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# Fast-charging lithium-ion batteries require a systems engineering approach



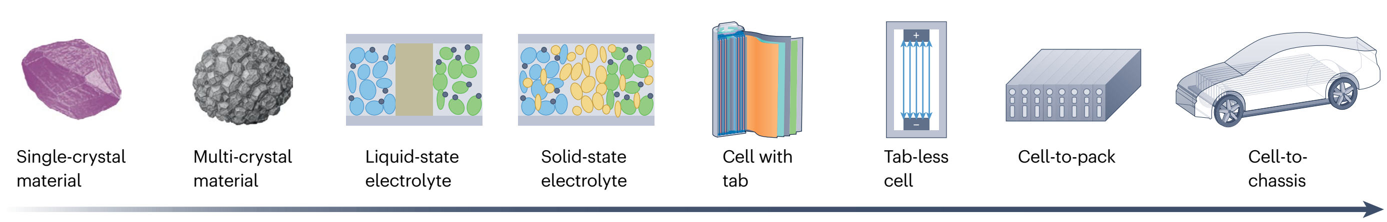
Fast charging has emerged as a key enabler for the widespread adoption of electric vehicles and portable electronics[1]. However, achieving fast charging without compromising battery lifespan, safety, or energy density remains a complex challenge[2]. At the core of this difficulty is the inherently multi-scale, multi-physics nature of battery behaviour, which spans materials[3], electrochemical kinetics[4], thermal management[5], and mechanical stability. A battery is inherently an active, non-equilibrium device, meaning that heterogeneity is an inevitable and even necessary consequence of its normal operation. Yet, these same heterogeneities can cause significant problems if they become too severe, either causing reductions in performance, shortened cycle life, or resulting in dangerous failure modes. In dealing with these, adopting a holistic systems engineering approach becomes necessary for advancing battery design.

Battery research is often conducted through a reductionist lens, with individual disciplines focusing on isolated components — most notably through a materials-centric approach aimed at maximizing local performance. However, a narrowly scoped optimization frequently overlooks critical system-level interactions and constraints. As a result, solutions that perform exceptionally well in controlled environments may offer limited value at the cell, module, or pack level — especially under demanding conditions such as fast charging. While industry tends to adopt a more product-oriented approach, aiming to deliver integrated solutions that balance performance, cost, and safety, this integration also has limitations. Departmental silos exist even in industry, and the few integrated industrial tools and models remain proprietary and inaccessible to the broader research community because they are considered extremely valuable. We believe that both academia and industry can accelerate battery development by breaking down disciplinary boundaries, sharing more openly, and embracing a systems engineering approach that aims to balance the different heterogeneities that emerge during operation.

First, it is essential to avoid the trap of subsystem optimization without being guided by a cascading optimal strategy. In siloed research or development settings, teams often concentrate on optimizing the battery aspect they deem most critical, whether materials, thermal management, or cell architecture, without fully considering system-level trade-offs. For example, although nickel-rich lithium nickel manganese cobalt oxide materials offer higher energy density at the material level, their system-level performance can converge with that of lithium iron phosphate-based batteries once factors like thermal management, safety, and cycle life are accounted for[6]. In other words, a material that performs well under idealized laboratory conditions may suffer significant performance loss or even premature failure, when subjected to real-world gradients in temperature, current density, or state of charge during fast charging. Beyond materials, for example, a highly optimized thermal management system that maintains temperature uniformity within a fraction of a degree across the pack may impose excessive system complexity. Similarly, cell balancing algorithms designed to minimize voltage variance under all conditions may increase computational load and reduce system fault tolerance. Ultimately, these trade-offs can diminish the overall robustness, manufacturability, or cost-effectiveness of the energy storage system as a whole.

Second, in the context of fast charging, where trade-offs between performance, safety, and cost are particularly pronounced, multi-scale modelling provides a crucial means to navigate these challenges and develop balanced, system-level solutions. For example, heterogeneity is unavoidable in battery systems and tends to intensify during fast charging, posing greater challenges for these trade-offs.

These factors include heterogeneity in active material loading, electrode thickness, compaction density and thermal conductivity,




**Materials level:** intrinsic properties of individual materials
(a) optimize electronic and ionic conductivity to reduce overpotential; (b) single-crystal versus multi-crystal; (c) excellent thermal diffusivity to minimize local hotspots; and (d) electrochemical stability to ensure structural and interfacial integrity under high-rate cycling.

**Electrode level:** how materials are integrated into electrode structures
(a) optimized particle properties: size, shape, structure; (b) porosity and tortuosity, influencing ion transport; (c) uniform distribution of active material ensuring consistent reaction; and (d) optimized electrode thickness to balance energy density and ion transport efficiency.

**Cell level:** balanced design of cell components
(a) proper current collectors enabling current distribution; (b) thermal management to minimize temperature gradients; (c) tab design (tabbed versus tab-less), for different current pathways and heat generation; and (d) built-in safety design, for example, current interrupt device.

**Module/pack level:** system-level uniformity and integration
(a) robust electrical connections, to ensure even current distribution and minimize failure points; (b) thermal management strategies, to reduce temperature gradients across cells; and (c) system-wide safety design, for example, battery management system.

**Fig. 1** | Key strategies advancing fast-charging battery design across multi-scale levels.

which can significantly influence current distribution, local degradation and thermal hotspot formation, especially under fast-charging conditions. However, most academic models still rely on idealized or symmetric assumptions, overlooking the spatial and temporal heterogeneities commonly found in real battery systems. Such simplifications limit the predictive power and real-world relevance of existing models, leading to models that cannot capture the full complexity of fast-charging systems, reducing their value for system-level design and control in the real world[7].

To enhance model accuracy and practical applicability for the fast-charging scenario, future frameworks should incorporate spatially resolved parameters, account for manufacturing and ageing variability, and simulate realistic fast-changing conditions. Take lithiation as an example – introducing a metric for inhomogeneous lithiation[8] can help investigate how inhomogeneities propagate and amplify over multiple cycles, ultimately leading to uneven degradation. Such physically grounded, non-idealized modelling approaches will offer deeper mechanistic insight and more actionable guidance for predicting electrochemical evolution and battery capacity during fast-charging operations.

Third, establishing standardized evaluation criteria is essential to elevate safer and high-performance design from an academic concern to an industry-wide requirement for fast-charging batteries. Targets drive change. For the design of fast-charging battery systems, acceptable degrees of heterogeneity at the system level should be more widely discussed, with community-wide recommendations and targets established. This would ensure that balanced and holistic optimization is not considered optional, but rather a fundamental condition. Certification protocols could include standardized metrics for assessing thermal, electrical, and structural aspects, which would become integral to safety and performance validation. Design tools and material databases could incorporate a 'heterogeneity sensitivity' label or index, quantifying the microstructural heterogeneity[9]. These indicators would enable battery designers to make more informed decisions in the early stages of development, reducing the likelihood of hidden reliability issues that emerge under fast-charging or non-ideal operating conditions.

Fourth, fast charging technologies including charging protocols and infrastructure can be accelerated by narrowing the gap between laboratory research and real-world application with a more open approach, particularly by sharing data. Industry would benefit in the long term from sharing real-world battery performance data, especially under fast-changing conditions where spatial and temporal heterogeneities play a decisive role. Access to anonymized datasets and federated learning[10] would enable academic researchers to design experiments and models that better reflect practical system behaviour. While we fully acknowledge the need to protect proprietary technologies, we strongly encourage industry stakeholders to consider the costs of going it alone versus contributing and benefiting from a community-based effort, and share non-sensitive, representative datasets wherever possible.

Battery innovation will be the most impactful when it stems from the collective efforts of diverse communities working towards system-level optimization through a multiscale, integrated design approach. To support this vision, we summarize the following framework (Fig. 1) to inspire researchers and engineers to consider key strategies for advancing fast-charging battery design. We hope to trigger more academic–industrial collaboration and encourage a more unified and efficient innovation community to develop better-optimized faster-charging batteries in the future.

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## Competing interests

The authors declare no competing interests.