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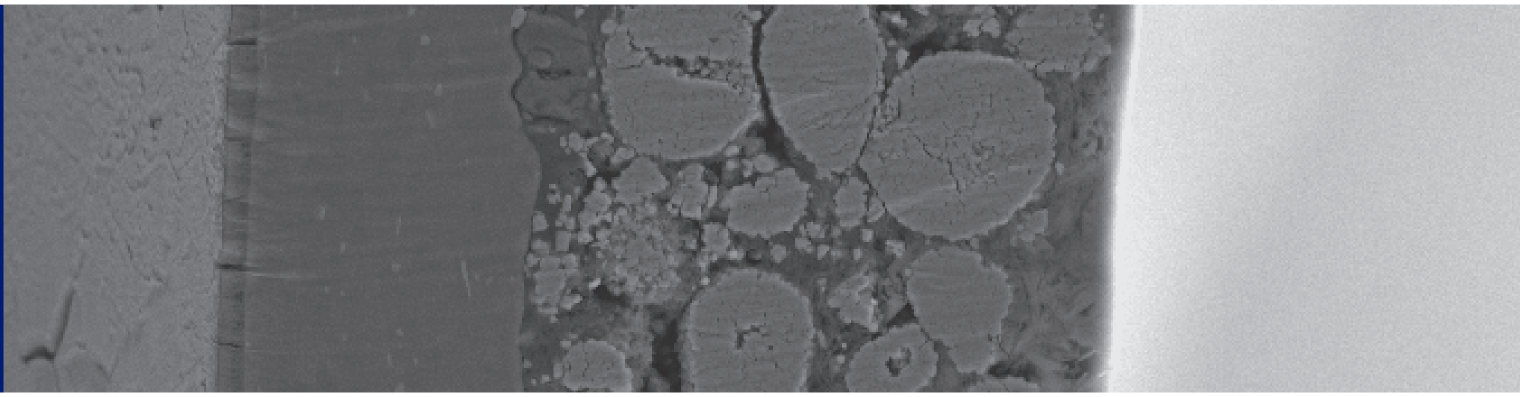
Solid-State Batteries: The Technology of the 2030s but the Research Challenge of the 2020s



The development of solid-state batteries that can be manufactured at a large scale is one of the most important challenges in the battery industry today. The ambition is to develop solid-state batteries, suitable for use in electric vehicles, which substantially surpass the performance, safety, and processing limitations of lithium-ion batteries. In contrast to research into lithium-ion batteries, which will provide incremental gains in performance toward theoretical limits, research into solid-state batteries is long-term and high-risk but also has the potential to be high-reward.

Introduction

Solid-state batteries (SSBs) are distinguishable from other batteries by their lack of a liquid electrolyte, their potential to store significantly more energy for any specific volume, and improvements in safety given that the solid-state electrolyte used is non-flammable. The superior stability and mechanical properties could, in principle, enable the use of more energy dense anodes such as lithium metal with a potential step change in volumetric and gravimetric energy densities (the energy density for a given volume or weight) compared to the current state of the art.

Solid-state electrolytes (SSEs) can be classed into two main categories: 'inorganic' solids (crystalline or glasses) and 'organic' polymers.

Attempts to use organic polymer SSEs have proved difficult to implement at scale; their lower ionic conductivity and poor mechanical properties require operation at temperatures in the 60-80°C range. The recent discovery of high-conductivity sulfide-based inorganic crystalline materials has prompted a resurgence of interest that has led SSBs to be considered among the most promising future battery technologies.

In the past, manufacturing techniques have generally limited SSBs to micro-scale devices operating at low power. However, a great deal of research is now being undertaken in SSEs to understand the fundamental issues that are limiting their implementation at scale, as an alternative to conventional lithium-ion batteries, which are fast approaching performance limits.

Main Advantages of Solid-State Batteries

There are four potential advantages to SSBs: (1) improved safety (2) higher energy density (3) faster-charging times (i.e. higher power density) and (4) longer life.

(1) Improved Safety

Perhaps the most important incentive for implementing SSEs derives from their potential to substantially improve safety relative to conventional lithium-ion batteries. The liquid electrolytes used in commercial lithium-ion batteries are flammable and, if damaged or incorrectly charged, can lead to them catching fire and even explode if the safety vents are unable to release the hydrocarbon gases created. Heat and fire failures have been reported in mobile phones, laptops and electric vehicles (EVs) but these are very rare events.[1,2]

SSBs would be preferable to lithium-ion batteries for use in EVs, as well as many other applications, where a higher level of safety or even a fail-safe design is required. This is because, in addition to being non-flammable, SSEs may also be impervious to the internal short circuits caused by damage to lithium-ion batteries. Preventing these short circuits is paramount to eliminating the possibility of heat and fire failures mentioned above.

Image courtesy of Christopher Doerrer.

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[1] Barnett, Roth, Thomas-Alyea and Doughty (2006). Abuse Tolerance versus Field Failure: Two Different Issues for Lithium-Ion Safety. Prepared for the International Meeting on Lithium Batteries, June 2006.

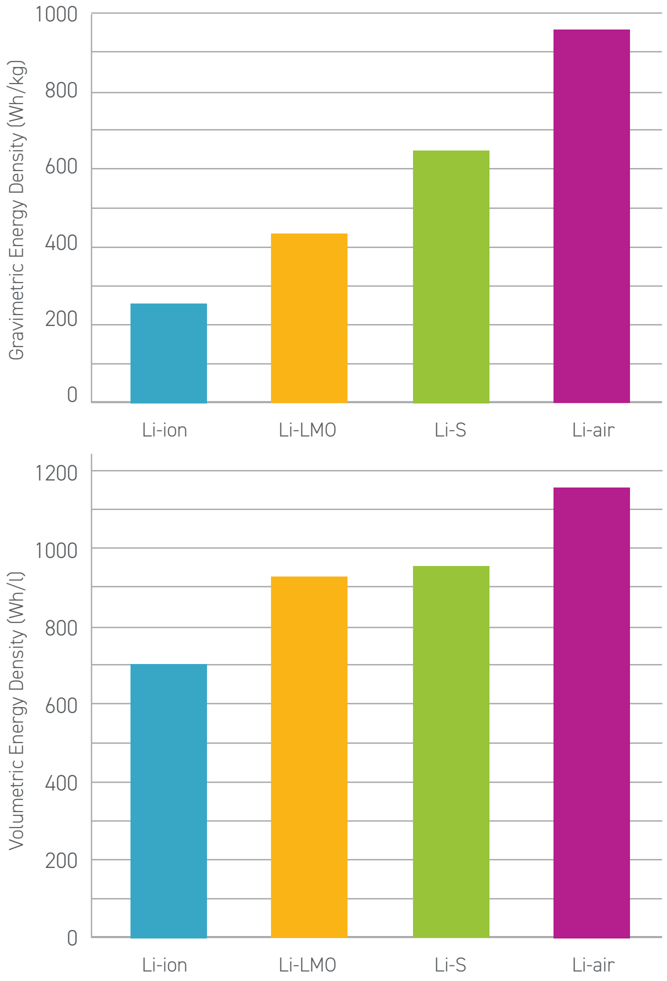
[2] National Renewable Energy Laboratory (2012). Vehicle Battery Safety Roadmap Guidance.

(2) Higher Energy Density

Lithium-ion batteries relying on a graphite anode can achieve a gravimetric energy density[3] and a volumetric energy density[4] of ~250 Wh/kg and ~700 Wh/l, respectively.[5] However, to keep up with demanding energy storage applications, lighter and smaller batteries with higher energy densities are required.

In theory, it is possible to overcome these storage limits by replacing the graphite anode with a lithium metal anode. A number of potential solutions have been investigated around this chemistry, but none have been highly successful to date as the lithium metal anode is severely limited by its reactivity and cannot be used directly with a liquid electrolyte. Using a SSE could offer a solution to this challenge. Chemistries such as lithium-lithium metal oxide (Li-LMO),[6] lithium-sulfur (Li-S), and lithium-air (Li-air) have the potential to improve gravimetric energy density and volumetric energy density by up to four and two times, respectively, as shown in Figure 1.

Figure 1: Estimated gravimetric energy density and volumetric energy density for conventional lithium-ion vs. lithium metal-based batteries



Source: Cui et al 2017, Reviving the lithium metal anode for high-energy batteries.

(3) Faster Charging Times

Faster charging times are highly desirable to EV consumers. The charging rate of current lithium-ion automotive batteries is fundamentally limited by the cell chemistry as well as the engineering required to protect the battery from exposure to high temperatures. SSEs have close to unity lithium-ion transference numbers and, in theory, negligible concentration polarisation, and higher thermal conductivity compared to liquid electrolytes.[7] These properties should allow SSEs to transport lithium ions efficiently with adequate dissipation of heat and therefore may be a route to faster charging automotive battery systems.

(4) Longer Lifetime

Typically, the life of lithium-ion batteries is dependent on the chemical reactivity within. Lithium-ion batteries degrade with time, use, and exposure to prolonged periods at elevated temperature. In the case of liquid electrolytes, one such degradation mechanism is referred to as 'cross-talk'. Cross-talk typically involves dissolution of transition metals from the positive electrode, and migration to, and subsequent poisoning of the negative electrode. This poisoning accelerates degradation of the liquid electrolyte, eventually leading to cell failure. There are major opportunities for a SSE to protect electrode materials from this metal migration and electrode poisoning. Solving such issues by employing SSEs could extend the lifetime of lithium-based batteries, which is highly desirable for a number of applications including automotive.

Solid-State Batteries for Commercial Applications

SSBs have been used in smaller-sized commercial applications for many years. Initial usage started in medical implants in the early 1970s when the world's first heart pacemaker was invented.[8] This was followed by applications in electronics such as integrated circuits, radio-frequency identification and high-end electronics.

Devices powered by SSBs are now being developed for other markets. Although it is hard to predict, the Faraday Institution considers that solid-state technology will steadily emerge into the global battery market in the coming decades through three discrete waves of technological diffusion (see Table 1).

The first wave through the 2020s is the expansion of SSBs from niche electronics and medical implants into mass-market consumer electronics, portable electronics (laptops, smartphones, tablets etc.) and wearables (i.e. smart electronic devices worn on the body or in clothes such as a watch or fitness device). Wave 2 and 3 diffusion will then occur through the 2030s and 2040s when SSBs become commercially viable in the EV market and the aircraft market respectively.

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[3] Gravimetric energy density defines battery capacity in weight terms, i.e. Watt hours per kilogram (Wh/kg).

[4] The nominal battery energy per unit volume, i.e. Watt hours per litre (Wh/l).

[5] Nature Nanotechnology (2017). Reviving the Lithium Metal Anode for High-energy Batteries. Lin, Liu, and Cui, Volume 12, March 2017

[6] A Li-LMO battery has a lithium metal anode paired with a conventional lithium-ion cathode (i.e. a lithium metal oxide).

[7] Nature Energy, Volume 1 (2016). A Solid Future for Battery Development, Janek et. al.

[8] Pioneers of the Medical Device Industry and Solid-State Lithium Battery: A New Improved Chemical Power Source for Implantable Cardiac Pacemakers.

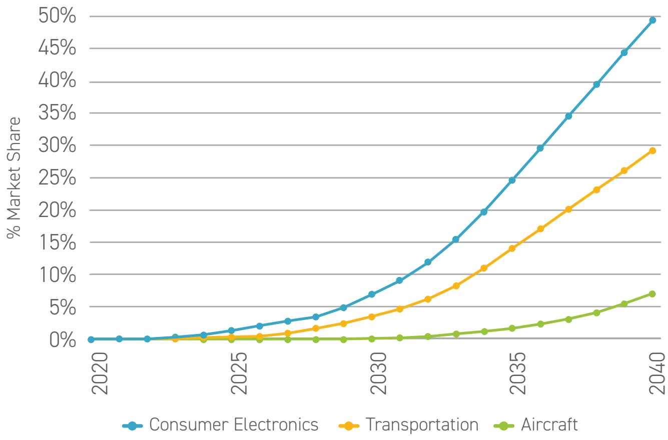
Table 1: Solid-state batteries - mass market applications to 2040

Wave 1 in the 2020s: consumer electronics, healthcare and wearables	Wave 2 in the 2030s: electric vehicles	Wave 3 in the 2040s: aircraft and aviation
• Small healthcare products and niche electronics already available. • Smaller applications in consumer electronics and wearables likely to hit the mass market as soon as 2022 (e.g. Ilika). • Barriers to entry low as the size of batteries required are very small. • Consumer products are often replaced frequently, so do not require a long lifecycle. • Most promising technology for use in extreme hot and cold temperature environments. • Ability to charge relatively quickly also important for viable consumer products.	• Addresses the safety issue of flammability in lithium-ion batteries. • Increased energy density of SSBs will deliver significant improvements in EV range and address the issue of range anxiety. • Commercial SSBs are already available in EVs (e.g. Blue Solutions) but need to operate at above room temperature. • Toyota plans to unveil a SSB-powered EV at the 2020 Olympics. • Too early to compare performance, safety and cost of SSB EVs with current EV models with liquid electrolytes.	• A leap forward in performance leads to large-scale roll-out across the aviation industry. Aircraft are heavy and aviation requires substantial amounts of energy. • SSBs likely to be introduced initially for smaller/narrow-body aircraft, helicopters and hybrid technologies, initially in the 2030s but with wider roll-out in the 2040s. • SSBs could be used in new concepts such as vertical take-off and landing for applications in urban transport. • Initial application to commercial aviation unlikely for 20+ years given long manufacturing lead-times in aerospace. • Norway meets its commitment to electrifying all short-haul flights by 2040.

Compared with global sales of lithium-ion batteries for EVs of $US 36 billion in 2020,[9] current global revenues from sales of SSBs are small, amounting to less than $US 100 million in 2020 and rising to only $US 1.5 billion by 2025.[10] The market is, however, expected to take off in the late 2020s as sales of SSBs used in consumer electronics and wearables strengthens and an embryonic EV market deploying SSBs emerges as research breakthroughs are commercialised.

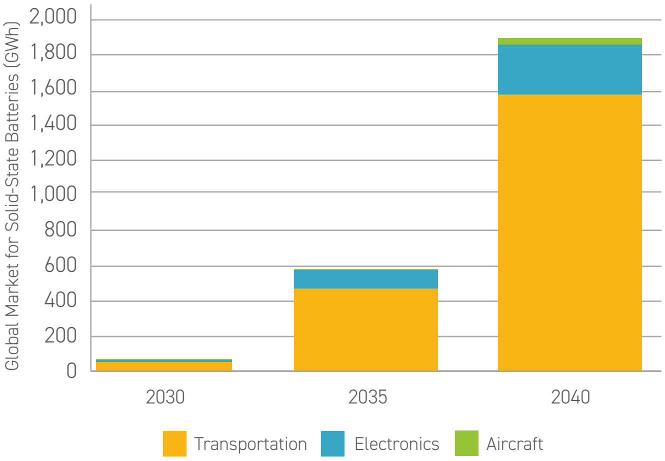
The Faraday Institution forecasts that in 2030 SSBs are likely to take a 7% share of the consumer electronics battery market globally and a 4% share of the EV global battery market (Figure 2). But it is not until 2040 that the market is predicted to become extensive. Global SSB demand in 2040 is expected to reach 300 GWh and 1,600 GWh per annum in the consumer electronics and EV market respectively (Figure 3).

Figure 2: Global market share of SSBs by application to 2040



Source: The Faraday Institution / various web sources

Figure 3: Global annual SSB GWh demand by application to 2040



Source: The Faraday Institution / various web sources

[9] Avicenne Energy (May 2019). The Rechargeable Battery Market and Main Trends 2018-2030.

[10] Allied Market Research (December 2018). Solid-State Battery Market by Type, Global Opportunity Analysis and Industry Forecasts (2018-2025).

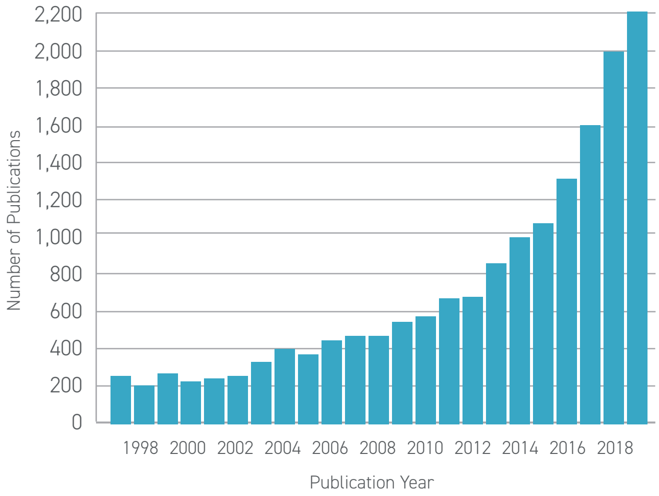
The Story of Technology Disruption

The usual story of technological disruption is that new products are initially successful in a niche market as a higher quality and premium product or by offering a novel or new way of delivering a service. These new products are often invented and commercialised by SMEs, start-ups or entrepreneurs, but as the product becomes cheaper and/or more effective over time, it enters the mass-market and is sold by more established firms. Personal computers, mobile telephony, digital photography, music streaming and printing are perhaps everyday examples of this innovation process.

SSBs will therefore need to deliver a step-change in cost and/or performance if they are to have any chance of displacing lithium-ion batteries in a similar vein to previous technological disrupters. In short, SSBs will need to deliver one or more of the following: reduced cost, increased energy density, increased power density, improved safety, increased pack life, wider temperature operating range or easier recyclability.

The lithium market is not standing still and gradual improvements in the cost and performance of lithium-ion batteries are expected to continue to 2025 before they tail off as the technology reaches its theoretical limits. It is then likely that a next generation battery technology will attract sufficient commercial investment to make it a viable alternative, leading to a slow replacement of the current generation of lithium-ion batteries. The Faraday Institution considers a more fundamental technological disruption could then happen in the 2030s, through SSBs entering the EV market at scale and as a major disruptor to the wider landscape of the global battery market.

Figure 4: Publications with "solid-state electrolyte" keyword



Source: Web of Science

Commercial Activity in Solid-State Batteries

The prospect of significantly improving the performance of conventional lithium-ion battery technology with SSEs has propelled research worldwide. Publications related to SSEs have risen tenfold over the past two decades (Figure 4), with patent activity increasing by a similar amount. Patents from US and Japan account for a large proportion, comprising nearly one-half of the 2,700 patents filed between 2000 and 2019.

Toyota leads the number of SSB patents filed by company, accounting for 43% of all patents filed since 2000. Toyota has plans for mass production of SSB EVs from the mid-2020s[11] and a joint venture with Panasonic researching SSBs.[12] Other major players in the global automotive industry, such as Ford, General Motors, BMW, Honda and Volkswagen, are also undertaking substantive research programmes on SSBs.

A promising start-up and developer of SSB technology is the US company Solid Power, a spinoff from the University of Colorado. SolidPower's SSB offering combines use of lithium metal anodes, a high ionic conductivity inorganic solid separator and a high capacity cathode. It has claimed that it has produced laboratory-scale cells at ~450 Wh/kg.[13]

Another US company, Ionic Materials, has developed a solid-state polymer electrolyte that exhibits high conductivity at room temperature. Rather than develop its own cells, Ionic Materials sees its novel electrolyte as an enabler across a variety of different chemistries, including lithium-sulfur and lithium-metal cells with conventional cathodes. To accelerate commercialisation of the technology, Ionic Materials has teamed up with A123 Systems to develop EV NMC (lithium nickel manganese cobalt oxide) /graphite lithium-ion cells and aims to begin manufacturing on a large scale as soon as 2022.[14]

In the UK, Ilika is developing lithium-ion technology using an inorganic solid-state electrolyte. Ilika's current products are micro-batteries designed for sensors, 'Internet of Things' devices and other small-scale applications. The company plans to scale up its technology to stationary power and EVs,[15] claiming that the new SSBs could reach 1000 Wh/kg with a 10-year operating life.

[11] Interview with Toyota's Chief Technology Officer Shigeki Terashi in (October 2019).

[12] Electrive.com (Aug 2019). Solid Electrolyte Batteries – the Next Big Thing

[13] A Brief Review of Current Lithium Ion Battery Technology and Potential Solid-State Battery Technologies, Andrew Ulvestad.

[14] Iconic Materials Press Release, 24 June 2019.

[15] Ilika (December 2019). Solid-state batteries technology. Capital Markets Day.

Research Challenges and Developments in the 2020s

There are currently two major types of SSEs that may rival liquid electrolytes: inorganic solids and organic polymers. The inorganic solids considered most likely to succeed can be further divided into sulfide and oxide materials. In order to compete with liquid electrolytes, SSEs need to possess exceptional fast charging performance (i.e. high lithium ionic conductivity), safe operation, and easy processability. Each of these types of solid electrolyte appears to have excellent performance in some areas, but poor performance in others (see Table 2).[16] One research challenge of the next decade will be to discover and deploy SSE materials combining acceptable properties in all three areas.

SSB research efforts over the past few decades worldwide have delivered mixed results. Micro-batteries and the elevated-temperature polymer battery can perhaps be described as notable breakthroughs. Ceramic solids, including garnet oxides and several sulfides, are sufficiently conductive that electrolytes are also no longer the biggest hurdle facing SSB development. The key barriers are preventing unwanted side reactions at the interface between the electrolyte and both electrodes and in improving the mechanics throughout the cell.

Table 2: Relative comparison of solid-state electrolyte chemistries

	Performance	Safety	Processing
Sulfide (Inorganic)	Excellent	Poor	Fair
Oxide (Inorganic)	Fair	Excellent	Poor
Polymer (Organic)	Poor	Fair	Excellent

It will also be a major challenge to manufacture SSBs commercially as SSEs are complex materials to process. At present, only very small, low-power SSBs are economically viable such as those incorporated in heart pacemakers. This is because as they become larger and more powerful, the problems related to performance, safety and processing, as well as financial cost, are amplified. So far, no one has been successful in solving these problems at scale.

Box 1 provides more detail on the different types of SSBs and some of the research challenges.

The Faraday Institution's SSB Research Project

The Faraday Institution's SOLBAT project, led by University of Oxford with five other university partners and six industrial partners, is researching SSBs and particularly sulfide-based, oxide-based and other hybrid SSEs.

SOLBAT's four work packages are focused on the major barriers preventing the progression of SSBs to market:

1: Plating and stripping Li or Na at the alkali metal anode/solid electrolyte interface (anode interfaces);

2: Ceramic-ceramic contact at the solid electrolyte (cathode interfaces);

3: Discovery of new SSEs (synthesis & discovery);

4: Integration of SSEs in full architectures (cell fabrication & cathode architecture).

Understanding and breaking down these four barriers should lead to batteries that are lighter and safer, with cost savings and less reliance on cooling systems.[17]

About the Faraday Institution and Faraday Insights

The Faraday Institution is the UK's independent research institute for electrochemical energy storage research and skills development. We bring together academics and industry partners in a way that is fundamentally changing how basic research is carried out at scale to address industry-defined goals.

Our 'Faraday Insights' provide an evidence-based assessment of the market, economics, technology and capabilities for energy storage technologies and the transition to a fully electric UK. The insights are concise briefings that aim to help bridge knowledge gaps across industry, academia and government. If you would like to discuss any issues raised in this 'Faraday Insight', or our wider battery research programme, please contact Stephen Gifford.

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[16] Another factor is the cost but as commercial manufacturing processes for solid-state EV batteries do not exist yet, it is not possible to benchmark cost.

[17] For more information see: www.faraday.ac.uk/research/beyond-lithium-ion/solid-state-batteries

Box 1: Technology review of key solid-state battery chemistries

Sulfide-based SSEs (inorganic), such as lithium superionic conductors (LISICON) and argyrodite electrolytes, have superior ionic conductivity at room temperature, meeting the industry standard set by liquid electrolytes. Their drawback is their reactivity with cathode and anode materials, which can hinder cycling performance. Further, upon exposure to air, the sulfides are prone to forming toxic H_2S, a potential risk for solid-state batteries based on these electrolytes. If it were not for this toxicity, sulfides would be relatively easy to manufacture as they are soft materials that behave similarly to a paste during processing. A promising solution could be to apply protective coatings to these electrolytes and/or electrode materials, which researchers are currently pursuing.

Oxide-based solid SSEs (inorganic) have good safety characteristics, as some have relatively minimal reactivity with lithium metal. The garnet electrolytes are the most promising oxides as they have conductivity approaching that of liquid electrolytes. However, the garnet electrolytes require high-temperature, energy-intensive processing, which leads to costly large-scale manufacturing. Investigating practical processing routes for oxides are a popular theme in research.

Polymer-based SSEs (organic) possess ideal processability and therefore are a practical choice for moving away from liquid electrolytes as scaling up production is viable. Their reactivity with electrode materials is not negligible but is an improvement compared to liquid electrolytes. However, the real bottleneck is that polymer-based electrolytes lack suitable ionic conductivity at room temperature compared to liquid electrolytes. For example, polyethylene oxide (PEO) polymer electrolytes require an operating temperature above 60°C to enable practical performance. New polymer electrolytes and additives are being developed in an attempt to overcome this hurdle.

Hybrid SSEs are a relatively new avenue of research and could be a key solution for EVs. For example, recent work by Nobel Laureate John B. Goodenough et al.[18] involves improving the performance of SSEs by using a combination of oxide and polymer-based electrolytes. Developing solid-liquid hybrid electrolytes,[19] where electrodes are protected by a solid electrolyte membrane and coupled with liquid electrolyte, is another promising avenue of research.

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[18] PNAS (2019). High-performance all-solid-state batteries enabled by salt bonding to perovskite in poly(ethylene oxide) John B. Goodenough et al., September 17, 2019.

[19] Nature Chemistry (2016). Dynamic formation of a solid-liquid electrolyte interphase and its consequences for hybrid-battery concepts. Martin R. Busche et, al., Volume 8, March 2016.

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