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Will the solid electrolyte battery be a challenger or game changer for liquid electrolyte?

Introduction

Batteries for electric vehicles (EVs) are among a rapidly evolving market landscape. The demand for EVs is soaring, which is driven by the urgent need for sustainable transportation solutions and regulatory pressure. This surge is intensifying the focus on battery performance and lifetime durability, where liquid electrolytes have traditionally excelled. However, the emergence of solid-state electrolytes introduces a new competitive dynamic, promising enhanced safety and energy density.

Case study instruction

As Chief Technical Officer (CTO), in charge of the technology and innovation at a European liquid electrolyte supplier for EVs, you are concerned about the emerging solid-state battery (SSB) technology. Based on the degree of maturity of SSBs, the risks for your company, in terms of the market, or adding or substituting for a

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completely new product, need to be considered. The purpose of this case study is to make informed decisions regarding your future investments, potential collaborations, and the evolution of your product offerings.

Questions that can help guide the strategy development are as follows :

- Will SSBs or Semi-SSB compete with existing batteries or complement them? If so, what chemistry/format would suit EV applications?
- Should the EU incentivizing in a similar way to the Chinese government's strategy? What other strategies can help push the scaling and commercialisation of SSBs?
- Are SSBs a risk to your company, in the context of the EV market? If yes, when are SSBs coming to the market and at what price point?

The following provides a basic overview of the main factors to be taken into consideration, with some key insights from industry.

Technical Overview of SSB Technologies

For the large-scale penetration of lithium-ion batteries (LIBs) into the EV market, a gradual modification of the cell components is taking place. With regard to this, the most talked about topic is the full or partial replacement of liquid organic electrolytes with solid inorganic and/or organic electrolytes. All the other major components of the cell like the anode, cathode and current collectors will not be affected. This is a big plus since the existing manufacturing and assembly lines for these components used in liquid electrolyte Li-ion cells can be adapted to the manufacturing of Li-ion SSB technology, reducing the capital cost and run-up time. It has to be mentioned that in SSB technology, the role of the separator is taken over by the electronically insulating solid electrolyte [1].

Exhibit 1 shows the difference between a conventional LIB and a Li-based SSB. The traditional LIB cells in EVs offer a significant risk of hazardous fires due to the inherent flammability of the organic electrolyte used, which usually contains EC, EMC, DEC, DMC etc. Additionally, the Li salt contains fluorine, which could produce corrosive HF gas in an undesirable thermal event. The solid electrolyte in Li-ion SSBs circumvents this issue since the evaporation rate of the solid materials is minimal, both in the case of solid organic and solid inorganic electrolytes. The usage of organic electrolytes also limits the ECSW to below 2.5 V, which results in the battery life being affected severely if it is overcharged or over-discharged above a specific limit. This necessitates the use of efficient BMS in EVs, which increases the capital cost. Additionally, for Li-ion SSB, the traditional electrolyte filling step is not needed, which reduces the cell finishing time since the wetting is usually carried out multiple times depending upon the contact angle properties of the electrolyte. This step is of considerable importance since the inhomogeneous filling of the electrolyte could lead to the cell being discarded and ending up as waste [2].

SSB technology promises an era of battery cells with enhanced energy density, cell voltage, longer cycle life, and increased safety. However, due to the lack of standardisation between various research groups regarding SSBs, it can be difficult for OEMs to pick a cost-effective and quality battery for their EV. Such confusion at the lab scale also challenges the reproducibility of their results.

The most important factor in the performance of SSB cells is the homogenous distribution of the cathode active material and solid electrolyte particles, as shown in Exhibit 2. In this system, the electrolyte and cathode should be co-formed before making a full cell. Here, high-intensity ball milling is done to break down the particle, but care should be taken not to overheat the active particles, which could lead to the irreversible chemical degradation of the cathode-electrolyte interface. This step also includes severe compaction of the cathode particles to reduce the porosity and increase the charge transfer and hence is a challenge in itself. [3]

Similar to the conventional LIBs, Li-ion SSBs can also be built with various anodes, cathodes and electrolytes, with different KPIs, and more materials are under research and development [4]. The comprehensive overview of different SSB chemistries is shown in Exhibit 3. Currently, for the Anode Active Material (AAM), lithium metal, composite Si/graphite and pure graphite are the main areas of research. In case the anode does not contain lithium at the cell assembly stage, it is characterised as either Li metal SSB or anodeless SSB. Graphite-based anodes do not provide a large boost to the energy density, while composite anodes do so at the expense of the cycle life, due to the mechanical instability of the electrode particle during cycling. Li metal anodes provide the highest energy density, but because of the inherent reactivity of the Li metal, large-scale manufacturing of SSBs could be a long way off.

Cathode Active Material (CAM) encompasses more choices due to the chemical and mechanical stability of the cathode and electrolyte interface. Promising candidates include Ni-rich NMC, Ni-rich NCA, LFP, and elemental sulfur, as in Li-S batteries. Sulphur cathodes have a high theoretical energy density, but because of the intermediator polysulphides formed during discharge, not all the sulfur is utilised to store the Li-ions.

The key component of an SSB is the solid electrolyte, which can be classified into organic polymer, inorganic oxide-based and inorganic sulfide-based electrolytes. Oxide electrolytes need high-temperature sintering to form, are brittle, and have poor intrinsic ionic conductivities, which negatively affect the charge transfer kinetics of the Li-ions. Sulfide electrolytes are more malleable, but the research on the compatibility between high-voltage CAM and sulfide electrolytes is still in the early stages. In terms of material availability and production routes, polymer electrolytes are setting the course of action for future SSBs. However, limited room temperature ionic conductivities and poor compatibility, with high voltage CAM, still limit applicability. Other than these three classes of material, a new group of inorganic materials, called halide perovskites, are being explored for solid electrolytes due to their wide ECSW of 4.5V.

In summary, the key issues that hinder the widespread use of Li-based SSBs are threefold [5]. Firstly, the amount of SE should be lower in the cathode, while the electrode should have a high thickness to increase the energy density. Secondly, a high-performance anode is of significant importance with regard to dendrite growth and stable interface. Lastly, although SSBs are safer than conventional LIBs, high nickel cathodes or Li metal anodes can still pose the risk of thermal runaway. It should be carefully noted that oxide electrolytes can contribute to unwanted reactions due to the presence of oxygen. Additionally, inorganic electrolytes have very low heat conductivities, which does not aid in dissipating the generated heat efficiently.

Performance comparisons of SSBs with Li-ion and next-generation batteries [6] to [17]

In conventional LIBs, the graphite anode is thermodynamically unstable when it comes into contact with the liquid electrolyte. During the first charge, the SEI (solid electrolyte interface) layer forms at the surface of the anode, through exothermic reactions. Without an efficient cooling system, when temperatures reach 100°C, decomposition of the SEI layer and electrolyte can occur, leading to further formation of SEI in some areas, which increases the heat accumulation. This can eventually result in a thermal runaway. A key component of the thermal runaway is the flammable liquid electrolyte. Additives engineered to manage and reduce the flammability of the electrolyte can significantly reduce the extinguishing times. These safety hazards and the need for higher performance make SSBs an attractive solution. There are various SSB technologies, and this case study compares them with current lithium-ion batteries, with both established and future SSB technologies.

The performance of an SSB is dependent on the type of chemistry involved. With mainstream lithium-ion battery cathode chemistries, mainly NCA, NMC and LFP, simply changing the liquid electrolyte to a solid may not guarantee a high-energy density battery. An example is LLZO (Lithium Lanthanum Zirconium Oxide), which is five times denser than the liquid electrolyte. Incorporating LLZO into a battery makes the battery heavier and reduces its capacity. Consequently, the lithium metal anode is required to achieve gravimetric energy densities above 300Wh/kg. Exhibit 4 shows the different gravimetric energy densities for the various cathode chemistries associated with graphite, silicon, or lithium metal anode. It is worth stating that battery chemistry is a complex combination of several materials that provide ambivalent results. Lithium metal is incompatible with liquid electrolytes due to issues such as dendrite growth, hence the need for solid-state electrolytes. Solid electrolytes that can reduce dendrite growth and have ionic conductivities similar to liquid electrolytes could be a solution to achieving high energy density, but that comes with its challenging practical barriers.

How do SSBs compare to LIBs?

Gravimetric And Volumetric energy density

Exhibits 5-6 show the NCA-based LIB, as it goes from material to device-level. The gravimetric and volumetric energy density is seen to reduce from the theoretical value to a final cell value of 264Wh/kg and 63`5Wh/L. In comparison, an NCA all-solid-state battery (Exhibit 7) shows a much higher theoretical gravimetric and volumetric energy. However, the final cell values show a drastic drop in energy density with a final value of 393Wh/Kg and 1143Wh/L. Lyten, a LIB company, unveiled their new SSB, which is projected to reach 900Wh/Kg, although details have not been disclosed. They claim to have solved the polysulphide shuttle that restricts long cycle life with a new 3D graphene structure. (Exhibit 8)

Fast Charging

According to Quantumscape, as shown in Exhibit 9, their solid-state battery with a lithium metal anode, can achieve 80% SOC (state of charge) in under 15 minutes, at a C-rate of 4C, at a temperature of 25°C and 45°C. They haven't published how these batteries perform under cold weather conditions. The cells can fast charge over 400 cycles while retaining 80% of their energy. Compared to conventional LIBs (Panasonic 2170), the cells degrade rapidly and energy retention falls below 80% after a dozen cycles.

Future battery lab compared two SSBs and two LIB technologies. The results are displayed in Exhibit 10. LFP batteries doped with silicon have the highest lifetime, with studies showing that 4000 cycles can be achieved. Although liquid electrolyte is expected to age faster, SSBs do not last longer due to the repetitive volume expansion leading to mechanical stress and stability issues. Regarding safety, LFP with solid state electrolytes are considered the safest due to LFP's high thermal resistance coupled with the elimination of flammable liquid electrolyte. In terms of cost, NMC with sulfide solid electrolyte is the most expensive due to the low commercialisation of the electrolytes.

Sustainability

To understand and make an informed decision, as to whether SSBs are more sustainable than lithium-ion batteries, it is worth considering the material supply chain, processing, and recycling of the batteries. Exhibit 11 shows the various stages involved in the supply chain of established LIBs. Considering anode-free SSBs, this could imply subtracting the extraction and processing of graphite anode from the supply chain, thus reducing the carbon footprint, as shown in Exhibit 12. The extraction and processing of anode materials according to the European Federation for Transport and Environment (EFTE), represents 20% to 30% of the global warming potential of conventional LIB manufacturing (Exhibit 13.). While this case study hasn't explored the sustainability and carbon footprint of an established SSB supply chain and recyclability, reports from Quantumscape indicate signs of a more sustainable solid-state battery. However, considering other technologies, such Solid Power's sulphide solid electrolyte (Exhibit 14.), this means replacing the carbon footprint of the extraction and processing of graphite, with that of sulphur and silicon. Does that make it more sustainable? More studies in this area are required to determine clear distinctions.

Emerging SSB technologies.

Emerging SSBs have tended to be more hype than a commercialisable product, with little details disclosed and a slow maturity rate. The hype cycle of battery technology is a semi-scientific assessment tool introduced by Gartner. This was to examine the attention a technology attracts (the visibility as a function of time) before it makes it into maturity. The cycle combines the inverted parabolic curve and the maturity gradient line into 5 distinct phases (Exhibit 15.). This assessment looked at the various stages of LIBs and highlights where SSBs are, i.e., in the trough of disillusionment. Based on the assessment they estimate that in 5-10 years, SSBs should transform the battery industry, reaching full market maturity (Exhibit 16.). This highlights the duration until SSBs reach full global productivity and maturity.

Here is a list of some of the announced SSB technologies and the expected timeline:

- Talent New Energy with composite oxide solid electrolyte at 720Wh/kg: first announced in 2024
- Samsung SDI at 900Wh/l: mass production in 2027
- Quantumscape with lithium metal with solid electrolyte at 400Wh/kg (prototype): commercialisation by 2025
- Solid Power with sulfur-based solid electrolyte at 560Wh/kg: commercialisation by 2026.
- ProLogium with solid-state ceramic battery at 450Wh/kg: first 0.5GW Gigafactory opened in 2024
- Lyten with lithium-sulfur with 3D graphene structure

Manufacturing

As seen in the previous sections, the battery industry has shown fast growth to improve performances (energy density, ability to 3/5C charge), safety, durability, and sustainability. To evaluate any technology, the manufacturing and development process must be taken into consideration, and it is important to ask how this technology can integrate into the manufacturing ecosystem that is already in place (or which will take place). Indeed, would you need to create a niche for this technology? Or will it be possible for that technology to be integrated into existing Li-ion manufacturing lines? This section addresses these questions by first comparing the manufacturing process of conventional LIBs and that of SSBs by assessing the reality and the scalability.

Let's zoom into the LIBs process [18] illustrated in Exhibit 17 and highlight the main differences with SSBs step by step.

Electrode Preparation - This includes mixing active materials (cathode and anode) with binders and additives, followed by coating these mixtures onto current collectors.

- Mixing: active materials like lithium cobalt oxide (for the cathode) or graphite (for the anode) are mixed with binders and conductive additives to form a slurry.
- Coating: the slurry is coated onto metal foils (aluminium for the cathode, copper for the anode) using techniques, such as doctor blade coating or slot die coating.
- Drying: the coated electrodes are dried to remove any solvent from the slurry, leaving a solid layer of active material on the foil.
- Calendering: the dried electrodes are pressed to ensure uniform thickness and density, improving the contact between particles.
- ❖ Depending on the SSB technology, coating the anode with metal foil is not necessary since the anode is itself the current collector [19]. Calendering is not required either, with interfaces already pre-formed.

Electrode Assembly - Stacking or winding the electrodes with separators to form a cell.

- Stacking: electrode sheets are stacked in layers with a separator in between to prevent short-circuiting.
- Winding: Alternatively, electrodes and separators can be wound into a cylindrical or prismatic shape, depending on the cell design.
- ❖ For SSBs, the solid electrolyte plays the role of separator, thus taking over the separator-adding step.

Electrolyte Insertion - Introducing the liquid electrolyte into the cell.

- Filling: the electrolyte, typically a lithium salt dissolved in organic solvents, is filled into the cell to enable ion transport between electrodes.
- Soaking: the cells are allowed to soak to ensure the electrolyte thoroughly wets the electrodes and separator.
- ❖ This step doesn't exist for SSBs.

Sealing - The cells are sealed using heat or laser welding.

Formation and ageing - performing formation cycles to stabilise the active materials creates SEI.

- Formation: Initial charging/discharging cycles are performed to form and stabilise the SEI layer.
- Degassing: Removing gases formed during electrolyte soaking and initial cycling.
- Ageing & degassing: This is the concluding phase in cell production, utilised for quality assurance purposes. [20]
- Resealing
- ❖ With a solid electrolyte, the SEI partially exists beforehand. Therefore, the formation step is shorter than that for conventional SSBs. Additionally, the two degassing and resealing steps are absent (as no degassing is need).

Taking into consideration these differences, we can see that there is clearly a reduction of steps. For all SSBs, there is no requirement for separator, electrolyte insertion, or degassing.

Some technologies, such as LiM anode /polymer electrolyte SSB, do not require a negative current collector.

Furthermore, sealing the cells is simpler with solid electrolytes, as there is no need to contain a pressurized liquid, reducing technical requirements and leakage risks. Additionally, in the absence of a liquid electrolyte, solvent management and associated waste disposal are eliminated, simplifying safety and waste treatment protocols.

Without being 100% exhaustive, we can already see that because the SSB process has fewer steps, it automatically induces a reduction of manufacturing time and machine needs, leading to a reduction of production cost and energy consumption, contributing to a decrease in the SSB cell carbon footprint.

Exhibit 18 shows that the enclosing step represents 12.45% of the total manufacturing cost. If we consider that the formation/aging step is reduced by taking off degassing and that SSB manufacturing allows less deal with solvent recovery, we could also respectively decrease the 32.61% and 4.6% of total process cost. That confirms our previous projections and allows us to approximately quantify a total reduction cost of about 20%.

Manufacturing SSBs could be less expensive than LIBs and more advantageous in light of global warming. Nevertheless, given the investment in LIBs, would it be profitable to adapt existing exploitation to SSB manufacturing? Chemistry-dependent modifications required for the production process can offer challenges and advantages.

Cell production

Due to the structuring required, SSBs are typically produced in pouch cell format. The solids involved are typically not suited to the rolling process employed in cylindrical or prismatic manufacturing. Prologium recently released an example of their production line for oxide-based SSBs, which visualises the process (Exhibit 19) [21].

A key challenge and opportunity relate to overhang. Overhang is a key part of the battery production process, whereby cells will be assembled with a partially oversized anode to ensure that alignment is achieved during assembly. Advanced automation and precision can reduce the level of overhang needed which can achieve higher energy density by having less inactive material in a cell.

For SSBs, a typical route to assemble a stack involves printing on the existing layers. High precision is needed here again to ensure the layer sits uniformly on top to avoid shorting the battery. In the Prologium example, this printing is achieved on the anode which resembles the traditional anode overhang from conventional LIB manufacturing, although other routes are under investigation.

Interface engineering is an important factor in the design of solid-state cells. A key parameter of the solid-state electrolyte is the ionic conductivity. To achieve comparable levels to a liquid electrolyte system typically high stack pressures are required. Processing of oxides to maintain high ionic conductivity typically requires sintering at higher temperatures to enhance this connectivity in the layers. This requirement represents a modification to existing production lines that would add complexity and cost.

In contrast, sulfides are ‘cold compressible’ and may be able to be handled using conventional routes for calendering. Solid Power is a key company working on these types of materials, which generally offer high ionic conductivity but can be prone to instability during electrochemical cycling. A pilot line setup or sulfide production has been established at the Technical University of Munich (TUM) [22]. The solid electrolyte may be formulated into a slurry and cast, which could offer an advantage if this can be done sequentially onto an existing coating using a second slot die head, representing a cutting of the steps. However, compatibility of the layers must be ensured.

Understanding how to maintain stack pressure to keep ionic conductivity high is important at the module and pack levels. Depending on the design, this may add weight to the cell and be detrimental to gravimetric energy density. Solutions that can apply pressure across a stacked SSB are desirable.

A solution to challenges of conductivity is to use a small amount of liquid electrolyte which enhances the ionic conductivity, i.e., a so-called 'semi-solid' battery. Many manufacturers are pursuing this as an interim solution [23]. It is expected that an increase in energy density will be realised by technologies adopting this technique, for example, NiO/WeLion New Energy Technology Co has announced an LFP semi-solid system purported to achieve 260 Wh/kg at the pack level, which is greater than conventional LFP at 160-180 Wh/kg. [24]. However, these systems may not convey the full expected safety benefits of all SSBs, namely puncture resistance and the absence of flammable electrolytes.

In summary, there are a number of steps in the process that need to be optimised for all-solid-state battery production. From the oxide/sulfide side, semi-solid systems are closer to commercial reality, with some manufacturers claiming that these will be commercially available in the late 2020s. There are several opportunities that could enhance the ability to streamline the manufacturing process, however modifications to existing LIB manufacturing lines are expected, which will come at a cost.

EV market for SSBs

EV sales are growing every year and in every region of the globe, balanced by the fact that the sales of ICE vehicles peaked in 2017. Sales of ICE vehicles need to stop by 2038 to help achieve Net Zero by 2050, which is deemed necessary to limit the global temperature increase to 1.5 °C and it is expected that there will be a balance of greenhouse gases (GHG) produced and the amount removed. We are currently on track to follow the Economic Transition Scenario, which reflects current trends with no new government policies or influence. This will lead to only 80% EV adoption by EV [25] (Exhibit 20, 21).

Almost 14 million electric cars were sold in 2023, with 95% of sales occurring in China, Europe and the United States. This brings the total number of electric cars on the world's road today to 40 million [26], still a paltry 3% of the over 1.4 billion cars total in the world [27]. This year, the top 5 selling EVs in Europe are from four manufacturers: Tesla, Volvo, Audi and Volkswagen [28]. Tesla reigns supreme in the US as well, where it is joined by Hyundai and Ford vehicles. Comparison of their acceleration rates, top speeds, battery capacity and efficiency all reveal very similar results (Exhibit 22, 23). For around $50,000 USD, it is easy to find an EV that can reach 60 mph in under 10 seconds, go over 100 mph and take you over 250 miles before needing to find a fast charger where you will stay no longer than 30 minutes before you zoom off again. However, if one were to compare the same top 5 best-selling ICE vehicles for Europe (Dacia Sandero, Renault Clio, Volkswagen Golf and T-Roc, and the Citroen C3), one would see that their average price is closer to $30,000 USD. Indeed, many believe that the slight dip in EV sales this year is the chasm between early adopters who are ready to pay a premium and the early majority who are only ready to pay slightly more for new technology.

A consumer looking to buy an EV today, whose batteries are all based on traditional LIB technology, can use a variety of properties as a way to compare vehicles. The specific battery performance manifests itself in several properties that are familiar to anyone who has ever driven, purchased a personal vehicle or even watched a commercial for one. Acceleration (how fast a vehicle can go from a “dead-stop” to 60 mph) and top speeds are common characteristics used to measure the performance of a vehicle. Previously, ICE vehicles would tout their fuel efficiency (miles per gallon, MPG) and total miles available to travel between fuel stops at a gas station. These values are being replaced by MPGe (miles per gallon of gasoline-equivalent) ratings and driving range between charging stations. These properties are directly related to the power density of the vehicle's battery. Passenger EVs can be broken down into different classes based on performance, mileage, and cost. There are “performance” vehicles that will have high power and speed and come with a higher price tag. There are also more economy cars, whose drivers are focused on fuel efficiency and reliability. The balance of these properties will determine what type of battery will be most tailored for their use.

The selected anode and cathode will dictate the overall cell's energy density. Solid-state batteries allow for the use of Li-metal anodes (notoriously reactive to liquid electrolytes), which have an extremely high energy density. The use of a high-energy anode allows matching with a thinner, potentially lighter cathode, which can increase the overall cell's energy density (Exhibit 24).

The development and adoption of new technologies cannot occur in a vacuum. Scientists are always searching for the next best “thing” and designing the new generation of batteries for electric vehicles has proven a rich playground for many as they race to achieve the highest energy density prototypes. Numerous public press releases can link start-ups to both automotive OEMs as well battery cell manufacturers through either JVA, funding opportunities, or investment in such companies. As these new technologies evolve and undergo further testing, other properties, such as cost, which are key drivers to the automotive industry, will prove important in order to promote the widespread industrialisation and mass adoption of electric vehicles.

USABC (United States Advanced Battery Consortium) was founded in 1991 under USCAR (United States Council for Automotive Research) with a mission to develop electrochemical energy storage technologies that can meet next-generation performance and cost goals for automotive applications. Member companies include Ford Motor Company, General Motors and Stellantis. One output is the publication of performance goals for electric vehicle batteries (Exhibit 25). Additionally, USCAR has similar goal charts for lithium anode-based cells (Exhibit 26).

Additionally, the US Department of Energy (DOE)’s Vehicle Technologies Office (VTO) provides over $100 million in R&D funding, working with USCAR and thus USABC. It has issued its own set of requirements for EV batteries (Exhibit 27 to 29), highlighting the areas where there is a need for improvement due to no commercial cells or packs meeting the requirement., notably in the cost and energy density categories (Exhibit 27. to 29.). In 2022, they also broke the cell technologies into 3 categories: "Current technology" (based upon a graphite anode and NMC-based cathode), "Next-Generation Lithium-ion" (containing some sort of silicon blend in anode plus a high nickel NMC-based cathode), and finally "Beyond Lithium", which is based on a lithium metal anode. Notably, this 3rd category is not called "Solid-State" as many researchers have found that lithium-metal anode can be used in conjunction with some wetting agents in the cell that are not the typical carbonate electrolyte solvents.

In 2022, the report showed that the current technology of cells costs over $200/kWh, but it was assumed that with the economy of scaling and process optimisation, that price could be lowered to $100-160/kWh. Only two years later, CATL announced their plans to produce a $56/kWh cell by mid-2024 [29]. Goldman-Sachs predicts a less drastic, but still significant drop to under $100/kWh by as early as 2025, compared to Bloomberg NEF's prediction of #113/kWh in 2025, but down to $80/kWh in 2030 (Exhibit 30).

A 6-hour online workshop was held at the peak of the COVID era in May 2020, hosted by the US-based Oak Ridge National Lab to discuss recent advances and outline roadblocks in realising Li-metal anode-based solid-state batteries [30]. It was noted that their advantages must still be classified as "theoretical", relying on technical successes which are not assured nor demonstrated on a commercial scale. The largest hurdles include typical technical challenges, such as control of the raw materials and interfaces, and expanding to more process-related issues, such as addressing processing challenges and cost and maintaining optimal stack pressure in a cost-effective manner, all of which will ultimately demonstrate performance which can exceed the advanced Li-ion batteries. They concluded that meeting requirements of performance, cost and manufacturability for a battery for a commercial vehicle in 5-10 years (from 2020) is "ambitious." However, that was four years ago, nearly a lifetime in the battery world.

Similar to the outlandish drop in the cost of traditional cells announced by CATL, the solid-state battery world was again shaken in May of 2024, when the Chinese government announced that it would invest more than 6 billion yuan ($830 million) with six companies to work on solid-state batteries, including CATL, WeLion New Energy, and BYD [31]. The goal of this investment would be to launch the large-scale commercial production of solid-state batteries for EVs before 2030, starting with smaller quantities as early as 2027.

Conclusion

EV sales are increasing globally, with nearly 14 million sold in 2023, mainly in China, Europe, and the US. Despite this growth, EVs still only represent 3% of the global car fleet. Current EVs rely on traditional lithium-ion batteries, but future advancements, including SSBs with high energy density, are expected. Cost reductions and technological improvements, driven by government investments and industry collaborations, aim to make EVs more affordable and efficient, potentially revolutionising the market by 2030.

Nevertheless, SSBs face three main technological challenges: reducing the solid electrolyte (SE) in the cathode while increasing electrode thickness for higher energy density; developing a high-performance anode to prevent dendrite growth; and managing the thermal risks associated with high nickel cathodes or Li metal anodes. Performance-wise, SSBs promise rapid charging (80% SOC in under 15 minutes), high energy density (up to 900 Wh/kg), and are projected to reach market maturity within 5-10 years. Manufacturing SSBs requires optimising production steps, with semi-solid systems nearing commercial viability by the late 2020s, though adapting existing lithium-ion battery (LIB) production lines will incur costs.

Questions that can help guide the strategy development are as follows :

- Will SSBs or Semi-SSB compete with existing batteries or complement them? If so, what chemistry/format would suit EV applications?
- Should the EU incentivizing in a similar way to the Chinese government's strategy? What other strategies can help push the scaling and commercialisation of SSBs?
- Are SSBs a risk to your company, in the context of the EV market? If yes, when are SSBs coming to the market and at what price point?

Exhibits

Exhibit 1 - Schematic showing the start of the art conventional LIB and Li metal SSB. [4]

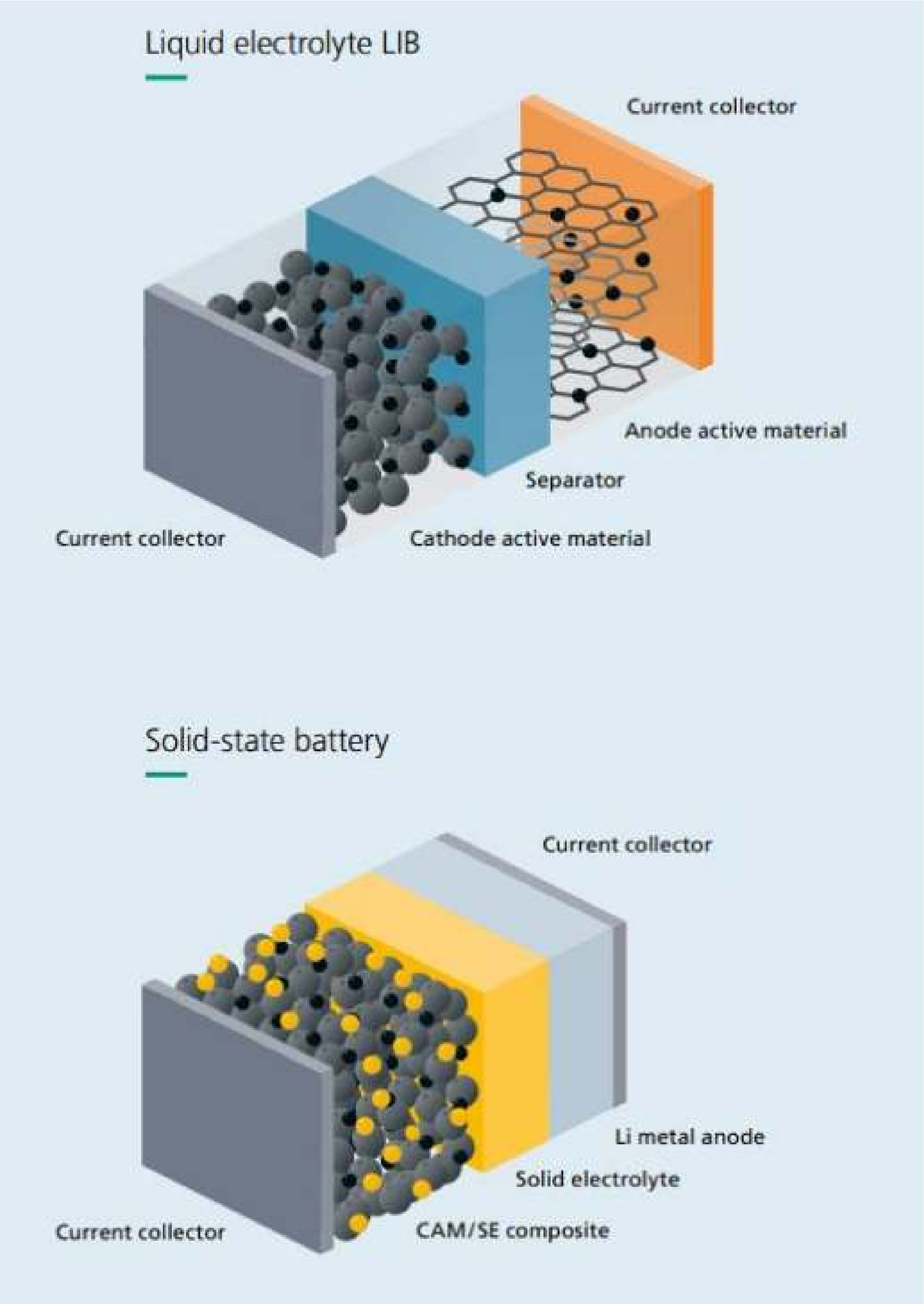


Exhibit 2. Schematic showing the microstructure of a standard Li-ion and SSB electrolyte and the current collector. [1]

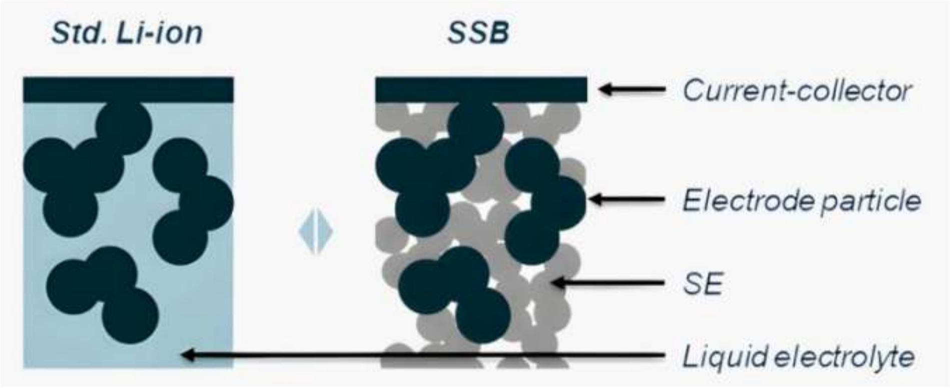
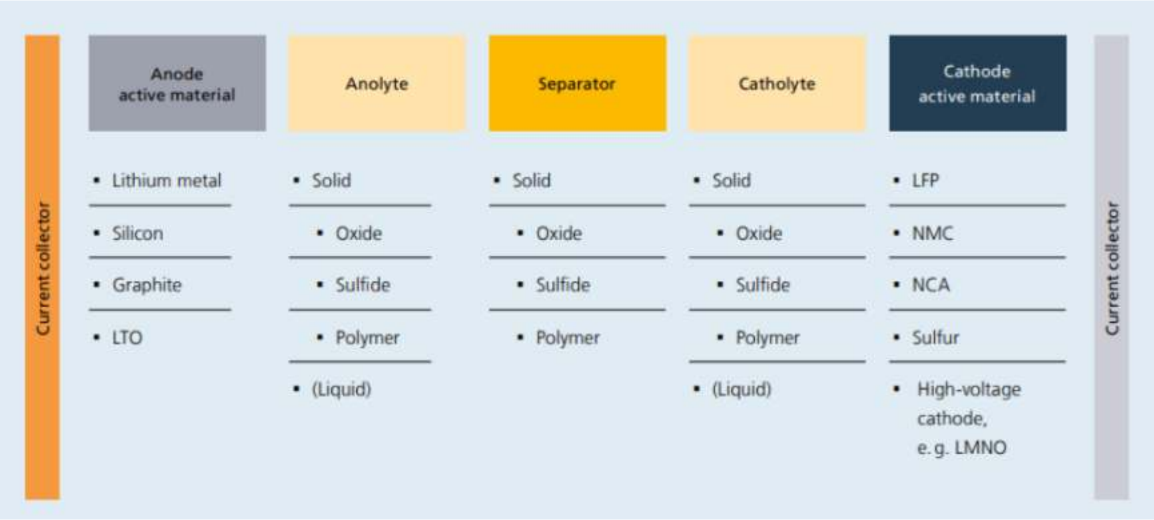


Exhibit 3. Schematic showing different chemistries for Li based SSBs. [4]



Anode active material	Anolyte	Separator	Catholyte	Cathode active material
Lithium metal	Solid	Solid	Solid	LFP
Silicon	Oxide	Oxide	Oxide	NMC
Graphite	Sulfide	Sulfide	Sulfide	NCA
LTO	Polymer	Polymer	Polymer	Sulfur
	(Liquid)		(Liquid)	High-voltage cathode, e.g. LMNO

Exhibit 4. Gravimetric energy density per cathode chemistry

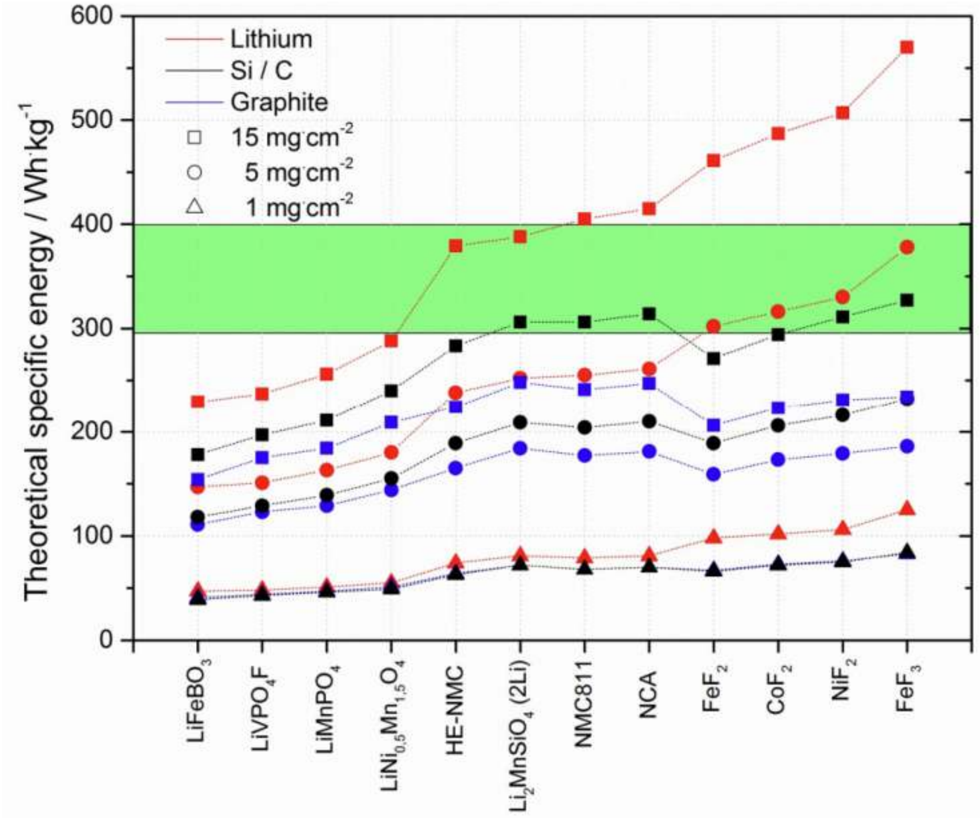
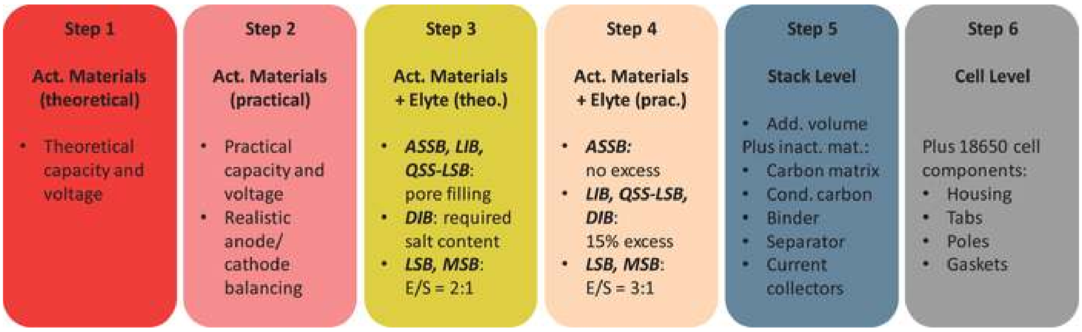
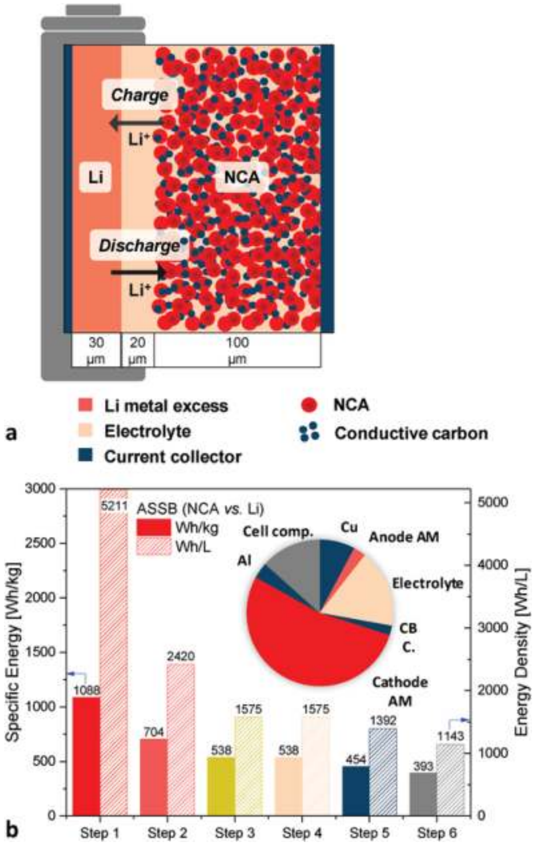


Exhibit 5. Steps from theoretical to cell's value



Step 1	**Step 2**	**Step 3**	**Step 4**	**Step 5**	**Step 6**
Act. Materials (theoretical)	**Act. Materials (practical)**	**Act. Materials + Elyte (theo.)**	**Act. Materials + Elyte (prac.)**	**Stack Level**	**Cell Level**
• Theoretical capacity and voltage	• Practical capacity and voltage • Realistic anode/ cathode balancing	• ***ASSB, LIB, QSS-LSB***: pore filling • ***DIB***: required salt content • ***LSB, MSB***: E/S = 2:1	• ***ASSB:*** no excess • ***LIB, QSS-LSB, DIB***: 15% excess • ***LSB, MSB***: E/S = 3:1	• Add. volume Plus inact. mat.: • Carbon matrix • Cond. carbon • Binder • Separator • Current collectors	Plus 18650 cell components: • Housing • Tabs • Poles • Gaskets

Exhibit 6. Steps for Li-ion NCA Exhibit 7. Steps for SSB NCA



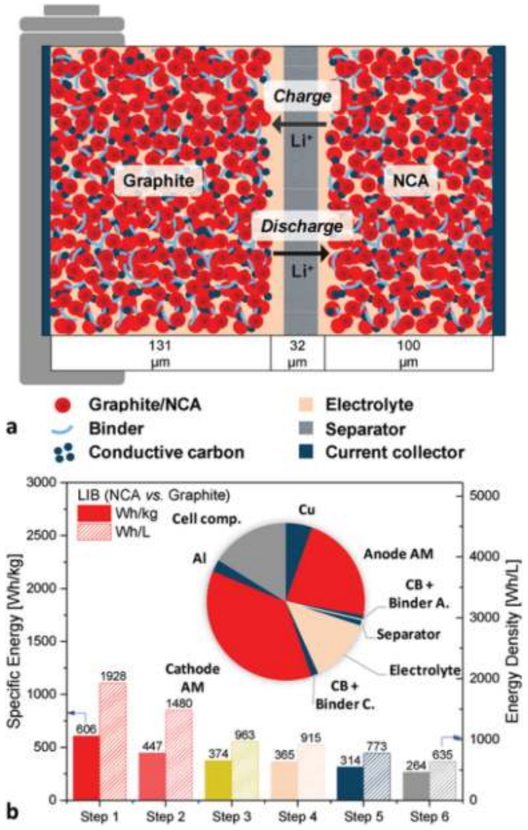


Exhibit 8. Lyten's 3D Graphene structure.

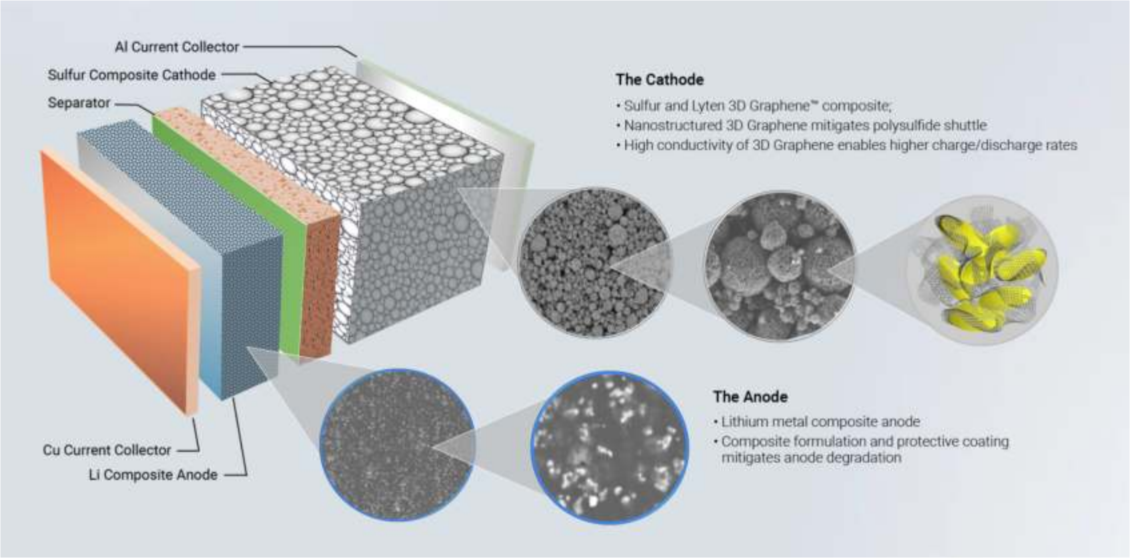
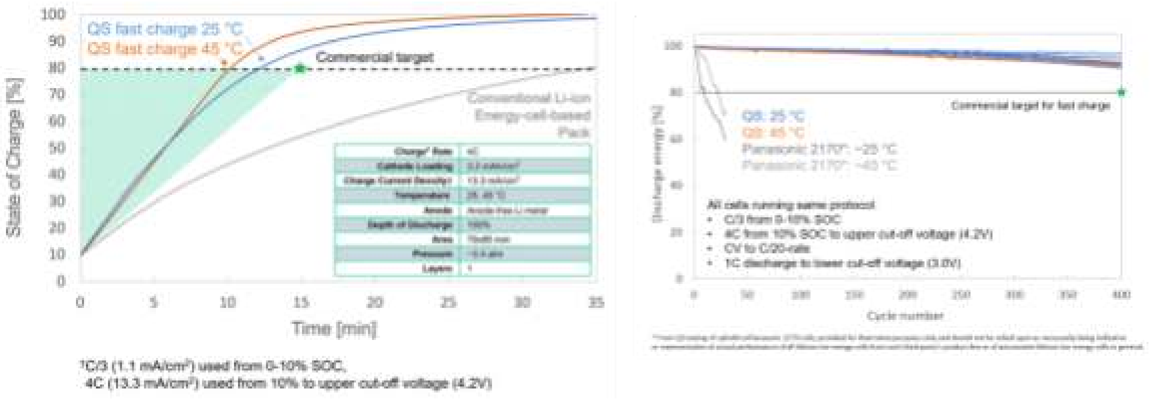


Exhibit 9. Quantumscape SSB performances



[1]C/3 (1.1 mA/cm²) used from 0-10% SOC,
4C (13.3 mA/cm²) used from 10% to upper cut-off voltage (4.2V)

All cells running same protocol
- C/3 from 0-10% SOC
- 4C from 10% SOC to upper cut-off voltage (4.2V)
- CV to C/20-rate
- 1C discharge to lower cut-off voltage (3.0V)

Exhibit 10. Future lab's comparison between 2 SSBs and 2 Li-on batteries

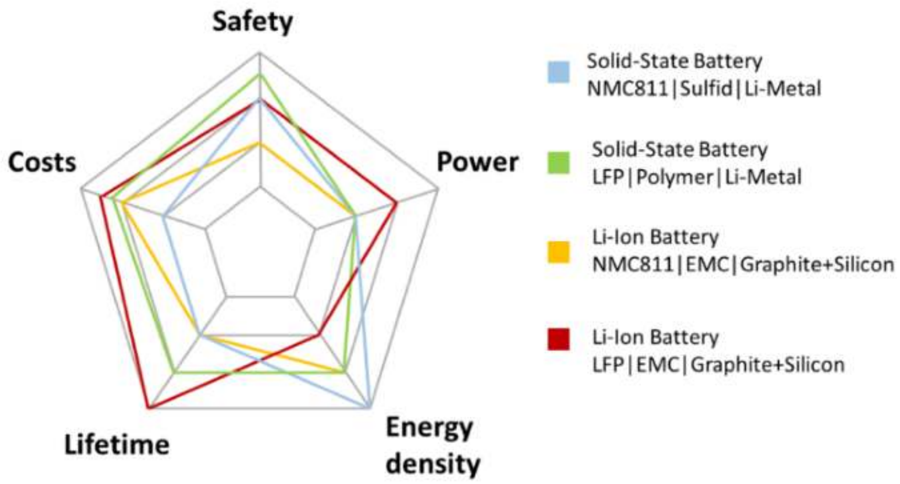
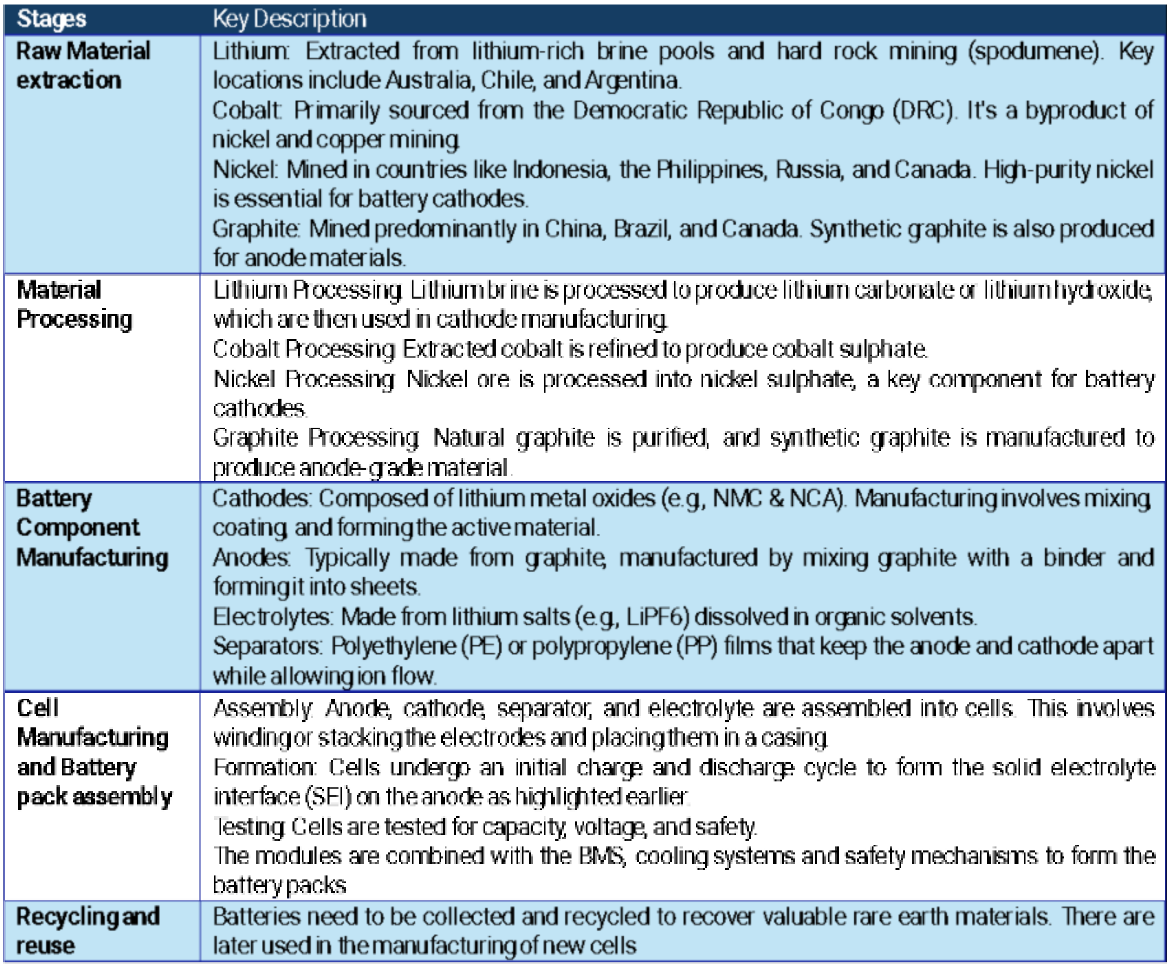


Exhibit 11. Supply chain stages in LIBs



Stages	Key Description
Raw Material extraction	Lithium: Extracted from lithium-rich brine pools and hard rock mining (spodumene). Key locations include Australia, Chile, and Argentina. Cobalt: Primarily sourced from the Democratic Republic of Congo (DRC). It's a byproduct of nickel and copper mining. Nickel: Mined in countries like Indonesia, the Philippines, Russia, and Canada. High-purity nickel is essential for battery cathodes. Graphite: Mined predominantly in China, Brazil, and Canada. Synthetic graphite is also produced for anode materials.
Material Processing	Lithium Processing: Lithium brine is processed to produce lithium carbonate or lithium hydroxide, which are then used in cathode manufacturing. Cobalt Processing: Extracted cobalt is refined to produce cobalt sulphate. Nickel Processing: Nickel ore is processed into nickel sulphate, a key component for battery cathodes. Graphite Processing: Natural graphite is purified, and synthetic graphite is manufactured to produce anode-grade material.
Battery Component Manufacturing	Cathodes: Composed of lithium metal oxides (e.g, NMC & NCA). Manufacturing involves mixing, coating, and forming the active material. Anodes: Typically made from graphite, manufactured by mixing graphite with a binder and forming it into sheets. Electrolytes: Made from lithium salts (e.g, LiPF6) dissolved in organic solvents. Separators: Polyethylene (PE) or polypropylene (PP) films that keep the anode and cathode apart while allowing ion flow.
Cell Manufacturing and Battery pack assembly	Assembly: Anode, cathode, separator, and electrolyte are assembled into cells. This involves winding or stacking the electrodes and placing them in a casing. Formation: Cells undergo an initial charge and discharge cycle to form the solid electrolyte interface (SEI) on the anode as highlighted earlier. Testing: Cells are tested for capacity, voltage, and safety. The modules are combined with the BMS, cooling systems and safety mechanisms to form the battery packs.
Recycling and reuse	Batteries need to be collected and recycled to recover valuable rare earth materials. There are later used in the manufacturing of new cells.

Exhibit 12. Supply chain stages in SSB

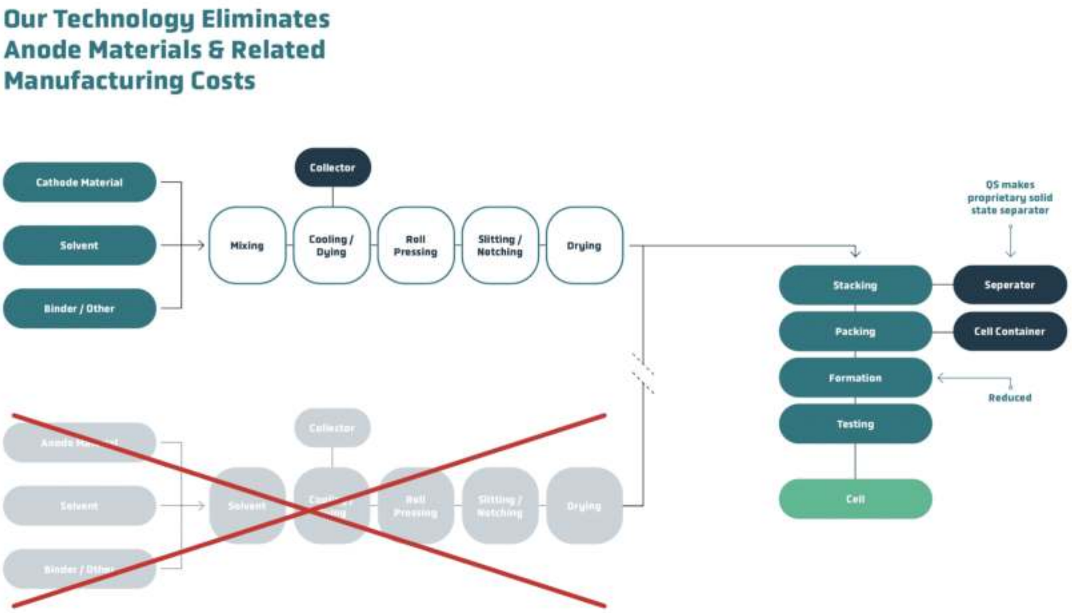
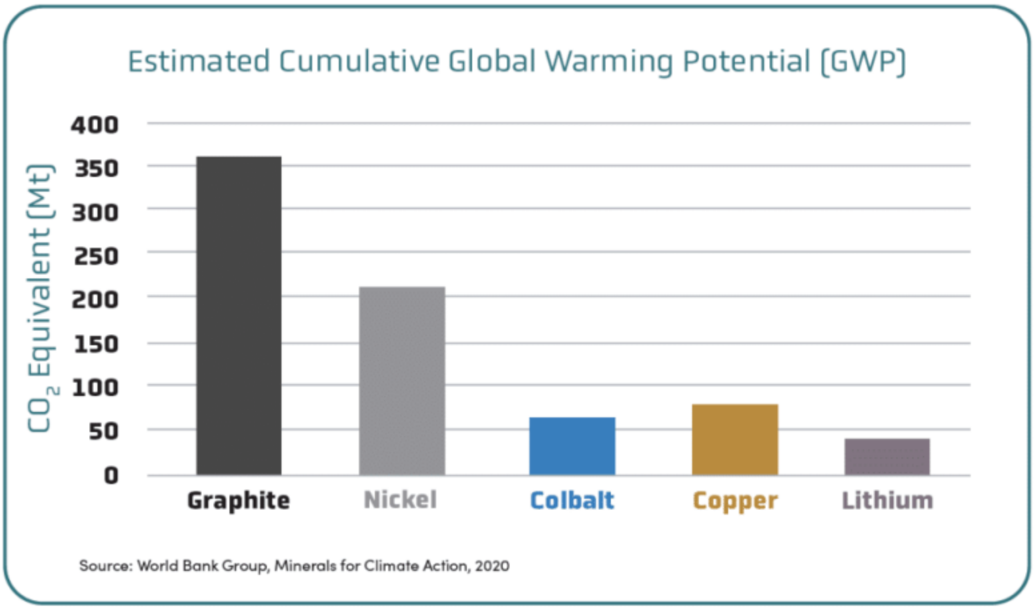
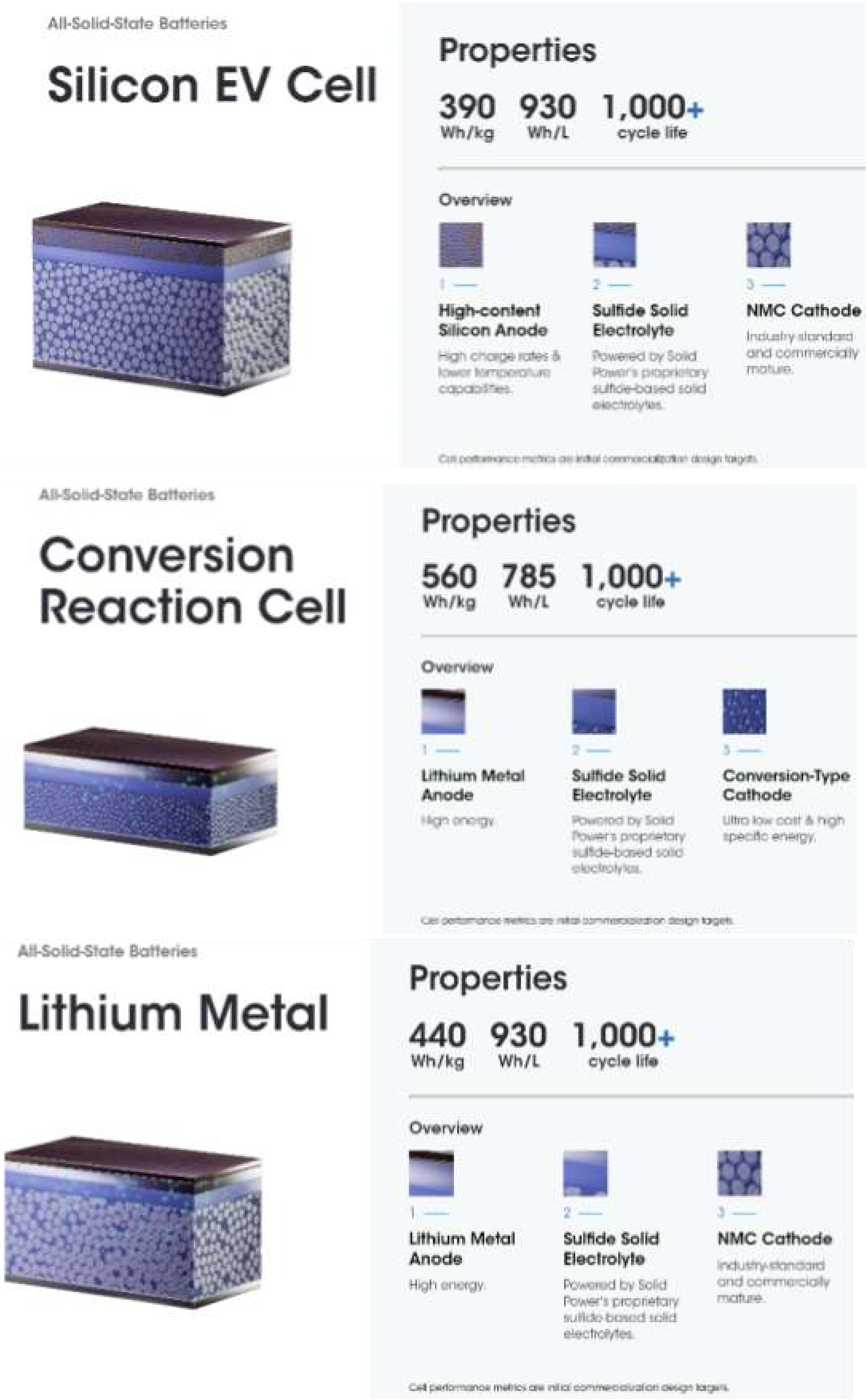


Exhibit 13. GWP in LIBs' manufacturing



Source: World Bank Group, Minerals for Climate Action, 2020

Exhibit 14. Different SSB technologies



All-Solid-State Batteries

Silicon EV Cell

Properties

390 Wh/kg 930 Wh/L 1,000+ cycle life

Overview

1 — **High-content Silicon Anode**
High charge rates & lower temperature capabilities.

2 — **Sulfide Solid Electrolyte**
Powered by Solid Power's proprietary sulfide-based solid electrolytes.

3 — **NMC Cathode**
Industry standard and commercially mature.

Cell performance metrics are initial commercialization design targets.

All-Solid-State Batteries

Conversion Reaction Cell

Properties

560 Wh/kg 785 Wh/L 1,000+ cycle life

Overview

1 — **Lithium Metal Anode**
High energy.

2 — **Sulfide Solid Electrolyte**
Powered by Solid Power's proprietary sulfide-based solid electrolytes.

3 — **Conversion-Type Cathode**
Ultra low cost & high specific energy.

Cell performance metrics are initial commercialization design targets.

All-Solid-State Batteries

Lithium Metal

Properties

440 Wh/kg 930 Wh/L 1,000+ cycle life

Overview

1 — **Lithium Metal Anode**
High energy.

2 — **Sulfide Solid Electrolyte**
Powered by Solid Power's proprietary sulfide-based solid electrolytes.

3 — **NMC Cathode**
Industry standard and commercially mature.

Cell performance metrics are initial commercialization design targets.

Exhibit 15. Hype cycle of battery technology - Gartner, and the 5 distinct phases of the Hype cycle.

Category	Description
Innovation trigger	This is what starts the excitement and gets people interested in the Innovation
Trough of disillusionment	Here, the Interest of stakeholder's wanes as experiments fail to deliver the expected benefits
Peak of inflated expectations	This is where you reach the highest level of expectation of the what the innovation will deliver, normally accompanied with failures.
Slope of enlightenment	This is the development of an understanding to how the technology will benefit the industry
Plateau of productivity	This is where mainstream adoption takes off, with established procedures and standards.

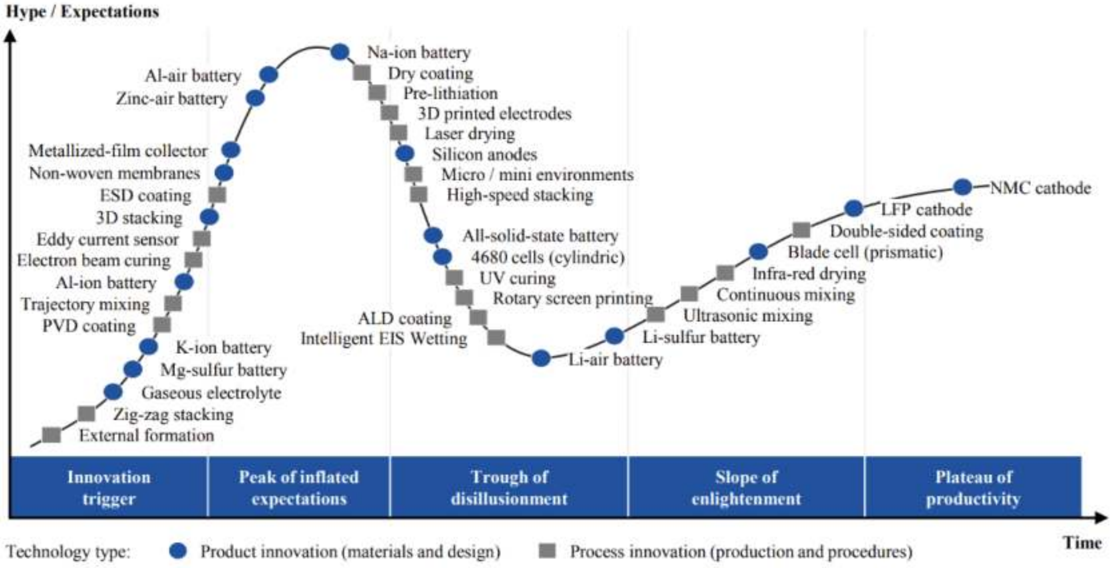


Exhibit 16. time to market versus technology potential

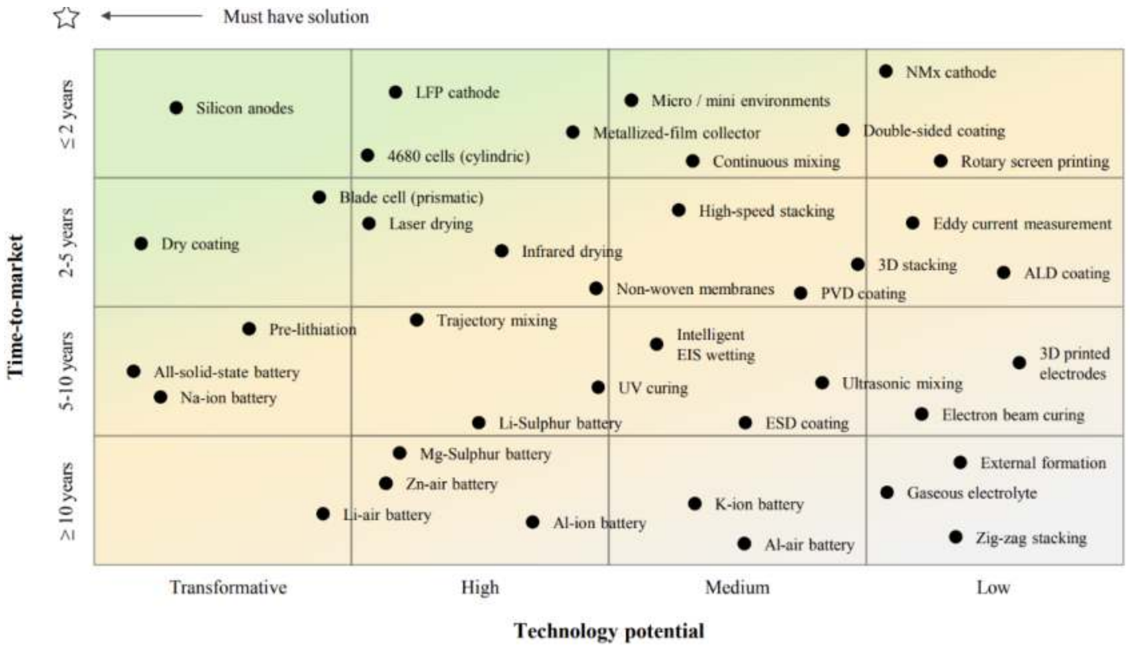


Exhibit 17. LIBs manufacturing process [18]

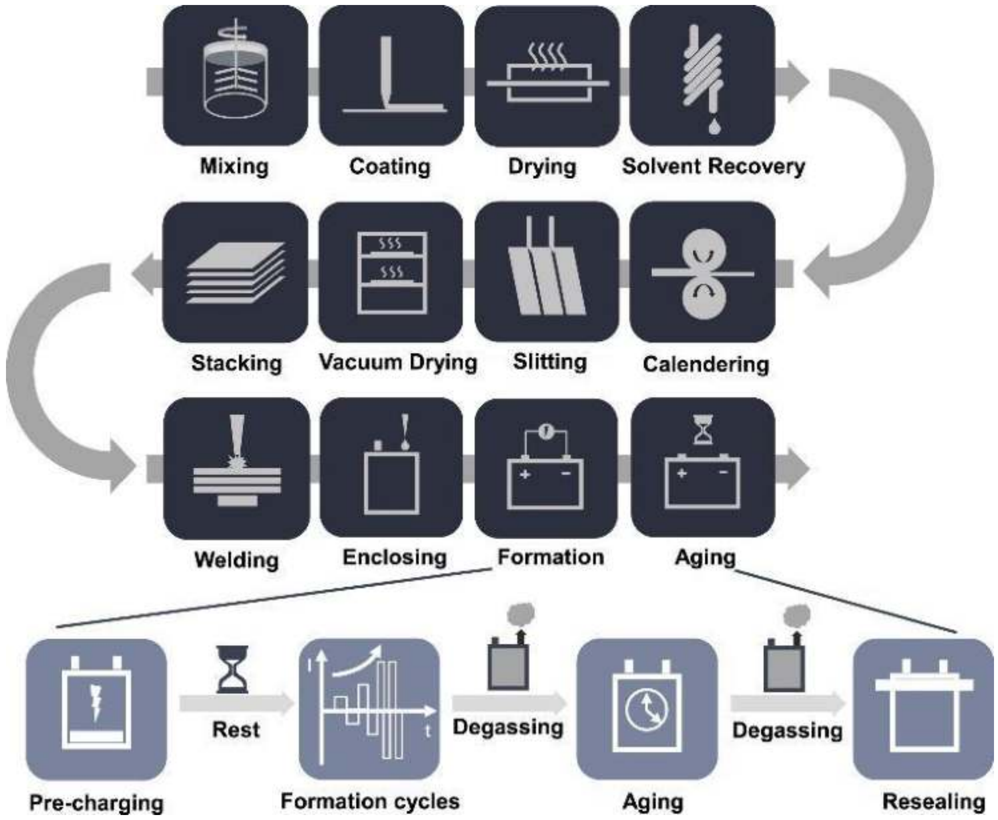


Exhibit 18. Cost and energy consumption breakdown of LIB manufacturing processes [18]

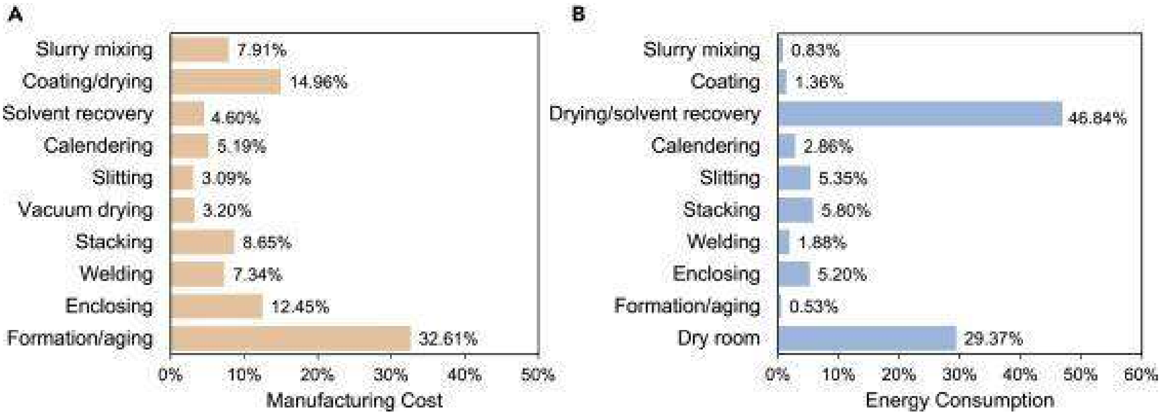
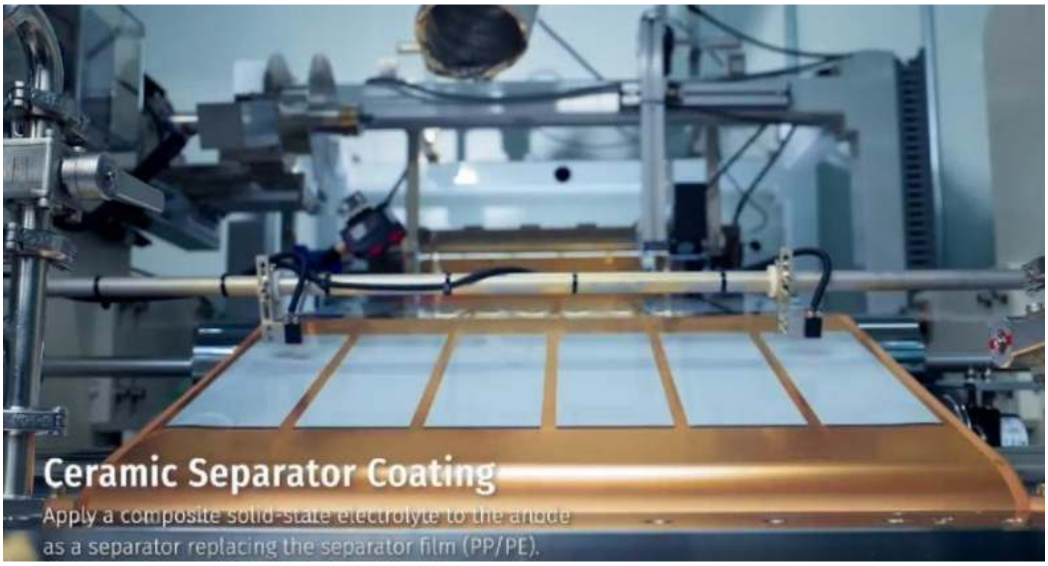


Exhibit 19. Oxide-based SSB's process.



Ceramic Separator Coating

Apply a composite solid-state electrolyte to the anode as a separator replacing the separator film (PP/PE).

Exhibit 20. Global Electric Car Stock (Millions) from 2013-2023 by region [32]

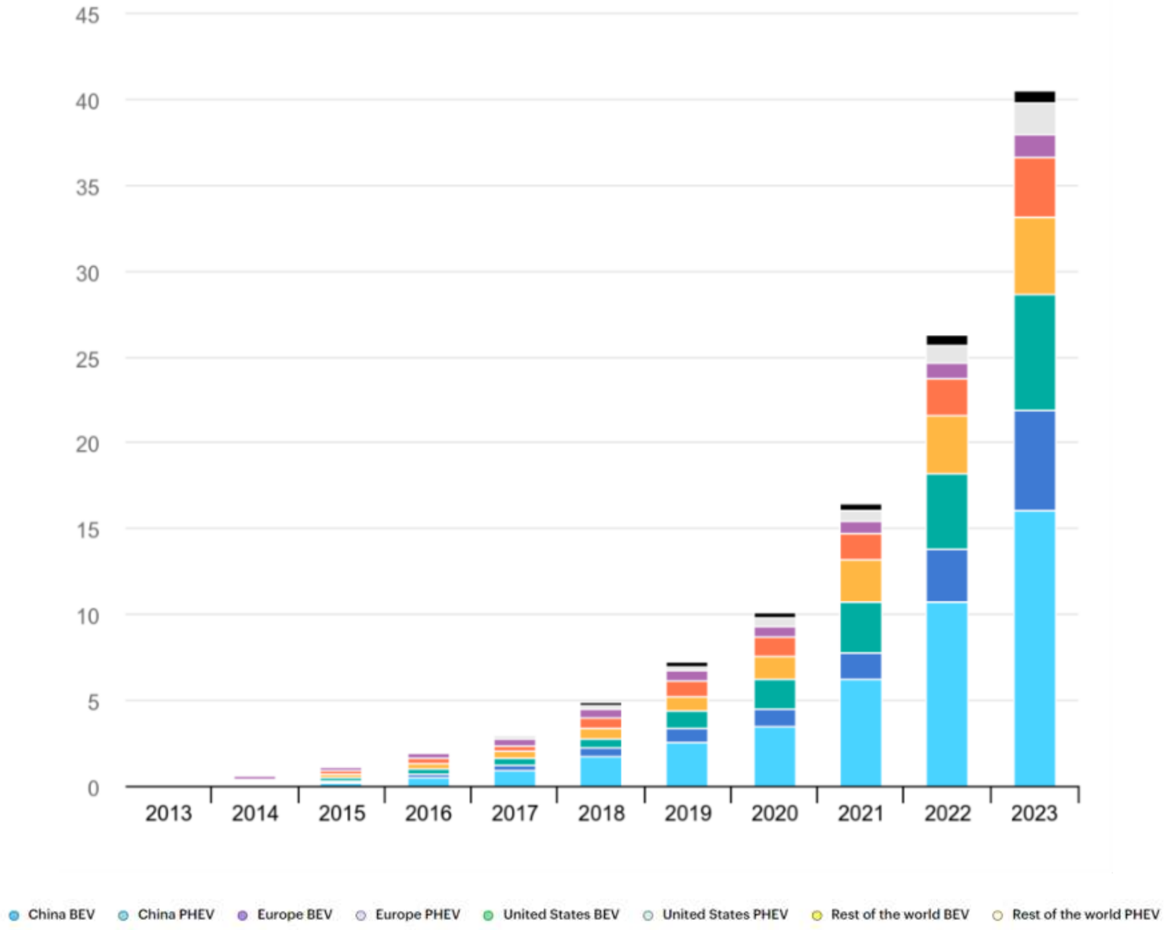


Exhibit 21. Global electric road vehicle sales-based on the Economic Transition Scenario (blue) or the Net Zero Scenario (purple).

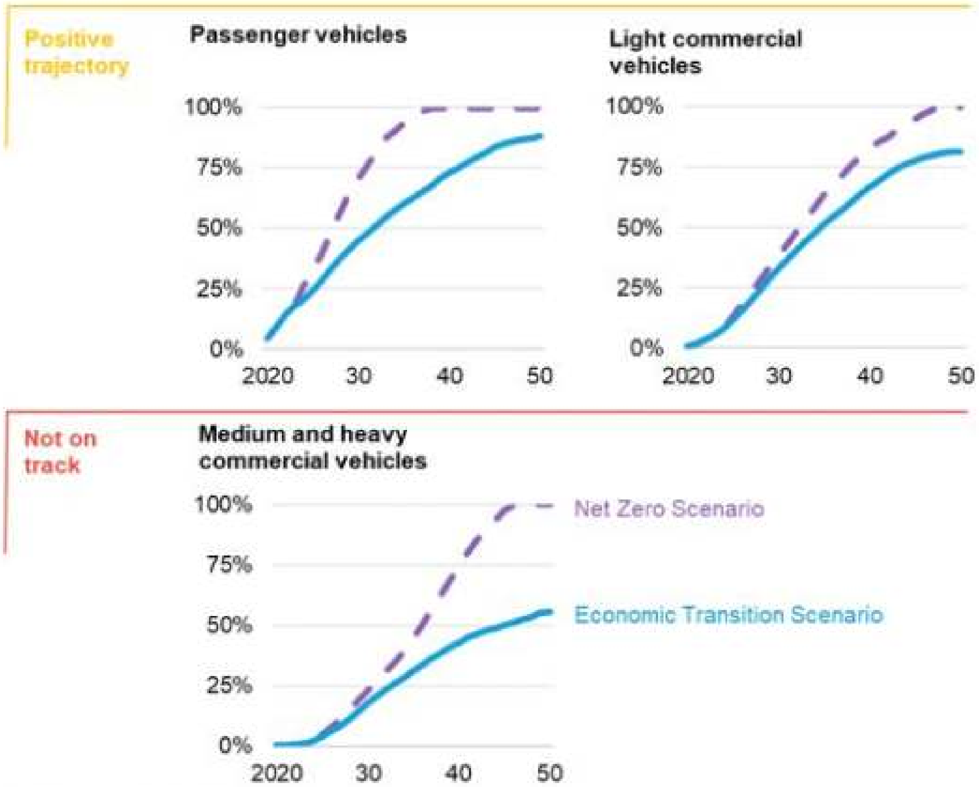
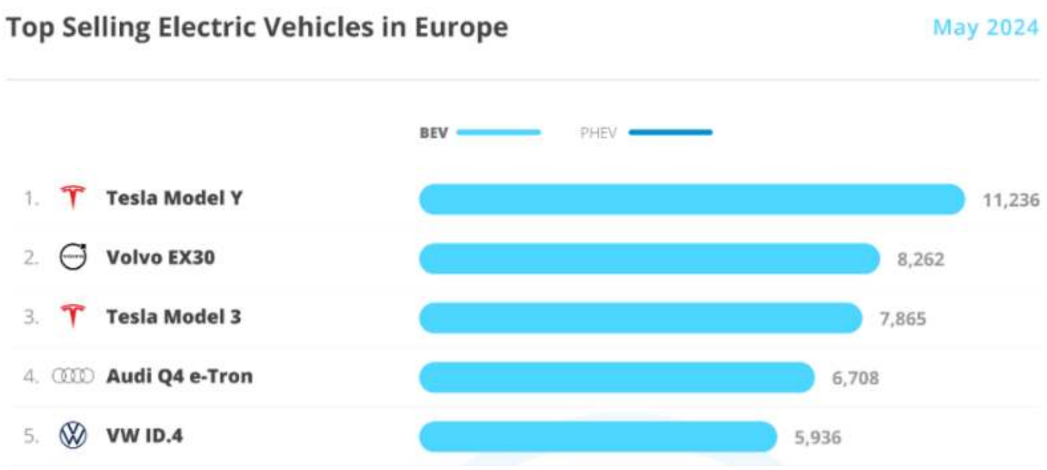


Exhibit 22. Top-selling EV in Europe.



(https://alternative-fuels-observatory.ec.europa.eu/general-information/news/europes-ev-market-update-may-2024)

Exhibit 23. Comparison of the top 5 selling EVs in Europe plus additional top-selling EVs in the US. [33]

	Time to 60 mph (seconds)	Top Speed (mph)	Range (miles)	Price ($USD)	Time to Charge DC Fast (0-100%)	Battery Capacity (kWh)	Efficiency (Wh/km)
Tesla Model Y	3.5-5.2	135-155	279-303	49,130-55,880	27 m	78.1	171
Volvo EX30	3.4	112	280-287	36,245-47,895 * 2025 price		69	153
Tesla Model 3	3.1-5.8	140-162	272-315	41,630-54,630	27 m	78.1	140
Audi Q4 e-tron	5	112	325	55,200-62,200	28 m	82	167
VW id.4	7.3	100	341	41,160-54,600	28 m	82	159
Hyundai Ioniq 5	4.4	115	260-303	41,800-53,500	16 m	77.4	179
Ford Mustang Mach-E	3.7	114	250-320	41,890-65,390	47 m	98.7	212

Exhibit 24. Anode and Cathode energy density per chemistry

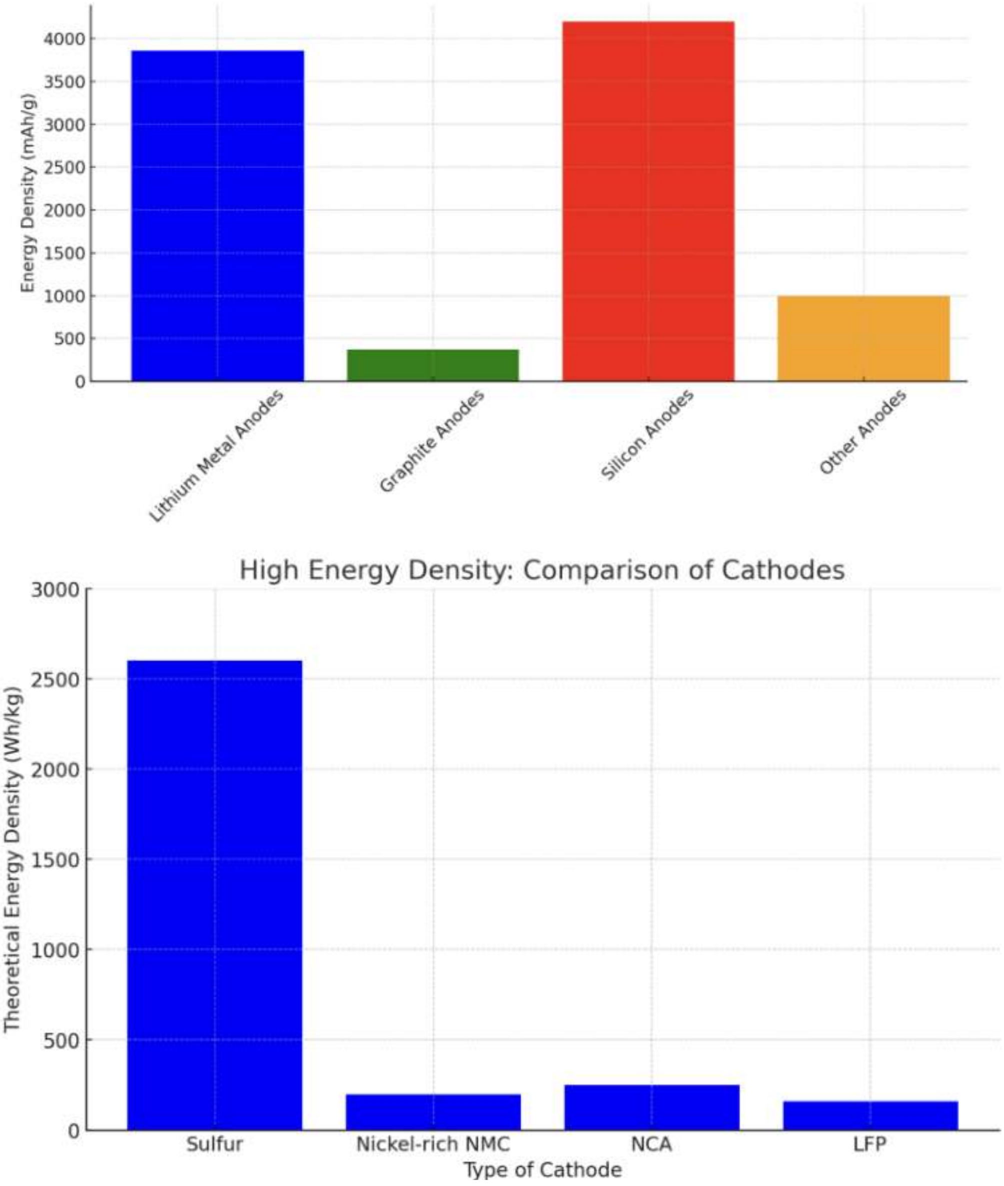
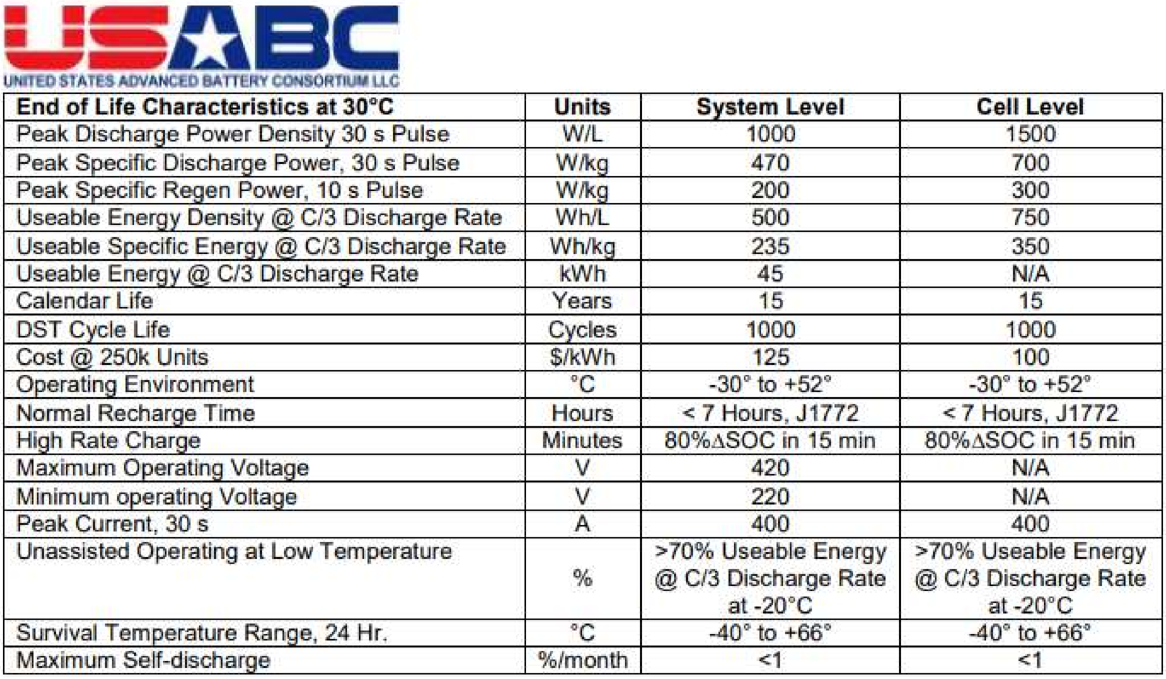
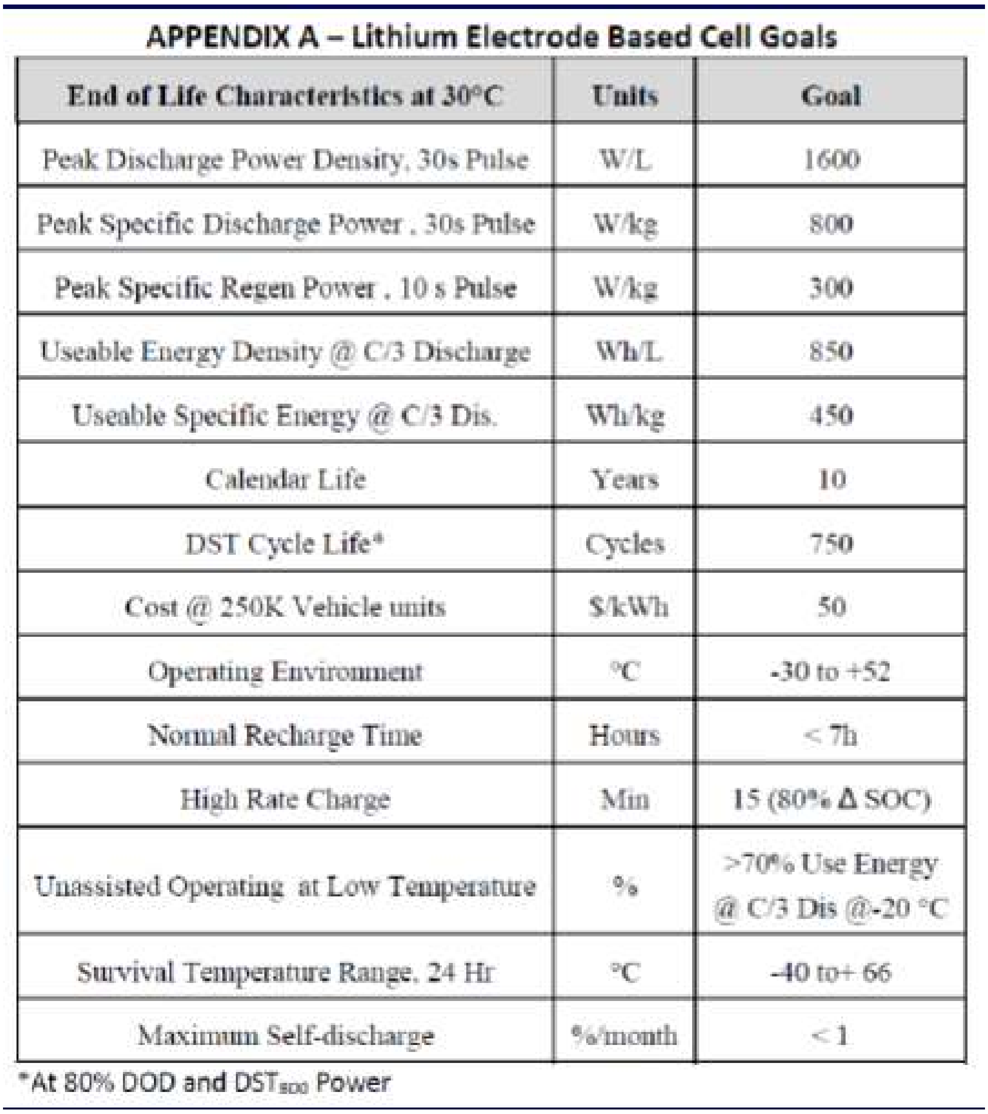


Exhibit 25. USABC Goals for Advanced High-Performance Batteries for Electric Vehicle Applications (2021)



End of Life Characteristics at 30°C	Units	System Level	Cell Level
Peak Discharge Power Density 30 s Pulse	W/L	1000	1500
Peak Specific Discharge Power, 30 s Pulse	W/kg	470	700
Peak Specific Regen Power, 10 s Pulse	W/kg	200	300
Useable Energy Density @ C/3 Discharge Rate	Wh/L	500	750
Useable Specific Energy @ C/3 Discharge Rate	Wh/kg	235	350
Useable Energy @ C/3 Discharge Rate	kWh	45	N/A
Calendar Life	Years	15	15
DST Cycle Life	Cycles	1000	1000
Cost @ 250k Units	$/kWh	125	100
Operating Environment	°C	-30° to +52°	-30° to +52°
Normal Recharge Time	Hours	< 7 Hours, J1772	< 7 Hours, J1772
High Rate Charge	Minutes	80%ΔSOC in 15 min	80%ΔSOC in 15 min
Maximum Operating Voltage	V	420	N/A
Minimum operating Voltage	V	220	N/A
Peak Current, 30 s	A	400	400
Unassisted Operating at Low Temperature	%	>70% Useable Energy @ C/3 Discharge Rate at -20°C	>70% Useable Energy @ C/3 Discharge Rate at -20°C
Survival Temperature Range, 24 Hr.	°C	-40° to +66°	-40° to +66°
Maximum Self-discharge	%/month	<1	<1

Exhibit 26 USCAR performance goals for lithium anode based



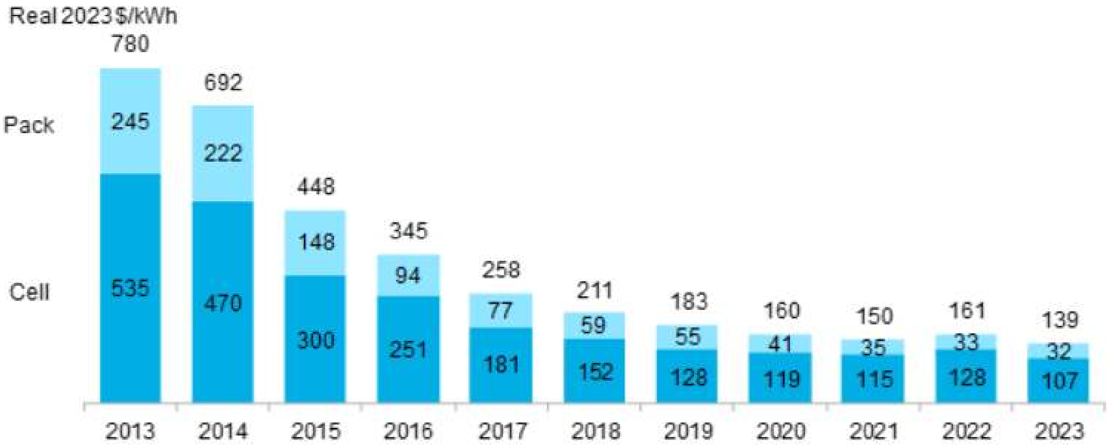
APPENDIX A – Lithium Electrode Based Cell Goals

End of Life Characteristics at 30°C	Units	Goal
Peak Discharge Power Density, 30s Pulse	W/L	1600
Peak Specific Discharge Power , 30s Pulse	W/kg	800
Peak Specific Regen Power , 10 s Pulse	W/kg	300
Useable Energy Density @ C/3 Discharge	Wh/L	850
Useable Specific Energy @ C/3 Dis.	Wh/kg	450
Calendar Life	Years	10
DST Cycle Life*	Cycles	750
Cost @ 250K Vehicle units	$/kWh	50
Operating Environment	°C	-30 to +52
Normal Recharge Time	Hours	< 7h
High Rate Charge	Min	15 (80% Δ SOC)
Unassisted Operating at Low Temperature	%	>70% Use Energy @ C/3 Dis @-20 °C
Survival Temperature Range, 24 Hr	°C	-40 to+ 66
Maximum Self-discharge	%/month	< 1

*At 80% DOD and DST_{800} Power

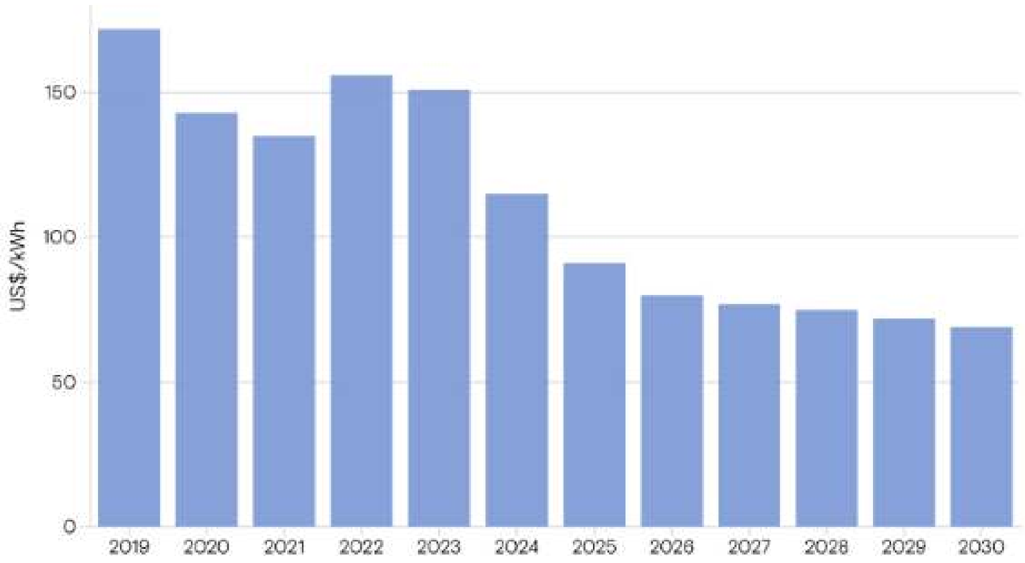
Exhibit 27. Volume-weighted average costs of pack and cell

Figure 1: Volume-weighted average lithium-ion battery pack and cell price split, 2013-2023



Source: BloombergNEF. Historical prices have been updated to reflect real 2023 dollars. Weighted average survey value includes 303 data points from passenger cars, buses, commercial vehicles, and stationary storage.

Exhibit 28. Battery price forecasts



Battery prices are forecast to fall

Global average battery pack prices

Source: Company data, Wood Mackenzie, SNE Research, BNEF, Goldman Sachs Research
2023-2030 are estimates

Goldman Sachs

Exhibit 29. Past and predicted future cost of traditional LiB cells compiled by Goldman Sachs and BloombergNEF [34]

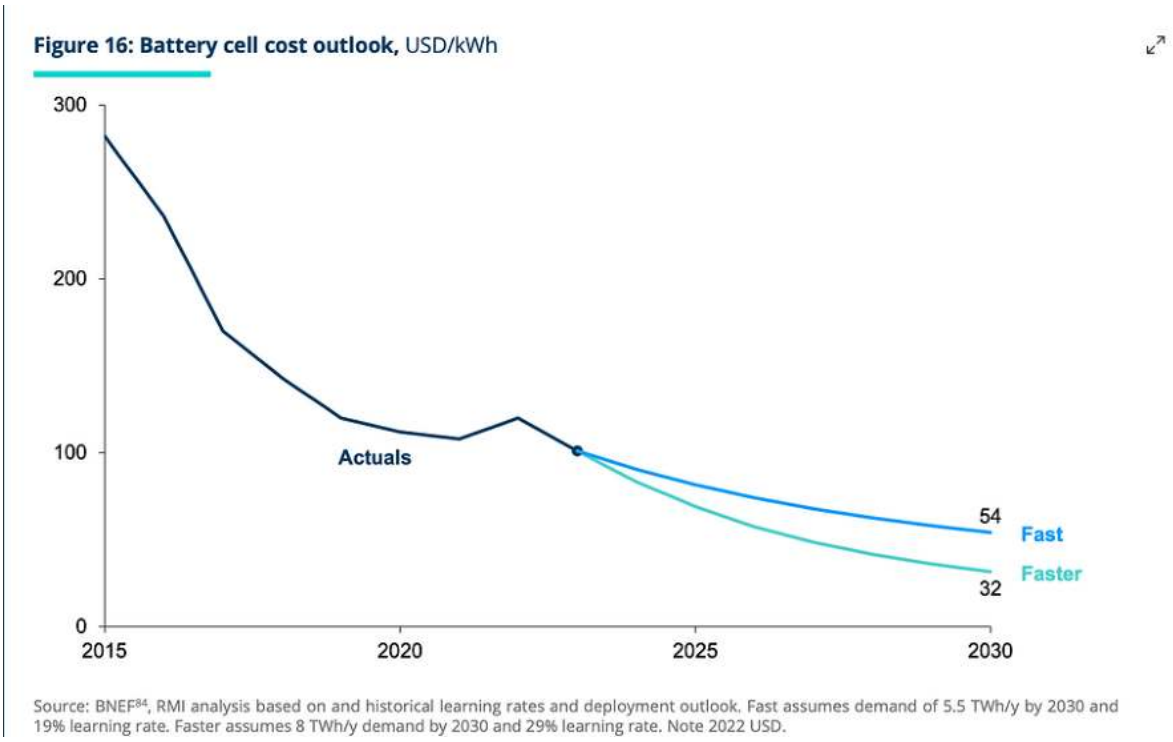


Figure 16: Battery cell cost outlook, USD/kWh

Source: BNEF[84], RMI analysis based on and historical learning rates and deployment outlook. Fast assumes demand of 5.5 TWh/y by 2030 and 19% learning rate. Faster assumes 8 TWh/y demand by 2030 and 29% learning rate. Note 2022 USD.

Exhibit 30. Bloomberg NEF’s prediction

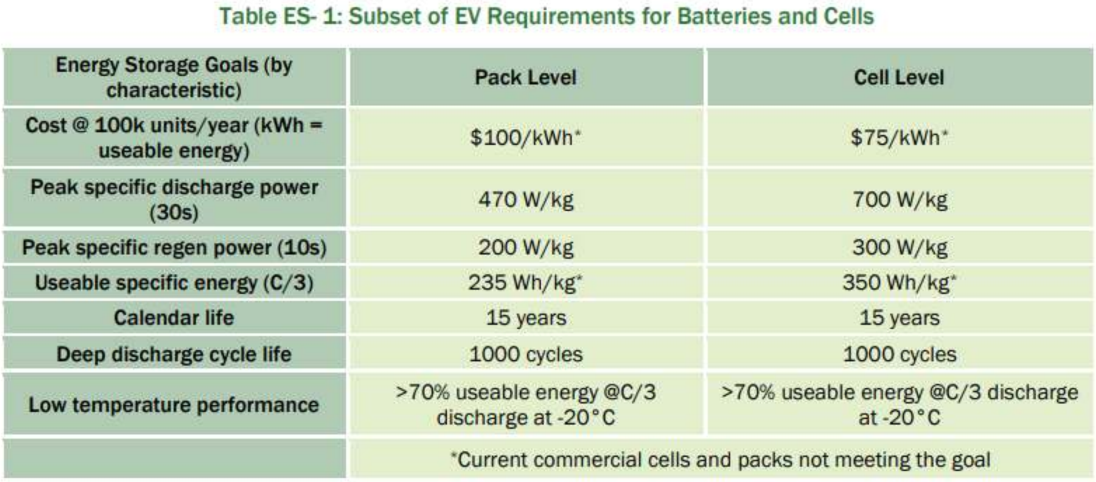
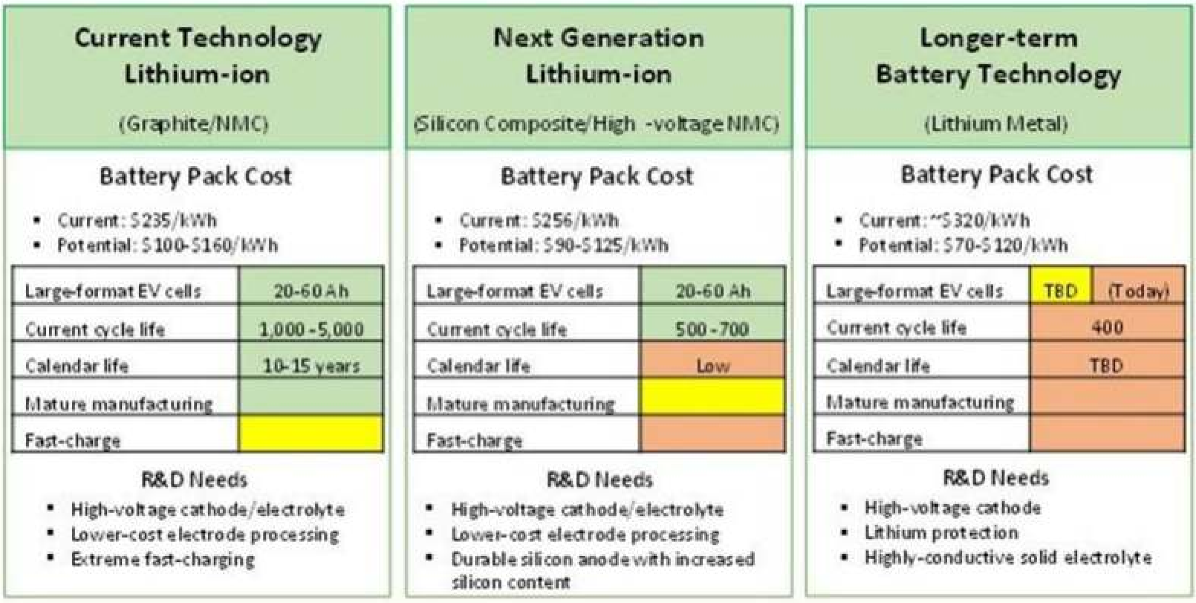


Table ES- 1: Subset of EV Requirements for Batteries and Cells

Energy Storage Goals (by characteristic)	Pack Level	Cell Level
Cost @ 100k units/year (kWh = useable energy)	$100/kWh*	$75/kWh*
Peak specific discharge power (30s)	470 W/kg	700 W/kg
Peak specific regen power (10s)	200 W/kg	300 W/kg
Useable specific energy (C/3)	235 Wh/kg*	350 Wh/kg*
Calendar life	15 years	15 years
Deep discharge cycle life	1000 cycles	1000 cycles
Low temperature performance	>70% useable energy @C/3 discharge at -20°C	>70% useable energy @C/3 discharge at -20°C
	*Current commercial cells and packs not meeting the goal	

https://www.energy.gov/sites/default/files/2023-10/VTO_2022_APR_Batteries_FINAL_Compliant_-min.pdf

2022 Batteries Annual Progress Report	Vehicle Technologies Office	2023	Batteries and Electrification	Report



Current Technology Lithium-ion

(Graphite/NMC)

Battery Pack Cost

- Current: $235/kWh
- Potential: $100-$160/kWh

Large-format EV cells	20-60 Ah
Current cycle life	1,000 - 5,000
Calendar life	10-15 years
Mature manufacturing	🟩
Fast-charge	🟨

R&D Needs

- High-voltage cathode/electrolyte
- Lower-cost electrode processing
- Extreme fast-charging

Next Generation Lithium-ion

(Silicon Composite/High -voltage NMC)

Battery Pack Cost

- Current: $256/kWh
- Potential: $90-$125/kWh

Large-format EV cells	20-60 Ah
Current cycle life	500 - 700
Calendar life	Low
Mature manufacturing	🟨
Fast-charge	🟧

R&D Needs

- High-voltage cathode/electrolyte
- Lower-cost electrode processing
- Durable silicon anode with increased silicon content

Longer-term Battery Technology

(Lithium Metal)

Battery Pack Cost

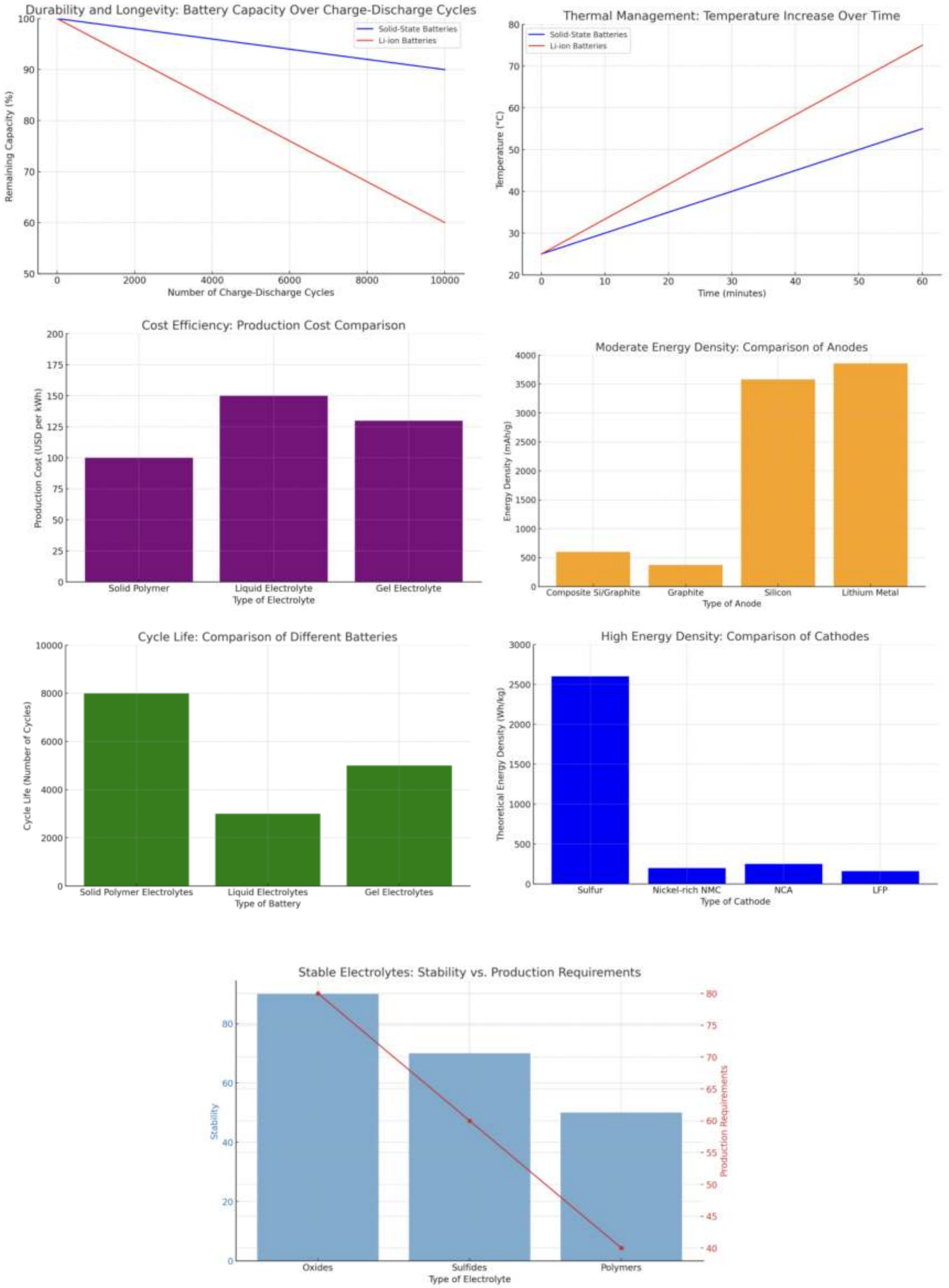
- Current: ~$320/kWh
- Potential: $70-$120/kWh

Large-format EV cells	TBD	(Today)
Current cycle life	400	
Calendar life	TBD	
Mature manufacturing	🟧	
Fast-charge	🟧	

R&D Needs

- High-voltage cathode
- Lithium protection
- Highly-conductive solid electrolyte

Exhibit 31. Main figures on performances and prices for SSB



Abbreviations

AAM	Anode Active Material
BMS	Battery Management System
CAM	Cathode Active Material
DEC	Diethylene Carbonate
DMC	Dimethyl Carbonate
EC	Ethylene Carbonate
EMC	Ethyl Methyl Carbonate
ECSW	Electrochemical Stability Window
EV	Electric Vehicle
HF	Hydrofluoric Acid
KPIs	Key Performance Indicators
LFP	Lithium Iron Phosphate
Li	Lithium
LIB	Lithium-Ion Battery
LiM	Lithium Metal
LLZO	Lithium lanthanum Zirconium Oxide
Ni	Nickel
NMC	Nickel Manganese Cobalt
NCA	Nickel Cobalt Aluminium
OEMs	Original Equipment Manufacturers
S	Sulphur
SEI	Solid Electrolyte Interface
SSB	Solid-State Battery

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