous and concurrent production technique as it is apparent that a leap in-cell technology would affect the production of cells at a different level and hence for faster absorption of change into the production environment the manufacturing models need to be developed more flexible.

1.6 Next Generation Battery Technology under Focus

A drastic increase in demand for batteries is expected in the coming decade with the rise in demand for various applications like EVs, Stationary decentralized energy storage devices, and portable electronic devices. With the increase in demand for batteries, the need for superior characteristics is also on the rise. From the market analysis, it is clear that the present Li-ion battery technology will continue to prevail in the coming decade with further advancements in the battery chemistry. Most of the researches related to next-generation Li-ion batteries are pivoted around the development of advanced anode, cathode and electrolyte materials.

The motivation driving all the developments in the field of battery technology is the requirements from its key customer segments; with the strongest pull arising from the EV segment. The acceptance of EV on the market strongly depends on the characteristics and the capability of the battery used. Recent fires on Tesla Model S electric car and Boeing 787 Dreamliner’s has developed concerns over the safety aspects of EV’s, for the end-users. Moreover, in order to gain a market advantage, it is required to develop batteries that could provide EVs with characteristics that can make them comparable and compatible with combustion vehicles.

With a strong drive from the market for advanced batteries that can ensure safety and provide enhanced energy density, the focus is now on the development and successful commercialization of technologies beyond Li-ion technology. The Li-S and All solid-state batteries remain the most promising candidates for replacing the Li-ion batteries and forming the next-generation batteries. However, as discussed in section 1.6, the market penetration of these technologies would take time, and the current Li-ion technology is expected to dominate the market for the coming decade. Irrespective of the concerns over the commercialization of next-generation batteries, projects 4 % and 2 % market penetration for Li-S and solid-state batteries by 2030 in the automobile sector. The credibility of the forecast is well demonstrated by a large number of well-funded start-ups, investment activities, research works, and patent applications. Examples include:

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- A joint venture from Toyota and Panasonic was announced in January 2019. The venture shall capitalize on the advancements made by Toyota on solid-state battery technology and utilize the capacity and capability of Panasonic as a battery manufacturer for the commercialization of the solid-state battery technology.
- Toyota has invested $13.9 billion in its battery business and plans to commercialize solid-state batteries by early 2020, and the company holds 233 patents or applications concerning the solid-state technology.
- The US-based EV maker Fisker Inc has applied for a patent for the development of flexible, high energy-density solid-state batteries, and the battery is expected to deliver 500 miles driving range on a single charge.
- In 2015, The engineering company Dyson acquired a US-based start-up Sakti3, which specializes in the development of solid-state batteries.
- The Automotive supplier Bosch bought SEEO, a developer of Polymer solid-state batteries, intending to cut energy storage cost by 75%.
- Renault-Nissan-Mitsubishi alliance has announced its investment in Ionic Materials, a US-based start-up company developing solid-state cobalt-free battery materials, to bring the technology into the market by 2030.
- The German automaker BMW has partnered with Solid Power, a spin-off from the University of Colorado, Boulder, to develop solid-state batteries for long-range EV applications, with a vision to produce its first solid-state battery-based EV model by 2026.
- The Volkswagen has invested $100 million in Quantum Scape, a US-based leading technology company for the development of solid-state batteries. The venture aims to enable the industrial level production of solid-state batteries.
- The BASF has invested $50 million in Sion Power, which is into the development of Li-S battery technology.
- There is a considerable rise in the number of patent applications by large corporates; the number of patent filings per technology is represented in the figure below.

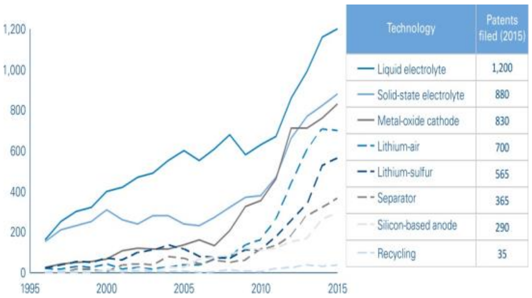

Fig 1.9 Patent Filing per Technology

With a focus on the European market, the European cell manufacturers must be a forerunner in the research and development of technologies like solid-state batteries and Li-S batteries in order to avoid over dependency on the Asian markets when these technologies enter a commercialization phase. The requirement is further highlighted by the European Commissions' SET Plan, which defines the key actions on batteries. The action plan was developed with an aim for Europe to become competitive in the global battery sector. The SET- Plan projects the development of higher voltage Li-ion batteries and solid-state batteries as the top priority for Europe and sets a timeline for its realization. According to the action plan, Europe should be able to reach TRL7(Technology readiness level), which include system/sub- system development for solid-state batteries by 2028 and should be able TRL9, which include system test, launch & operation by 2030. On analyzing the future roadmap, it has become more evident that the development and commercialization of solid-state batteries would be the main focus in the second half of the period from 2020 to 2030. However, Li-S battery technology is also expected to grow during this period, but the commercialization of the technology is expected to take more time, with more efforts required to make the technology more reliable and efficient.

1.7 Solid Battery Outlook

The need for technologies that can ensure a sustainable long-term energy generation, conversion, and storage drives the quest for new battery technologies. The future roadmap analysis has made it more evident that the solid-state battery technology would be under the spotlight in the coming decade with extensive research and development of the technology, focusing on enabling the technology for commercialization.

All solid-state batteries (ASSBs), the key difference comes in the electrolyte used. The ASSBs employs a solid electrolyte instead of liquid electrolyte. The growing interest in the ASSBs from different market segments has to be understood in the context of the challenges faced by the existing technologies, especially Li-ion battery technology. As compared to Li-ion batteries, the ASSBs are considered to be safer, have longer cycle life, have a higher power and energy density, have fewer requirements on packaging and state of the art charge monitoring system, as well as wider operating temperature. The less packaging constraints enhance the capability of the cell design by allowing in-series stacking and bipolar structure, thereby improving the packaging efficiency of the battery.

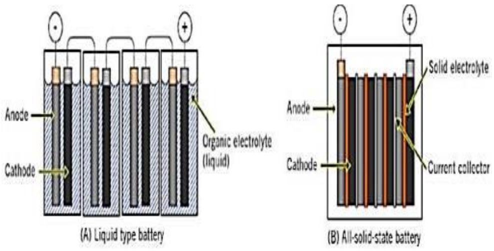

Fig 1.10 Solid Battery Outlooks

For ASSBs the key component is the solid electrolyte, and the coherent choice of the electrolyte is determined by a series of requirements including high ionic conductivity, good mechanical properties and compatibility with electrode materials. The solid electrolytes are generally defined as electronically insulating solid materials with high mobility and selective transport of charged ionic species within their structure. The solid electrolytes are primarily classified into two categories (as shown in the figure below): polymeric and inorganic.

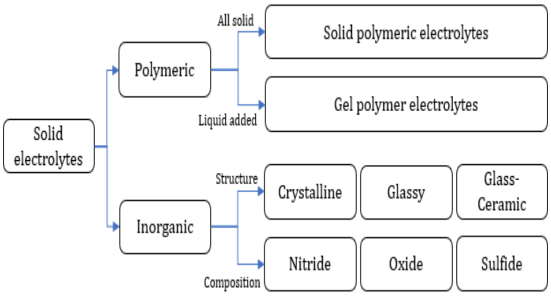

Fig 1.11 General Classification of Solid Electrolyte

The Inorganic solid electrolytes possess high elastic moduli, good thermal and chemical stability, wide electrochemical window, high ionic conductivity, and low electronic conductivity, which make it more suitable for rigid battery design. On the other hand, with the solid polymer electrolyte, it is possible to have various geometries, high flexibility and requires low cost and simplified production processing, even though its ionic conductivity is lower than that of inorganic solid electrolytes. Besides, an effective electrode-electrolyte interface can be formed with solid polymer electrolyte, which improves the electrochemical performance of the system and battery life.

The main difference between a traditional Li-ion battery and an ASSB is that the solid electrolytes replace the organic liquid electrolyte and separators in Li-ion batteries. However, the working principle of Li-ion batteries and ASSBs are the same. During charging the Li-ions deintercalated from the cathode are transported through the solid electrolyte and solid electrolyte-electrode interface to the anode, while the electrons move from cathode to anode through the external circuit. While discharging the Li-ions deintercalated from the anode are transferred to the cathode via the solid electrolyte, and the electrons migrate through the external circuit and drive the connected device to work. The figure given below is a schematic representation of the ion transfer taking place in a lithium-based solid-state battery and some of the possible materials for the anode, cathode and the electrolyte.

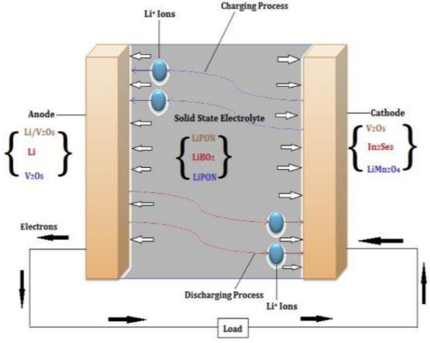

Fig 1.12 Schematic Representation of Ion Movement in Lithium Based SSB

Among the different solid electrolytes, the inorganic solid electrolytes have gained more attention compared to polymer solid electrolytes due to their better electrochemical stability, non-flammability, robustness preventing Li-ion dendrite growth, single ion conduction mechanism and higher compatibility with higher potential cathode materials to increase energy density. Furthermore, among the inorganic solid electrolytes, the sulfide-based inorganic solid electrolytes have several advantages of high ionic conductivities and ease to form framework structures, etc., however, on the contrary, these electrolytes are hygroscopic and have less chemical stability. Moreover, considering the oxide-based inorganic solid electrolytes, the key advantages are its stability in air and its stability with respect to lithium metal and high voltage cathodes, while the drawbacks include the low process ability, low conductivity, and manufacturability.

Besides, the garnet type electrolytes, especially the lithium stuffed garnets, are particularly attractive in recent years due to their relatively high conductivity, relatively good stability, and wide electrochemical window. The garnet-type oxide-based solid electrolyte (LLZO – Lithium lanthanum zirconate) has overall Li-ion conductivity of 10-4 S/cm at room temperature and exhibit higher chemical stability in ambient condition as well as in contact with lithium metal. Moreover, it is of interest because of application in ASSBs and Li-air batteries. ASSBs enable the use of lithium metal as anode material, which is considered as the primary driver for the commercialization of ASSBs. The use of lithium metal as anode material can increase the total energy density by approximately 20%. Moreover, the use of electronic devices and the demand for EVs are on the rise, and with that, the demand for new lightweight batteries with better cycle life, energy density, power density, and improved safety is also increasing, which has created a strong drive towards the successful commercialization of ASSBs.

When it comes to the commercialization of ASSB technology, there exist certain difficulties, which need to be overcome. The insufficient conductivity of the electrolyte under room temperature, the poor interface compatibility between the electrode and the electrolyte, the lack of understanding of the interfacial process after charging/discharging and the development of various cost-effective fabrication processes and structural design are some of the challenges required to be overcome before the successful commercialization of the technology.

CHAPTER 2
LITERATURE REVIEW

2.1 Research & Development

It has to be stressed, that R&D is still the most important and the only really established part of the value chain for SSBs. The perfect material combination for a high energy density and other targeted properties is still to be found. For the landscape of solid electrolytes for li-ion Solid-State Batteries around 5800 patents grouped in 2460 patent families can be found. Behind these patents are more than 1140 patent applicants29. This shows that there is still a high diversity of different approaches. Research landscape and relevant players The strongest R&D-Players in 2018 identified by Yole Development were in the US, Europe and Japan30. As there are so many actors in the research on SSBs, here only the most relevant European Players in R&D are listed31. Before, a short overview of R&D US: Texas University Austin, University of Michigan, University of California, University of Houston, University of Colorado Boulder, Washington State University, Stanford University

2.2 Samsung SDI

Samsung SDI is currently working on developing the solid-state battery. We are also jointly developing the battery with other institutes such as Samsung Advanced Institute of Technology, Samsung R&D Institute Japan and others. Samsung SDI has been presenting mid-to-long term solid-state battery technologies at the motor show or battery exhibitions since 2013. And we are currently at the element technology development phase for commercialization. We also said in the second quarter 2020 earnings conference call that "we have seen the possibility of developing a high-energy density and high-safety battery by combining tested materials technology and our new materials such as solid electrolyte." In March, the Samsung Advanced Institute of Technology showed the research result of a solid-state battery that can be charged/discharged over 1,000 times with 800km of mileage on a single charge. The study about the technology that increases life cycle and safety, and reduces the size of a solid-state battery in half was published in the ‘Nature Energy’, a global scientific journal. We must develop the solid-state battery to make the EV that goes farther and runs safely. There may be many obstacles ahead since we are at the early stage of development, but Samsung SDI will do our best to develop the ‘super-gap’ technology.

2.3 Quantum Scape’s Approach

Many solid-state announcements either do not show any data at all, or leave out some of the above parameters when they report data, leaving an incomplete picture at best. At QuantumScape, we have developed a solid-state ceramic separator capable of meeting these requirements without requiring the compromised test conditions described above. We have presented data showing single-layer versions of our solid-state lithium-metal cells can cycle more than 1000 cycles and retain over 90% of their initial energy when cycling at aggressive 1C rates of power, near room temperature, and with modest pressure. More recently, we have presented data showing multilayer cells cycling to close to 800 cycles with similar capacity retention. We have compiled data on key performance metrics across major solid-state battery technology efforts based on information we have been able to obtain, infer or derive from publicly disclosed materials and presentations. This data is presented in the chart below, and is current as of March 4, 2021. We hope that this paper helps our stakeholders understand the broader technology landscape of solid-state battery technology and Quantum Scape’s distinctive approach.

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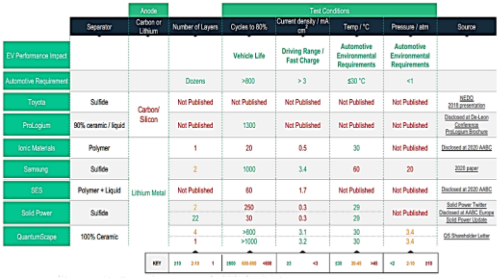
Table 2.0 Quantum Scape's Analysis Table



		Anode		Test Conditions				
	Seperator	Carbon or Lithium	Number of Layers	Cycles to 80%	Current density / mA cm²	Temp / °C	Pressure / atm	Source
EV Performance Impact				Vehicle Life	Driving Range / Fast Charge	Automotive Environmental Requirements	Automotive Environmental Requirements	
Automotive Requirement			Dozens	>800	> 3	≤30 °C	<1	
Toyota	Sulfide	Carbon/ Silicon	Not Published	Not Published	Not Published	Not Published	Not Published	NEDO 2018 presentation
ProLogium	90% ceramic / liquid		Not Published	1300	Not Published	Not Published	Not Published	Disclosed at De-Leon Conference ProLogium Brochure
Ionic Materials	Polymer	Lithium Metal	1	20	0.5	30	Not Published	Disclosed at 2020 AABC
Samsung	Sulfide		2	1000	3.4	60	20	2020 paper
SES	Polymer + Liquid		Not Published	60	1.7	Not Published	Not Published	Disclosed at 2020 AABC
Solid Power	Sulfide		2 22	250 30	0.3 0.3	29 29	Not Published	Solid Power Twitter Disclosed at AABC Europe Solid Power Update
QuantumScape	100% Ceramic		4 1	>800 >1000	3.1 3.2	30 30	3.4 3.4	QS Shareholder Letter
		KEY	≥10 2-10 1	≥800 600-800 <600	≥3 <3	≤30 30-45 >45	<2 2-10 ≥10	

2.4 Toyota SSB Debut

A trip of 500 km on one charge. A recharge from zero to full in 10 minutes. All with minimal safety concerns. The solid-state battery being introduced by Toyota promises to be a game changer not just for electric vehicles but for an entire industry. The technology is a potential cure-all for the drawbacks facing electric vehicles that run on conventional lithium-ion batteries, including the relatively short distance traveled on a single charge as well as charging times. Toyota plans to be the first company to sell an electric vehicle equipped with a solid-state battery in the early 2020s. The world's largest automaker will unveil a prototype next year. The electric vehicles being developed by Toyota will have a range more than twice the distance of a vehicle running on a conventional lithium-ion battery under the same conditions. All accomplished without sacrificing interior space in even the most compact vehicle. Solid-state batteries are expected to become a viable alternative to lithium-ion batteries that use aqueous electrolyte solutions. The innovation would lower the risk of fires, and multiply energy density, which measures the energy a battery can deliver compared to its weight.

It would take roughly 10 minutes to charge an electric vehicle equipped with a solid-state battery, cutting the recharging time by two-thirds. The battery can extend the driving distance of a compact electric vehicle while maintaining legroom. Toyota stands at the top of the global heap with over 1,000 patents involving solid-state batteries. Nissan Motor plans to develop its own solid-state battery which will power a non-simulation vehicle by 2028. The shift toward the new battery technology will also have an effect on companies further down the supply chain. Japanese auto materials makers are rushing to set up the necessary infrastructure to supply automakers. Mitsui Mining and Smelting, commonly known as Mitsui Kinzoku, will start up a pilot facility that will make solid electrolytes for the batteries. The production site, located at a research and development center in Saitama Prefecture, will be able to produce dozens of tons of solid electrolyte annually staring next year, enough to fulfill orders for prototypes. Oil company Idemitsus Kosan is installing solid electrolyte production equipment at its Chiba Prefecture site with the aim of beginning operation next year. Manufacturing solid electrolytes requires solidifying sulfides, which is a specialty of the metal and chemical industry. Sumitomo Chemical is developing material as well.

Japanese manufacturers like Sony and Panasonic have been pioneers in commercializing battery cells for vehicles. But since the late 2000s, Chinese rivals have emerged to prominence. Contemporary Amperex Technology Co. Limited, also known as CATL, is now the world's largest supplier of lithium ion batteries. Japan's Asahi Kasei, once the global leader in battery separator material, gave up the crown last year to Shanghai Energy. Electric vehicles are anticipated to become commonplace amid the global shift away from carbon. The Japanese government has been encouraging the domestic development of solid-state batteries, under the outlook that most of the technology relating to automotive performance will depend on China if the status quo holds. The government is putting together a fund of about 2 trillion yen ($19.2 billion) that will support decarbonization technology. Policymakers will consider using those funds to provide subsidies of hundreds of billions of yen that will fund the development of the new batteries. The goal is to support the development of a mass-production infrastructure within Japan. Because solid-state batteries use lithium, an element with limited global reserves, the government will assist in procuring the material.

2.4 Honda Fluoride-ion Battery

As automakers commit to building more electric cars, the search for better batteries is ongoing. Honda claims to have made a major breakthrough in that area. Working with the California Institute of Technology (Caltech) and NASA's Jet Propulsion Laboratory (JPL), the Japanese automaker claims to have developed new battery chemistry called fluoride-ion that could outperform current lithium-ion batteries, with a less-severe environmental impact. The fluoride-ion battery chemistry, detailed in a paper published in Science, aims to solve some of the biggest problems with today's lithium-ion batteries. Honda claims fluoride-ion batteries offer 10 times greater energy density, meaning they can store more electricity in a given volume. That equates to greater range for an electric car without making the battery pack bigger. The batteries also don't pose a safety risk from overheating and don't require rare metals like lithium and cobalt, according to Honda. The low atomic weight of fluorine, the main ingredient in this type of battery chemistry, makes fluoride-ion batteries' increased performance possible, says the automaker. The material's potential benefits were previously known, but there was a major drawback: batteries needed temperatures of around 150 degrees Celsius (302 degrees Fahrenheit) to work.

But Honda claims to have found a way to make these batteries operate at room temperature. That's thanks to a new fluoride electrolyte (the material that conducts electricity within a battery) developed by researchers. Honda says researchers have successfully tested this in the lab, but that doesn't necessarily mean the technology can be commercialized. Promising lab results don't always work in the real world. It's also unclear what Honda would do with the technology in the United States. In a press release, Honda said fluoride-ion batteries could power future electric cars (or be used for energy storage), but the automaker hasn't shown much interest in cars powered by batteries for this market. With its short range, the current Clarity Electric feels like an afterthought.

CHAPTER 3
METHODOLOGY

This chapter discusses the methodology of study adopted to develop a comprehensive overview of the current and future solid state battery market. Furthermore, the use of research data for identifying the battery technology that shall be of increased importance in the future; with a focus on the period, 2025 to 2030 is elaborated.

3.1 Research design

The research process was designed to fulfill the aim of the study, which was to investigate the future of the battery market in Europe based on emerging technologies and how to devise a manufacturing strategy for the scaled production of identified technology that shall be of increased demand in the coming decade. The research design keenly focuses on developing a structured theoretical framework towards achieving the research purpose. The research process was designed to provide the beneficiary with a detailed overview of the current battery market and future battery market. Also, to provide a perspective on the possibilities to successfully integrate the scaled production of identified battery technology in the existing production facilities for the large scale production of Li-ion batteries.

The research design entirely relies on the theoretical framework for complementing the research process and the journey towards fulfilling the purpose of the study. Owing to the current immature state of the investigated case, the availability of a diverse and credible source of data was limited. Hence a combination of qualitative and empirical analysis was performed in order to collect data relevant to complement the observations made at different stages of the research. The limited research on promising technologies limited the data resources to credible online webpages and articles.

3.2 Research process

The research process consisted of different stages. The initial objective was to define the aim of the research and to define the research questions. The research questions were framed based on the objective, which was defined based on iterative and in-depth discussion with the commissioning company. With the project scope defined, an extensive research study was performed based on scientific publications and reliable websites for initially understanding the battery market and then identifying the battery technologies that are being developed as a potential successor to Li-ion battery technology. The research questions were several times scrutinized and adapted to the findings from literature during the research, to better match the problematization. Since the research questions were explorative, it demanded the research process to be iterative. The second half of the research was focused on defining the identified battery technology that is of increased demand in the coming decade. A manufacturing model which can be used for the scaled production of the identified solid state battery technology in existing facilities for the conventional Li-ion batteries was further defined. The research process was structured to give the beneficiary a reliable and credible overview of the current battery market and to guide the beneficiary through the advanced battery technologies and to deliver a foundation for future explorations on the identified technology. The research process is visualized in the figure below.

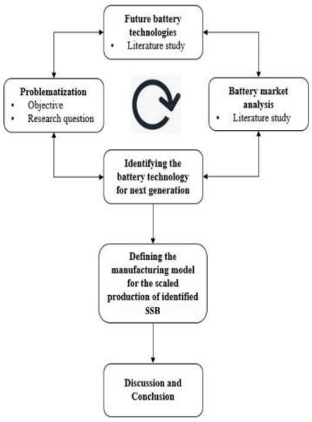


Fig 3.0 Research Framework

3.3 Data gathering

The data gathering was mostly dependent on reviewing the relevant literature and referring to articles published online regarding the growth and developments happening in the field of battery technology. Reviewing the scientific journals and relevant white papers provided significant insight into the current state of the Li-ion battery technology, the market trends and on the developments related advanced battery technologies that are considered as a potential replacement for conventional Lithium-ion batteries. During the literature review, it was realized that the number of scientific journals to support the investigation into future battery technologies and its market is limited, and hence most of the data about future battery technologies are referred from credible white papers from different sources. The literature review was performed in three parts. The initial phase was focused on developing a deep understanding of the current state of conventional Li-ion battery technology. Activities included reviewing technical reports of lithium-ion battery cells and focused on particular battery components such as; cathode, anode, electrolyte, and separator to gain a technical understanding of the battery cell technology. The gathered data is presented in chapter 3. In the second part of the research, the core focus was on understanding the battery market and the future technologies that are being developed with a potential to replace the conventional Li-ion battery technology and thereby developing a roadmap for the inception of future technologies.

The key activities for this part involved reviewing reports from conferences held on battery technology and the annual reports from different sources like EUROBAT, Bloomberg, and European Commission documents. The gathered insights are presented in chapter 3. Furthermore, in the last part of the research, the focus was on developing a manufacturing model for the scaled production of solid-state batteries, which was identified as the most promising technology to replace the Li-ion battery technology in the coming decade. Due to the limited availability of data from scientific journals or white papers on this technology for scaled production, the framework for scaled production was proposed based on the work done by J.Schnell et al. in “All-solid-state lithium-ion and lithium metal batteries – paving the way to large-scale production.” Moreover, additional scientific papers were referred to support the adopted manufacturing model for the scaled production of all-solid-state batteries. The data gathered on this topic is presented in chapter 4 and 5

CHAPTER 4
EXPERIMENTAL SETUP

4.1 Design and functionality

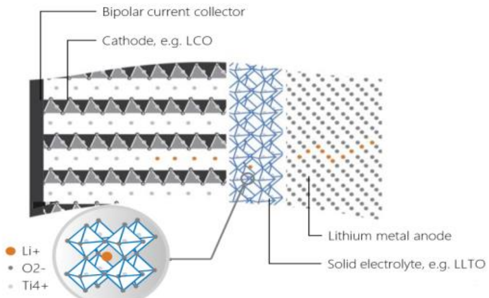


Fig 4.0 General Layout of ASSB

- In an all-solid-state Battery, an ion-permeable solid electrolyte provides both spatial and electrical separation between the cathode and anode; it also serves as a separator.
- Different cell designs are possible. The figure above shows a thin film cell. Thicker layers can be built up with a composite cathode.
- When discharging an all-solid-state Battery, lithium ions move from the anode through the solid electrolyte to the cathode. At the same time a current flows at the external load.

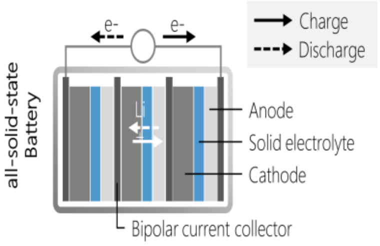


Fig 4.1 ASSB

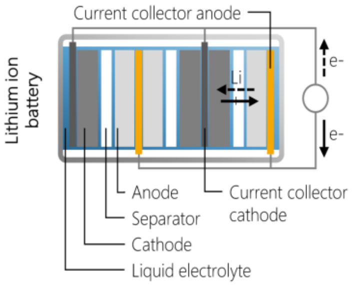


Fig 4.2 Lithium ion battery

- The resistance at the interface between anode and electrolyte is a decisive factor for the performance of the battery cell. This can be reduced by an additional layer, e.g. a polymer or an aluminum alloy.
- The right-hand figure shows the cell stack of an all-solid-state Battery compared to a lithium-ion battery.
- Due to the solid electrolyte, bipolar stacking is possible. This results in a serial connection of the elementary cells

4.2 Materials of solid state battery

4.2.1 Electrolyte

Solid electrolytes can be divided into organic and inorganic electrolytes. For inorganic electrolytes, the advantages for safety are predominant as they are non-flammable and do not contain toxic materials. Therefore, this brochure focuses on inorganic electrolytes. The following figure gives an overview of the material categories and contains a selection of specific structure types.

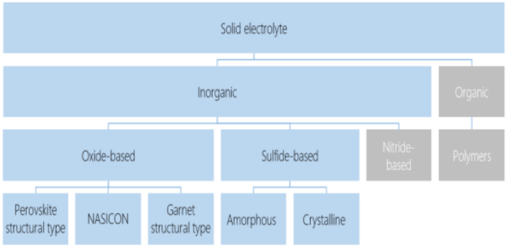


Fig 4.3 Solid Electrolyte Classification

- Oxide-based electrolytes usually have good chemical stability and are compatible with high-energy cathode materials. However, the ion conductivity is lower than for sulfide-based electrolytes.
- Among the oxide-based electrolytes, materials with perovskite or garnet structure as well as NASICON are promising. The following figure shows a qualitative classification of the properties. Further representatives are LiPON, LISICON, lithium halides and lithium hydrides.

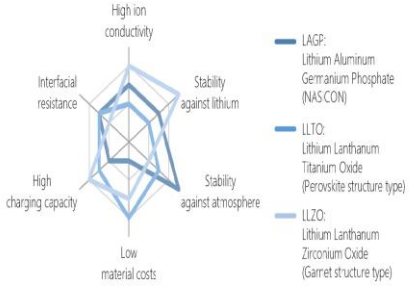


Fig 4.4 Radar view ASSB

- Sulfide-based electrolytes generally have a higher ionic conductivity, but are more chemically unstable.
- The amorphous lithium tin phosphorus sulfide (LSPS) is inexpensive and has very high ion conductivity at room temperature. However, incompatibilities with lithium metal are problematic.
- The ion conductivity of crystalline lithium-germanium-phosphorus sulfide (LGPS) is comparable to that of liquid electrolytes. However, LGPS is highly sensitive to moisture and lithium metal, and germanium is very cost-intensive.

4.2.2 Anode

- Lithium metal anodes are considered ideal because of their high theoretical capacity to achieve the highest energy density. However, metallic lithium tends to form dendrites, which must be prevented by the solid electrolyte. In addition, handling under an inert atmosphere is necessary, as lithium forms a passivating layer with the ambient oxygen.
- Silicon as an anode material promises very high energy densities, but undergoes extreme volume changes during alloy formation with lithium.

4.2.3 Cathode

- The cathode consists of a metal oxide. In most cases, established cathode materials are used, since there are almost no materials that have been specially developed for the all-solid-state Battery.
- Theoretically, depending on the electrolyte, a large number of established cathode materials can be used, ranging from inexpensive and safe materials such as lithium iron phosphate (LFP) to lithium nickel manganese cobalt oxide (NMC). In practice, only lithium cobalt oxide (LCO) as cathode material in combination with LLZO as electrolyte shows sufficient stability and performance.

4.3 Construction of SSB

- The production of an all-solid-state Battery can be divided into three overall steps: Electrode and electrolyte production, cell assembly, and cell finishing.
- A generally valid process chain does not exist; instead, a large number of alternative process chains may be applied. These differ in part from the manufacturing process of a lithium-ion battery.
- This brochure presents two possible process alternatives that differ primarily in electrode and electrolyte production.
- Both process alternatives refer to the production of pouch cells with inorganic solid electrolytes. The pouch cell format appears to be the most suitable for all-solid-state batteries:

4.3.1 Round or prismatic cell

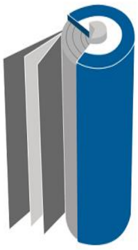


Fig 4.5 Round or prismatic cell

Windings are associated with great challenges due to the solid components of an all-solid-state Battery. Cracks can appear in brittle ceramic layers. In addition, the question of sufficient layer adhesion has not yet been answered.

4.3.2 Pouch cell

Fig 4.6 Pouch cell

Stacking is advantageous for all-solid-state batteries as the flat layers are not deformed. In addition, the layer compound is formed already during electrode and electrolyte production, so that only the elementary cells are stacked afterwards.
Due to the reactivity of the materials with the environment, a dry room is required for production. When handling metallic lithium, an inert atmosphere, e.g. argon, is preferable.
For each process step, a qualitative assessment of the transferability of expertise gained in the production of lithium-ion battery cells is made.

4.4 Manufacturing Process (Alternative A)

4.4.1 Electrode and electrolyte production

- In electrode and electrolyte production, the composite of cathode, electrolyte and anode is produced.

- After electrode and electrolyte production, an elementary cell is present.
- The main feature of process chain A, which is initially presented, is a continuous extrusion process in which the layers are subsequently laminated.
- This process chain is particularly suitable for sulfide-based all-solid-state batteries.

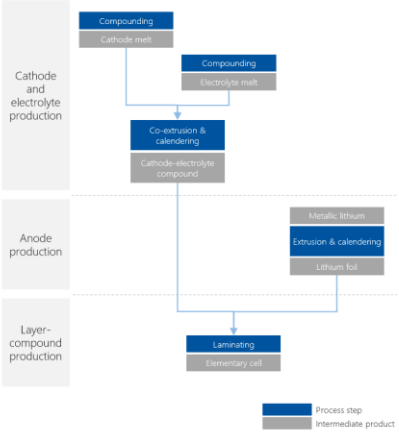


Fig 4.7 Process Chain

4.4.2 Compounding Cathode and electrolyte production

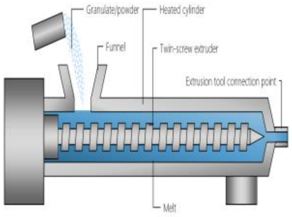
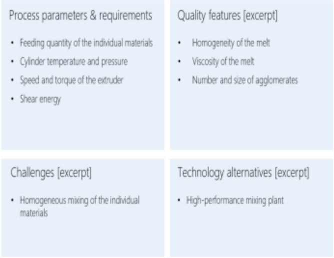


Fig4.8 Compounding Process

4.4.2.1 Production process

- The cathode and electrolyte melts are produced in two separate compounding processes.
- The materials components are fed to the heated barrel of a twin-screw extruder and can be supplied as granulate or powder.
- Rotational movements of the extruder bring in energy into the material components. The result is a homogeneous melt.
- In addition to cathode active material, electrolyte particles, which reduce the resistance between cathode and electrolyte, as well as binders and additives, are mixed for the cathode. Additional information
- The material components of the electrolyte are electrolyte particles and polymer binders.

Table 4.0. Compounding process of SSB



Process parameters & requirements	Quality features [excerpt]
• Feeding quantity of the individual materials • Cylinder temperature and pressure • Speed and torque of the extruder • Shear energy	• Homogeneity of the melt • Viscosity of the melt • Number and size of agglomerates
Challenges [excerpt]	Technology alternatives [excerpt]
• Homogeneous mixing of the individual materials	• High-performance mixing plant

4.4.3 Co-Extrusion Cathode and electrolyte production

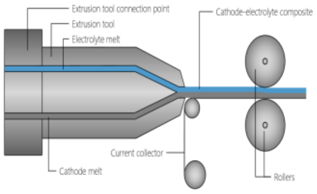
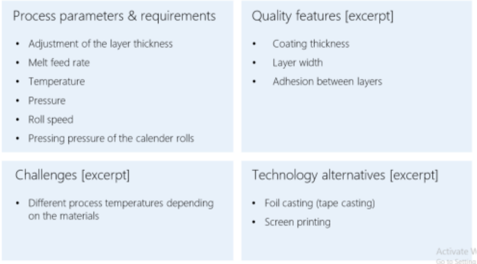


Fig 4.9 Co-extrusion process

4.4.3.1 Production process

- The cathode and electrolyte melts are co-extruded in a suitable die. This creates a composite of cathode and electrolyte layer.
- Cathode and electrolyte melts are fed through the extrusion die via separate channels.
- The melts pass through the channels to the outlet of the extrusion die. Here the melts are extruded via a slot die onto a current conductor.
- After extrusion, the bond is calendared to improve adhesion between the individual layers and achieve the desired layer thicknesses

Table 4.1. Co-extrusion



Process parameters & requirements	Quality features [excerpt]
• Adjustment of the layer thickness • Melt feed rate • Temperature • Pressure • Roll speed • Pressing pressure of the calender rolls	• Coating thickness • Layer width • Adhesion between layers
Challenges [excerpt]	**Technology alternatives [excerpt]**
• Different process temperatures depending on the materials	• Foil casting (tape casting) • Screen printing

4.4.4 Extrusion and Calendaring (Anode production)

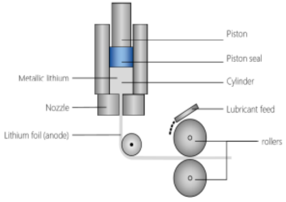
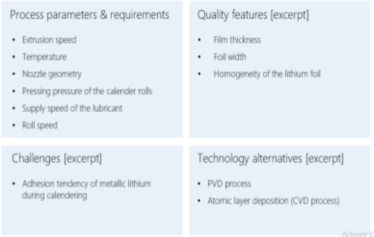


Fig 4.10 Extrusion and Calendaring (Anode production)

4.4.4.1 Production process

- A metallic lithium foil can be used as the anode of an all-solid-state Battery. This lithium film can be produced by extrusion with subsequent calendaring.
- For this purpose, liquid lithium is filled into the cylinder of a piston extruder. The lithium is then pressed through a piston into a nozzle.
- Homogeneity and desired film thickness are ensured by calendaring after extrusion. For this purpose, the film is rolled under pressure by two rollers with the addition of a lubricant.
- The rollers must be compatible with the adhesive properties of lithium. This can be achieved by polymer-coated rollers, e.g. made of polyacetal.

Table 4.2 Extrusion and Calendaring



Process parameters & requirements	Quality features [excerpt]
• Extrusion speed • Temperature • Nozzle geometry • Pressing pressure of the calender rolls • Supply speed of the lubricant • Roll speed	• Film thickness • Foil width • Homogeneity of the lithium foil
Challenges [excerpt]	**Technology alternatives [excerpt]**
• Adhesion tendency of metallic lithium during calendering	• PVD process • Atomic layer deposition (CVD process)

4.4.5 Laminating Layer Compound Production

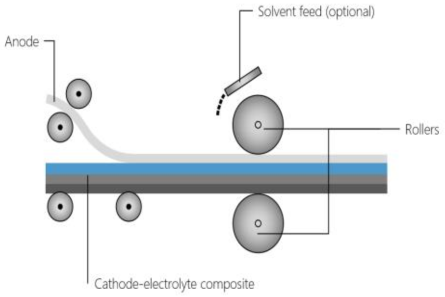
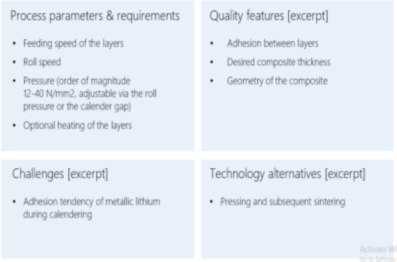


Fig 4.11 Laminating Layer Compound Production

4.4.5.1 Production

- After the lithium foil has been manufactured, it is laminated onto the cathode-electrolyte composite. For this purpose, the two layers are brought together via rollers.
- In the next step, the two layers are pressed together by two rollers. These are heated in order to achieve higher adhesion forces. During heating and pressing, polymers penetrate from one layer to the other, forming the bond between the anode and electrolyte.
- A distinction can be made between dry and wet lamination. With wet lamination, the contact surfaces are moistened with a solvent before lamination. This allows lamination with lower temperature and pressure.

Table 4.3 Laminating Layer Compound Production



Process parameters & requirements	Quality features [excerpt]
• Feeding speed of the layers • Roll speed • Pressure (order of magnitude 12-40 N/mm2, adjustable via the roll pressure or the calender gap) • Optional heating of the layers	• Adhesion between layers • Desired composite thickness • Geometry of the composite
Challenges [excerpt]	**Technology alternatives [excerpt]**
• Adhesion tendency of metallic lithium during calendering	• Pressing and subsequent sintering

4.5 Manufacturing Process (Alternating A)

- The main feature of the process chain B presented below is a physical vapor deposition (PVD) process with which the individual layers are applied one after the other.
- This process chain is particularly suitable for oxide-based all-solid-state batteries and shows the production steps of a thin-film cell.

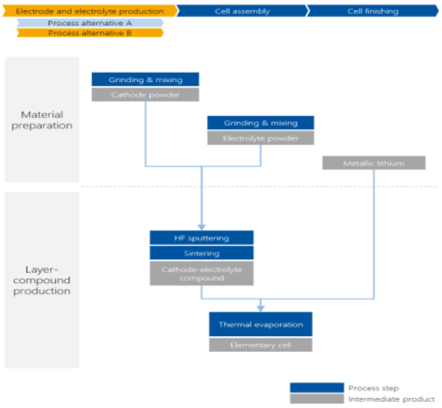


Fig 4.12 Process Chain

4.5.1 Grinding and Mixing

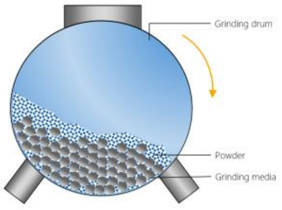


Fig 4.13 Grinding and Mixing

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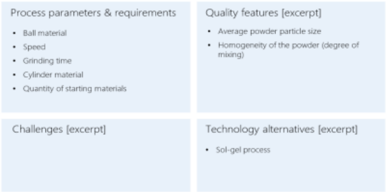
4.5.1.1 Production Process

- The cathode powder and the electrolyte powder are each produced separately in a ball mill.
- For this purpose, the respective starting materials are fed into a cylindrical grinding drum. In this grinding drum there are balls which are used as grinding media.
- The starting materials are mixed by the rotational movements of the cylinder. In addition, the rotational movement ensures a relative movement between the grinding media and the starting material, whereby the latter is ground.
- The powder is then calcined to obtain the desired powder properties.

Table 4.4 Grinding and Mixing



Process parameters & requirements	Quality features [excerpt]
• Ball material • Speed • Grinding time • Cylinder material • Quantity of starting materials	• Average powder particle size • Homogeneity of the powder (degree of mixing)
Challenges [excerpt]	**Technology alternatives [excerpt]**
	• Sol-gel process

4.5.2 High Frequency Sputtering

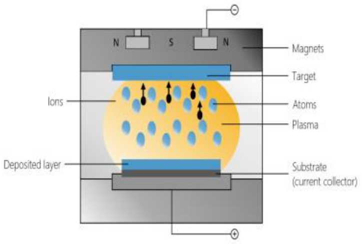


Fig 4.14 High Frequency Sputtering

4.5.2.1 Production Process

- The cathode and electrolyte layers are built up from the cathode and electrolyte powders by means of high-frequency sputtering. First, the target for the sputtering process is produced from the powders by die or hot pressing.
- The current collector also serves as the substrate of the process. In the first step, the cathode layer is deposited. Subsequently, an electrolyte layer is deposited on the cathode layer.
- The target of the sputtering process is shot with ions. In this process, atoms are knocked out of the target, which then enter the gas phase and are accelerated to the substrate. On the surface of the substrate, the layer is thus built up atom by atom.
- High-frequency sputtering takes place in a vacuum chamber.

Table 4.5 High Frequency Sputtering

Process parameters & requirements	Quality features [excerpt]
• Temperature • Deposition time • Process pressure • Ambient atmosphere • Process power/power density • Target diameter & target distance	• Layer thickness of the current collector • Layer thickness of the cathode and the electrolyte
Challenges [excerpt]	**Technology alternatives [excerpt]**
• Slow process with low throughput • Low layer thicknesses lead to low energy densities	• Chemical Vapor Deposition

4.5.3 Sintering

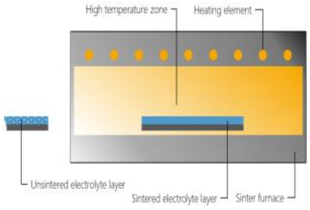


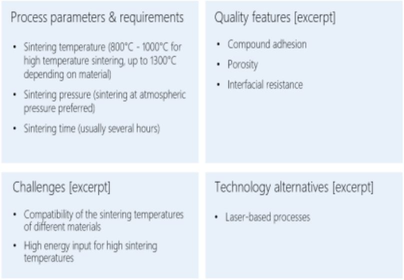
Fig 4.15 Sintering

4.5.3.1 Production Process

- Sintering compresses the cathode and electrolyte layers. Thus the resistance at the interface electrolyte – electrode can be reduced by improving the bond between the two layers.
- The cathode – electrolyte compound passes through a sintering furnace. The material is heated to a temperature below the melting point.
- Depending on the selected process parameters, the resulting porosity of the materials can be adjusted.
- The sintering process takes place in an inert atmosphere or in a vacuum to prevent reactions with the environment.

- Sintering is particularly necessary for oxide-based solid electrolytes in order to achieve a sufficiently low interfacial resistance.

Table 4.6 Sintering



Process parameters & requirements	Quality features [excerpt]
• Sintering temperature (800°C - 1000°C for high temperature sintering, up to 1300°C depending on material) • Sintering pressure (sintering at atmospheric pressure preferred) • Sintering time (usually several hours)	• Compound adhesion • Porosity • Interfacial resistance
Challenges [excerpt]	**Technology alternatives [excerpt]**
• Compatibility of the sintering temperatures of different materials • High energy input for high sintering temperatures	• Laser-based processes

4.5.4 Thermal Evaporation

- Thermal evaporation is suitable for applying the anode to the cathode – electrolyte compound. Metallic lithium is used as the anode material.
- In thermal evaporation, the metallic lithium is heated to temperatures around the boiling point, e.g. by an electron beam evaporator, so that it passes into the vapor phase. The steam spreads homogeneously in the vacuum chamber.
- The layer is formed by condensation on the surface of the electrolyte, which has a lower temperature.
- Like sputtering, thermal evaporation takes place in a vacuum chamber.

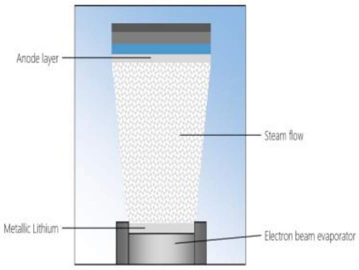
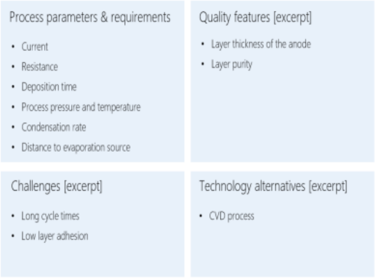


Fig 4.16 Thermal Evaporation

Table 4.7 Thermal Evaporation



Process parameters & requirements	Quality features [excerpt]
• Current • Resistance • Deposition time • Process pressure and temperature • Condensation rate • Distance to evaporation source	• Layer thickness of the anode • Layer purity
Challenges [excerpt]	**Technology alternatives [excerpt]**
• Long cycle times • Low layer adhesion	• CVD process

4.5.5 Cell Assembly and Finishing

- During cell assembly, the battery cell is made up of existing elementary cells.
- Compared to conventional lithium-ion battery production, the cost- and time-intensive formation and aging can be simplified for the all-solid-state Battery. In addition, electrolyte filling and degassing is no longer necessary.
- The battery cell is subjected to various tests for grading and quality assurance.

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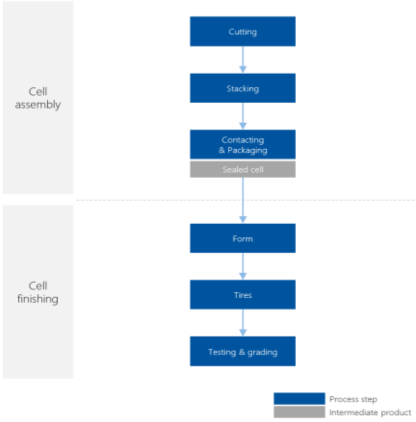


Fig 4.17 Cell Assembly and Finishing

4.5.5.1 Cutting Cell Assembly

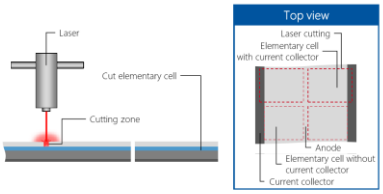
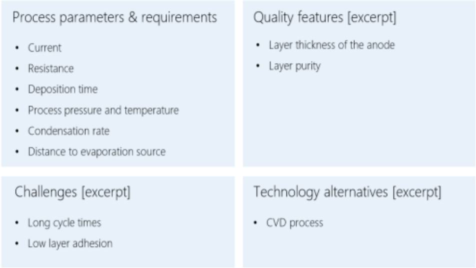


Fig 4.18 Cutting Cell Assembly

- After the layer lamination has been completed, the elementary cells must be cut to size so that they can be stacked in the next process cut. This can be done by laser cutting.
- A fiber laser, for example, can be used for the laser-cutting process.
- A burr-free cut can be achieved with the correctly set energy input into the layer compound. It is particularly important to ensure that the respective layer materials are not melted, which would lead to an electrical connection of the layers and thus to a short circuit.

Table 4.8 Cutting Assembly



Process parameters & requirements	Quality features [excerpt]
Current Resistance Deposition time Process pressure and temperature Condensation rate Distance to evaporation source	Layer thickness of the anode Layer purity
Challenges [excerpt]	Technology alternatives [excerpt]
Long cycle times Low layer adhesion	CVD process

4.5.2 Stacking Cell Assembly

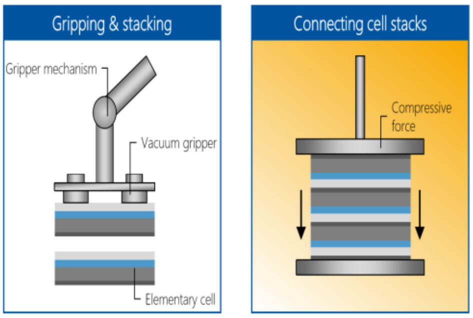
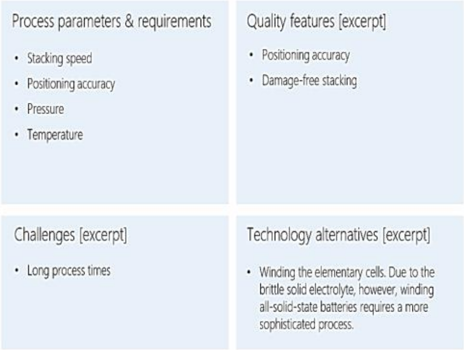


Fig 4.19 Stacking Cell Assembly

- The elementary cells can be stacked directly in bipolar configuration. The resulting series connection of the cells enables a multiplied cell voltage. The elementary cells are positioned on top of each other with grippers. When selecting the gripping technique, make sure that the surface is free of damage.
- An additional current collector is required for the completion of a cell.
- The elementary cells are then laminated together by applying pressure and heat. The result is a bipolar cell stack.

Table 4.9 Stacking Cell Assembly



Process parameters & requirements	Quality features [excerpt]
• Stacking speed • Positioning accuracy • Pressure • Temperature	• Positioning accuracy • Damage-free stacking
Challenges [excerpt]	**Technology alternatives [excerpt]**
• Long process times	• Winding the elementary cells. Due to the brittle solid electrolyte, however, winding all-solid-state batteries requires a more sophisticated process.

4.5.3 Contacting and Packaging

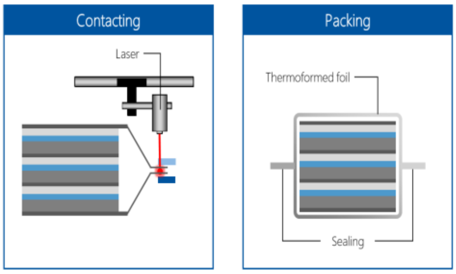
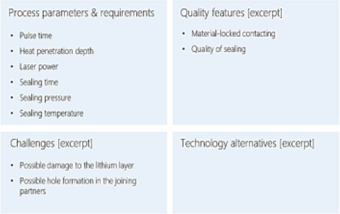


Fig 4.20 Contacting and Packaging

- In the bipolar cell stack, only the two outer current collectors have to be contacted with the contact tabs. It is potentially possible to use cheaper materials for the current collectors.
- Contacting can be achieved by laser beam or ultrasonic welding.
- After contacting, the all-solid-state Battery cell is placed in an electrically insulated packaging and sealed to protect it from environmental influences. Foils made of metal-plastic mixtures are suitable as packaging materials. The external current collectors must be inserted into the foil in an electrically insulated manner. The packaging is completely sealed using impulse or contact sealing.

Table 4.10 Contacting and Packaging



Process parameters & requirements	Quality features [excerpt]
• Pulse time • Heat penetration depth • Laser power • Sealing time • Sealing pressure • Sealing temperature	• Material-locked contacting • Quality of sealing
Challenges [excerpt]	**Technology alternatives [excerpt]**
• Possible damage to the lithium layer • Possible hole formation in the joining partners	

4.5 Formation

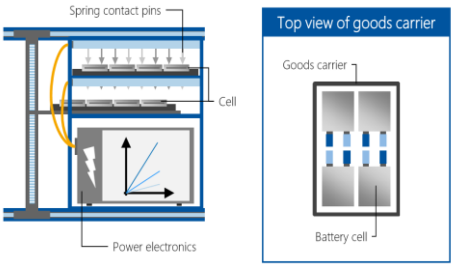


Fig 4.21 Formation

- During formation, the battery cell is exposed to the first charging and discharging cycles. When assembled, an all-solid-state Battery with lithium metal anode is already charged.
- The cell is contacted in formation racks by spring contact pins.
- An interface layer is formed between the electrolyte and the electrodes. This layer significantly influences the ion conductivity and thus the performance of the cell. Compared to lithium-ion batteries, however, this layer is thinner and is fully formed already after a few cycles.

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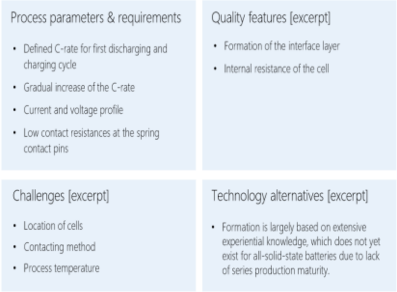
- Even after one discharge/charge cycle, the capacity and internal resistance of the battery cell remain substantially constant.

Table 4.11 Formation



Process parameters & requirements

- Defined C-rate for first discharging and charging cycle
- Gradual increase of the C-rate
- Current and voltage profile
- Low contact resistances at the spring contact pins

Quality features [excerpt]

- Formation of the interface layer
- Internal resistance of the cell

Challenges [excerpt]

- Location of cells
- Contacting method
- Process temperature

Technology alternatives [excerpt]

- Formation is largely based on extensive experiential knowledge, which does not yet exist for all-solid-state batteries due to lack of series production maturity.

4.6 Aging

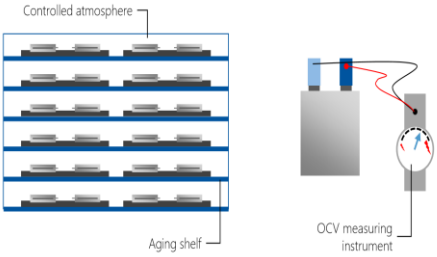
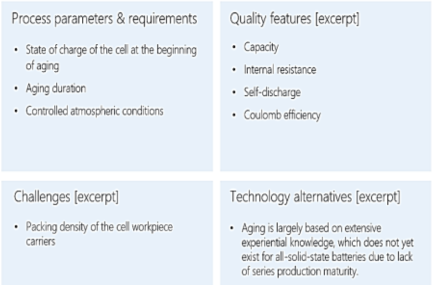


Fig 4.22 Aging

- Aging is the final step in cell production and serves quality assurance.
- During aging, changes in cell properties or cell performance are monitored by regular measurement of the open circuit voltage of the cell under controlled atmospheric conditions.
- The cells are stored in aging shelves and/or towers. Compared to lithium-ion batteries, a shorter aging time is expected, since the solid electrolyte enables the cell to achieve stable properties more quickly.

Table 4.12 Aging



Process parameters & requirements

- State of charge of the cell at the beginning of aging
- Aging duration
- Controlled atmospheric conditions

Quality features [excerpt]

- Capacity
- Internal resistance
- Self-discharge
- Coulomb efficiency

Challenges [excerpt]

- Packing density of the cell workpiece carriers

Technology alternatives [excerpt]

- Aging is largely based on extensive experiential knowledge, which does not yet exist for all-solid-state batteries due to lack of series production maturity.

4.7 Testing

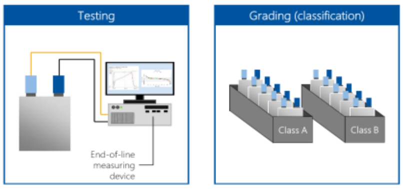


Fig 4.23 Testing

- In a final step, the properties of the finished battery cell are tested. In addition to an optical inspection for damage, this includes above all the characterization of the electrochemical properties.
- On the basis of the measurement results and the capacity determined during formation, the all-solid-state batteries are divided into grades according to their electrochemical properties, which is referred to as grading.
- There is no standard for grading, so that different grades do not allow to draw direct conclusions about the quality, but merely combine cells with similar properties.

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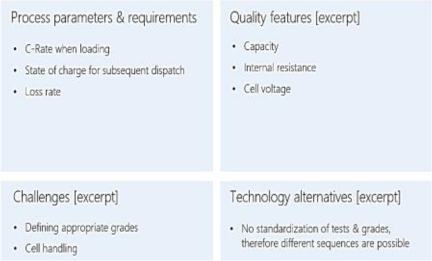
Table 4.13 Testing



Process parameters & requirements

- C-Rate when loading
- State of charge for subsequent dispatch
- Loss rate

Quality features [excerpt]

- Capacity
- Internal resistance
- Cell voltage

Challenges [excerpt]

- Defining appropriate grades
- Cell handling

Technology alternatives [excerpt]

- No standardization of tests & grades, therefore different sequences are possible

CHAPTER 5

RESULT AND DISCUSSION

Table 5.0 Specification

SPECIFICATION	
Dimensions (mm^3)	7.25*160*227
Weight (g)	496
Capacity (Ah)	20
Energy Content (Wh)	65
Maximum discharge content (A)	3C constant current /10C impulse
Maximum charge voltage (V)	3.6
Specific power (w/kg)	2400
Energy density	247
Operating temperature (^0C)	-30 to 55

- In this chapter highlights the key findings from the extensive research conducted on the topic SSB. Lastly, the contribution of the research is discussed together with suggestions for further research.
- The research has identified the core reason driving the transformation as the series of challenges posed by the Li-ion battery technology when it comes to safety and performance.
- Hence, the focus on other technologies which offer improved safety and performance has improved. The key technologies which are being widely explored and developed for the future include the next-generation lithium-ion batteries, redox flow batteries, sodium-ion batteries, metal-sulfur batteries, metal-air batteries, and solid-state batteries.
- With a detailed analysis of the technology roadmaps for future battery technologies, it became more evident that the solid-state battery technology and lithium-sulfur batteries are the two important battery technologies that will have significant market penetration in the coming decade.
- Of the two technologies, solid-state battery technology is expected to gain more market going forward. The study indicated that the solid-state battery technology is expected to achieve 2% EV market penetration by 2030, which shall improve to 12% by 2035. The technology roadmap is defined based on the developments happening in the European battery market, about the advanced battery technologies.
- From the research, it has become evident that the solid-state battery technology is one of the most promising technologies for replacing conventional Li-ion battery technology. The solid-state batteries, compared to Li-ion batteries, offer better safety due to the absence of liquid electrolyte. Furthermore, the solid-state batteries offer longer cycle life, higher power density, energy density, and more packaging efficiency compared to the Li-ion batteries.
- The process sequence for the industrial scaled production of ASSB's is highly dependent on the chemistry involved in the anode, cathode, and the solid-electrolyte used for the fabrication of ASSB's. From the market analysis.
- There is a limitation in executing the production of both the Li-ion batteries and ASSB's under one roof; it is possible to make use of the production technology with additional alterations and additions to satisfy the requirements for manufacturing ASSB's.

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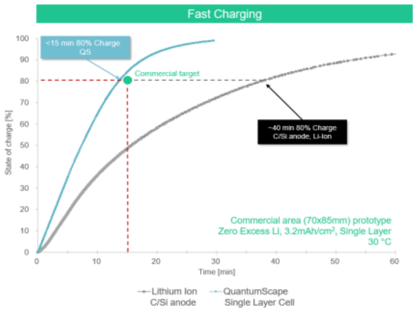

Fig 5.0 Fast Charging

- Fast charge capability exceeds commercial targets with commercial area single layer prototype 80% Charge in 15 minutes. Lithium Ion batteries currently only get to <50% in 15 minutes.

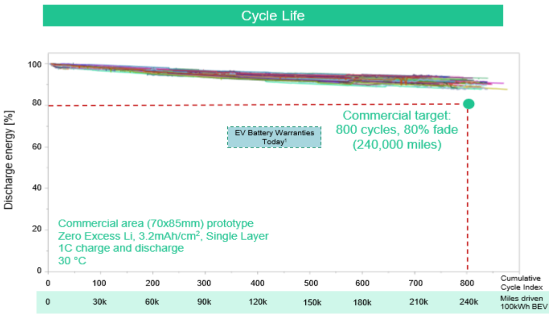

Fig 5.1 Cycle Life

- Meets commercial target with commercial area single layer prototype Cycling with >80% energy retention in 800+ cycles (still on test) Chart based on accelerated testing (3x automotive rates).

Table 5.1 Lithium Ion Batteries VS Solid State Batteries

Lithium Ion Batteries	Solid State Batteries
Low processing cost.	Excellent thermal stability.
Flexible separators can withstand high mechanical stress.	Comparatively less self-discharge.
High ionic conductivity only at room Temperature.	High ionic conductivity over a board range of temperature.
Self-discharge may reduce shelf life.	Electrolytes used are non-volatile.
Electrolytes used are flammable; It can cause combustion.	Electrolytes are nonflammable and thus, safe.
SEI layer formation affects life cycle.	High energy density.
Limited choice of cathode materials due to electrolyte reaction	High tolerance.
poor thermal stability.	Ceramic separators used are rigid and it may break with additional stress.
Sensitive to overcharge.	No SEI layer formation, and thus, a longer life cycle.

CHAPTER 6
CONCLUSION

- Solid-state electrolytes can provide advantages of superior thermal stability, lower flammability, improved durability and battery design simplicity, over the conventional organic liquid electrolytes, even though the room-temperature ionic conductivity in solid electrolytes is still lower than that in liquid electrolytes.
- The inorganic electrolyte is more suitable for rigid battery design, as it possesses better thermal/chemical stabilities, higher mechanical strength and exhibits an obvious conductivity advantage over a wide temperature range.
- The chemical stability in sulfide-based inorganic electrolyte need to be further developed in the future research; while for NASICON-based inorganic electrolyte, its wetting with sodium metal should be enhanced, in order to improve the energy density and cycling life in the resultant SIB with metallic Na as anode.
- The high flexibility in electrolyte could also provide higher electrode compatibility, which reduces the electrode-electrolyte interface resistance and improves the electrochemical performance and cycle life of the battery cells.

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- So far, the intrinsic conductivity performance in the polymer-based and ceramic-polymer composite electrolytes is still unsatisfied and greatly enhanced room-temperature ionic conductivity is strongly desired, which is also suggested as the future research direction.

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