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INSIGHTS

The Future of Solid-State Batteries in Electric Vehicles

Technology Insight

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Executive Summary

Solid-state battery technology occupies a consequential middle position: past the stage of laboratory curiosity, not yet within reach of mass-market deployment.

The six contributors to this edition agree on the basic chronology - pilot lines exist, OEM roadmaps are public, and limited commercialization begins around 2028 - but they diverge meaningfully on what that commercialization will mean for the electric vehicle industry and on which structural obstacles remain most consequential.

Taken together, their perspectives map both the technology's genuine promise and the conditions under which that promise will be realized.

The cost imperative

The most notable structural tension in this analysis concerns cost. Some contributors frame scaling as primarily an execution challenge, with identifiable pathways - yield improvement, manufacturing process innovation, and eventual convergence around dominant electrolyte platforms - to bring solid-state production costs within range of conventional lithium-ion.

Others point to the steepness of that trajectory: lithium iron phosphate cells are already landing below $65 per kWh in Western production and below $40 per kWh from leading Chinese manufacturers.

Fastmarkets sets a provisional threshold of $85 per kWh as a key proof-of-concept gate for mass-market scalability, a figure that usefully anchors the economic debate and against which industry progress can be tracked.

The safety proposition

The safety narrative is broadly supported across contributors but carries important nuance. Replacing flammable liquid electrolytes addresses a well-understood thermal risk, and several contributors identify this as a defining structural advantage of solid-state architectures.

At the same time, the management of lithium metal anodes under fast charging conditions, particularly the behavior of lithium dendrites at higher states of charge, remains an active area of engineering development.

This is not a settled question: field data from OEM validation programs will provide the first substantive real-world evidence.

Architecture in transition

Beneath the headline questions of timeline and cost, a structurally meaningful shift is underway in battery architecture. The anodeless design - where lithium plates onto a copper current collector during charging rather than intercalating into graphite - has moved from academic interest to commercial deployment, with CATL announcing self-forming anodeless technology for 2025 production.

Fastmarkets identifies this as a potential manufacturing inflection point: by avoiding the need to handle lithium metal directly during cell assembly, anodeless architectures reduce some of the most operationally demanding aspects of solid-state production.

This manufacturing dimension tends to receive less attention than energy density gains but may prove equally significant for commercial scale-up.

Vehicle design and OEM strategy

On vehicle design and architecture, the contributors broadly agree that higher energy density enables smaller, lighter packs, but differ on how OEMs will deploy that advantage.

The near-term commercial reality is that manufacturers are more likely to apply density gains as extended range options within existing platform architectures than to undertake fundamental vehicle redesigns. The longer-term vision of thinner skateboard platforms and reimagined vehicle proportions is architecturally plausible, but it depends on OEM strategic decisions that will unfold over time.

The more immediate case for weight-driven redesign is in heavy-duty commercial vehicles, where payload economics create direct financial incentives that the passenger-car market does not yet provide in equal measure.

The IP landscape

The intellectual property landscape is a structural factor that this edition's analysis brings into sharp relief. The sector has moved from materials science patenting to industrialization patenting, with more than 6,150 new patent families published in 2025 covering manufacturing equipment, pack integration, and recycling infrastructure.

Companies are positioning not just for technical validation but for freedom-to-operate and licensing advantage. The density of patent activity across critical manufacturing processes means that IP will become an increasingly significant competitive variable as the field moves from development into production, carrying implications for both established players and newer entrants.

Geopolitical and supply chain dimensions

Geopolitical context shapes the solid-state battery landscape in ways that extend past individual company timelines. Chinese cell manufacturers are advancing on accelerated schedules, with levels of capital concentration and supply chain integration that have enabled rapid transition from pilot to production across other battery technologies.

The cost benchmarks established by Chinese LFP manufacturing set the competitive floor against which all solid-state commercialization arguments must be tested.

Convergence around a dominant electrolyte material platform - most likely sulfide-based - will be a precondition for the kind of coordinated global supply chain investment that enables meaningful cost reduction, and the timing of that convergence will be among the most consequential signals of the next five years.

Strategic implications

The strategic implications for industry stakeholders are correspondingly layered. For OEMs, the most considered near-term position is to maintain active development partnerships while managing platform strategy around timelines that remain genuinely uncertain.

For tier-one suppliers, the more pressing strategic question may not be when solid-state arrives, but which manufacturing processes and materials will dominate once it does, and whether current IP and manufacturing capacities position them to participate.

For the industry, solid-state batteries represent a technology where the gap between promise and delivery is narrowing in a way that remains analytically legible, and where the next several years of field data and production milestones will significantly sharpen the picture.

Expert Perspectives

Question 01

How mature is solid-state battery technology today for EV applications, and how close is it to commercial readiness?

Few technology assessments reveal the range of expert perspectives as clearly as a readiness question. The five contributors share a common starting point - solid-state batteries have moved from laboratory validation to pilot production - but bring meaningfully different views on what this pre-commercial stage implies for the road ahead.

The distinction between those who see the remaining hurdles primarily as execution challenges and those who emphasize the structural difficulty of cost reduction is not a divide between optimists and pessimists. It reflects genuinely different analytical perspectives, each grounded in a specific vantage point on the technology. Both are coherent and worth holding in parallel.

What the cross-reading of this section reveals is that ‘pre-commercial’ covers substantial ground: it encompasses a wide range of maturity levels and commercial scenarios. Understanding that range, rather than resolving it prematurely, is part of the value this edition offers.

Expert Perspectives

Q1: How mature is solid-state battery technology today for EV applications, and how close is it to commercial readiness?

Dr. Wolfgang Bernhart

Senior Partner, Roland Berger

All-solid-state batteries have reached pilot and demo-fleet stage but are not yet mass-produced for volume electric vehicles.

While some Japanese companies state they target 2027/2028 for commercialization, we remain skeptical about the viability of solid-state outside a few niche applications - for example, sports cars with limited packaging space - because of high costs. For all OEMs, reducing battery costs is a much higher priority than increasing pack capacity and driving range.

Overall, the technology is at an advanced pre-commercial stage: validated in labs and early pilots, with concrete OEM roadmaps, but short of high-volume, cost-competitive automotive production.

Alex Louli

Principal Applications Engineer, QuantumScape

Solid-state battery technology has reached a pivotal inflection point. Electric vehicles, AI data centers, and industrial electrification are all hitting lithium-ion's performance ceiling simultaneously, accelerating the need for a step-change in performance. Solid-state lithium-metal batteries aren't a better lithium-ion battery - they're a different category altogether: the generational leap the electro-tech economy needs to scale.

QuantumScape battery technology is based on a proprietary solid-state ceramic separator, which enables the use of a pure lithium-metal anode - a transformative innovation that is designed for exceptional energy and power density, fast charging, and a robust safety profile.

We are now focused on ramping up our pilot production line. Four of the top ten global automotive OEMs are actively working with us, with two joint development agreements in place, one technology evaluation already completed, and field testing with Volkswagen's PowerCo planned for 2026. In partnership with Ducati, PowerCo, and Audi, we debuted the world's first live demonstration of an electric vehicle powered by our solid-state batteries at IAA Mobility in September 2025.

Each of these milestones brings us one step closer to commercialization.

Dr. Xin Li

Director, eMobility Innovation Center, BASF

Solid-state batteries involve several technological pathways. The most common are:

1) all-solid-state batteries, represented by sulfide electrolytes;

2) hybrid solid-state batteries (often referred to as semi-solid-state batteries), represented by in-situ solidification of polymers and oxide electrolytes;

3) polymer solid-state batteries, represented by PEO-based systems.

Among these pathways, hybrid solid-state batteries are relatively more mature and are approaching industrial-scale manufacturing readiness. In parallel, the most active industry development efforts are currently focused on sulfide-based all-solid-state batteries. While this technology shows strong long-term potential, further progress is still needed to address key technical challenges before broader commercialization.

At the battery-pack and materials level, BASF has already been showcasing a concept solid-state battery pack together with research and industry partners to demonstrate solutions in lightweighting, thermal management, safety, and sustainability, signaling active industrial development even as solid-state cell technologies continue to mature along different pathways.

BASF also characterizes solid-state batteries as a promising next-generation technology offering high energy density and superior safety performance.

Connor Watts

Battery Raw Material Demand Analyst, Fastmarkets

Solid-state batteries remain some distance from meaningful deployment in electric vehicles. This reflects, first, the nascent state of manufacturing processes and scale-up technologies and, second, the limited maturity of supply chains for critical components, most notably solid-state separators and their precursor materials.

Expert Perspectives

Q1: How mature is solid-state battery technology today for EV applications, and how close is it to commercial readiness?

Current cell capacities remain too small, resulting in poor volume utilization and cost inefficiencies in high-energy applications such as passenger vehicles. This helps explain why several solid-state developers are targeting lower-capacity-amenable markets, such as drones and motorcycles, as initial commercial outlets.

Production yields also remain insufficient to support large-scale manufacturing without costs escalating unsustainably. While this is not unexpected at an early stage of industrialization, yields must improve materially before volumes can ramp.

Encouragingly, the industry expects incremental improvements as OEMs iterate and accumulate manufacturing know-how. CATL's emphasis on a "defects per billion" quality benchmark highlights the challenge ahead: achieving quality standards that exceed parts-per-million thresholds is typically only possible in highly mature, well-understood industries.

Solid-state manufacturers will ultimately have to compete on these terms. Despite these challenges, we expect a small number of producers to commercialize solid-state cells from around 2028, with mobility-related applications becoming the main source of volume growth from approximately 2031.

Dr. Fleur Thissandier

Senior Patent and Technology Analyst, KnowMade

Solid-state batteries for electric applications are in an advanced pre-commercialization phase, focused on validating real-world performance, large-scale manufacturing, and costs. The sector is moving from breakthrough validation to industrial execution, with commercialization now reliant on manufacturability, supply chains, and scalable production.

Major OEMs and global SSB developers are announcing joint ventures and progress on pilot lines aimed at vehicle integration before 2030. Chinese cell makers are accelerating timelines through rapid pilot deployments and in-vehicle demonstrations.

As a result, the focus is shifting from laboratory results to manufacturing yield and process robustness, while scaling solid electrolytes into commodities remains a key bottleneck. Investors now prioritize credible scale-up roadmaps and industrial readiness over record energy density.

From an IP perspective, the field has clearly moved beyond exploratory science and entered an industrialization race, with more than 6,150 new patent families (i.e., new inventions) published in 2025.

Patent portfolios are diversifying beyond materials, electrode-electrolyte interfaces, and cell designs toward downstream value-chain topics, including pack integration, recycling, manufacturing equipment, and infrastructure specifically designed for solid-state batteries and solid electrolytes. This signals that companies are positioning themselves for commercialization, future freedom-to-operate, and licensing battles.

> While some Japanese companies state they target 2027/2028 for commercialization, we remain skeptical about the viability of solid-state outside a few niche applications - for example, sports cars with limited packaging space - because of high costs. For all OEMs, reducing battery costs is a much higher priority than increasing pack capacity and driving range.
>
> **Dr. Wolfgang Bernhart**

Expert Perspectives

Question 02

Beyond range and charging speed, how could solid-state batteries reshape EV design, architecture, and the overall ownership experience?

The design and architecture question tends to attract confident claims, and the responses here reflect both the genuine potential and the practical complexity involved. Energy density gains, in principle, translate into reduced pack weight; their impact on vehicle design depends on OEM strategic choices, platform economics, and consumer demand signals that are less predictable than the underlying chemistry.

The near-term commercial reality may be for OEMs to deploy density gains as extended range options within existing platforms rather than as architectural reinventions - a rational response that would still represent meaningful product improvement.

The more structurally distinct argument concerns commercial vehicles, where payload economics create direct financial incentives for weight reduction and the design implications are more concrete. Two contributors also raise thermal management as an underappreciated variable: higher operating temperatures in all-solid-state cells could allow battery thermal management to be partly decoupled from the vehicle's main cooling system, with real engineering and packaging consequences.

Expert Perspectives

Q2: Beyond range and charging speed, how could solid-state batteries reshape EV design, architecture, and the overall ownership experience?

Dr. Wolfgang Bernhart

Senior Partner, Roland Berger

Solid-state batteries promise to enable anode-free designs that are more energy-dense than lithium-ion batteries with graphite or silicon anodes. However, liquid anode-free approaches will be even more energy dense than any solid-state cell. Despite low electrolyte flammability, most ASSBs have troubling safety performance due to the reactivity of the cathode and anode.

Higher gravimetric and volumetric energy density could allow OEMs to downsize packs while maintaining range, reallocate volume to cabin or cargo space, or design thinner skateboard platforms that change vehicle proportions and aerodynamics.

These benefits, however, are hard to realize, since OEMs would more likely want to offer a "long-range" option in the same vehicle, besides a cost-optimized "base version" that would still require the larger packaging space.

Alex Louli

Principal Applications Engineer, QuantumScape

Today's conventional lithium-ion EV batteries fall short on several metrics, limiting performance. Solid-state batteries have the potential to bridge this gap, offering longer range, faster charging, and enhanced safety for electric vehicles.

QuantumScape's solid-state technology is designed to be safer than today's batteries. Our dense ceramic separator replaces flammable polymer materials and addresses major consumer safety concerns around lithium-ion battery fires. Our solid-state batteries are engineered to perform reliably across a wide temperature range, making them well-suited for EVs in different climates.

Dr. Xin Li

Director, eMobility Innovation Center, BASF

Range and charging rate are often used to describe battery performance, and they are primarily linked to energy density and internal resistance. However, other intrinsic battery properties can also influence EV design and system architecture.

For example, all-solid-state batteries typically operate at higher temperatures compared with conventional lithium-ion batteries. This could drive a rethinking of EV thermal management architectures, potentially allowing the battery pack's heating and thermal-balancing functions to be decoupled from the vehicle's main cooling system, and instead integrated with lower-power auxiliary systems.

Consistent with this shift, BASF highlights the growing importance of battery-pack-level thermal management and structural safety, including the use of advanced polymer materials that enable safer operation at high temperatures and improved temperature uniformity across the battery pack.

In addition, higher-energy-density solid-state batteries could enable new design flexibility, particularly for electrified vehicle architectures such as range-extended EVs. With higher energy density, it may become possible to significantly increase electric driving range within a similar size and weight envelope, thereby enhancing overall vehicle usability and reducing charging frequency for daily commuting.

At the same time, range-extending capability would still be retained for longer-distance travel, offering a differentiated ownership experience compared with pure battery electric vehicles.

Connor Watts

Battery Raw Material Demand Analyst, Fastmarkets

A key benefit of mature solid-state batteries that is often underappreciated is the potential for meaningful vehicle weight reduction while maintaining long driving ranges. Lower vehicle mass directly improves energy efficiency, reducing energy consumption and operating costs for consumers.

This effect could be compounded by the superior safety characteristics of solid-state cells, which may allow them to be integrated structurally into vehicles in high-capacity, blade-like formats. Such designs maximize active material utilization while minimizing the need for ancillary components, further reducing overall system weight.

Improved safety also lowers the risk of thermal runaway, while any fires that do occur are likely to be less self-

Q2: Beyond range and charging speed, how could solid-state batteries reshape EV design, architecture, and the overall ownership experience?

fueling than those involving conventional lithium-ion batteries. These advantages would benefit all vehicle segments but may be most visible in smaller cars, where consumers increasingly criticize EVs for feeling heavy and less nimble.

At the other end of the spectrum, heavy-duty commercial vehicles stand to gain materially from solid-state integration. Battery weight directly constrains allowable payload, limiting profitability for freight operators. Weight reductions enabled by solid-state cells would increase payload capacity while improving drivetrain efficiency, strengthening a sector where electric trucks are already being marketed with lower total cost of ownership than diesel alternatives.

Heavy-duty commercial vehicle design would also benefit greatly from the availability of price-competitive solid-state cells, as heavier trucks require lower payloads, which in turn limit profitability. We're already seeing electric trucks advertised with a lower total cost of operations than diesel; weight reductions from solid-state integration would mean greater payload capacity and greater motor efficiency, further strengthening their commercial position.

Dr. Fleur Thissandier

Senior Patent and Technology Analyst, KnowMade

Beyond improvements in range and charging speed, the real potential of solid-state batteries lies in their ability to reshape vehicle architecture. Higher gravimetric and volumetric energy densities, combined with improved intrinsic safety, could enable more compact, lighter battery packs that are easier to integrate into vehicles. This may reduce structural oversizing and, in some cases, simplify thermal management systems.

Automakers could optimize pack architecture, reduce overall vehicle mass, and improve system-level efficiency, making EVs less "battery constrained." Designers gain flexibility in wheelbase, floor height, silhouette, and balancing performance, space, and weight, supporting new vehicle formats and packaging strategies.

From an innovation and IP perspective, this shift will likely translate into new patenting activities around pack architectures, thermal management solutions, manufacturing process control software, and vehicle design concepts enabled by solid-state integration.

In terms of the ownership experience, however, the impact may be more indirect. Battery chemistry and management typically remain a "black box" for consumers. Most users will see the performance improvements and the vehicle design without being aware of the battery technology used in their car.

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>
> **Dr. Fleur Thissandier**

> Higher-energy-density solid-state batteries could enable new design flexibility, particularly for electrified vehicle architectures.
>
> **Dr. Xin Li**

Expert Perspectives

Question 03

Of the remaining technical and manufacturing hurdles - from interface stability to scalable production - which are the most critical to solve first?

Technical hurdle questions often yield lists of challenges that, on examination, prove interdependent rather than sequential. The contributors here reflect that complexity while bringing different emphases.

Interface stability - the management of contact and chemistry at the boundary between solid electrode and solid electrolyte - is the most frequently cited fundamental challenge, and the one with the longest research history. Several contributors argue, however, that manufacturing scalability and cost need to be addressed in parallel, and that waiting for materials science to be fully resolved before engaging with industrialization is not a viable strategy.

One structurally significant observation is that the practical solution to interface connectivity challenges in scaled production may involve small amounts of liquid electrolyte, retaining meaningful safety and energy density advantages while tackling real-world manufacturing constraints. Commercially viable architectures frequently sit between theoretical poles; the relevant question is which configurations deliver the best combination of performance, safety, and manufacturability.

Expert Perspectives

Q3: Of the remaining technical and manufacturing hurdles - from interface stability to scalable production - which are the most critical to solve first?

Dr. Wolfgang Bernhart

Senior Partner, Roland Berger

There are three main hurdles to overcome: reliable solid–electrolyte interfaces, manufacturability at scale, and, most importantly, competitive costs.

1) Technology: Interface stability between the solid electrolyte and high-energy cathodes or lithium-metal anodes is central because it governs cycle life and dendrite suppression. Enabling low temperature operation and reducing cell pressures are additional challenges.

2) Scale-up: Industrialization challenges (process integration, yield, equipment, and supply chains) are at least as critical as remaining lab-scale performance issues, particularly for automotive-size cells.

3) Material and process costs must fall significantly to compete with "conventional cells". LFP landed cell costs (without margin add-on) range from $40 (from China Tier-1 companies) to $65 (production in Europe with a European supply chain), and NCM costs range from $60 to $84 without a margin add-on.

Alex Louli

Principal Applications Engineer, QuantumScape

The critical challenge for us is scaling up production of our pilot line, including our solid-state separator.

Our separator production process delivers 25x faster processing with substantial energy efficiency gains, though scaling to gigawatt-hour facilities will require extensive iteration.

Beyond speed and cost, consistency and yield rates at scale are paramount. Our highly automated pilot facility serves three functions: producing customer test cells, enabling partners to scale the technology in their facilities, and achieving efficient output. Advanced AI models integrated into the pilot line drive substantive progress on cell quality and reliability - a virtuous cycle benefiting all customer programs.

Dr. Xin Li

Director, eMobility Innovation Center, BASF

The remaining challenges differ between all-solid-state batteries and semi-solid-state batteries.

For sulfide-electrolyte-based ASSBs, interface stability remains a critical challenge. At the cell level, achieving stable and reliable solid-state interfaces under relatively low external pressure is essential. At the battery-pack level, additional challenges include applying and maintaining appropriate pressure across modules while managing interface changes caused by cell expansion and contraction during charge and discharge cycles.

For semi-solid-state batteries, a key challenge is ensuring consistent uniformity during scalable production, particularly when using in-situ solidification processes. Continued innovation in polymer chemistry and process control will be central to addressing this challenge.

Dr. Luke Sweeney

Senior Analyst, Battery Raw Materials, Fastmarkets

The nature of solids means there will always be challenges around interface connectivity between solid–solid interactions. In solid-state batteries, maintaining consistent electrical and ionic contact between cathode particles and the solid electrolyte/separator has long been a major hurdle.

Fortunately, scientists are constantly coming up with weird and wonderful workarounds: nanowires, liquid metals, polymer gels, or even applying up to 200 atmospheres of pressure.

The real challenge, however, is translating these solutions onto an assembly line capable of producing cost-competitive batteries. We suspect that one key solution adopted by large companies is the introduction of small amounts of liquid electrolyte. While solid-state batteries theoretically don't require a liquid electrolyte, in practical terms, they often do. Even in academic research, very small amounts are added solely to improve solid-solid interface connectivity.

Whilst we suspect companies will add small amounts of electrolyte, it will be much less than previously used in non-solid-state batteries. Reducing electrolyte levels reduces flammability, dramatically improving the safety profile and enabling the use of ultra-energy-dense

Expert Perspectives

Q3: Of the remaining technical and manufacturing hurdles - from interface stability to scalable production - which are the most critical to solve first?

lithium metal anodes.

So, while we are confident that large cell manufacturers can produce solid-state batteries in specialized research labs or small demonstration lines, the real challenge lies in scaling those processes into high-yield, mass-production lines without charging customers eye-watering sums of money. Scalability, profitability, and manufacturing consistency will no doubt be at the forefront of every manufacturer's mind over the coming years.

Dr. Fleur Thissandier

Senior Patent and Technology Analyst, KnowMade

All improvement pathways for solid-state batteries can be pursued in parallel. This is reflected in the dense patent landscape, where inventions span the entire value chain: solid electrolytes, adapted electrode materials, solid-state battery cells and packs, tailored-designed vehicles, equipment, and production lines. As a result, freedom-to-operate is itself a major challenge, with the risk of a patent thicket that covers critical technologies.

Several solid-state electrolyte strategies coexist, balancing performance, manufacturability, and scalability rather than converging on a single solution. Different cell chemistries are validated at lab scale and are now entering large-scale testing, where performance must be confirmed in full packs under realistic conditions. These tests will also highlight remaining durability limitations, especially the stability of performance under mechanical and chemical stresses at electrode-electrolyte interfaces.

Manufacturing pathways diverge significantly between near-term semi-solid approaches that can leverage existing Li-ion infrastructure and longer-term all-solid-state batteries, which will require fundamentally new processes, equipment, and production lines.

Once a technological target is identified, large-scale manufacturing constraints should be considered as early as possible in the development process. Achieving high-yield, reliable, and cost-optimized large-scale production remains a major challenge, even for conventional battery technologies.

> A key challenge is ensuring consistent uniformity during scalable production, particularly when using in-situ solidification processes.
>
> **Dr. Xin Li**

> The critical challenge for us is scaling up production of our pilot line, including our solid-state separator. Our separator production process delivers 25x faster processing with substantial energy efficiency gains, though scaling to gigawatt-hour facilities will require extensive iteration.
>
> **Alex Louli**

Expert Perspectives

Question 04

Which specific advances in materials, cell architectures, or manufacturing processes are most likely to unlock commercially viable solid-state batteries - and how close are they?

Specific advances in materials, architectures, and manufacturing are easier to identify than to sequence. The contributors offer a dense range of innovation pathways - sulfide electrolytes, oxide systems, halides, dry processing, anodeless architectures, and lithium-metal anodes - in simultaneous development across multiple companies and geographies. Patent activity, as KnowMade's IP analysis shows, is diversifying rather than converging, reflecting a field that has not yet settled on a dominant technological path.

The anodeless architecture receives notable attention for both its energy density and manufacturing implications. The observation that anodeless cells allow manufacturers to avoid directly handling lithium metal during production is a substantive point that performance-focused analyses tend to underweight.

Whether the manufacturing advantages prove as commercially significant as the performance gains remains open, but the wider theme is clear: commercial viability is more likely to emerge from combined advances across the value chain than from a single breakthrough.

Expert Perspectives

Q4: Which specific advances in materials, cell architectures, or manufacturing processes are most likely to unlock commercially viable solid-state batteries - and how close are they?

Dr. Wolfgang Bernhart

Senior Partner, Roland Berger

Oxide, sulfide, and polymer-based solid electrolytes, sometimes in composite form, are being engineered for higher ionic conductivity, wider electrochemical stability windows, and better mechanical properties to suppress dendrites.

Proprietary separator or electrolyte-layer processes might enable higher-volume production of lithium-metal cells. On the anode side, lithium-metal or silicon-rich designs promise major gains but require tightly controlled interfaces and stack pressure; several OEMs link their solid-state roadmaps to such architectures. Pilot and demo lines indicate that cell architectures have progressed beyond coin cells and small prototypes into automotive-relevant formats for validation, though still at limited scale.

We expect meaningful volumes - but still only focusing on the top 10% performance end of the portfolios - only in the early 2030s.

Alex Louli

Principal Applications Engineer, QuantumScape

The QuantumScape Cobra separator process delivers a 25x improvement in heat-treatment speed and occupies a fraction of the physical space of earlier processes. Incorporated into our highly automated pilot line, it demonstrates scalable manufacturing beyond laboratory concepts.

Our technology is designed to overcome the major shortfalls of legacy lithium-ion batteries and usher in a new era of energy storage with two major innovations: an anodeless architecture and a proprietary solid ceramic separator.

Eliminating graphite and having lithium pass through the separator and plate to form the anode during the first charge maximizes energy density and enables fast charging.

Dr. Xin Li

Director, eMobility Innovation Center, BASF

At the battery-pack level, one important area is the development of materials that accommodate cell expansion while maintaining continuous contact between components.

At the battery-cell level, advances in material dispersion will play a key role, particularly as particle sizes continue to decrease. In parallel, interface-engineered polymer materials with high ionic conductivity, strong electrochemical stability, and effective interface-modification properties are increasingly important.

In parallel, BASF indicates that progress toward commercial viability is being supported by materials designed to be compatible with existing production lines and scalable to commercial volumes, as well as battery-pack components that deliver substantial weight reduction compared with metal designs.

There is also growing demand for specialized adhesive solutions tailored to solid-state battery architectures. In addition, reducing the cost of lithium sulfide production is widely recognized as a critical factor for enabling cost-competitive, large-scale manufacturing of sulfide-based solid-state batteries.

Dr. Luke Sweeney

Senior Analyst, Battery Raw Materials, Fastmarkets

One of the major advances that has made solid-state batteries look increasingly feasible is the so-called anodeless battery - well... mostly anodeless. The term itself would raise eyebrows in the scientific community because, by definition, every battery must have an anode. But the combination of genuine scientific innovation and the marketing appeal of the term has allowed for some leeway.

Anodeless batteries are lithium-ion batteries that use lithium metal or a lithium-metal derivative rather than a traditional graphite anode. What makes them anodeless is that the lithium metal exists only on the copper current collector at certain times, specifically when the cell is charged. Upon discharge, the lithium metal is stripped from the copper current collector and migrates back to the cathode, intercalating into the crystal structure of the cathode particles.

Eliminating graphite is a significant achievement. It increases the overall gravimetric energy density of the battery and increases fast charging capabilities. But the real manufacturing revolution, which receives far less

Expert Perspectives

Q4: Which specific advances in materials, cell architectures, or manufacturing processes are most likely to unlock commercially viable solid-state batteries - and how close are they?

attention, is that these batteries can be manufactured without directly using lithium metal.

Lithium metal is exceptionally challenging to work with. Highly reactive, extremely sensitive to air and moisture, flammable, and very sticky. While lithium metal can be managed during early development and small-scale production, scaling its use to industrial volumes introduces significant operational challenges, which can cause production costs to spiral out of control. In developing anodeless battery technology, Chinese manufacturers have completely circumvented the use of lithium metal.

In terms of timelines, CATL has already announced its self-forming anodeless technology for 2025. Whilst there will no doubt be a slow implementation period with high initial costs and low production capacity, we estimate this will be a gamechanger in future battery design, paving the way for solid-state batteries.

Dr. Fleur Thissandier

Senior Patent and Technology Analyst, KnowMade

Commercially viable solid-state batteries will likely emerge from combined advances in solid electrolytes, electrode/interface engineering, and scalable manufacturing processes, rather than from a single breakthrough.

On the materials side, the key challenge for solid-state electrolytes is achieving the right balance between high ionic conductivity, electrochemical stability, and processability.

Two main development pathways are currently observed. The first focuses on mature electrolyte systems such as some sulfides and oxides, which have already demonstrated proof of concept in lab-scale cells. The main challenge now is scaling their production and integrating them into battery manufacturing processes.

The second pathway explores emerging electrolytes, such as halides, that appear promising but still require improvements in composition and performance before validation in small cells.

At the electrode level, innovation targets electrode-electrolyte interface engineering, including optimized electrode compositions, more tolerant interface materials, and cathode materials specifically designed for solid-state batteries. Improved interfacial compatibility is critical because long-term performance depends on the stability of the cathode-electrolyte interface. Regulatory constraints, such as evolving PFAS restrictions affecting polymers and binders, must also be considered.

Finally, manufacturing innovation will be decisive. Beyond chemistry improvements, scalable production processes, including emerging dry-processing approaches, are gaining attention as potential enablers of cost-effective large-scale manufacturing.

> Eliminating graphite is a significant achievement. It increases the overall gravimetric energy density of the battery and increases fast charging capabilities.
>
> **Dr. Luke Sweeney**

> Reducing the cost of lithium sulfide production is widely recognized as a critical factor for enabling cost-competitive, large-scale manufacturing of sulfide-based solid-state batteries.
>
> **Dr. Xin Li**

Expert Perspectives

Question 05

What does a realistic timeline look like for solid-state batteries to move from niche applications to mainstream EV adoption, and what milestones will signal the tipping point?

Timeline questions carry an inherent tension between the desire for precision and the genuine uncertainty of complex industrial transitions. The most useful contributions here are not the date estimates themselves, which span from late-decade optimism to more cautious assessments, but the identification of specific, observable milestones that would signal genuine progress.

Cost parity with NCM prismatic cells, convergence around a dominant separator material, commercialization of lithium-manganese-rich cathodes, and demonstration of adequate manufacturing yields represent a set of trackable conditions against which progress can be assessed.

The deeper question is whether the EV market's pull for what solid-state batteries offer is as clear as the technology's capabilities suggest. If safety and energy density advantages remain contingent on manufacturing and field validation still underway, the path to mainstream adoption may be more gradual than linear projections imply: a basis for realistic planning, not pessimism.

Expert Perspectives

Q5: What does a realistic timeline look like for solid-state batteries to move from niche applications to mainstream EV adoption, and what milestones will signal the tipping point?

Dr. Wolfgang Bernhart

Senior Partner, Roland Berger

Fast charging will not be superior to lithium-ion batteries with ASSB, and driving range will not be the main driver for the ASSB market. The only major driver would be safety.

Although battery suppliers officially claim that 'ASSB is safer than lithium-ion batteries,' in reality, battery engineers are struggling with lithium dendrite formation during charging, especially at higher SoC levels during fast charging. For this reason, safety may be more compromised than with lithium-ion batteries.

If safety is proven through field data by OEMs as an important milestone (with technological innovations to prevent lithium dendrite formation, such as enhancing the mechanical and chemical properties of solid electrolytes against lithium growth), this will be a tipping point not only for battery suppliers but also for OEMs, who are currently unconvinced about ASSB technology

We are skeptical that mainstream adoption of ASSBs in electric vehicles will occur at all, since we don't see how costs can be brought down to the level of conventional cells.

Alex Louli

Principal Applications Engineer, QuantumScape

Mainstream adoption will unfold in phases over the coming years, with Volkswagen Group's timeline as a leading indicator. Its progress and commitment to next-generation solid-state technology signal industry readiness.

Key tipping points will include demonstrating scalable production for customer testing, completing real-world demonstrations, and additional JDAs indicating industry confidence.

While automotive remains our core focus, we're also seeing increasing interest in our technology from other industries that rely on batteries approaching their performance limits, such as AI data centers, defense, and aerospace.

Dr. Xin Li

Director, eMobility Innovation Center, BASF

From an industry perspective, semi-solid-state batteries are expected to reach large-scale production earlier than all-solid-state batteries. These technologies are likely to coexist rather than replace one another, each serving different performance and cost requirements.

The transition from niche applications to broader adoption is generally expected to occur first for semi-solid-state batteries toward the latter part of this decade, with all-solid-state batteries following in the early 2030s, subject to continued technological progress.

For semi-solid-state batteries, an important milestone will be the development of optimized polymer or monomer systems that enable consistent uniformity in mass production through in-situ solidification.

For all-solid-state batteries, key milestones include achieving significant cost reductions in lithium sulfide production, bringing sulfide electrolytes closer to the cost of liquid electrolytes, and further breakthroughs that enable stable interfaces under lower external pressure.

Connor Watts

Battery Raw Material Demand Analyst, Fastmarkets

The first major milestone for mainstream EV adoption of solid-state batteries will be cost competitiveness with conventional high-nickel NCM lithium-ion cells, which still sit above roughly $75/kWh for prismatic formats. Demonstrating cell manufacturing costs below $85/kWh would provide strong proof that solid-state production can scale sufficiently for mass-market deployment.

Achieving full price parity would materially alter the competitive landscape, enabling solid-state cells to more rapidly displace incumbent technologies, potentially as early as **2029** in a bull case, or **2032–33** in a more conservative scenario.

A second critical milestone will be the convergence of solid-state separators around a dominant material system. Standardization at this level would allow global supply chains to evolve in unison rather than in parallel, accelerating scale-up and cost reduction.

The third milestone is the commercialization of lithium-manganese-rich (LMR) cathodes. Solid-state architectures have been instrumental in advancing

Expert Perspectives

Q5: What does a realistic timeline look like for solid-state batteries to move from niche applications to mainstream EV adoption, and what milestones will signal the tipping point?

high-voltage cathodes such as LMR, which combines low bill-of-materials costs with high operating voltages. As a result, LMR sits at the core of several solid-state strategies, including those pursued by manufacturers such as China's Qingtao Energy.

Dr. Fleur Thissandier

Senior Patent and Technology Analyst, KnowMade

Based on the industry announcements and trends, the most realistic timeline for solid-state batteries moving from niche use to mainstream EV adoption unfolds in three stages.

2026–2028: demonstration and early limited launches. This period will likely feature technology demonstrators, validation fleets, pilot production lines, joint ventures, and materials partnerships.

Premium prototypes, test vehicles, and small production series may appear as companies validate performance, manufacturing processes, and costs.

2028–2030: niche commercial phase. Solid-state batteries may first be introduced in high-value segments, such as premium or performance vehicles, where higher costs are acceptable. At this stage, the competitive landscape may also start to see the first significant IP disputes as companies defend their technological positions.

Early 2030s: potential transition to broader adoption, but only if several milestones are reached simultaneously: automotive-qualified cells with credible lifetime performance, pilot lines converted into reliable industrial production with good yields, secured supply chains for key materials, and pack costs approaching those of advanced lithium-ion solutions.

The real tipping point will occur when high-volume production lines, validated chemistries, and real customer vehicles converge with competitive costs, signaling industrial feasibility rather than just technological promise. Political or geopolitical decisions could also accelerate or delay this transition.

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>
> Connor Watts

> An important milestone will be the development of optimized polymer or monomer systems that enable consistent uniformity in mass production through in-situ solidification.
>
> Dr. Xin Li

Signals for the Next Decade

The following signals are derived from cross-expert analysis. They are directional rather than predictive, and structural rather than tactical. Each reflects a pattern that, if it holds, will shape the competitive landscape for solid-state battery technology across the next ten years.

01 Cost benchmarks set by conventional chemistries will define the competitive threshold

The reference point for solid-state commercial viability is not set by previous-generation lithium-ion but by current LFP production economics, which have reached below $40/kWh in Chinese manufacturing. The timeline for mainstream solid-state adoption will be shaped significantly by how quickly production costs close this gap. Fastmarkets' $85/kWh threshold for proof-of-concept scalability provides a useful near-term marker.

02 Anodeless architecture as a manufacturing inflection, not only a performance gain

The significance of anodeless battery designs may be as much operational as chemical. By removing the need to handle lithium metal directly during cell assembly, this architecture addresses one of the more demanding barriers to industrial-scale production. CATL's 2025 self-forming anodeless announcement merits tracking as closely as electrolyte development milestones.

03 Safety advantages are real but require field validation at scale

Replacing flammable liquid electrolytes is a meaningful safety improvement. At the same time, the behavior of lithium metal anodes under fast charging at higher states of charge, particularly dendrite dynamics, remains an active area of development. Field data from OEM validation programs from 2026 onward will provide the first substantive real-world evidence.

04 Patent portfolio depth in manufacturing processes will shape competitive access

The shift in solid-state patent activity from materials science to manufacturing infrastructure and pack integration means that freedom-to-operate across the production value chain is increasingly a strategic consideration. Companies building solid-state programs that do not account for the IP landscape in manufacturing processes may face constraints that performance benchmarks alone will not resolve.

05 Semi-solid architectures may serve significant markets as a long-term category, not a bridge

Hybrid or semi-solid-state configurations are approaching commercial scale earlier than all-solid-state alternatives and may serve substantial market segments on a persistent rather than transitional basis. The coexistence of multiple electrolyte architectures serving different performance and cost requirements is the more probable near-term scenario than a clean technology succession.

06 Commercial vehicle economics represent a structurally distinct early-adoption case

The financial case for solid-state integration is more direct in heavy-duty commercial vehicles - where battery weight constrains payload and profitability - than in passenger cars. Early deployment in this segment would generate manufacturing learning and cost data with broader applicability, making it a meaningful leading indicator for the technology's commercial trajectory.

07 Chinese production economics and timelines are setting the competitive reference frame

Chinese cell manufacturers are advancing solid-state and anodeless programs at pace, reflecting levels of capital and supply chain integration that have a structural dimension beyond individual company strategy. The cost levels established by Chinese LFP manufacturing set the competitive benchmark that all solid-state programs must meet.

08 Convergence around a dominant electrolyte system is a prerequisite for supply chain scaling

Global supply chains for solid-state precursor materials will invest at scale only once a dominant electrolyte chemistry is established. Convergence - likely around sulfide-based systems, though not yet confirmed - will be one of the most consequential signals of the next five years, and its timing will materially influence when cost reduction trajectories begin to steepen.

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