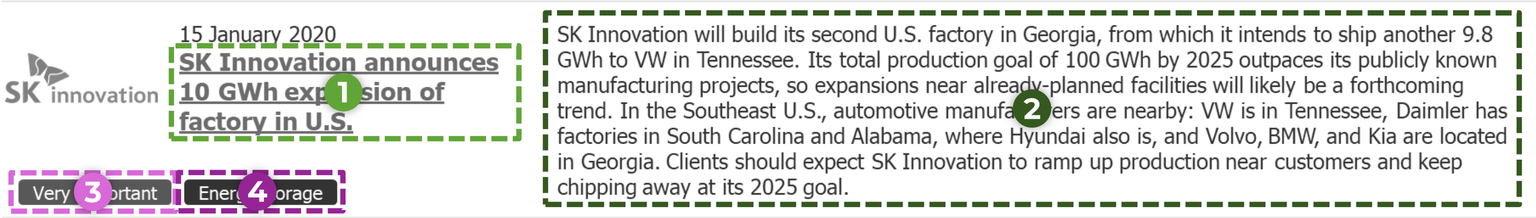
Singapore Battery Consortium Q2 2023 Newsletter

June 2023

SINGAPORE BATTERY CONSORTIUM

Understanding curation of recent industry developments and technology news

Recent industry and technology news are specifically curated based on the relevance to the progression and impact on the battery industry. Each news event is categorized based on importance as rated by Lux's subject matter experts and area of focus (see below for description for both).



1. **Link**: Hyperlink to original news article. Note some news articles may be behind paywall.
2. **Analysis**: Writeup of the news event as it relates to industry development and recommendations for action.
3. **Importance**: Take on the potential importance of the event from "Truly Disruptive" to "Ignore"
4. **Area of Focus**: Category of the news event based on the to the topic.

Importance	Description
Truly Disruptive	A game-changing, landmark development
Very Important	Significant news that will have strong implications
Average Importance	Worth noting, but not likely to be too important or disruptive
Low Importance	An over-hyped development, which is not worth monitoring closely
Ignore	Misleading or irrelevant development, worth being cautious about

Area of Focus	Description
Strategy and regulations	Strategic developments as well as policies with transformational impact on new battery technology developments
Battery developments	Technology developments in electrochemical energy storage, such as Li-ion and solid-state batteries
Electric mobility	Battery deployments for powering road, rail, aviation, and shipping – includes movement of goods and people
Residential energy storage	Hardware and software technologies for commercial and residential battery applications
Stationary storage	Utility-scale and long-duration battery storage for grid services and renewables integration

NCA’s position in the future of Li-ion batteries are further fortified by decade-long supply deals between major battery stakeholders

Mercedes-Benz

Mercedes-Benz tests its electric trucks in extreme winter conditions

Average Importance | Electric mobility

Mercedes-Benz tested its eActros LongHaul and eActros 300 vehicles at temperatures down to –25 °C in Rovaniemi, Finland. In these tests, the company examined the effects of cold on ergonomics, drive performance, thermal management, charging properties, and sensor management among others. The company claims the tests showed that its trucks are fully operational in such extreme wintry conditions. With electrification in suitable trucking segments likely to increase in the coming years, such tests are crucial to ensure good performance in extreme conditions.

VOLVO

Boliden partners with Volvo to deploy electric trucks in underground mines

Average Importance | Electric mobility

Boliden plans to use two Volvo trucks in its Kankberg mine in Sweden. The first truck, a Volvo FH Electric, will transport rock bolts and other equipment into the underground mine. Based on its success, another truck will be deployed to transport rock and ore. Given that electric equipment reduces operating costs and emissions, mining companies have been actively adopting solutions over the last few years and are looking to go further. In addition, electric equipment improves the working environment by reducing noise and vibration. Electrification of mines is expected to continue to increase over the next few years.

posco

POSCO enters USD 32.6 billion pact with Samsung SDI to supply NCA cathodes for EV batteries

Very Important | Battery developments

POSCO was already making nickel manganese cobalt and nickel manganese cobalt aluminum cathodes and had been supplying Ultium Cells; with this contract, it will dive into high-nickel-content cathode manufacturing. POSCO's cathode production plant in South Korea can produce 90,000 tonne annually and will go online in 2023; a second plant in South Korea with annual production capacity of 30,000 tonne is also under construction. The company also is building a cathode production plant with General Motors in Canada and has plans to expand in China, Europe, and North America. The lengthy term of this contract indicates confidence in NCA's longevity and ups the stakes on the security of battery material supply.

Building a domestic battery supply chain remains a top priority as automakers continue to move up the value chain

GM invests in its EV supply chain, focusing on battery cathodes and rare earth magnets

Very Important | Battery developments

GM made two notable announcements in its supply chain for electric vehicle (EV) components. First, a joint venture with POSCO to build a cathode manufacturing plant in North America, and next a second supply agreement with MP Materials to ensure access to rare earth magnets used in motors. The investment in rare earth magnets is one of the first for an automaker. China's control over rare earth magnets has pushed many automakers to move toward less efficient induction motors. GM's move is as an important one in building domestic supply chains around rare earth magnets.

Amprius announces silicon anode Li-ion battery having 500-Wh/kg energy density

Very Important | Battery developments

Amprius has developed a silicon anode Li-ion cell with an energy density of 500 Wh/kg and a specific energy of 1,300 Wh/L at 25 °C. Mobile Power Solutions verified the performance metrics, and the company is targeting the aviation and electric mobility markets for these cells. Due to the silicon anode, these cells can provide higher energy density at a lower weight, facilitating better output. However, even after smaller battery size requirements, as the company claims, the cost is still not on par with that of incumbent Li-ion technology.

EnergyHub expands its EV solution in partnership with Fermata Energy to provide V2G services

Average Importance | Electric mobility

Leveraging its existing platform, EnergyHub will deliver utility signals to the Fermata platform, which interfaces them with additional variables and analyzes them using an AI algorithm. The results are communicated to fleet customers as "simplified" signals to connect the EVs and provide V2G or V2B. This partnership will strengthen the EnergyHub platform by offering a new capability and helps Fermata leverage the existing customer base of EnergyHub, which consists of more than 60 utility customers.

Automakers and utilities are joining forces to accelerate the deployment of charging infrastructure as federal-level initiatives lag

FLUENCE
A Siemens and AES Company

Fluence launches advanced energy storage system Ultrastack for grid stability

Average Importance | Stationary storage

Fluence recently launched an energy storage system for transmission and distribution services known as Ultrastack. This system integrates network operation control, provides grid and power operation support by inertia, black start, and oscillation damping, and integrates renewable energy sources. In 2021, the company did the pilot with Litgrid for a 1-MW/1-MWh system; after the successful results of the pilot, the company worked on two storage-as-transmission projects of 200 MW and 250 MW in Europe using Ultrastack, providing generators and operators with flexibility and intelligent insights to modify and upgrade the grid.

DAIMLER TRUCK

Daimler form JV Greenlane to create charging and refueling network

Very Important | Electric mobility

Daimler Truck North America, NextEra Energy Resources, and BlackRock Alternatives have put USD 650 million into creating the joint venture Greenlane, which will install and operate a charging and hydrogen refueling network across the U.S. with the first site targeting Southern California. An expansive charging network is critical to the electrification of heavy-duty transport. Since public authorities are unlikely to build such a network for trucks, this project is a big step in the right direction. This is similar to the Ionity and European Daimler-Traton-Volvo networks, which are funded by a group of companies for their common use.

Fraunhofer IWS

Fraunhofer launches research project to develop sulfur-silicon batteries with solid-state electrolyte

Average Importance | Battery developments

Fraunhofer IWS has kicked off its Material Innovations for Solid-State Sulfur-Silicon Batteries project to optimize a sulfur-silicon cell that achieves 350 Wh/kg and 300 cycles. The EUR 2.9 million effort will draw on expertise from six research institutions and manufacturers to optimize each cell component. Most notably, this research project is using silicon anodes rather than lithium metal and is a trending preference toward silicon over lithium metal in the solid-state space. Lithium metal anodes still face significant technical challenges, and silicon anodes are edging toward commercialization that would enable lower cell costs.

Electric aviation continues to face technical and regulatory challenges – defense use cases offer near-term opportunities

Altech Batteries launches a 1-MWh GridPack design for SAS batteries

Average Importance | Stationary storage

Altech Batteries, in collaboration with Fraunhofer Institute for Ceramic Technologies and Systems, recently unveiled a plug-and-play 1-MWh GridPack of sodium alumina solid-state (SAS) batteries. The technology is based on that of sodium-nickel-chloride batteries and utilizes a well-known beta alumina solid electrolyte, though Altech claims improved energy capacity and lower costs. The battery has 90% efficiency, can operate in the temperature range of –20 °C to +60 °C, and does not require a heating or cooling system.

Joby Aviation secures USD 180 million equity investment from Baillie Gifford

Average Importance | Electric mobility

Baillie Gifford is purchasing 44 million shares at USD 4.10 each, which will net Joby USD 180 million. Joby plans to use these funds to speed up production for its "near-term revenue" opportunities without affecting its longer-term plan of certifying its electric vertical and takeoff landing aircraft for passenger operations. These near-term revenue operations likely refer to the company's contract with the U.S. Department of Defense. Given that military- or government-related applications do not require Federal Aviation Administration certification, the industry can expect an increase focus on these in the shorter term.

AM Batteries and ATL for joint development program for dry electrode technology

Average Importance | Battery developments

AM Batteries develops a dry electrode processing technology that uses electrostatic spray deposition. This technique involves mechanically milling cathode active material, conductive additives, and a binder to create uniform secondary particles. Those particles are then charged and sprayed onto a grounded current collector. The resulting electrode is then passed through a heated roller to melt the binder and create a dense, uniform electrode. Dry electrode processing eliminates harmful solvent use and can reduce cost; however, it is challenged by the nonuniform mixing of particles and capacity loss during cycling.

Next-generation batteries continue to gain momentum with production capacity announcement and electric vehicle adoption

BMW and PG&E will test V2G capabilities to maximize renewable energy use and balance the grid

Low Importance | Electric mobility

Currently, the companies are testing how EVs maximize charging during high renewables generation and discharge throughout the day to balance household consumption. Both companies agreed to extend their partnership until 2026, including working together on a pilot project in which an EV fleet will be implemented in day-to-day operations at the BMW office in California to "balance the grid." In the current vehicle-to-grid (V2G) project, the EV battery is potentially cycled daily, translating into high stress and battery degradation.

ProLogium will build its first gigawatt factory for semisolid batteries in Europe

Very Important | Battery developments

The company plans to invest USD 5.62 billion for a 48-GWh battery plant and R&D center. Construction is set to begin in 2024, with production projected to start by end of 2026. Initially, the company couldn't reach the planned 1.5-GWh production capacity by 2020 and reset the target to 1 GWh by 2023, perhaps partially due to machinery supply issues. Setting up a factory in France would make ProLogium a pioneer in introducing semisolid batteries in Europe, and its partners VinFast and Mercedes-Benz will likely be early customers.

Mercedes-Benz will use silicon anodes from Sila NanoTechnologies for its EQG G Wagen

Very Important | Electric mobility

Sila Nanotechnologies recently updated its 2022 announcement that its mass-produced Titan silicon anodes will be used in the Mercedes EQG G Wagen: The Titan is now commercially available, debuting in the Mercedes. The company claims this silicon anode can store 10 times more charge than graphite, cut battery weight by 15%, and lessen manufacturing CO2 emissions per kWh by 50%–75%. This will be the first time silicon anodes will be used commercially in electric vehicles. While manufacturing volumes will be lower since the G Wagen has limited production, but this production deal can lead to silicon anode penetration at a faster rate and ahead of the scheduled timeline of 2025.

Regions with increasing penetrations of renewable energy will accelerate long-duration energy storage deployments

AEMO releases tender for 550 MW of long-duration energy storage

Very Important | Stationary storage

The Australian Energy Market Operator (AEMO) issued a tender for long-duration energy storage (LDES) projects with at least eight hours of capacity in New South Wales (NSW), and projects are expected to be announced by the end of 2023. NSW enacted the Electricity Infrastructure Investment Act 2020, which has a goal of at least 2 GW of LDES by the end of 2029, and all projects must meet the set reliability standard. AEMO released its first tender in 2022 for 600 MW of LDES, with winning bids expected to be announced by mid-2023. This tender is one of the largest offered for LDES and positions Australia as a potential leader in deploying these technologies.

Comau research project to automate battery dismantling for second-life applications

Average Importance | Stationary storage

Italian automation company Comau will continue its participation in Flex-BD, a research program led by EIT Manufacturing, which is building an automated battery dismantling process. Second-life battery company Evyon is a collaborator in the project as well. Comau has finished its first proof of concept for dismantling electric vehicle packs and is now working toward dismantling packs for reuse applications. Battery dismantling is one of the most labor-intensive steps in battery end-of-life processing, and it adds substantial cost to second-life systems.

Factorial earns UN 38.3 safety certification to ship 100-Ah lithium metal solid-state battery

Very Important | Strategy and regulations

Factorial has received UN 38.3 certification for transporting its Li-metal solid-state batteries. The UN 38.3 standards were revised in 2015 to include battery safety precautions and Li-metal anodes. It broadly enforces eight testing procedures that ensure safety under stress, high and low temperatures, and overcharge. Solid-state batteries are hyped in the market for safety and higher energy density. However, due to dendrite formation and thermal runaway risk, Li-metal anodes were always a concern. The certification will expand Factorial's reach for testing, but commercialization is still far off, as the company struggles with lower cycle life.

The promise of solid-state batteries are coming to fruition with growing investments and strategic developments

SAIC further solidifies its EV battery stand by investing in solid-state battery maker QingTao

Very Important | Battery developments

SAIC recently announced another investment of USD 283.5 million in QingTao to increase its share in the company and seize the supply of solid-state batteries at a nascent stage. QingTao has already conducted a pilot of solid-state battery installation in cars and, over the years, has launched various solid-state battery materials for electric vehicles (EVs), heavy-duty vehicles, and electronics. SAIC's strategic plan can make QingTao's technology a pioneer in the solid-state domain even beyond China. However, its penetration level will have to compete with a previous heavy investment in gigawatt factories.

Ascend Elements signs USD 1 billion deal for precursor cathode material supply

Average Importance | Battery developments

Starting in 2024, Ascend Elements will enter into a USD 1 billion supply contract to a battery manufacturer in the U.S. It will be supplying precursors for cathode active materials (CAMs) as a product of its battery recycling technology. Ascend Elements develops a technology that co-precipitates CAMs from shredded battery material know as black mass; notably, this supply contract is for precursor CAMs, which would mean the company is using traditional hydrometallurgy to supply nickel, manganese, and cobalt sulfates.

ESS Tech lands biggest order to date with 50-MW flow battery

Very Important | Stationary storage

ESS announced it would supply its iron flow batteries to German energy company LEAG. Following the company's order from San Diego Gas & Electric, this represents its largest contract, and one of the largest non-vanadium flow battery projects in the world. Flow batteries are a good fit for applications with frequent duty cycle and deep discharge, and at this scale, iron flow batteries use widely available materials preferable to vanadium flow batteries. ESS Tech's production capacity expansion is expected to face a long timeline; the 100-MW vanadium redox flow battery on the Dalian Peninsula in China took years to complete, even with Rongke Power scaling up its production capacity.

The Solid-State Battery Roadmap

Solid-state batteries promise improved energy density and performance over those of incumbent Li-ion batteries

In the wake of demand for lower cost, higher energy density, and safer battery technologies, solid-state batteries have emerged as the most promising option, as liquid electrolytes typically contain organic and fluorinated solvents that increase fire risk.

- **Solid-state batteries enable Li-metal anode integration**, increasing energy density and fast charging. However, Li-metal anodes are more susceptible to dendrite formation with liquid electrolytes, leading to short circuits. Theoretically, solid-state batteries with Li-metal anodes have five times more cycle life than incumbent Li-ion batteries.
- **A simplified cell design leads to lower emissions** than liquid battery systems. A study by Minviro suggests that solid-state batteries with an NMC* 811 cathode and oxide electrolyte enable a 24% reduction in CO_2 per kWh.

Despite the potential for solid-state batteries, the technology still faces operational and manufacturing challenges. Key disadvantages include the following:

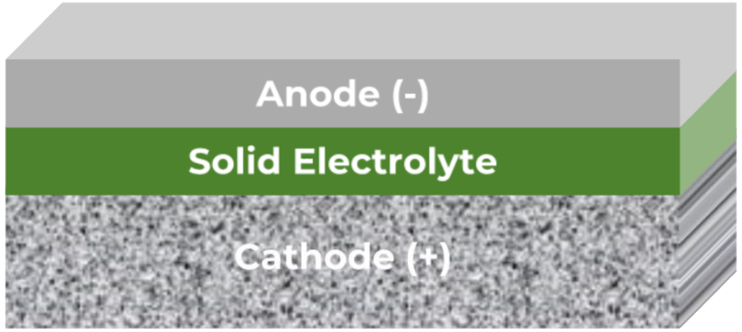
- **High manufacturing or operational temperatures** are often required to aid in ion transport, and higher internal resistance reduces ionic conductivity within the battery cell.
- **External pressure** as high as 5 atm is applied to cells to maintain internal contact between the solid electrolyte and electrodes.
- **An immature supply chain** for electrolyte materials and challenges in roll-to-roll manufacturing hinder the production of solid-state batteries at the commercial scale.

Solid-state batteries are made of a solid electrolyte and are not restricted to lithium-based chemistries

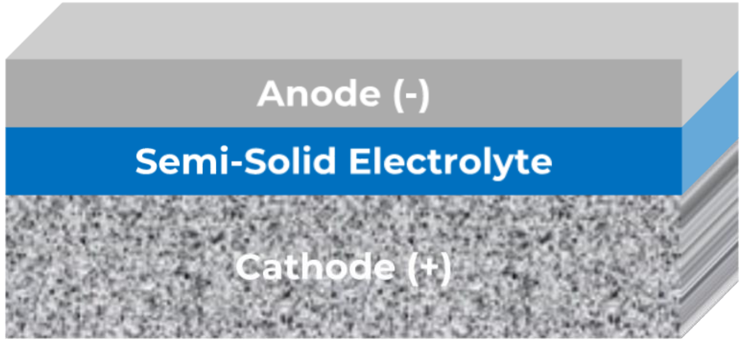
Solid-state batteries use an electrolyte made of ion-conducting materials like polymer, oxide, sulfide, or hybrid

Solid-state batteries are considered the next generation to incumbent Li-ion technology but are not restricted to present Li-based chemistries. The other chemistries explored are Li-air, Li-sulfur, and alkaline batteries, such as zinc based. The cathodes used are transition metal oxide-based cathode materials (LCO*, NCA**), LFP†, vanadium oxide, and high-nickel NMC. The solid-state electrolyte is also compatible with Li-metal anodes and silicon-based anodes.

The key to the solid-state battery is its four solid electrolytes at different maturity levels, which have varied technical metrics. However, the technology still faces interfacial resistance issues. Some companies are working with gel-type electrolytes (semi-solid batteries) to maintain contact between the electrode and electrolyte, but it increases manufacturing cost without any incremental effect on performance compared to that of incumbent technology.



The cell contains a completely solid electrolyte.



The cell contains part liquid in a solid electrolyte.

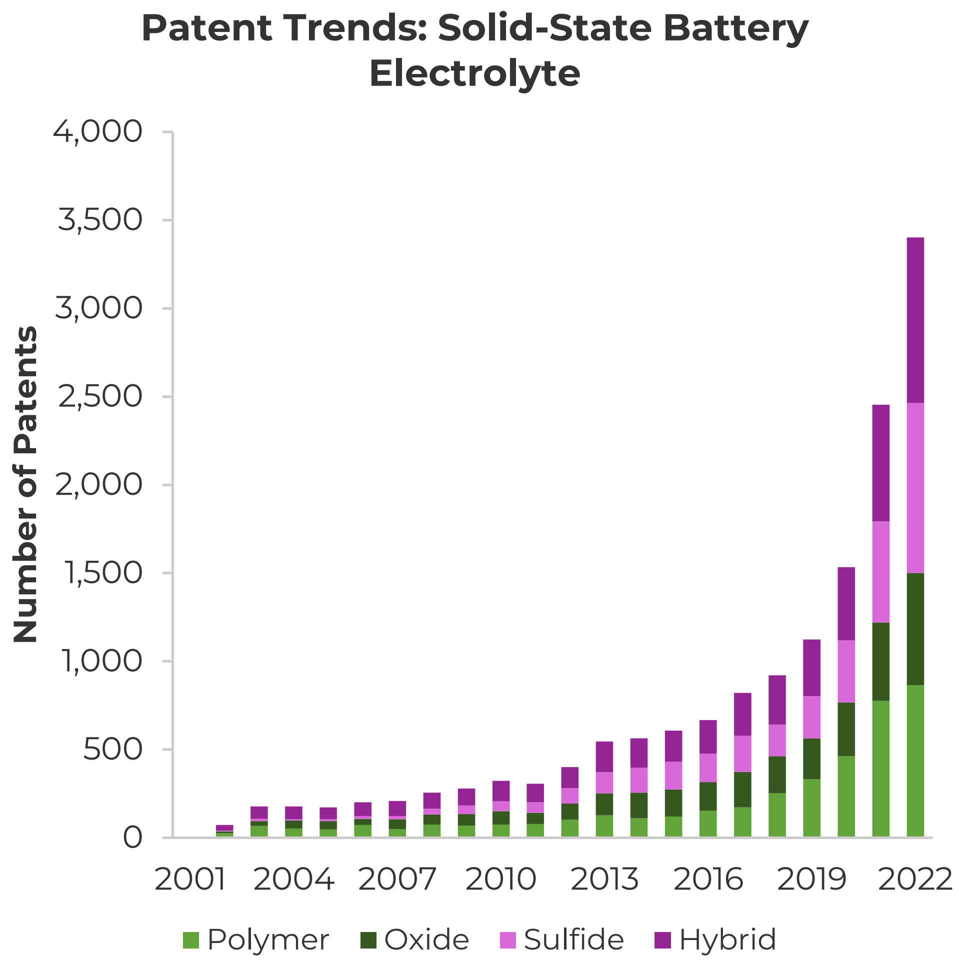
*LCO, lithium cobalt oxide; **NCA, nickel cobalt aluminum; †LFP, lithium iron phosphate

Patent activity in solid-state batteries indicates research beyond materials science in cell integration and battery management systems

The last three years of patent activity showed an equal and growing interest in all electrolyte types

Solid-state batteries have matured to the point that it's not only about materials science. Overwhelming activity in Japan and China is due to the advantages of companies or academic institutes such as Toyota and the Chinese Academy of Sciences and is reflective of the EV market in APAC. However, in the U.S., startups such as Ampcera and Blue Current are steadily commercializing research activities.

Clients interested in electrolytes that are near commercialization should focus on startups working on polymer and sulfide electrolyte batteries or oxide electrolytes in semi-solid batteries. Those interested in early stage research are encouraged to investigate hybrid electrolytes, as research is still looking for the proper compound integration among sulfides, polymers, and oxides for improved metrics and ease of implementation.

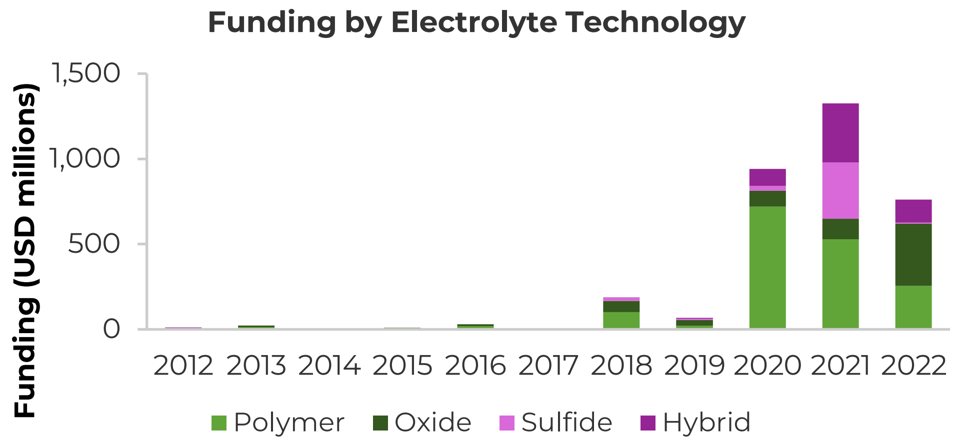


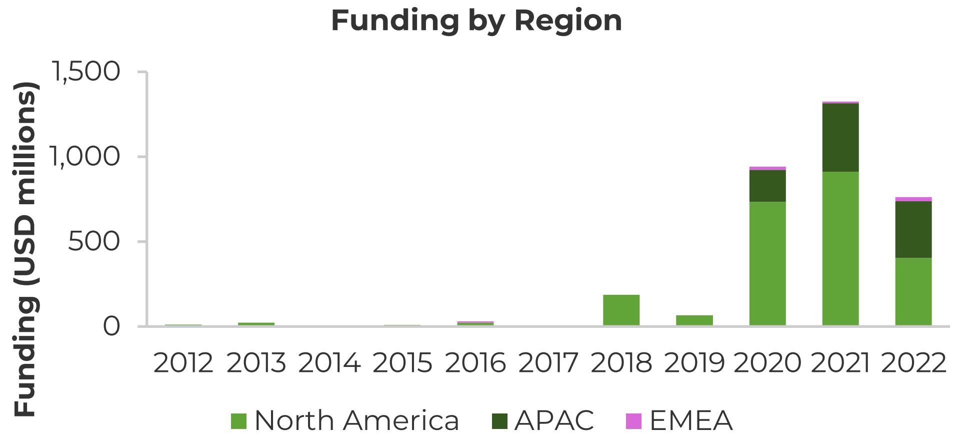
Investments in solid-state batteries are ballooning rapidly; even early stage companies are well funded

Automobile companies have significantly driven investment in solid-state batteries in the last three years

From 2012 to 2017, investment in the solid-state battery industry was negligible and used for consumer electronics and health equipment applications. In 2018, the situation started changing, with the next three years showing a total investment of USD 3 billion.

Clients interested in funding early stage startups should pay attention to academic research that can evolve into commercial applications, particularly emerging hybrid electrolytes. Clients looking for more mature technologies should focus on startups innovating processing technologies that improve solid-state electrolyte cell integration. Although China's investment is higher in the solid-state battery market, the government funding is concentrated in larger companies. North American startups will continue to see increased funding as research gets converted into commercial entities like Blue Current and QuantumScape.

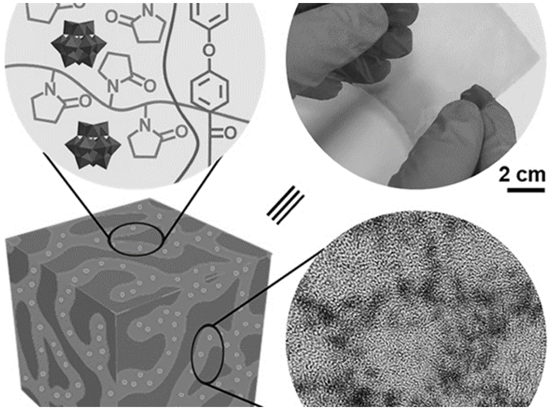




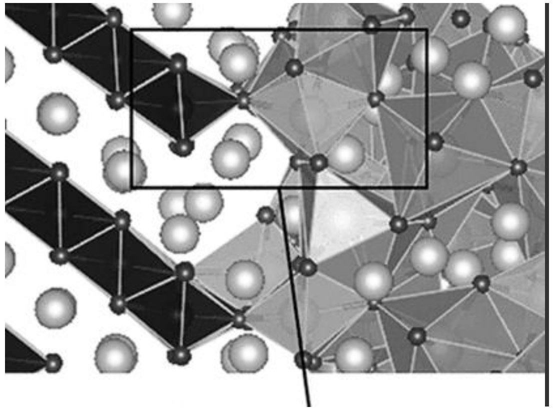
Understanding and analyzing the electrolyte types and properties used for solid-state batteries

The report provides a comprehensive analysis of polymer, oxide, sulfide, and hybrid solid electrolytes by evaluating the following three key components:

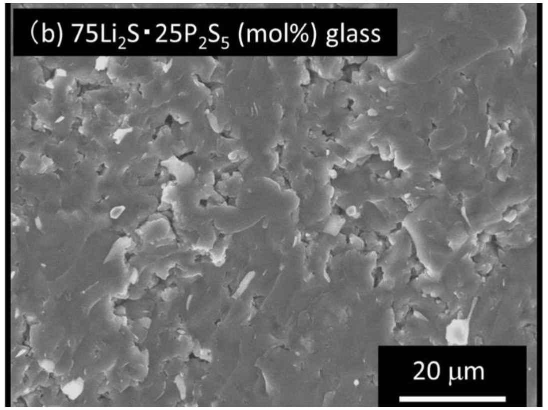
- **Electrolyte characteristics.** A summary of critical features for four solid electrolyte types, their formulations, a discussion of fundamental differentiators, and the development focus and challenges.
- **Performance metrics.** A rating of the electrolyte's performance metrics based on our criteria as they are critical for technology commercialization.
- **Key players.** Highlights of key players across corporates, startups, and academia developing the technology.



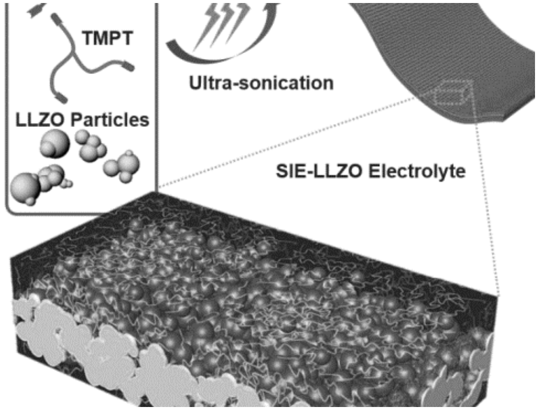
Polymer Electrolyte[1]



Oxide Electrolyte[2]



Sulfide Electrolyte[3]



Hybrid Electrolyte[4]

Image sources: 1, 2, 3, and 4

Metrics of solid-state battery components

This report compares six core properties of solid-state components with those of incumbent Li-ion liquid batteries.

The scoring rubric is based on scores 1–4, which are defined as follows:

- Considerable Improvement
- Moderate Improvement
- Slight Improvement
- No Improvement

Properties	Description
Ionic conductivity	How well the solid electrolyte can transport lithium ions between electrodes.
Stability with lithium	Electrolyte compatibility with lithium as it tends to react negatively with certain materials, causing irreversible capacity loss or safety issues.
Voltage limits	The window of electrochemical stability as next-generation, high-voltage cathodes like LMNO* may cause a solid electrolyte to break down.
Cell integration	The performance metrics of cells, such as ionic resistivity, pressure, operating temperature, and cycle life. Also, the ease of integration into EV battery packs.
Processability	How compatible the electrolyte is with roll-to-roll manufacturing and the ease with which it can be stacked or wound.
Commercial activity	Industrial activity including research and investment activity, notable partnerships, startup activity, and manufacturing timelines and what the future goals among key players are.

*LMNO, lithium manganese nickel oxide

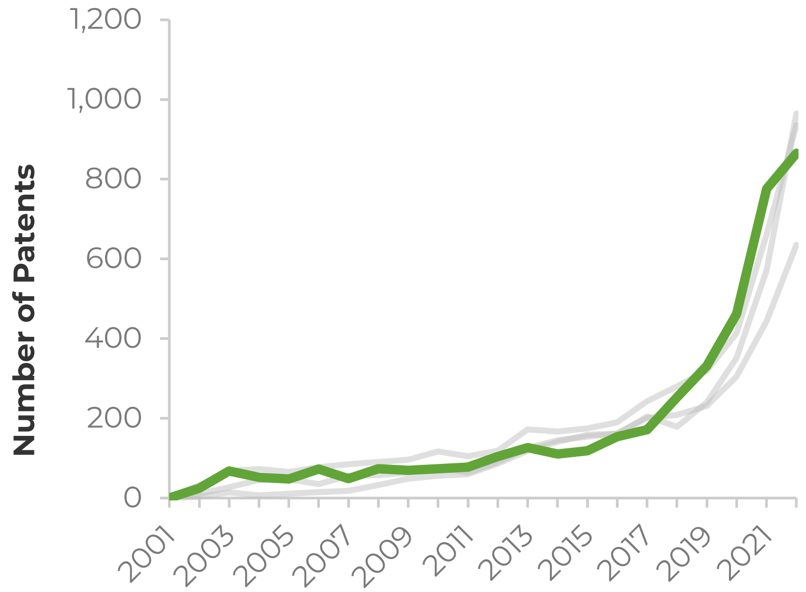
Polymer solid-state electrolyte
Lithium-salt and polymer matrix formulation

Technology

Polymer solid electrolytes are considered one of the most mature technologies and are popular due to their semi-crystalline structure and flexibility, which improve ionic conductivity. The metrics of polymer electrolytes depend on the polymer matrix and lithium salt additives.

Development Focus and Challenges

Polymers conduct ions better at higher temperatures, requiring cell heating that can reduce pack-level energy density. Research focuses on improving conductivity at lower temperatures using additives and reducing dendrite formation with anode coatings.



Key electrolyte compositions

- Poly(ethylene oxide) (PEO)
- Poly(propylene carbonate) (PPC)
- Poly(trimethylene carbonate) (PTMC)
- Polyvinylidene fluoride (PVDF)

LUX TAKE

Polymer solid electrolytes have inherent flexibility and thermal stability. They have a higher chance to enter the market first due to their adaptability to incumbent manufacturing processes if solutions to operate them at room temperature are successful.

Polymer solid-state electrolyte

Performance metrics

Ionic conductivity	At room temperature, the ionic conductivity of polymer solid electrolytes is as low as 1 mS/cm. They offer higher conductivity at operating temperatures greater than 60 °C. The semi-crystalline structure and addition of lithium salts improve Li-ion transport.
Stability with lithium	Polymer solid electrolytes provide high stability toward lithium metal. They can also resist dendrite formation, but their mechanical strength is reduced when additives are added.
Voltage limits	The voltage for most SPEs is limited to 4 V, indicating lower electrochemical stability. This restricts the use of high-potential cathodes.
Cell integration	Due to their high flexibility, polymer solid electrolytes require low external pressure to maintain interfacial contact. Research has shown that these cells can reach as high as 3,000 cycles if mechanical stability is achieved.
Processability	The cells can be produced as prismatic or pouch cells. Due to the polymer's flexibility, they can be manufactured using a roll-to-roll process, providing high productivity and cost benefits.
Commercial activity	The polymer solid electrolyte industry received USD 1.5 billion in investments in the last three years. Research activities reflect the interest of corporates such as LG Chem and Samsung. Small-format batteries are already in use for consumer electronics and drones.

Polymer solid-state electrolyte

Case study: Materials research to improve ionic conductivity

Factorial Energy recently demonstrated a 100-Ah cell using a polymer-based all-solid electrolyte

The solid electrolyte is made of poly(lithium acrylate), a hydrophilic polymer, a lithium salt, and a Lewis acid. The company uses an acrylate-type polymer because it increases flexibility in the material and improves ionic conductivity. The Lewis acid contains hydrogen or hydroxide ion, which accepts a pair of nonbonding electrons, increasing ionic conductivity. Also, the company also uses a method that instills urea or carbamate with UV crosslinking, which, due to rigid hydrogen bonds, helps dissociate lithium salts, leading to improved conductivity.

LUX TAKE

Along with increasing ionic conductivity, SPEs can function at temperatures between −20 °C and 60 °C and lower pressure, which can work positively with its flexibility and stability with Li-metal anodes. If successful, SPEs is promising for commercialization.

HQ Location	U.S.
Technology	Poly(lithium acrylate)
TRL* Score	7
Founded Date	2019
Funding Received	USD 240 million

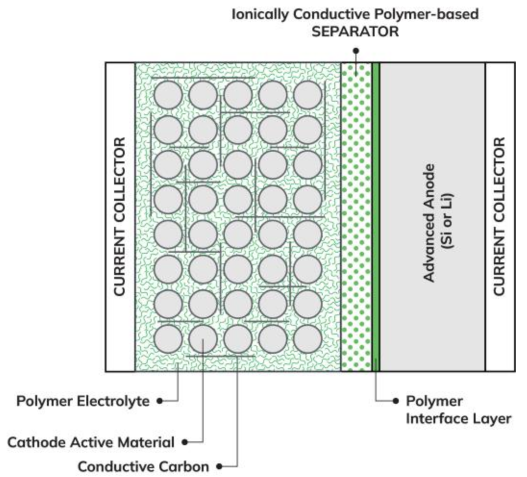
*TRL, technology readiness level; image source: MetalTech News

Polymer solid-state electrolyte
Case study: Achieving voltages beyond 4 V

Ionic Materials develops SPEs that can achieve an ionic conductivity above 1.3 mS/cm and is stable at voltages as high as 5.5 V

The polymer material is made of a monomer that can bond in different ways with carbon, oxygen, nitrogen, or chlorine to form other homopolymers. The company tested a cell in which it developed its catholyte, anolyte, LCO cathode prepared with a mixture of polyphenylene sulfide, chloranil powder, and LiTFSI*, and a Li-metal anode. This combination provided voltage stability above 5 V.

HQ Location	U.S.
Technology	Non-PEO polymer
TRL Score	8
Founded Date	2011
Funding Received	USD 65 million



LUX TAKE

The voltage stability above 5 V and compatibility with Li-metal anodes are evidence of a successful streak for polymer electrolytes. However, the temperature requirement is still at least 20 °C, which can reduce the efficiency of the battery.

*LiTFSI, lithium bis(trifluoromethanesulfonyl)imide; image source: Ionic Materials

Oxide solid-state electrolyte
Lithium-oxide compound with glass, garnet, or perovskite structure

Technology

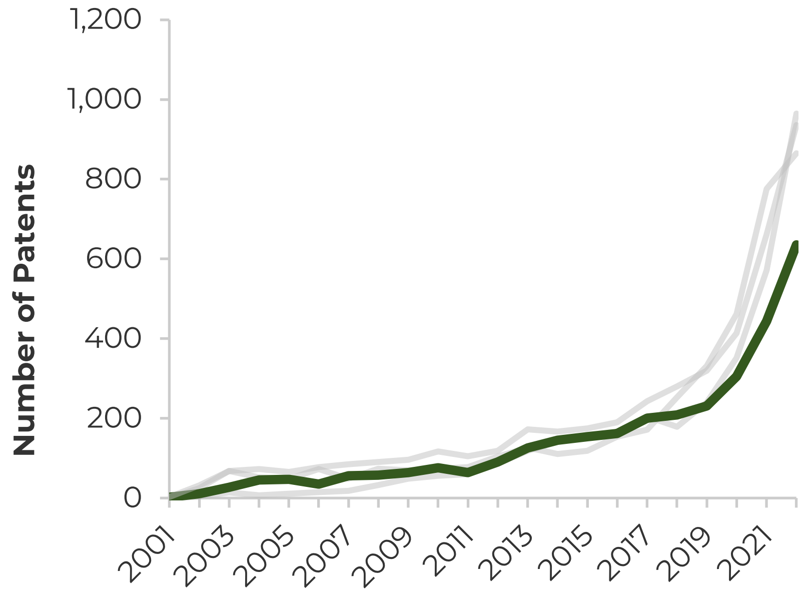
Inorganic oxide solid electrolytes consist of compounds with lithium and oxide. The oxide electrolytes are formulated using aluminum, zirconium, titanium, and chromium. This provides a different crystalline structure, leading to high ionic conductivity, electrode stability, and flexibility during production.

Development Focus and Challenges

They are brittle; achieving high ionic conductivity requires sintering at high temperatures to reduce resistance. The oxide electrolytes used today are semi-solid, which have a gel-like consistency to improve interfacial contact and reduce external pressure needs.

LUX TAKE

Oxide electrolytes can be made thin; they are stable toward Li-metal anodes and can be used with various cathodes. However, to use oxides in commercial applications, the complexity of manufacturing must be addressed.



Key electrolyte compositions

- LiPON*
- NASICON**
- Garnet
- Perovskite

*LiPON, lithium phosphorus oxynitride; **NASICON, sodium super ionic conductor

Oxide solid-state electrolyte
Performance metrics

Ionic conductivity	The ionic conductivity of solid oxide electrolytes is lower than sulfides, below 1 mS/cm. To improve this metric, the material needs sintering at temperatures as high as 800 °C, which increase the cost of manufacturing. Also, this low conductivity is unsuitable for thick catholytes; companies often opt for thinner options or hybrid electrolytes.
Stability with lithium	The stability of oxide solid electrolytes with Li metal depends on the material. LiPON can be stable after treatment, and garnet-type is the most stable. However, NASICON and perovskite are not stable with Li metal.
Voltage limits	They have a high voltage range, up to 4.6 V, indicating high electrochemical stability, which makes it compatible with high-potential cathodes.
Cell integration	Due to the stiff material, they require constant external pressure to maintain interfacial contact. This can affect the mechanical system of the packs. Research has shown that these cells can reach 1,000 cycles.
Processability	Due to the brittle and stiff nature of oxide electrolytes, winding can strain the electrode layers and lead to cracking/degradation. Stacking is the safest process for this type of electrolyte; to reduce internal resistance, they must be hot pressed.
Commercial activity	Solid oxide electrolytes gained traction in 2022, but funding is still minimal due to the complex manufacturing process required. They are used in thin-film batteries for medical devices due to their high electrochemical stability and temperature range.

Oxide solid-state electrolyte

Case study: Research to improve metrics and manufacturing of oxides

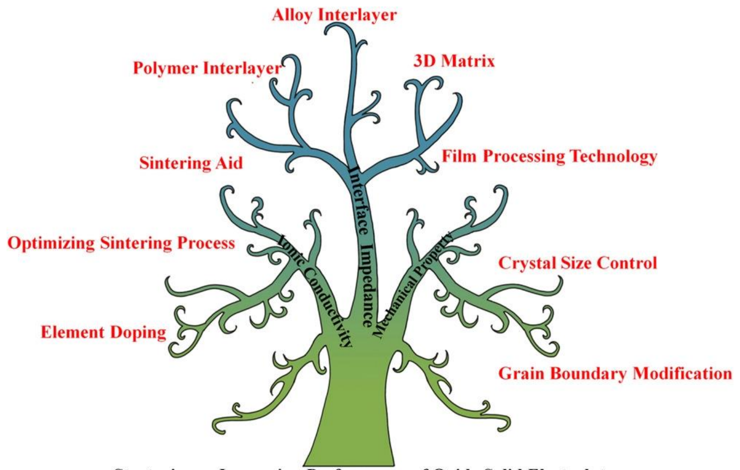
Research improves ionic conductivity and flexibility of oxide electrolytes and optimizes sintering to avoid cracking

Research discusses the effects of doping, casting, and sintering on oxide electrolyte performance and its stability with Li metal, claiming that increasing Li content in garnet-type electrolytes, doping NASCION with trivalent ions, and formatting the structure of perovskite can provide ion conductivity to 3×10^{-3} S/cm. Plasma sintering technology claims to provide simultaneous heating and mechanical stress leading to the efficient integration of multilayer batteries without cracking.

LUX TAKE

The research aligns with our understanding of doping oxides to achieve better ionic conductivity at room temperature and reduce brittleness. The plasma sintering method is the latest used in the industry, which can save energy and costs.

HQ Location	China
Technology	LLZO*
TRL Score	2
Founded Date	2021
Funding Received	---



Strategies on Improving Performance of Oxide Solid Electrolytes

*LLZO, lithium lanthanum zirconium oxide; image source: [Challenges, fabrications, and horizons of oxide solid electrolytes for solid-state lithium batteries]

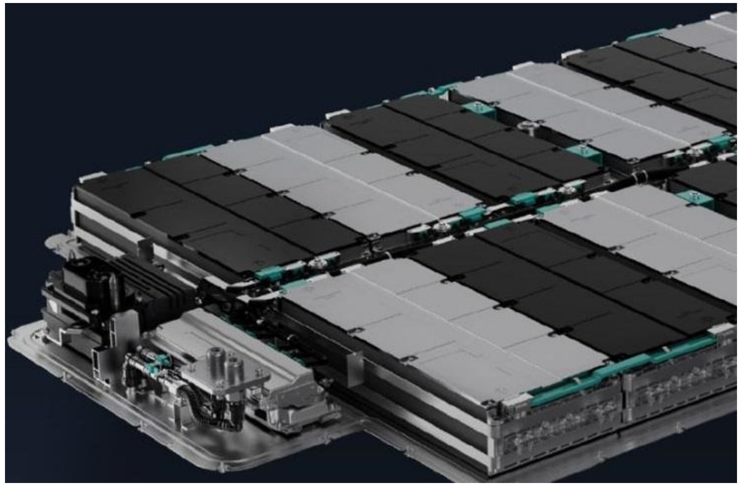
Oxide solid-state electrolyte

Case study: Pioneer in the commercial market

Beijing WeLion New Energy Technology develops a semi-solid oxide-based battery to be used in Nio cars by 2023

The company's patents reveal work on a NASICON-type oxide solid electrolyte with germanium and titanium compounds and Li salt as additives. Another patent discusses a polymer-oxide composite electrolyte with 0%–50% liquid content. It is also experimenting with solutions for silicon-carbon composite anodes and nano-dispersion of liquid on solid electrolytes. The company announced the commercialization of a semi-solid battery in 2023, with an energy density of 360 Wh/kg and a cycle range of 1,000 km. Future plans involve the development of a fully dry, solid-state battery.

HQ Location	China
Technology	Inorganic oxide in a polymer matrix
TRL Score	7
Founded Date	2016
Funding Received	USD 303 million



LUX TAKE

This product launch will give the industry a glance at semi-solid electrolyte performance metrics under realistic conditions. For Beijing WeLion, battery swapping will help gather data and realistically check battery health.

Image source: CHINAPEV

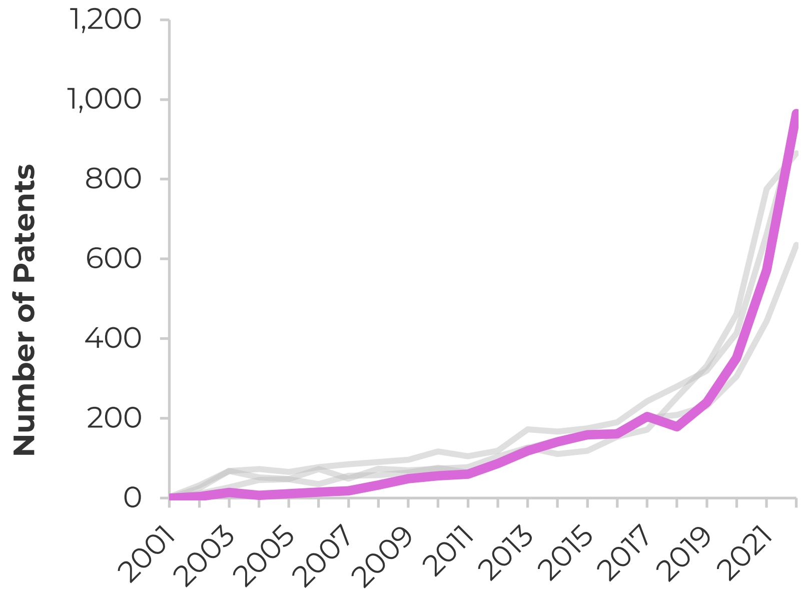
Sulfide solid-state electrolyte
Lithium-sulfur compounds with carbon group components

Technology

Inorganic sulfide-based solid electrolytes consist of lithium and sulfur with other components such as silicon, germanium, and phosphorous. They are considered a promising technology for the large-format battery market due to their high ionic conductivity and ease of manufacturing.

Development Focus and Challenges

Research is being carried out to formulate electrodes with a stable sulfide interface to improve electrochemical stability and avoid dendrite formation. The other major challenge is to prevent toxic hydrogen formation during leakage.



Key electrolyte compositions

- Lithium phosphorous sulfide (LPS)
- Thio-LISICON*
- Lithium germanium phosphorous sulfide (LGPS)
- Argyrodite

LUX TAKE

Sulfides have ionic conductivity equivalent to that of liquid electrolytes but a very low electrochemical stability. The requirement of a controlled environment for manufacturing poses an extra cost. It will be the first to enter the market if research can resolve the issue of electrode compatibility for high energy density.

*LISICON, lithium super ionic conductor

Sulfide solid-state electrolyte
Performance metrics

Ionic conductivity	Sulfides have the best ionic conductivity. Using argyrodites can provide a conductivity of 2 mS/cm.
Stability with lithium	The sulfides have very low electrochemical stability, leading to lithium-metal reactions. Solid electrolyte interphase deposition on anodes influences dendrite formation.
Voltage limits	Solid sulfide electrolytes have a low voltage range of 1.7–2.3 V, indicating low electrochemical stability. This makes sulfides react with lithium metal at low and high voltages and cathode at high voltage. This reactivity restricts the use of high-potential cathodes without coatings.
Cell integration	The plasticity of sulfides facilitates good interfacial contact, but to manage volumetric changes, they still require high external pressure, which can affect the mechanical system of packs. Certain developers have indicated that approximately 1,000 cycles can be achieved.
Processability	The cells can be pouch or prismatic using a stacking methodology as winding creates interfacial and layer contact issues. During cell assembly, external pressure is applied to improve interfacial contact. However, it does not require a hot press process.
Commercial activity	Solid sulfide electrolytes are the least funded due to their low electrochemical stability. In 2022, they gained traction as new coatings and a solution for lithium metal were introduced. Solid Power and Svolt are some of the best known companies working successfully with sulfides.

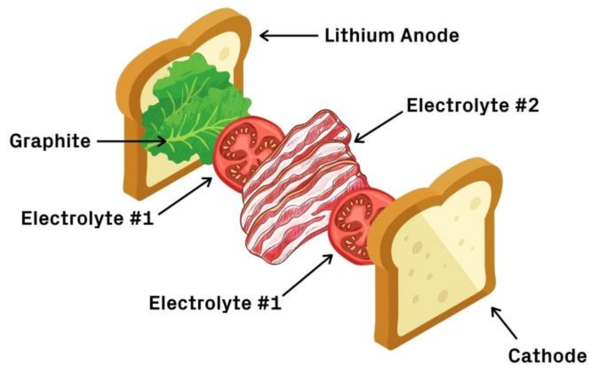
Sulfide solid-state electrolyte

Case study: Achieving lithium stability

HQ Location	U.S.
Technology	Argyrodite, LGPS
TRL Score	2
Founded Date	2021
Funding Received	---

The development of multilayer and multi-material batteries to control dendrite formation

The Harvard University BLT sandwich battery structure has six layers: 1) a lithium anode with 2) a graphite coating, 3) a cathode, and 4–6) three layers of two types of solid sulfide electrolytes: argyrodite and LGPS. Not all sulfide materials are compatible with Li-metal anodes, but in this structure, argyrodite is moderately compatible with lithium-metal anodes, and LGPS is immune to dendrite formation. This middle immunity stops the dendrite from reaching the cathode, which avoids thermal runaway.



LUX TAKE

The technology resolves the most significant energy density barrier of sulfide compatibility with lithium metal. However, due to decomposition, LGPS is prone to solid electrolyte interphase formation, which increases internal resistance.

Image source: The Harvard Gazette

Sulfide solid-state electrolyte

Case study: Making pressure commercially viable

Solid Power develops and produces semi-solid and solid-state batteries using a sulfide-based electrolyte compatible with high nickel and conversion cathodes and silicon composite anodes

Sulfide-based electrolytes provide better interfacial contact due to their flexibility, but they cannot manage volumetric changes. Solid Power uses external and internal carbon plates to apply pressure on the battery, thus maintaining interfacial contact. The operational loading required is about 170 lb. and uses sensors and digital signals to maintain equal pressure distribution across the stack. The company claims that this methodology can provide an energy density of 550 Wh/kg and 1,000 cycles.

LUX TAKE

Every battery contains a plate pack with constant pressure, which increases the cell's weight and poses a concern for operations. Solid Power has forged a strong partnership; if operational concerns are addressed, it will be a strong player in the long-term market.

HQ Location	U.S.
Technology	Sulfide-based
TRL Score	7
Founded Date	2012
Funding Received	USD 382 million

Image source: Solid Power

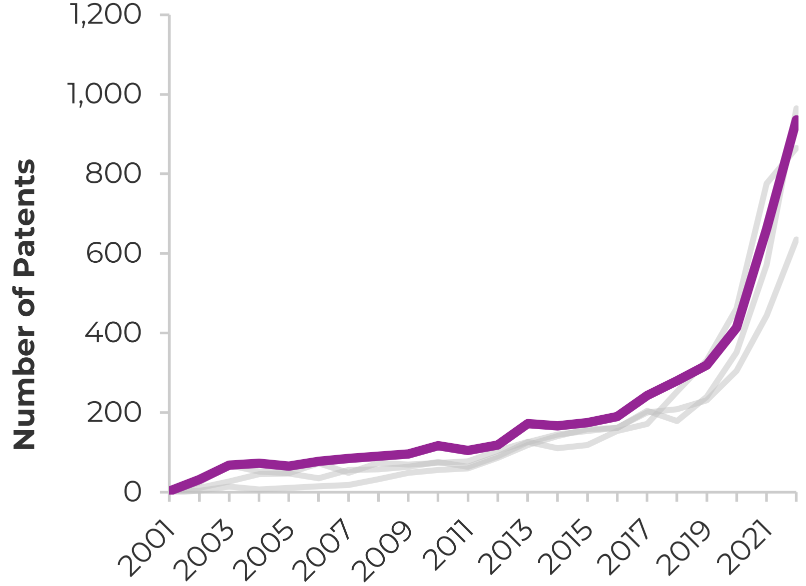
Hybrid solid-state electrolyte
Combination of electrolytes

Technology

Hybrid solid electrolytes combine solid materials, mostly a polymer matrix, with either sulfide or oxide. The prepared composite is polymer ceramic, either solid or gel-type, for ease of polymer manufacturing and ceramic conductivity.

Development Focus and Challenges

The development of hybrid electrolytes is relatively recent; hence, it has yet to standardize performance metrics and solution categories. The development focus is to improve interfacial contact, eliminate or reduce external pressure, and improve ionic conductivity.



LUX TAKE

Hybrid electrolytes can resolve the shortcomings in solid electrolytes if research successfully identifies a composition that uniformly distributes the electrolytes and is compatible with high-potential electrodes. Clients should engage with companies or research organizations with promising technologies.

Key electrolyte compositions

- Polymer
- Non-PEO polymer ceramic

Hybrid solid-state electrolyte
Performance metrics

Ionic conductivity	Ionic conductivity achieved by hybrid electrolytes is improved due to the presence of ceramic materials. However, researchers and companies are still exploring methods to reduce pressure while improving conductivity.
Stability with lithium	Hybrid electrolyte batteries use lithium-metal anodes and can mitigate dendrite formation by arranging compatible components toward the anode, such as polymers.
Voltage limits	The voltage of some hybrid electrolyte compositions ranges from 3–4 V.
Cell integration	The presence of gel in the electrolyte and the elasticity of the polymer provides higher interfacial contact, and the pressure requirement is less than 1 atm in specific scenarios. Certain companies were able to achieve approximately 800 cycles at the pilot stage.
Processability	Winding and stacking are currently the two types of cell assembly. However, composites with higher polymer content can make the manufacturing process easier due to their flexibility.
Commercial activity	Hybrid electrolytes gained traction in the last three years as solid-state batteries began to gain traction in the automobile industry. Research activity is high in APAC, mirroring the EV market and commercial activities in that region.

Hybrid solid-state electrolyte

Case study: Solution to improve interfacial contact

Blue Current develops a composite polymer-ceramic solid-state-electrolyte battery with a graphite-silicon composite anode

To reduce interfacial resistance, solid-state batteries require either pressure or liquid in the electrolyte to maintain contact between the electrode and the electrolyte. Blue Current has a completely dry cell, and to maintain contact, it uses a crosslinked polymer system that binds the glassy sulfide and provides elasticity to enhance contact. Pressure is applied during the polymerization of the precursor that is mixed with inorganic particles, generating contact. Once contact is made, the applied pressure is removed, but particles remain in place due to the crosslinked polymer network.

LUX TAKE

The crosslinking of the polymer technology decreases the need for pressure and liquid, resolving the central issue in solid-state battery usage. However, it still needs to improve cycle life beyond 500 cycles to commercialize.

HQ Location	U.S.
Technology	Polymer ceramic
TRL Score	5
Founded Date	2014
Funding Received	USD 50 million

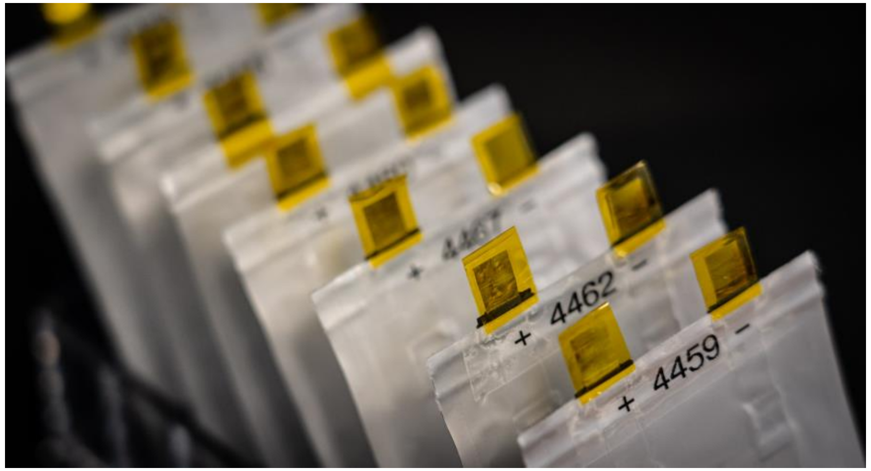


Image source: Blue Current

Hybrid solid-state electrolyte

Case study: ProLogium's history of missing timelines

ProLogium's semi-solid batteries address technological concerns but need to catch up on commercialization timelines

ProLogium's core battery metrics do not provide much improvement but claim to resolve the issue of interfacial contact and dendrite formation. Since 2019, the company has not scaled beyond 40 MWh, even after setting a target to scale up to 1.5 GWh by 2020. The new target is to establish a 1-GWh facility by 2023; however, even after an investment of USD 360 million in the last two years and partnerships with VinFast and Mercedes-Benz, it still lacks definitive commercialization timelines.

HQ Location	Taiwan
Technology	Ceramic oxide and PEO mixed with gel
TRL Score	7
Founded Date	2006
Funding Received	USD 670 million

LUX TAKE

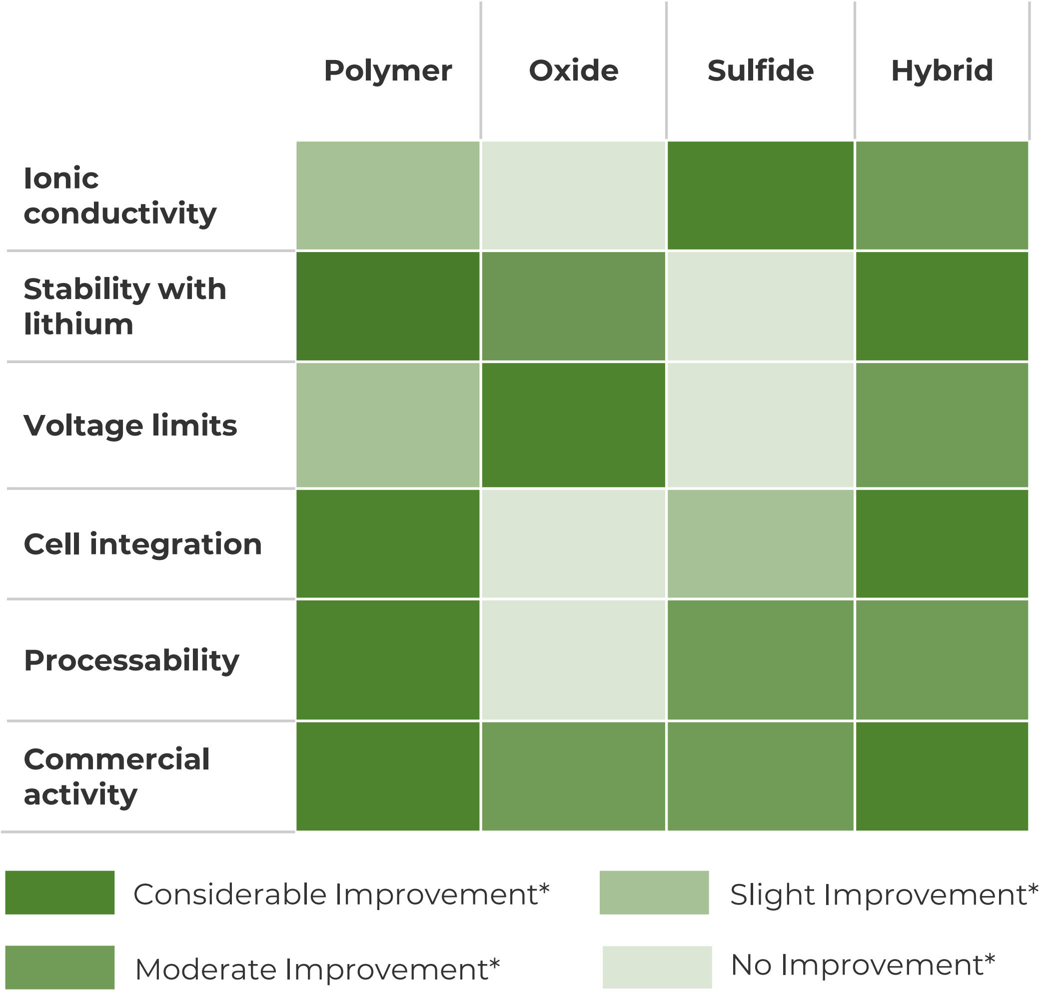
ProLogium has missed production expansion targets multiple times but aims to reach 120-GWh scale by 2030 without progress during the last three years. This delay is likely the result of a lack of improvement in technology performance metrics.

Hybrid electrolyte technology has the potential to disrupt the incumbent Li-ion industry with various performance improvements

Lux's methodology and heat map provide a better understanding of technology development, process convenience, challenges, and commercial timeline. Companies at an **early stage** should focus on a single aspect of batteries as developing a comprehensive technology requires greater research investment and a longer timeline. Hybrid or composite electrolytes will see higher investments in the coming years due to the drawbacks of individual electrolyte types.

Bringing a **lab-scale prototype to commercial demonstration** takes multiple years as a result of long testing times, misalignments of technology and industry needs, challenges in the composition of materials, and proving advantages over incumbent Li-ion batteries.

It is also advisable to have early partnerships with battery materials producers and automotive companies to test various compositions and get clarity on market expectations. This can help achieve materials security, long-term contracts, and joint ventures for **commercialization**.



*The scale is in comparison to incumbent Li-ion battery technology.

Solid-state batteries will emerge to dominate the electric vehicle market in the coming decade

Solid-state batteries can prove to be a solution for some EV woes	Solid-state batteries, if certain concerns are addressed, can provide high energy density, facilitate fast charging due to their compatibility with high-potential cathodes, and be safer to transport without leakage concerns.
The interfacial resistance between electrode and electrolyte is the key to commercializing solid-state batteries	Currently, pressures above 1 atm are required to achieve comparable ionic conductivity with that of incumbents. This also requires better battery management and components, increasing battery weight and complexity of operations.
Compatibility with Li-metal anodes and high-potential cathodes can provide increased energy density and route to lower costs	Using Li-metal anodes with compatible electrolytes or strategic arrangement of layers of hybrid electrolytes can provide high energy density. However, the solution's success will depend on the performance metrics of large-format batteries and their valuation compared to that of incumbent liquid electrolyte batteries.

Document prepared by Lux Research

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