

What's next in energy science: From storing energy to governing it

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Energy science is being reshaped by forces that extend well beyond the laboratory. The global energy system is undergoing a rapid and uneven transition, driven simultaneously by climate imperatives, geopolitical uncertainty, and structural changes in how energy is produced and consumed. Renewable electricity is expanding at unprecedented speed, yet its inherent variability places increasing strain on power systems that were historically designed for steady, centralized generation. At the same time, electrification is accelerating across transport, industry, and buildings, compressing decades of infrastructure evolution into a few critical years.

In this context, energy storage has moved from a supporting role to a central pillar of system stability. Electrochemical storage now underpins the integration of renewables, enables flexible grid operation, and increasingly acts as the guarantor of reliability in a highly dynamic energy landscape. However, as storage technologies scale in size, density, and deployment, they expose a deeper challenge confronting energy science today: **the transition from storing energy to controlling it safely and predictably.**

This shift marks a turning point. For much of the past three decades, progress in energy storage has been guided by a narrow set of performance metrics—energy density, power density, cycle life, and cost. These benchmarks have driven remarkable advances, particularly in lithium-ion batteries, but they have also obscured systemic vulnerabilities. The growing frequency and visibility of safety incidents, especially those involving thermal runaway, signal that the limits of single-metric optimization are being reached.

ENERGY STORAGE AT THE CENTER OF A STRESSED SYSTEM

As energy storage systems become larger and more tightly integrated into critical infrastructure, their operating conditions are changing fundamentally. Storage is no longer confined to controlled devices or pilot installations; it is embedded in urban environments, co-located with renewable generation, and deployed at grid scale. These systems are expected to respond rapidly, operate continuously, and endure increasingly aggressive duty cycles.

Such demands compress safety margins. High energy density concentrates risk, while scale amplifies consequences. A localized failure that once would have been an engineering inconvenience can now propagate across cells, modules, or entire facilities, with impacts extending beyond the energy sector itself. The question confronting energy science is therefore not whether failures can occur, but whether they can be **anticipated, constrained, and governed.**

Thermal runaway has emerged as the most emblematic expression of this challenge. Often framed as an accident or defect, it is more accurately understood as a manifestation of how energy, heat, and matter interact within confined, reactive systems. Its growing prominence reflects not a lack of engineering effort, but a gap in fundamental understanding.

Artificial intelligence as both a stress test and an enabling tool

Artificial intelligence introduces a dual and increasingly consequential dynamic into contemporary energy systems.¹ On the one hand, the rapid expansion of large-scale data centers, cloud computing, and AI model training has turned computational power into a fast-growing source of electricity demand. This demand is continuous, highly concentrated, and acutely sensitive to reliability, placing unprecedented strain on power systems and their supporting energy storage infrastructure. In this respect, AI functions as a **stress test**, exposing the limits of existing design paradigms and narrowing

operational safety margins.

On the other hand, AI is emerging as an exceptionally powerful tool for advancing energy science itself. Data-driven methods are beginning to transform how materials are discovered, how complex systems are modeled, and how failure is anticipated. In the context of energy storage, AI offers new possibilities for identifying subtle, multivariate signatures that precede thermal instability—signals that are often invisible to conventional threshold-based monitoring. When combined with operando diagnostics and physically grounded models, machine learning can help bridge the gap between microscopic processes and macroscopic behavior, enabling earlier intervention and more nuanced control.

The challenge, and the opportunity, lies in integration. AI cannot substitute for physical understanding of transport, interfaces, and reaction microenvironments, but it can dramatically accelerate insight when embedded within such frameworks. Used judiciously, AI has the potential not only to reveal where current energy systems are most vulnerable, but also to guide the design of storage technologies that are safer, more predictable, and more resilient under real operating conditions. In this sense, AI sharpens the relevance of safety while simultaneously expanding the scientific toolkit available to address it.

Thermal runaway as an emergent scientific phenomenon

Thermal runaway is frequently attributed to specific material failures—a damaged separator, an unstable electrolyte, or an internal short circuit. While such triggers are real, they do not fully explain why failures propagate so rapidly or so destructively.² At its core, thermal runaway is an **emergent phenomenon**, arising from nonlinear feedback among electrochemical reactions, heat generation, mass transport, and mechanical degradation.

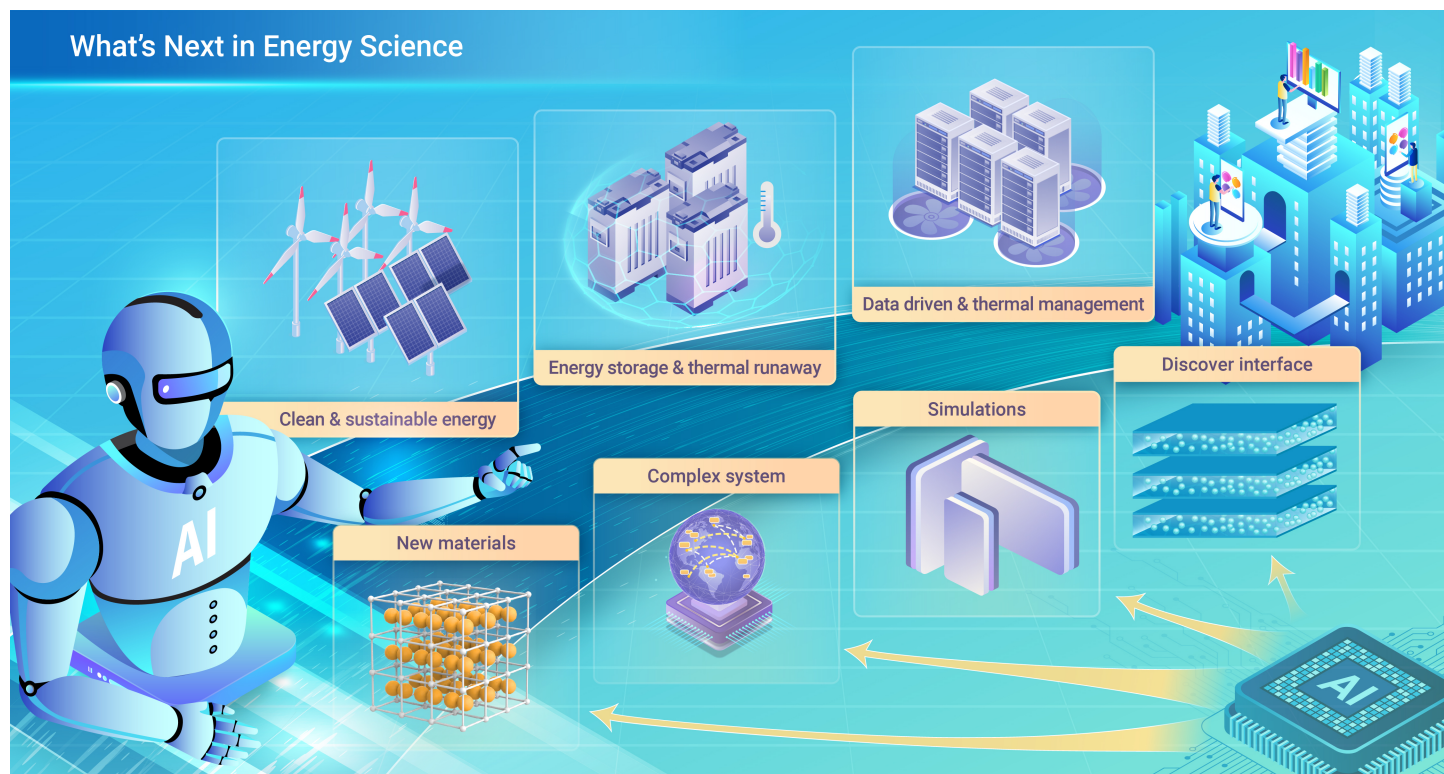
These processes unfold across multiple length and time scales. Localized heterogeneities in current distribution or microstructure can generate hotspots that accelerate parasitic reactions. Heat accumulation alters reaction pathways, which in turn further increase heat release. Once a critical threshold is crossed, dissipation can no longer compete with generation, and failure becomes self-sustaining.

Understanding this cascade requires energy science to move beyond static descriptions of materials toward a dynamic, systems-level perspective. Safety cannot be reduced to a checklist of protective components; it is an outcome of how energy flows, concentrates, and transforms under real operating conditions.

A parallel transformation is already underway in energy conversion research. There, it has become increasingly clear that catalytic performance under practical conditions cannot be predicted from intrinsic activity alone. Instead, efficiency emerges from the structure and dynamics of the reaction microenvironment, particularly at complex gas–liquid–solid interfaces.³

Energy storage systems face an analogous challenge. Electrodes, electrolytes, and interfaces form confined microenvironments where ions, electrons, heat, and mechanical stress continuously interact. Thermal runaway often originates within these microenvironments, where small deviations from uniformity can trigger disproportionate effects. Treating batteries as dynamic “nanoreactors” reframes safety as a problem of **interfacial and transport design**, rather than solely of materials selection.

This perspective suggests that future advances in safety will depend on how effectively energy science can engineer microstructures and architec-



tures that regulate transport processes. Controlling how heat is generated and dissipated, how reactions are spatially distributed, and how failure is localized may prove as important as discovering new chemistries.

SAFETY, SCALE, AND ENERGY EQUITY

As energy storage deployment expands globally, safety becomes inseparable from broader questions of energy equity. Regions with limited infrastructure, regulatory capacity, or emergency response resources are often those most exposed to technological risk. At the same time, they are among the primary beneficiaries of decentralized energy systems that rely heavily on storage.

Reframing safety as a fundamental scientific challenge aligns with arguments that energy equity must be understood not only as a moral obligation, but as a strategic necessity for global stability and innovation.

Technologies that are intrinsically safer and more predictable expand the contexts in which clean energy systems can be deployed, while unsafe or poorly understood systems risk undermining trust and reinforcing inequality.

In this sense, safety is not a secondary consideration that competes with performance or cost. It is a prerequisite for scalability, legitimacy, and long-term societal acceptance of the energy transition.

Looking ahead: governing complexity rather than eliminating it

Looking forward, the trajectory of energy systems points toward greater complexity rather than simplification. Electrification, renewable integration, digital control, and large-scale storage are converging into tightly coupled systems where physical processes and operational decisions interact continuously. In such systems, failures are rarely linear or isolated.⁴

Thermal runaway thus marks a boundary of current understanding. It reveals where assumptions of uniformity, equilibrium, and linear response break down. Progress will depend on whether energy science can embrace complexity as a design space rather than a liability—developing frameworks that prioritize predictability, controllability, and resilience under stress.

Future storage technologies are likely to be judged not only by peak performance, but by how they behave during fast charging, aging, abuse, and unexpected operating regimes. Graceful degradation and transparent failure modes may become as valuable as incremental gains in energy density. This represents a shift in what constitutes success in energy research.

FROM INTELLIGENT ENERGY TO RESPONSIBLE ENERGY

The rapid expansion of energy storage marks one of the defining technological achievements of the low-carbon transition. Yet it also confronts energy science with a paradox: as the capacity to store energy increases, so too does the responsibility to control it. Thermal runaway is not merely a hazard to be mitigated; it is a diagnostic signal, highlighting where current scientific frameworks fall short.

What's next in energy science is therefore not defined by a single breakthrough material or chemistry. It lies in a deeper integration of disciplines, scales, and perspectives—linking electrochemistry, thermal science, mechanics, and system dynamics under realistic operating conditions. By shifting focus from how much energy can be stored to how reliably and safely it can be governed, the field can mature in step with the systems it enables.

Ultimately, the success of the energy transition will be measured not only in terawatt-hours or cost curves, but in trust. Energy systems must be not only efficient and intelligent, but dependable across societies increasingly reliant on both electrons and algorithms. Embedding safety and thermal resilience into the foundations of energy science is therefore not a constraint on ambition, but its necessary evolution.

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DECLARATION OF INTERESTS

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