# Navigating the Solid-State Battery Hype: An Industry-Driven Assessment of Potential and Limitations

April 19, 2023

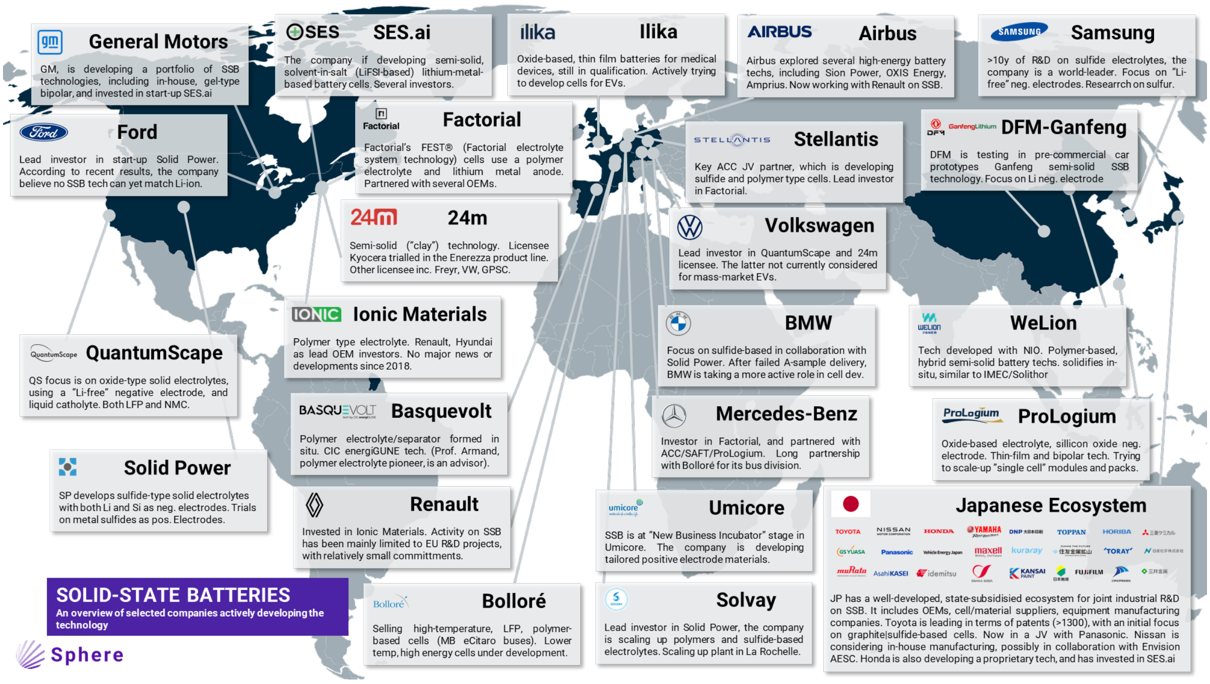

## Executive Summary:

The emergence of the Solid-State Battery (SSB) has created much excitement in the battery market due to its potential to be a big step forward for energy storage technologies. With their ability to offer significant improvements in capacity and charging speed while enhancing safety, SSBs are a highly anticipated development within the industry.

Given the increasing demand for lithium-ion batteries in the electric vehicle and stationary storage markets, major players, e.g. automakers, are partnering with emerging SSB technology and material suppliers to stay ahead of the competition, making SSBs one of the most hyped battery technologies of the decade.

However, to truly evaluate the potential of this promising innovation, it is crucial to take a more analytical approach and assess the benefits and limitations of different solid-state battery categories in practical applications. Understanding the technologies that have a realistic possibility of disrupting the market and at what cost is crucial.

In this article, we will examine SSB technology from an industry-relevant point of view and explore the benefits and limitations of different solid-state batteries.

## Introduction

With over 10 million electric vehicles sold in 2022, equivalent to roughly 400-600 GWh of lithium-ion batteries for automotive traction sold globally, and a fast-growing stationary storage market led by a shift towards renewables, it is safe to say that the so-called “electric revolution” is here to stay.

The Lithium-Ion Battery (LIB) market, now worth roughly 400bn USD, has provided a massive opportunity for new value creation. However, with Chinese, Korean, and Japanese companies dominating this market, several automotive Original Equipment Manufacturers (OEMs), especially those based in the US and the EU, face a strategic supply challenge and seek long-term opportunities in technology leapfrog to stay competitive. 2022 saw established automotive OEMs strengthen their partnerships with new battery cell and material suppliers to secure access to new technologies and, therefore, an advantage over competitors.

> *“Sphere's white paper does a fantastic job explaining the different solutions that are being developed in this field, their benefits and the challenges of these approaches. While the "what is real and what is not" section sets the record straight on some of the common myths about solid-state batteries.”*
>
> \- **James Frith,** Principal at Volta Energy Technologies

This has undoubtedly contributed to making the so-called “solid-state batteries” (SSB) one of the most hyped battery technologies of the decade. With promises such as “significantly scaling the storage capacity compared to classical LIBs”, “fast charging under 15 min”, and “tremendously improving safety”. But the biggest expected benefit is potentially coming from increased energy density and most importantly, lower cost. The breakthrough of such a battery could reshuffle the competitive landscape.

But one is often prone to fall for simplified marketing. Due to the battery hype cycle, it is common for new technologies to be oversold and for complex science to be overlooked. This article expands the message delivered by James Frith, Matthew Lacey, and Ulderico Ulissi in “A non-academic perspective on the future of lithium-based batteries”, a perspective published in Nature Communications. The focus of this white paper is on lithium-based SSB, and we provide an analytical overview of this promising innovation, including its benefits and limitations. We add an industry-relevant point of view of which technologies can potentially disrupt the market and which we consider overhyped.

## What makes the SSB technology so appealing?

The general idea of Solid State Batteries is to replace the liquid electrolyte of conventional lithium-ion batteries with a solid, which would also act as an electron-insulating separator. In theory, this could lead to benefits; These perspective advantages are visually summarised in Figure 1, with a focus on battery cells, as pack-level performance is still premature to assess. Below, we highlight the ones with the biggest impact on industrial applications.

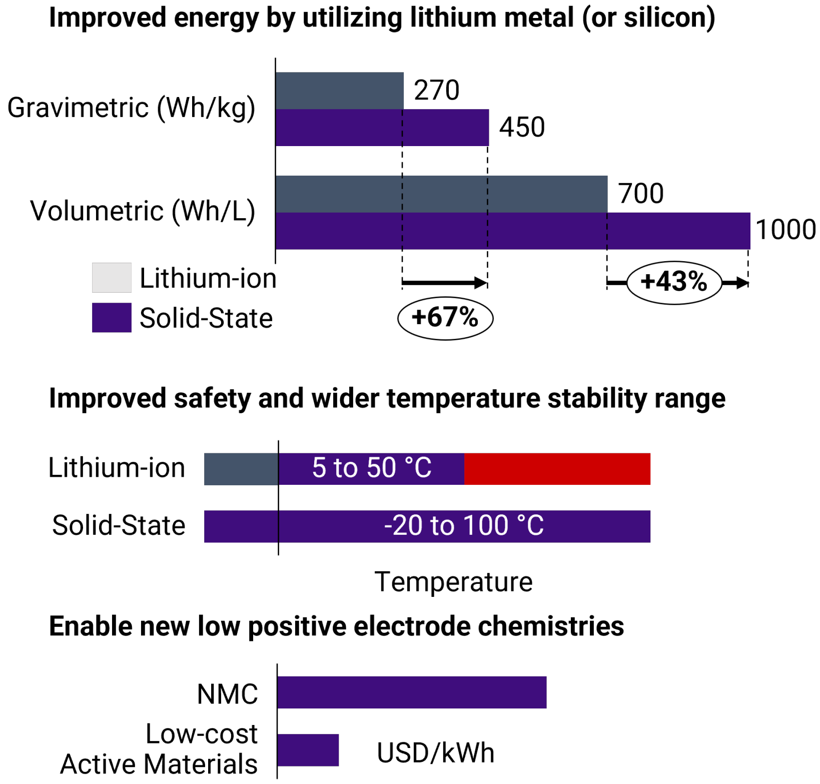



*Figure 1 Perspective advantages of SSB versus state-of-the-art liquid-based lithium-ion batteries, with a focus on cell performance. The charts highlight potential advantages in terms of gravimetric and volumetric energy, temperature stability, and the potential to enable low-cost cathode chemistries, particularly manganese-based.*

- **Use of new active materials enabling higher energy densities on the cell level.**
  A factor limiting the performance of next-generation lithium-based battery chemistries is the relative instability of the electrodes/electrolyte interface. For example, for conventional LIBs, forming a stable passivation layer (Solid Electrolyte Interphase, SEI) between the electrolyte and graphite-based negative electrode is possible, enabling long-term cell cycling. Forming stable passivation layers is still challenging with several new negative (lithium metal, silicon) and positive (low cobalt, low nickel, manganese-rich materials, sulfur) electrode active materials. Some electrode/electrolyte interfaces are unstable due to high reactivity and/or active materials' solubility. Some solid electrolytes can throttle solubility and enable the formation, or the engineering, of more stable layers that can allow the long-term cycling of these novel materials. Cells based on these materials could benefit from increased energy or long-term decreased cost. New performance levels, hardly attainable today in commercially available LIB cells, would be possible.

- **Better thermal properties for higher energy density and lower cost on a pack level.**
  Conventional battery packs employ various technologies for temperature control, which is key to maximizing the batteries' performance and safety. Liquid electrolytes are the main component that limits conventional lithium-ion working temperature to ca. 5-50°C. Operating a conventional lithium-ion cell outside this temperature range can lead to decreased performance and battery lifetime due to elevated degradation. For example, fast charging: Charging a battery cell at high currents and low temperature leads to a high risk of lithium plating and dendrite formation, resulting in rapid performance deterioration

and potentially undesired thermal events. Exceeding temperatures of 50°C for longer times will also limit cell lifetime and lead to thermal runaway if heat is not dissipated. Some, but not all, solid electrolytes could benefit from a wider operating temperature range, which can lead to lithium-based cells that can operate between -20 to 100 °C, meaning less stringent requirements in terms of thermal management. The resulting battery pack can be lighter and less voluminous, leading to higher energy and cheaper battery systems.

- **Higher safety through a lowered risk of fire or gas formation.**
  Higher safety can be claimed due to the removal of the organic liquid electrolyte, which is highly flammable. In theory, several solid electrolytes can be less flammable and/or release fewer gases in the event of combustion, improving the final device (battery pack) safety. However, battery packs for automotive traction using liquid electrolytes today are safe for their intended use. Moreover, one should make no mistake - a large battery pack, e.g. for automotive traction, could potentially be a dangerous device: it is high-voltage and stores large amounts of energy, which can be released dangerously in case of mishandling. Safety and thermal properties, in particular, are still poorly characterized and understood for solid-state battery cells and systems, which warrants further studies.

In practice, all (and many more) of these beneficial properties have yet to be demonstrated for cells manufactured at scale and tested in a controlled environment, under standardized conditions, and in compliance with standards and regulations.

Moreover, the situation is even more complex, considering that "solid-state battery" is not used to identify a specific product or technology but rather a whole class of energy storage systems.

The term "solid-state battery", with different adjectives and identifiers (all-, semi-, quasi-, pseudo-), is used to describe a vast portfolio of battery technologies (or chemistries). To shed some light on using this term, we propose Figure 2, adapted from one of our recent publications.

*"As with any new technology, there are a lot of claims around the promise of solid-state batteries. As development in the industry expands, it is becoming increasingly hard to break through the noise of what is real and what is forward looking. Sphere Energy's white paper does a great job of distilling down the state of solid-state battery technology with a realistic look at where we are and where we still need to go."*

- **Factorial Inc. (Factorial Energy)**

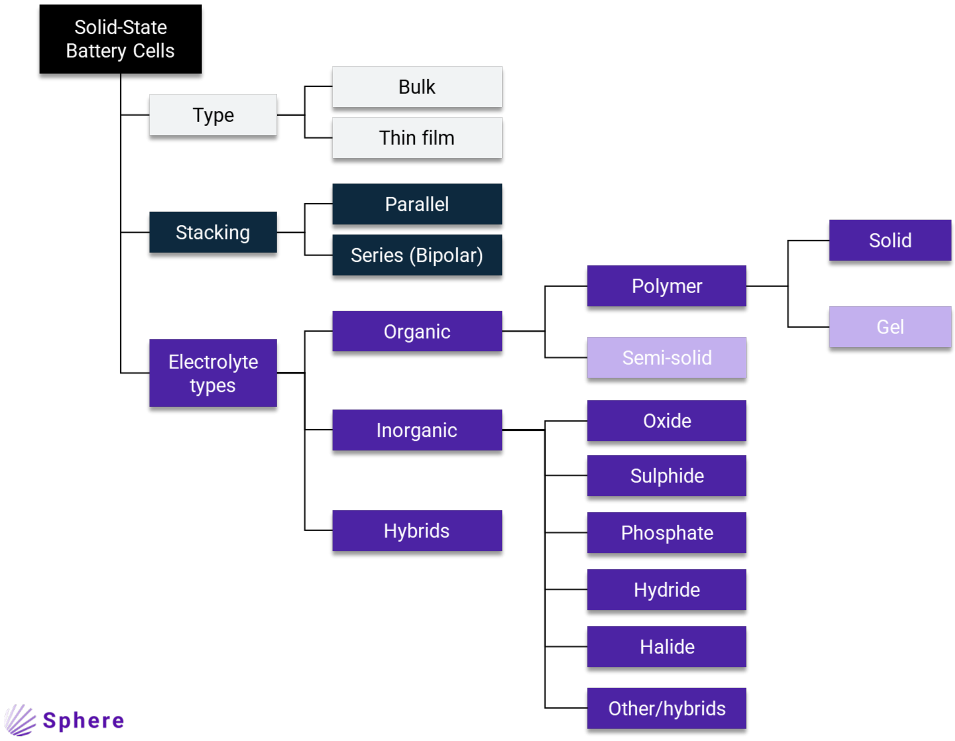



*Figure 2 Categories of solid-state batteries, based on internal construction (type, grey), stacking configuration (blue), and electrolyte type and chemistry (purple). Semi-solid and gel electrolytes are highlighted (light purple boxes), as these should be considered viscous fluids or mostly liquid rather than purely solid-state. Stacking refers to the internal battery structure, whereas parallel stacking is the structure of a conventional, state-of-the-art lithium-ion battery. Figure adapted from "Frith, J.T., Lacey, M.J. & Ulissi, U., A non-academic perspective on the future of lithium-based batteries. Nat. Commun- 14, 420, 2023".*

### Type of solid-state batteries – Thin-film versus Bulk

We can start by identifying two main categories, or types, of all-solid-state battery cells:

- Thin film batteries, with capacities in the µAh-mAh (or µWh-mWh) range. These are already commercially available for niche applications but are not relevant for powering consumer electronics or automotive traction. This is due to the very small size and a radically different manufacturing process compared to conventional lithium-ion. A modern smartphone, for example, uses a 15-20 Wh battery composed of one or two cells. One 60 kWh battery pack, a realistic size for an electric vehicle with a 300-500 km range, would require 60 million cells with an energy of 1 mWh: rather unrealistic.

- Bulk-type, which are comparable, in principle, to current generation commercial lithium-ion batteries, i.e., with thick electrodes (~100µm) and sizes ranging between 2-200Ah. These solid-state battery cells today are still in the early prototype stage but can theoretically have a play in, e.g. the large automotive market. The focus of this article is on this category of battery cells.

**Cell internal structure – Electrode stacking and the open challenges with bipolar batteries**

The second category, “stacking”, identifies the battery’s internal structure. Conventional lithium-ions are assembled as single battery cells with electrodes connected in parallel. This requires additional components and materials to move electrons between the positive and negative in an external circuit. In the bipolar design, the cells are composed of bipolar electrodes: the single cells are connected in series, and electrons flow without an additional external circuit (Figure 3). This internal structure can reduce heat generation during cell operation and lead to the direct manufacturing of large battery modules instead of battery cells, enabling lighter and less voluminous battery packs with easier thermal control.

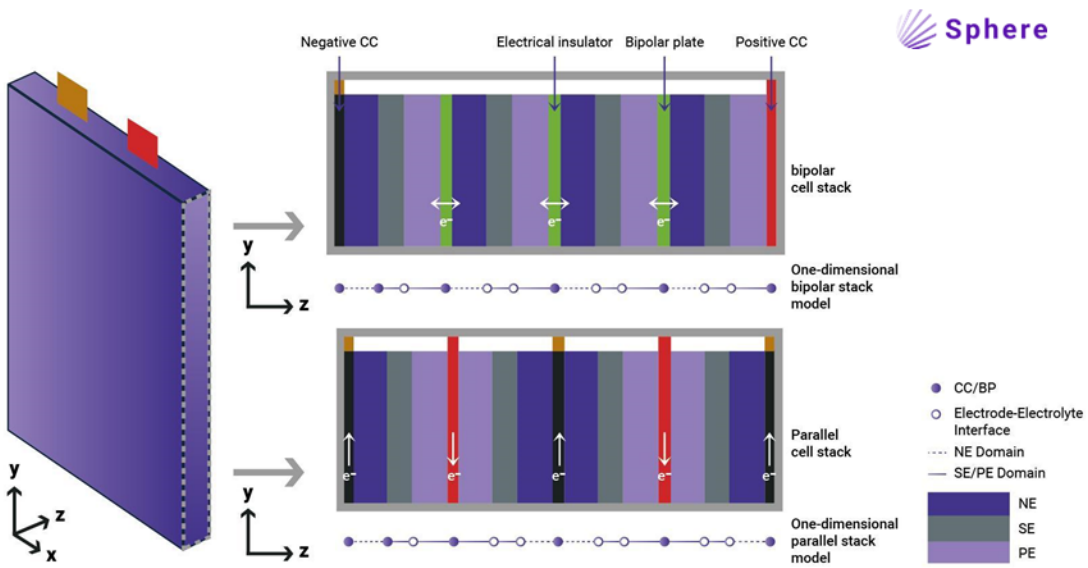



*Figure 3 Internal structure of bipolar and parallel cell stacks, highlighting electron pathway. Figure adapted from “Pang, M.-C. et al. Large-Format Bipolar and Parallel Solid-State Lithium-Metal Cell Stacks: A Thermally Coupled Model-Based Comparative Study—Journal of The Electrochemical Society vol. 167 160555 (2020)”, used under CC BY license.*

**While promising, lithium-based batteries using bipolar technology today are still very far from commercialization.** Using a liquid electrolyte or any other electrolyte that is not fully immobilized leads to a very high risk of electrolyte leakage, which can, in turn, cause an internal short-circuit, as the positive and negative electrodes are already in direct contact. Solid electrolytes can enable this stacking technology, which several companies are developing, including General Motors, which created a proprietary technology using a solid-state, most probably gel-type electrolyte, and Prologium, using an oxide-type solid electrolyte. We speculate Prologium is also using a gel-type electrolyte, as we’re not aware of any oxide currently having high enough conductivity, particularly at the positive electrode side.

Bipolar batteries are complex and expensive to manufacture at scale. The first battery, made by Volta, had a bipolar design back in 1800. However, only a handful of rechargeable battery chemistries are commercialized using a bipolar stacking technology, the most notable being Nickel Metal Hydride (NiMH) in niche markets: these are radically different from lithium-ion and have started to be commercialized only in recent years.

Commercially relevant prototypes of conventional, non-bipolar lithium-ion were built in the late 1980s. While it is unlikely, we will need to wait hundreds of years for functional prototypes of bipolar lithium-ions, we will not see the technology becoming commercially relevant during the next five to ten years for automotive traction.

Manufacturing bipolar modules require very high precision, and fault, or scrap rate, must be low. Sub-components (such as electrolytes, active materials, and electrodes) must also be produced at high quality to achieve high yield, requiring scale. The problem is amplified with a bipolar design. As the cell/module size increases, a single reject in a manufacturing line would amount to more than ten times the material and energy wasted if a single cell is rejected: a single 80Ah lithium-ion cell can have an energy of 0.3 kWh, while a single module in an EV is usually 5-10 kWh or bigger. Faults when manufacturing battery cells are often detected only at the final steps before shipping the cell to the customer. Moreover, bigger cells/modules also lead to a more complex system to manage heat and safety in case of abuse.

## Solid-state electrolytes – A portfolio of several unique chemistries

Finally, we have various electrolyte chemistries that can be split into organic and inorganic. These are paired with a variety of different positive and negative electrode active materials, and each specific pairing would lead to cells with very different performance and safety characteristics. Some key players are reported in Table 1 below and discussed in the following paragraphs.

| | Chemistry and cell components design | | | | | |
|---|---|---|---|---|---|---|
| **Company** | **Type(s)** | **Negative** | **Electrolyte** | **Positive** | **Separator** | **Other** |
| GanfengLithium | Semi-solid<br>Polymer | Graphite<br>Li metal | Hybrid liquid-PVDF-inorganic PEO-based | LFP, LCO, NMC | Polyolefin (PP, PE), 12-20 µm | |
| SES | Semi-solid | Li metal | LiFSI 4M (solvent-in-salt) | NMC | Polyolefin (PP, PE), 12-20 µm | |
| 24M | Semi-solid | Graphite<br>Li metal (Research) | Conventional liquid organic and other organic liquids | LFP,<br>NMC (Research) | Polyolefin (PP, PE), 12-20 µm | Catholyte/Anolyte likely contain a redox mediator and other additives. Non-standard electrolyte for low volatility (likely ionic liquid) |
| ProLogium | Oxide | SiOx<br>Li metal | Inorganic (oxide) | NMC | Inorganic, oxide (thickness unclear) | |
| QuantumScape | Oxide | Anode-free | Oxide (oxide, likely Garnet-type) | NMC, LFP | Inorganic oxide; thickness: "lower tens of microns". We speculate 30-50 µm | Liquid catholyte, we speculate a PVDF/liquid gel, based on patents |
| Bolloré | Polymer | Li metal (20 µm) | Polymer (PEO-based) | LFP,<br>NMC (Research) | Conductive polymer (PEO-based) | |
| WeLion | Semi-solid<br>(several others in research) | Graphite,<br>C/Si composite | Organic | NMC | Polyolefin (PP, PE), 12-20 µm | In-situ gel formation of electrolyte |
| Factorial | Polymer | Graphite<br>Li metal (≤ 50 µm)<br>Anode-free | Organic (polymer) | NMC | Conductive polymer (FEST® system) | Complex polymer system, initially acrylate-/ethylene glycol-based. Fabrication likely includes the polymerisation step |
| BASQUEVOLT | Polymer | Li metal | Polymer, in-situ formation | NMC | In-situ polymerization | |
| TOYOTA | Sulfide | Graphite<br>Li metal | Sulfide<br>Oxysulfide | NMC | Sulfide | |
| SAMSUNG | Sulfide<br>Oxide | Graphite<br>Anode-free (Ag-C) | Sulfide | NMC, NCA | Sulfide (< 30 µm) | The oxide cell design uses an ionic-liquid-based catholyte |
| | Sulfide | Silicon<br>Li metal | Sulfide | NMC,<br>FeS | Sulfide (25 µm) | |

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*Table 1 List of players actively developing different solid-state battery chemistries. The focus is on cell chemistry and sub-component selection. The list is non-exhaustive and is based on publicly disclosed data, including patents. It presents some of the electrolytes, negative and positive electrode active materials used by the companies, and the most likely separator type.*

## Organic solid electrolytes

In the **polymer category**, we often find included gel-type electrolytes. These can contain varying quantities of immobilized organic liquids or plasticizers, making it challenging to draw a line between “liquid” and “solid” electrolytes for this category, as we believe most should be considered viscous fluids. In this category, we find commercially available, gel-type “PVDF”-based (polyvinylidene fluoride) electrolytes and gel-type “PEO”-based (polyethylene oxide) electrolytes, such as those commercialized by Bolloré. Although this company launched several pilot car-sharing programs to use this cell technology in electric city cars, this kind of lithium-metal-polymer (referred to as LMP®) battery never reached mass market adoption in passenger cars. One factor contributing to its poor commercial adoption is that it can only be used at relatively high temperatures (50 to 80 °C), requiring pre-heating. The electrolyte chemistry is incompatible with high-voltage positive electrode active materials like NMC. This limits the cell energy ceiling. Nevertheless, these batteries are now deployed in commercial vehicles like the Mercedes eCitaro city bus, making this specific technology fairly mature. Unfortunately, there is no demonstration of prototype cells (e.g. at TRL5) that work at room temperature (i.e. at around 25 °C) using a purely solid-state polymer electrolyte and a lithium metal negative electrode.

Another example is the technology developed by Factorial, formerly known as Lionano, a US start-up. The specific chemistry employed by the company has not been disclosed. Early prototypes, based on publicly released data and patents, hint at polyacrylates mixed with (poly)ethylene glycol, i.e., “short-chain” polyethylene oxide. However, the company has been investigating several undisclosed new electrolyte chemistries, which now constitute the proprietary Factorial Electrolyte System Technology (FEST®). The company initially focused on using graphite-based negative electrode active materials to demonstrate the scalability of its technology, e.g. at the pre-A-sample stage for cells or Technology Readiness Level (TRL) 5. It is now testing 20-100 Ah lithium metal-based cells.

**The *semi-solid category***, erroneously considered a solid-state battery, is very broad and probably close to reaching the market: Chinese companies like Ganfeng Lithium and WeLion are close to complete automotive qualification for their first generation of semi-solid battery cells. The electrolyte chemistry that these companies are using has not been fully disclosed. The key differentiator is that they usually employ varying amounts of non-immobilized conventional liquid electrolytes, soaked in conventional polyolefin separators, graphite-based negative electrode active materials, and can employ small amounts of inorganic solid electrolytes as separator coatings or polymers partially or completely solidified “in-situ”, i.e., post-cell assembly to optimize the production process.

This category also includes highly viscous electrolytes: these can be visualized as having viscosities comparable to thick oil or honey but are still fluid and not immobilized. These electrolytes must usually be embedded in a solid, inert separator, such as polypropylene. The most developed semi-solid electrolytes are the so-called “solvent-in-salt” mixtures. A point of concern for concentrated electrolyte mixtures is the relatively high content of fluorinated salts, which also brings into question the lithium content (i.e., $kg_{Li}/kWh_{cell}$) and environmental impact of such a class of electrolytes. One example of start-ups using this approach is SES.ai, a company backed by American General Motors, Korean Hyundai-Kia, LG Group and SK On, Japanese Honda, Chinese Geely and SAIC, and Taiwanese Foxconn, among others. The company uses a high concentration of LiFSI, a salt often used as an electrolyte additive in extremely low concentrations, in current-generation lithium-ion cells. A key advantage is that some semi-solid electrolytes can be prepared using commoditized chemicals. They could be easier to integrate into EVs versus cells comprising components under development without an established value chain, such as ceramic separators.

Another example is 24M's "SemiSolid" cell design, licensed to small or emerging cell suppliers and start-ups, such as Kyocera, Freyr, Fujifilm, GPSC, and VW/PowerCo SE. The technology uses a clay-like electrode, which does not require binders, and eliminates a few steps in manufacturing. So far, Kyocera has been the only company that claimed to have commercialized the technology for small stationary storage with its Enerezza product line.

**Inorganic solid electrolytes and hybrids**

Here, we include glasses, ceramics, and other solid-state materials: these are usually also described as "all-solid-state", a terminology that should be used only when no component is liquid or fluid. Some inorganic-based technologies are already available in niche commercial electrochemical energy storage devices, such as high-temperature rechargeable, liquid electrode Na-S, $Na\text{-}NiCl_2$ batteries used for stationary energy storage, phosphate-based thin-film cells, and primary $Li\text{-}I_2$ batteries.

Sulfide and oxide-based chemistries are among those receiving the most attention today, hence our focus on these two. However, they are still only at the early prototype stage when considering battery cell deployment in the automotive segment.

**Sulfides** offer potential advantages at the material level, such as high lithium conductivity, comparable to liquid electrolytes. High-temperature sintering is generally not required for fabrication at the electrode level, making the manufacturing process and its $CO_2$ footprint potentially more favorable. However, some sulfides are combustible at high temperatures and can release gases, such as $H_2S$, in contact with water. How much depends on the specific chemistry and material design. The susceptibility to water needs to be assessed using appropriate, specific tests.

Japan has been leading in this technological development, an effort spearheaded by Toyota as an automotive OEM with over 1330 related patents. In Japan, large state-subsidized consortia aim to create a domestic value chain and include all major Japanese transport OEMs and several suppliers. This effort has resulted in several milestones. For example, Toyota has shown early vehicle prototypes and is working with Panasonic as part of the Prime Energy JV to make solid-state batteries a commercial reality. Mitsui Kinzoku has a vast portfolio of sulfide-type electrolytes and is scaling up production. Nissan Motor has also announced plans to use sulfide-based solid-state batteries for its vehicles. It is targeting in-house production with a pilot-scale cell manufacturing plant. Other companies, like Hitachi Zosen, a Japanese engineering corporation, showcased a small, all-solid-state 140 mAh pouch cell prototype for space-based applications that will be trialed on the International Space Station (ISS). Samsung is another Asian leader and pioneer in this technology, with several prototypes showcased by its Japanese and Korean subsidiaries. The technology was first incubated in the Samsung R&D Japan research center, in efforts mainly led by the group of Dr. Yuichi Aihara for well over ten to fifteen years. The company has been prolific in terms of patents (covering a large number of different chemistries) and also often publicly disclosed innovative designs, such as a proprietary lithium-free silver-carbon negative electrode. The technology transfer to the korean samsung reserach center has most probably contributed to the formation of a SSB ecosystem, albeit smaller, in Korea, with companies like EcoProBM and POSCO now also working on materials development.

The Chinese ecosystem is also slowly developing, albeit at a slower pace. Solid-state technologies are present in the roadmaps of several leading cell suppliers, such as CATL, the biggest cell supplier in the world by market share. The company is actively developing cells based on several inorganic electrolytes, as demonstrated by recent patent filings. Other companies have been more vocal about their achievements, such as SVOLT, which claims to have manufactured 20 Ah sulfide-based solid-state battery cell prototypes with a gravimetric energy of 350-400 Wh/kg. It needs to be clarified under which conditions these cells are being tested, who is supplying the active and inactive materials, and when the company plans to start commercial sampling.

In Europe, we have seen a few larger companies leading efforts in materials research, such as Umicore, where solid-state is in the "new business incubator" phase, and BASF, which has mainly led collaborations with academia. A notable example in this field is Solvay, setting up a pilot-scale plant in La Rochelle, France, to manufacture sulfide-based electrolytes. As for cell manufacturing, SAFT/ACC have solid-state battery technologies in their portfolio and mainly focuses on sulfide-type (and polymer-type) cells, with cell sizes still not over 1Ah (TRL4). In the US, the effort in the inorganic-based solid-state cell is led by start-ups. One of them is Solid Power (sulfide). This company has attracted funding from several automotive OEMs and suppliers, such as German BMW, North American Ford, Korean Hyundai-Kia, SK On, and Samsung.

To date, the sulfide technology showcased by Samsung and Solid Power is the only truly "solid-state" as cells do not employ any fluids. However, this is still at the prototype stage (pre-A-sample, TRL4-5). Cells are mostly tested above room temperature, with 29°C a typical example from Solid Power. It is estimated that about 5-10 MPa of pressure is usually applied to 2Ah cell stacks. Samsung has also shown promising results without applying pressure, but only by cycling at high temperatures (60°C). These high temperatures and pressures would make large-scale deployment in automotive largely unfeasible.

**Oxides,** finally, are more on the long-term horizon. This is viewed as a more stable chemistry; for example, it releases no gases when in contact with water. For this reason, it is considered by many as an end game. However, some materials still degrade in performance when in contact with ambient air. The major limitation is the high density of oxides: one cubic centimeter of a typical oxide-type electrolyte would weigh two times more than a sulfide-type. The materials are also harder to process, meaning that fabrication of an oxide-based separator usually requires either a pre- or post-manufacturing sintering process, conventionally over 800-1000°C. Reaching industrially relevant thicknesses of about 20 µm or less is also challenging at large scale. While this has been demonstrated at a laboratory scale (see, e.g. Sastre et al., Adv. Mater. Interfaces 2020, 7, 2000425), we're currently not aware of any scaled-up industrial process to mass manufacture self-standing oxide-based separators (e.g. manufacturing of over 80 $m_{separator}$/min). Finally, given the hardness of the material, it is complex to create good contact with other cell components, particularly with the positive electrode active material: it is akin to making intimate contact between two stones that do not deform. This means that liquids, particularly catholyte, are generally required to achieve satisfactory performance, meaning that oxide-based cells are assembled in hybrid "solid-liquid" cell configurations. This is, for example, the strategy employed by QuantumScape, a US-based start-up backed by the Volkswagen group. According to Sphere Energy research, the company has been developing several cell chemistries. The focus appears to be on a specific family of oxides (garnet-type), and, according to an analysis we performed of its patent portfolio, it could be using a gel-type electrolyte confined in the cathode (catholyte) based on fluorinated binders mixed with a conventional, organic-based, electrolyte, comparable to what is used in standard lithium-ion. This is solely our speculation. The company has also not publicly released any figure or realistic projection of what it can achieve in terms of energy per unit of mass or volume. We speculate this could be due to the weight or volume of its separators or due to other inactive cell components. The company hasn't clearly stated how thick the separators are, only that they are in the low tens of microns. We suppose it could be in the 30-50 micrometer range, but we cannot currently substantiate any value.

**Industrially relevant performance**

Demonstrating a working battery device in a controlled lab environment is one thing, but the real complex, resource-intensive part is scaling these technologies: manufacturing cells and all sub-components at scale and testing them under commercially and industrially relevant conditions. For example, manufacturing the solid-state electrolyte layer (separator) is a complex process for all these chemistries. Regardless of the battery chemistry, it is necessary to fabricate dense (~100%), non-porous, and thin (e.g. <20 μm) solid electrolyte films at a high yield (e.g. >80 m/min). The weight and thickness of the separator and the exact nature of the chemicals involved are crucial variables that must be tuned to reach specific energy and energy density at the cell level of ≥350 Wh/kg and ≥900 Wh/l, respectively, as expected for the first generation of commercial products. Depending on cell format, these commercial cells must be mass manufactured, with minimum sizes of 10-100 Ah.

As a reference, we report below, in Table 2, the typical parameters of commercially available lithium-ion cells comparable to those found in the current generation of modern EVs. These are not the chemistries solid-state batteries will be competing with, as these LIBs have already been available in the market for 5-7 years, and next-generation lithium-ion batteries show already improved performance.

| **Automotive Li-ion pouch cell (VW ID.3, 78 Ah)** | | |
|---|---|---|
| **Key Performance Indicators - Cell** | | |
| Specific Energy (Wh kg$^{-1}$) | 273 | |
| Energy Density (Wh L$^{-1}$) | 685 | |
| Cell Weight (kg) | 1.101 | |
| Cell Volume (L) | 0.438 | |
| Cell Energy (kWh) | 0.3 | |
| **Key Performance Indicators – Electrodes** | | |
| Electrode | Positive | Negative |
| Chemistry | NMC721 | Graphite |
| Coating weight (kg, cell) | 0.480 | 0.352 |
| Areal capacity (mAh cm$^{-2}$) | 5.02 | 5.23 |
| Coating Thickness (μm) | 85 | 115 |
| Foil thickness (μm) | 14 (Al) | 12 (Cu) |
| **Key Performance Indicators – Other** | | |
| N/P ratio | 1.04 | |
| Separator thickness (μm) | 17 | |
| Electrolyte loading (g Ah$^{-1}$) | 1 | |

| **Li-ion cylindrical cell (LG M50 21700, 4.9 Ah)** | | |
|---|---|---|
| **Key Performance Indicators - Cell** | | |
| Specific Energy (Wh kg$^{-1}$) | 265 | |
| Energy Density (Wh L$^{-1}$) | 750 | |
| Cell Weight (kg) | 0.068 | |
| Cell Volume (L) | 0.024 | |
| Cell Energy (kWh) | 0.18 | |
| **Key Performance Indicators – Electrodes** | | |
| Electrode | Positive | Negative |
| Chemistry | NMC811 | Graphite-$SiO_x$ |
| Coating weight (kg, cell) | 0.025 | 0.015 |
| Areal capacity (mAh cm$^{-2}$) | 4.5 | 5.0 |
| Coating Thickness (μm) | 75 | 85 |
| Foil thickness (μm) | 16 (Al) | 12 (Cu) |
| **Key Performance Indicators – Other** | | |
| N/P ratio | 1.11 | |
| Separator thickness (μm) | 12-14 | |
| Electrolyte loading (g Ah$^{-1}$) | 0.9-1.1 (estimated) | |

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*Table 2 presents some of the key performance indicators of incumbent lithium-ion battery cells. Most of these design parameters are not publicly shared by cell suppliers, including in datasheets, and need to be evaluated by performing cell teardown and using complex analytical techniques. These cells have been commercial for several years, and solid-state batteries will compete in cost and performance against future generations of lithium-ion cells. The data presented here is from Günter et al., Chen et al., and our calculations.*

For comparison, we summarise our research on the key performance indicators revealed by the previously described players via press releases, conference talks, analyst reports, or patents in Table 3. One challenge is that cells of different sizes and at different technological maturity are tested under various conditions and are often erroneously compared. Looking at the table, it becomes clear that the field is still rather opaque regarding data reporting. Power is highlighted in grey, as this is relatively hard to compare. Generally, companies report only current, or "C-rate" values, which hardly represent the key performance indicators required at the cell and system levels. While one can understand that for these rather young companies, it is extremely important to protect their intellectual property, it is challenging for investors, analysts, and any other market participant to understand the true potential of these technologies since much data is simply not available (fields highlighted in purple).

| Company | Key Performance Indicators | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Cell Size | Safety Testing | Energy (cell) | Energy (System) | Cycle Life | Current/Power (Peak)* | Current/Power (Prolonged)* | Temperature | Pressure |
| GanfengLithium | Up to 120 Ah (Gen1) | Passed GB38031-2020 | 240 Wh/kg, 500 Wh/L (Gen.1) | 160 Wh/kg (Pack) | 1500 | 3C, 150 kW (pack) | 1C, 50 kW (pack) | -20 to 60 °C | N/A (standard expected) |
| SES | Up to 102 Ah (untested) 50 Ah (Preliminary test) | Only for transport (UN38.3, IATF) | Up to 300-350 Wh/kg (initial), ca. 700 Wh/L | N/A | 200 | 3C (unclear power) | C/3, ca. 60-70 W | -10 to 45 °C | N/A (likely above standard, i.e., likely 3-10 atm based on 3rd parties) |
| 24M | N/A (5-10Ah estimated) | N/A | N/A (150-170 Wh/kg, 250-350 Wh/L estimated based on patents) | N/A | N/A (2-10k expected) | N/A (Likely low) | N/A (Likely low) | -20 to 40 °C | N/A |
| ProLogium | 50 Ah | N/A | Depends on SiOx percentage. From 240 Wh/kg, 600 Wh/L to 300 Wh/kg, 700 Wh/L | 180 Wh/kg, 370 Wh/L | 500-700 | 5C (format unclear) | C/3 | -20 to 45 °C | Undisclosed (above the standard expected) |
| QuantumScape | 1-5Ah | N/A | N/A | N/A | 800 | 5C (small format only) | 1C | -10 to 45 °C | 1-5 atm |
| Bolloré | 105 Ah | Passed | 255 Wh/kg, 380 Wh/L | 255 Wh/L (Module) | 3500 (70% DOD) | N/A | C/4 (charge) 1C (discharge) | ≥ 60 to 105 °C (heating always required) | N/A (standard expected) |
| WELION | 30 Ah | Passed | 270 Wh/kg, 600 Wh/L | 250 Wh/lg, 490 Wh/L (Module) | 1200-1500 | N/A | 2C (charge), 5C (discharge) | 0 to 45 °C (Charge) -20 to 55 °C (Discharge) | N/A (standard expected) |
| Factorial | 40 Ah (graphite) 20-100 Ah (Li) | N/A | N/A | N/A | 1500 (graphite) N/A (Li) | N/A | 0.5C | Room temperature | N/A |
| BASQUEVOLT | 1 Ah (multilayer) | N/A | 460 Wh/kg, 960 Wh/L | N/A | N/A | N/A | C/5 | 25 to 40 °C | 2 to 3 atm |
| TOYOTA | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| SAMSUNG | >5-15 Ah | N/A | 420 Wh/kg, 900 Wh/L | N/A | > 1000 | N/A | 0.5C | ≥ 45-60°C | Undisclosed (above the standard expected) |
| | 20 Ah | N/A | 390 Wh/kg, 900 Wh/L (Roadmap, Si Cell) | N/A | 200-1000 (Coin cell, mAh) | 2C (Coin cell, mAh) | C/5 | ≥ 29-60°C | Undisclosed (5-20 atm expected) |

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*Table 3 List of players actively developing different solid-state battery chemistries. The focus is on Key Performance Indicators at the cell level. The list is non-exhaustive and is based on publicly disclosed data, including patents. The "power" section is highlighted in light grey, as these values hardly represent real cell requirements. We highlight where data was unavailable (N/A) in purple and provide informed estimates based on patents or our calculations, where possible.*

### Creating value chains and upstream considerations

It is worth noting that no real "solid-state" battery cell is manufactured in similar formats and sizes with competitive performance to lithium-ion and has passed the automotive qualification stage for mass market, consumer EVs. This process can take several years, and the series production of cells and their subcomponents is a requirement. This is challenging for several cell chemistries based on solid-state electrolytes and lithium metal foils for example, there is no supply chain for cells using sulfide or oxide electrolytes - by the way, neither for metallic Lithium anodes.

Therefore, companies must ramp up their supply chains while developing cell technologies. When considering garnets, for example, it was estimated that production of just 200 GWh of solid-state batteries would require over 50,000 tons of lanthanum, equivalent to the annual production of the commodity in 2019. In this case, we only consider one commodity.

Each chemistry is different, and these aspects should be evaluated for all components. The chart below, in Figure 4, considers materials intensity for several different chemistries as kg per kWh of a battery cell and shows that, while some chemistries could be more lithium intense, solid-state batteries based could be, overall, less material intense. This would drastically affect the cost and potentially be one of the key drivers for such a technology. However, a battery cell, battery pack teardown, and full bill of materials are necessary to perform a correct analysis.

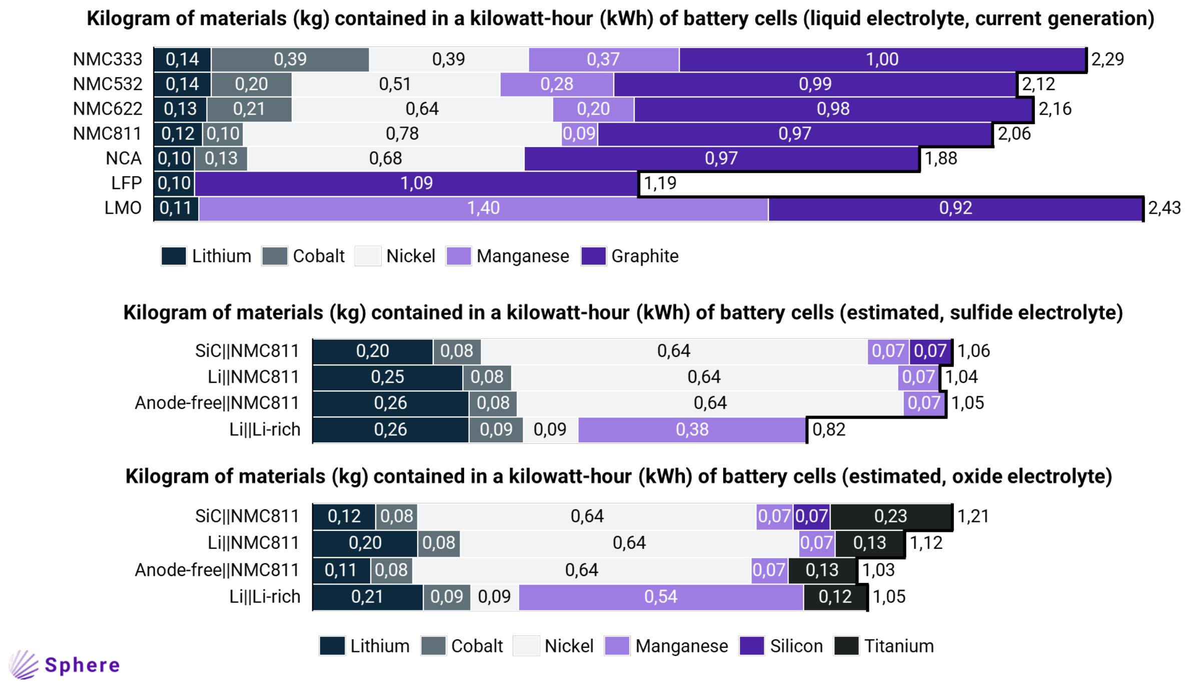


*Figure 4 Material intensity of different incumbent and next-generation cell chemistries, data reported in terms of a kilogram of material contained in a kilowatt-hour battery cell. For the oxide-type, we use $Li_{1.5}Al_{0.5}Ti_{1.5}(PO_4)_3$ (LATP) as an example to highlight the potential need of new raw materials, such as titanium. To date, also given instability of LATP against lithium metal, there is no viable large format cell representative of this cell chemistry. The solid-state battery data is estimated based on calculations—data from Sun et al. and own analysis.*

We also do not consider or discuss that some specific chemistries or lab processes can use toxic, unsustainable, or hazardous chemicals, which could pose an additional barrier to effectively scaling up the manufacturing of battery cells and sub-components, having a tremendously negative impact on the sustainability aspect of such a battery.

**The lengthy and complex process required to qualify batteries for automotive application**

Even with a mature value chain, supplying parts to the automotive industry is non-trivial. Suppliers who wish to engage with the automotive industry must undergo a standardized, rigid qualification process. The process aims to evaluate and ensure that suppliers can reliably manufacture safe, high-quality parts with minimum defects, for example, < 10 cells in a million or 10 ppm. The most common automotive standards for part qualification are published by the German Verband der Automobilindustrie (VDA) and the Automotive Industry Action Group (AIAG).

For example, following VDA "Maturity Level Assurance for new Parts", automotive qualification for new cells would generally start at the A-sample, a prototype cell at TRL5. The focus is on validating the concept. The A-sample cell does not need to be series produced, but it must be safe, functional, and close to the final design both in terms of performance and geometry: cell footprint and size are fixed, meaning that an A-sample pouch cannot be, for example, a 2 Ah cell. This prototype can compromise lifetime and performance but should satisfy most requirements to lead to the qualification of B-samples, where the cell design is unalterable. The B-sample is when the design is validated. Past the B-sample stage, the focus is on manufacturing and its quality. A larger number of trial modules/packs are assembled, and cells are series produced, which constitutes the C-sample stage (TRL6) when the manufacturing process is validated. The cell would undergo the final qualification stage and enter the Production Process & Product Approval (PPA) phase. Completing it would constitute production validation, with the part classified as D-sample (TRL7).

Testing requirements can increase tenfold, from hundreds of cells for A samples to tens of thousands for C samples. The type of tests required includes performance and safety, with the latter being a strict requirement at any stage. Tests and safety requirements are also rigorously defined in standards, guidelines, and regulations (such as by the International Electrotechnical Commission, IEC 62660, by the United Nations, UN38.3, UN ECE R100) or routine testing (e.g. United States Advanced Battery Consortium LLC, USABC, guidelines). All in all, it is still a long way before these technologies can reach the market.

In Figure 5, we present our solid-state battery tracker. The scale on the left highlights the typical minimum time to move between each "phase". For example, it takes on average approximately 5-7 years, to move from a research/laboratory (coin cell) to a GWh scale when developing new technologies. The shape of the pyramid plot also highlights that only a fraction of the technologies developed in research laboratories ultimately reach the market. The risk of technologies not transitioning to the next step is higher at the early stage of development. As the pyramid is "climbed", each phase becomes increasingly more capital intensive, shifting the focus towards manufacturing. We use this plot also to highlight that data shared by these companies is usually not independently verified by third parties that do not have a direct conflict of interest or are an investor in the company. The chart highlights that third-party validation has been performed only on very early prototypes, which are not representative of the final performance. These small prototypes are also hardly usable to benchmark battery safety, which can only be correctly assessed for large battery cells and at the pack level.

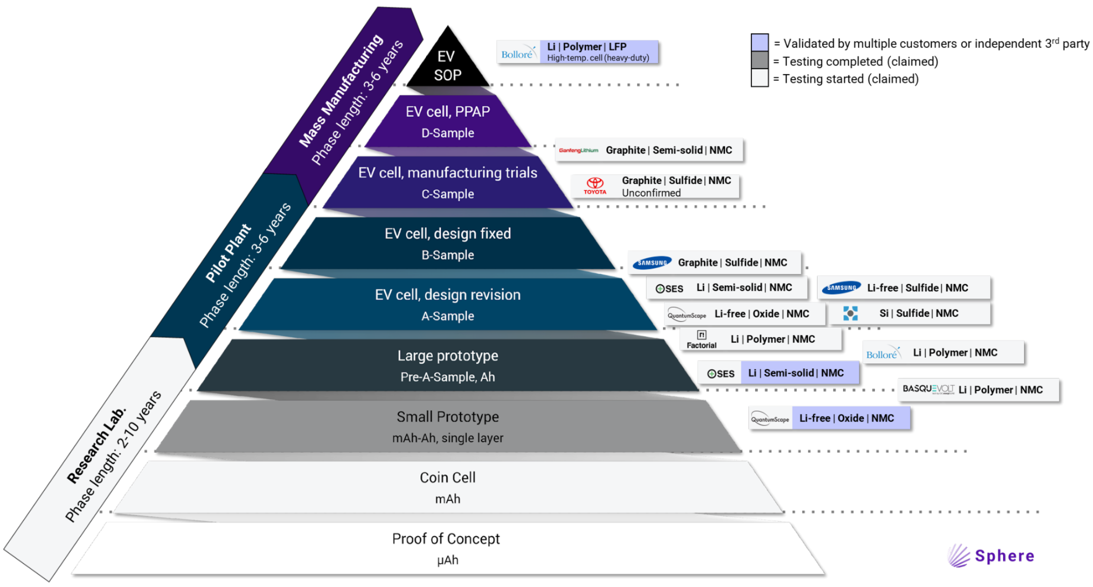


*Figure 5 The solid-state battery tracker showing how far each supplier has advanced in technology validation. The scale on the left highlights the typical minimum time to move between each "phase" when considering new technology development. On the right, we have highlighted a few cell chemistries from different companies. The light blue colour indicates cell that have been validated independently by third parties, with published public reports. The pyramid plot highlights that only a fraction of the technologies developed in research laboratories ultimately reach the market. We use this plot also to highlight that third parties do not independently validate most technologies in the field of solid-state batteries. Those that have been only assessed for very early prototypes, which are not representative of final performance and, most importantly, are not representative of battery safety, which can only be correctly assessed for large prototypes and at the pack level.*

A more direct comparison is provided in Table 4, where we summarise the stage of technology development, or Technology Readiness Level (TRL) described in our solid-state battery tracker, and also summarise the scale manufacturing in terms of GWh per year of battery cells, as well as the potential risks in the supply chains for each player.

| | Scale and Manufacturing | | |
|---|---|---|---|
| **Company** | **TRL, Sample** | **Cell Manufacturing** | **Supply Chain Concerns** |
| GanfengLithium | C-/D-Sample | Up to 2GWh (2023) | No major bottlenecks |
| SES | Pre-A-/A-Sample | Pre-pilot | High purity, high quantity LiFSI salt |
| 24M | Non automotive (Pre-A) | Pilot | Catholyte/Anolyte unclear |
| ProLogium | A-/B-Sample | Pilot (2 GWh) | Oxide electrolyte (unclear), Li metal foil |
| QuantumScape | Pre-A/A-Sample | Pre-pilot | Oxide electrolyte |
| Bolloré | Commercial (only buses) | Small scale (600 MWh globally) | Li metal foil |
| WeLion | C-Sample | Pilot, GWh-plant underway | Unclear electrolyte |
| Factorial | Pre-A-Sample | Pilot | Electrolyte and additives. |
| BASQUEVOLT | Pre-A-Sample | Pre-pilot, pilot underway | Li metal foil |
| TOYOTA | B-/C-Sample (expected) | Pilot | Sulfide electrolyte |
| SAMSUNG | A-/B-Sample (expected) | Pilot underway | Sulfide electrolyte, Ag-C electrode |
| | Pre-A/A-Sample | Pre-pilot | Sulfide electrolyte |

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*Table 4 List of players actively developing different solid-state battery chemistries. The focus is on scale and manufacturing. The list is non-exhaustive and is based on publicly disclosed data, including patents.*

**Safety of solid-state batteries**

Today, as confirmed by the Ford Motor Company, no solid-state battery has demonstrated better safety than current generation lithium-ion. Very few companies have reported or disclosed appropriate safety testing. Where batteries will be safe to use, it is also important to remember that, regardless of chemistry, the amount of energy that a battery in single-cell format can release is a function of several factors, but primarily of the electrical and thermal energy stored. A solid-state battery cell acts under the same physical laws. It is not intrinsically safe, as the Renault-Nissan-Mitsubishi VP of Research Kazuhiro Doi stated. A holistic, system-level view and safety testing are ultimately required, as in the event of a fire, plastic, casing, and pack materials could contribute to uncontrolled combustion. Safety can also be influenced by several other factors, such as state of charge and state of health, meaning that an aged or cycled cell or pack can be more prone to uncontrolled combustion.

In conclusion, while several solid-state battery chemistries look promising on paper, standardized and comparable data have yet to be published. Therefore, it is of fundamental importance to test and perform a correct and realistic assessment for each prospective technology and supplier, by looking in detail at their product and procurement strategy, as well as the complexities and potential pain points in their manufacturing processes.

**In summary – what is real and what is not**

- **“Solid-state batteries are the holy grail”**
  **Sphere opinion:** The technology is promising on paper, but nobody has delivered on promises yet. There are still fundamental issues to solve, and standardized data sets in academia and industry, would tremendously help to make this complex technology comparable and understandable - to finally move from hype to reality.

- **“Solid-state batteries are cheaper”**
  **Sphere opinion:** Not yet, but they will have to be if they want to make it to the market. Their material footprint would allow for a lower production cost, but they will not be in the beginning. As this technology is new to the supply chain, economies of scale for cell and sub-component manufacturing will need to be developed. These goods are not yet commoditized. This will likely take an additional five to ten years from initial commercialization. Some chemistries could be on a trajectory to become cheaper than lithium-ion in the long term (over 10-15 years from today). Also, cheaper is a function of cell chemistry. Solid-state could enable some potentially cheaper positive electrode chemistries, like manganese-rich, and could enable cheaper manufacturing techniques. However, more Lithium will most likely be needed; hence, a strong dependency on the Lithium price is expected.

- **“Solid-state batteries will be commercial by 2025-2027”**
  **Sphere opinion:** We could see C-samples by 2026, and even some commercial demonstrator projects by 2027. With e.g. Factorial having announced a joint Start of Production (SOP) for ASSB cells together with Stellantis, serious players are betting on a commercialization before 2030.
  We believe that also other industries, like Power Tools, with high-performance demands and less pressure on cost, could be markets where ASSB cells are integrated before 2030.

> *“In order for the wider electrification of mobility to happen it is critical to bring to the market a battery technology with a significant cost reduction. Current lithium-ion batteries have reached a high maturity level now and with current cost level achieving a very high penetration of BEV will not be possible, at least not without a massive public subsidy scheme.”*
>
> **- Francisco Carranza, CEO Basquevolt**

- **“Solid-state batteries are safe/safer/safest”**
  **Sphere opinion:** No energy storage device is “safe” per se. No one has yet demonstrated the higher safety of solid-state batteries compared to current-generation lithium-ion. Here fundamental research is still lacking, and the help of academic labs is needed to understand the underlying phenomena governing materials’ and cells’ safety. Also, an assessment of safety will need to be done on large cells (e.g. 100 Ah), with cell tests in different conditions and at the pack level.

- **“Solid-state batteries have higher energy”**
  **Sphere opinion:** Solid-state separators are generally heavier than those used in liquid-type batteries. This has not been demonstrated in an industrially relevant environment. Moreover, energy needs to be evaluated and compared at the system (pack) level: operating cells at high pressure or thick separators will greatly decrease pack energy. What will enable higher energy is the use of alternative negative and positive electrode active materials, with the most promising being lithium metal and silicon-rich. Solid-state electrolytes are currently the most promising to enable these chemistries. Nevertheless, such technologies will only be lighter if advantages can be demonstrated at the system level. For example, pressure regulators are necessary today to compensate for large volume changes of some negative electrodes, such as those based on lithium metal.

- **“Solid-state batteries can be operated in a wide temperature range”**
  **Sphere opinion:** this is incorrect. It depends on the chemistry of the electrolyte and the active materials. Some solid electrolytes can operate at very low temperatures, and they don’t freeze. Some, however, can only operate at very high temperatures. It is ultimately important to understand the system-level temperature requirements, and test thermal properties at least at the “5-10 Ah” cell level. There are still many unknowns.

- **“Solid-state batteries enable fast-charging”**
  **Sphere opinion:** fast-charging would be favored at the material level due to better diffusion kinetics. At the electrode level, however, introducing solid or liquid catholytes and anolytes will likely be required to ensure effective ionic percolation. Fast charging is another property that must be demonstrated for large prototypes and battery packs, as

thermal characteristics must be evaluated in realistic conditions. Effective materials and cell modeling can offer some additional insights. Unfortunately, materials' and cells' thermal properties are largely unknown and undisclosed today. Poor thermal performance could lead to a very poor cycle life. So it is still unsure if this will be the case.

- **"Solid-state batteries are more/less resource intensive"**
  **Sphere opinion:** Several solid-state battery chemistries will likely be more lithium intensive, but they are expected to be less resource intensive than conventional lithium-ion, for example, if graphite is substituted with another material. However, this needs to be considered for every single technology. Some chemistries might have hidden bottlenecks upstream or midstream in the value chain. It is also important to consider all the sub-components involved and what chemicals will be needed to process and manufacture battery cells.

- **"Solid-state batteries are easier to recycle"**
  **Sphere opinion:** this is false and based on speculation. No factual data from cell manufacturers are available concerning solid-state battery recycling. Recycling is hard to assess, as most fine chemicals (particularly solid-electrolytes) are not produced at scale. Removing fluorinated salts, solvents, and binders could help on paper. In practice, there is no real test for recycling large-format solid-state batteries.

**Solid-state batteries are a promising technology**, but in most cases, **many claims are not backed by data**. Understandably, companies with high value at stake want to protect their IP but unfortunately this generates a lot of confusion within the field, leading to resources being squandered based on misleading or unproven claims. There is an urgency for impactful innovation, and a different approach is needed. At Sphere, we live in the century of "Data" and as the world is turning towards the power of data-driven intelligence, we believe so should the battery field.

Third-party, **independent but also confidential** assessments performed according to industrial standards are sorely needed. We believe only when both, a thorough analysis of a technology while also keeping the integrity of intellectual property are met, confusion in the market can be properly eliminated.

This is our current focus and proposed solution to help accelerate the energy transition. Ultimately, this approach is an effective solution and will help sharpen the focus on technologies with real market potential.

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