Xinhai Yuan, Lijun Fu, Lili Liu, Yuping Wu

Solid-state batteries: Facts and fiction

Solid-state batteries (SSBs) are widely viewed as a promising route for next-generation energy storage [1]. By replacing flammable liquid electrolytes in conventional lithium-ion cells with solid-state alternatives, they offer the potential for improved safety and higher energy density. This shift could enable practical use of lithium metal anodes and high-voltage cathodes, pushing energy densities beyond 500 Wh/kg. Such advances might extend electric vehicle (EV) driving ranges and support applications in grid storage, aviation, robotics, and portable electronics. Market analyses estimate that the global SSB market could reach around $120 billion by 2030, with China potentially capturing 40% of this share.

Despite this optimism, substantial technical and economic hurdles persist. It remains uncertain whether SSBs can deliver on these expectations in the near term, or if they will remain a technology still under development for years to come.

Solid electrolytes: Too many choices, too few solutions

At the heart of any SSB is its solid electrolyte, which must efficiently transport lithium ions, insulate electrons, and maintain chemical and mechanical stability. Numerous electrolyte chemistries have emerged, each with their distinct advantages and severe limitations. A comparison of typical energy densities and ionic conductivities for batteries based on different solid electrolytes versus conventional liquid electrolyte systems is summarized in Fig. 1. As shown, while SSBs designs can theoretically enable higher energy densities, their ionic conductivities often remain significantly lower than those of liquid electrolyte systems, underscoring a fundamental performance gap that ongoing research continues to address.

Oxide-based solid electrolytes, such as garnet-type $Li_7La_3Zr_2O_{12}$ (LLZO), NASICON, perovskite, anti-perovskite, and LISICON structures, are valued for thermal stability and wide electrochemical windows [2]. Room-temperature ionic conductivities typically range from ~10^{-4} to 10^{-3} S/cm, driven by low activation energies (~0.3 eV). However, achieving dense microstructures often demands sintering above 1000 °C, raising costs and complicating manufacturing. Ionic mobility also hinges on controlling defect chemistry – point defects, grain boundaries, and dislocations all significantly influence transport properties.

Sulfide-based electrolytes like $Li_{10}GeP_2S_{12}$ (LGPS) stand out for liquid-level conductivities (>10^{-2} S/cm) and good electrode contact due to mechanical softness [3]. Yet, their extreme moisture sensitivity and release of toxic H_2S gas necessitate stringent dry-room conditions, increasing production complexity and cost.

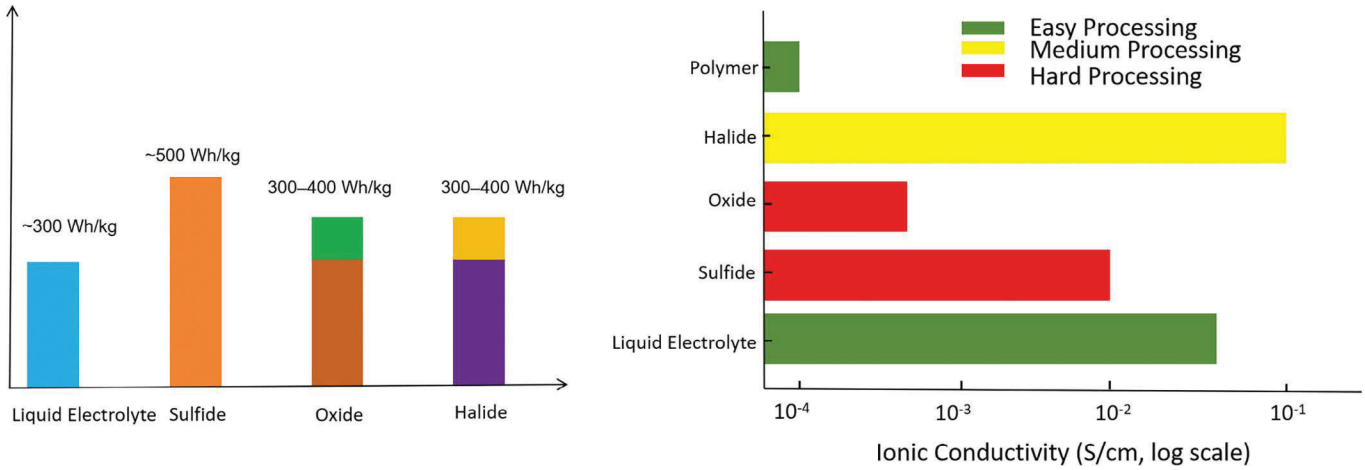

Fig. 1: Comparison of energy densities (left) and typical ionic conductivities (right) of batteries based on solid electrolytes versus those using conventional liquid electrolytes.

Polymer-based systems such as polyethylene oxide (PEO)-Li salt complexes are easy to process and flexible but fall short in conductivity (often below 10^{-4} S/cm at room temperature) and stability at higher voltages [4]. Crystallization at lower temperatures further hampers ion transport.

Halide electrolytes like Li_3YCl_6 have gained attention for moderate conductivities (~1 mS/cm) and compatibility with lithium

Dr. Xinhai Yuan[1], Prof. Dr. Lijun Fu[1], Prof. Dr. Lili Liu[1], Prof. Dr. Yuping Wu[1,2]
[1] State Key Laboratory of Materials-oriented Chemical Engineering, School of Energy Science and Engineering, Nanjing Tech University, Nanjing, 211816, Jiangsu Province, China
[2] Confucius Energy Storage Lab, School of Energy and Environment & Z Energy Storage Center, Southeast University, Nanjing 210096, China
Correspondence: wuyp@fudan.edu.cn

DOI-Nr.: 10.26125/3pam-tg05

metal and high-voltage cathodes [5]. Despite promising properties, they remain confined to laboratory studies without clear industrial pathways.

To overcome these limitations, increasing attention has turned toward composite or hybrid solid electrolytes that blend inorganic fillers with polymer matrices. This approach aims to combine the numerous lithium-ion transport pathways offered by ceramic particles with the mechanical flexibility and ease of processing provided by polymers. Many composites now surpass ionic conductivities of 10^{-4} S/cm at room temperature, with some reaching values near 10^{-3} S/cm when operated around 35 °C [6-8]. Techniques such as roll-to-roll coating and dry lamination support are promising for scaling up these materials. Nevertheless, practical challenges remain, including achieving uniform filler dispersion, ensuring stable interfaces during cycling, and controlling side reactions, which continue to limit large-scale commercial adoption.

Interface issues: The achilles' heel persists

SSBs face persistent problems at solid–solid interfaces [9]. Unlike liquid electrolytes, solids cannot flow to fill gaps at electrode surfaces, leading to voids and higher interfacial resistance. Mechanical strain during lithium plating and stripping changes electrode volume, often causing cracks and loss of contact. This uneven stress can create paths for dendrite growth or form resistive layers that block ion flow. Interlayers and engineered interphases are under study to improve contact and prevent short circuits. However, these solutions can bring new resistance or mechanical fragility. Imaging and spectroscopy continue to reveal how these interfaces evolve, showing that solid–solid contact remains one of the key technical barriers for solid-state batteries.

Industrial prospects: More hope than reality?

High-profile companies like Toyota and QuantumScape have publicly demonstrated impressive laboratory results. Toyota recently announced sulfide-based SSB prototypes delivering approximately 450 Wh/kg, and QuantumScape presented ceramic-based cells retaining over 80% capacity after 800 cycles. Yet these optimistic results come with serious trade-offs: Toyota's sulfide batteries demand ultra-dry conditions (dew points below -60 °C), inflating production complexity and cost. QuantumScape's cells operate effectively only at elevated temperatures (60–70 °C), posing considerable practical limitations for real-world EV applications. In China, leading battery companies such as CATL, BYD, and Ganfeng Lithium have showcased prototypes nearing or surpassing 500 Wh/kg. CATL plans hybrid sulfide-polymer SSB production in small batches by 2027. BYD also targets initial small-scale production by 2027 and full-scale commercialization by 2030.

Despite such advances, severe challenges remain: current fully SSB production costs range between 4–10 CNY/Wh, dramatically higher than polymer-oxide hybrids (~0.5 CNY/Wh) and conventional liquid lithium-ion batteries (~0.4 CNY/Wh). Manufacturing yields of thin solid electrolyte films remain disappointingly low (<60% in pilot lines), further limiting scalability.

Nevertheless, market forecasts point toward significant future growth. According to the China SSB Industry Development White Paper (2024) released by EVTank, global solid-state battery shipments are projected to exceed 10 GWh in 2025 and surge beyond 600 GWh by 2030, translating to a penetration rate of roughly 10% within the broader lithium battery market. In monetary terms, the global SSB market could surpass RMB 250 billion by 2030, with much of this expansion driven initially by semi-SSBs already entering early commercialization phases. This projected growth trajectory is illustrated in Fig. 2, which shows the forecasted global shipment volumes of SSBs and semi-SSBs over the coming decade.

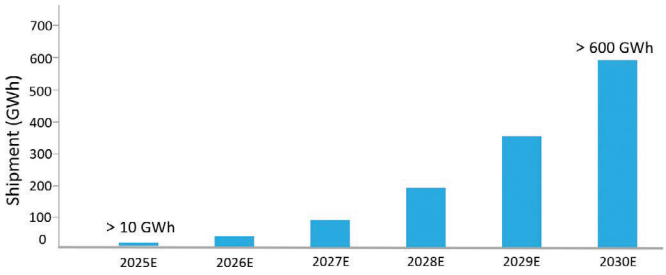

Fig. 2: Projected global shipment volumes of SSBs and semi-SSBs through 2030, based on forecasts from the China SSBs Industry Development White Paper (2024).

Another notable trend is artificial intelligence (AI)-driven material and battery design. Initial AI-based studies have significantly accelerated material screening and electrolyte optimization, potentially reducing R&D timelines by more than an order of magnitude and cutting related costs dramatically. Still, these efforts remain preliminary, requiring validation in larger-scale applications.

Conclusions: Solid-state batteries at the crossroads

SSBs undeniably possess substantial transformative potential. Yet, despite impressive laboratory achievements, their widespread industrial deployment remains uncertain. Persistent technical barriers – particularly at interfaces – and significant economic challenges temper current optimism. Realistic assessments indicate that meaningful commercial deployment may not occur until at least 2027–2030, with earlier predictions (such as widespread use by 2025) appearing increasingly unrealistic.

Hybrid electrolyte systems and targeted interface engineering represent more immediately practical pathways forward. Ongoing developments, including AI-driven research, may eventually overcome existing barriers. For now, however, SSBs remain at a critical crossroads – neither fully mature nor mere scientific curiosities. Progress continues, though perhaps at a slower pace than initial enthusiasm suggested.

SSBs are neither pure fiction nor a guaranteed solution. They hold clear technical advantages and remain an important focus of research and industrial planning. But moving from laboratory results to large-scale commercial reality will require steady advances in materials, interfaces, and manufacturing processes – and perhaps a more measured view of how quickly this transformation can occur.

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Dr. Xinhai Yuan

After receiving his doctor degree, Xinhai Yuan joined the faculty of the School of Energy Science and Engineering at Nanjing Tech University, where he is currently an Associate Professor. His research focuses on high-energy-density aqueous battery materials and systems. To date, he has published more than 40 SCI papers, which have been cited over 3,700 times, and holds 3 issued patents. He has an H-index of 21.

Prof. Dr. Lijun Fu

Lijun Fu is a distinguished professor at Nanjing Tech University. She got her Ph.D. degree in 2010 from Fudan University, Shanghai, China. She was a research fellow in Shanghai Institute of Ceramics, Chinese Academy of Sciences and Max Planck Institute of Solid State Research, Germany. Her main current research interest is electrochemical performance and interfacial properties of electrode materials for batteries and supercapacitors.

Prof. Dr. Lili Liu

Lili Liu is a professor of the School of Energy Science and Engineering, Nanjing Tech University. She received her bachelor degree from Xiangtan University (2009) and her Master's degree from Fudan University (2012). She obtained her PhD degree from Fudan University (2015) and University of Wollongong (2017). From 2017 to 2019, she conducted postdoctoral research as a Humboldt Fellow at the University of Freiburg, Germany.

Prof. Dr. Yuping Wu

Chair Professor of Southeast University, Nanjing, China, Fellow of the African Academy of Sciences, Corresponding Member of the Saxon Academy of Sciences at Leipzig in Germany, and Fellow of Royal Society of Chemistry (UK). His research focuses on electrochemical energy storage and conversion systems, and their key materials. He has published more than 600 SCI-indexed papers with an H-index over 112 (WoS). Since 2014, he has been listed among the Highly Cited Researchers globally, and in 2015, he was named one of the "World's Most Influential Scientific Minds" by Thomson Reuters. He serves as the founding editor-in-chief of *Energy Z* and *Energy Materials* (IF = 11.2), associate editor of *Energy & Environmental Materials* (IF = 14.1).