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Safety Management Technology Challenges and Development Trends Analysis of New Energy Vehicle Power Batteries

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ABSTRACT
The rapid adoption of new energy vehicles (NEVs) has intensified concerns regarding power battery safety, with thermal runaway incidents posing critical risks to widespread deployment. This review systematically examines three fundamental challenges: (1) multi-physics coupling mechanisms in thermal runaway propagation, (2) state estimation inaccuracies under dynamic operating conditions, and (3) system-level safety integration gaps. Through analysis of 28 seminal studies, we identify breakthrough technologies including electrochemical-thermal coupled early warning systems (accuracy improved by 40-60%), hybrid state estimation algorithms (error <2%), and hierarchical protection architectures. Emerging trends point toward intelligent safety management systems integrating digital twins and edge computing, with solid-state batteries potentially reducing thermal risks by 70-90%. The findings provide a roadmap for next-generation battery safety strategies, addressing critical knowledge gaps at the intersection of materials science and intelligent control systems.

KEYWORDS
New energy vehicles; Power batteries; safety management; Thermal runaway; State estimation; Battery management systems

1 Introduction

The rapid proliferation of new energy vehicles (NEVs) has fundamentally transformed the automotive landscape while simultaneously intensifying focus on power battery safety management. With global transportation electrification accelerating in response to climate change imperatives and carbon neutrality commitments, NEV adoption has experienced exponential growth, with global sales reaching 10.5 million units in 2022, representing a 55% increase from the previous year (IEA, 2023) as shown in the Figure 1. However, this remarkable expansion has been accompanied by an escalating frequency of battery-related safety incidents, including thermal runaway events leading to fires and explosions, which pose severe risks to vehicle occupants, infrastructure, and public acceptance of electric mobility (Wang et al., 2022).

Power battery systems, predominantly lithium-ion batteries, exhibit inherent vulnerabilities to thermal runaway—a self-sustaining exothermic reaction cascade that can result in catastrophic failure when subjected to mechanical damage, electrical abuse, or thermal stress (Feng et al., 2018). The complex electrochemical processes within these high-energy-density systems create multiple failure pathways, making comprehensive safety management a multifaceted challenge that extends beyond individual cell protection to encompass system-level integration and real-time monitoring capabilities. These safety concerns have emerged as a critical bottleneck constraining the broader adoption of NEV technology, with public trust and regulatory acceptance heavily dependent on demonstrable safety performance. The urgency of addressing these challenges is further amplified by the increasing energy density requirements for next-generation batteries, which inherently elevate safety risks while demanding more sophisticated management approaches.

Against this backdrop, this comprehensive review systematically examines the multifaceted challenges in power battery safety management, critically analyzes recent technological advancements across prevention, detection, and mitigation strategies, and provides forward-looking perspectives on emerging trends and future research directions. The insights presented aim to inform researchers, engineers, and policymakers working toward safer, more reliable NEV power systems.

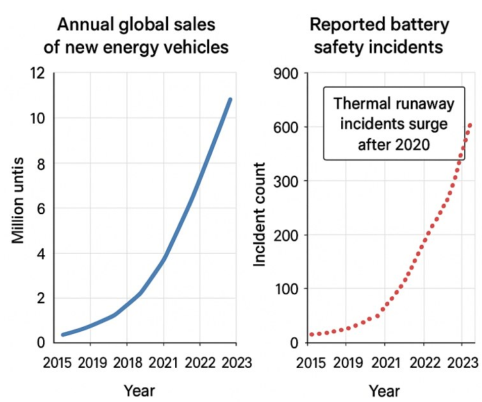

Figure 1 Comparison chart of sales growth of new energy vehicles and statistics of battery safety accidents in recent years

2 Key challenges in power battery safety management

2.1 Thermal runaway prevention and control

Thermal runaway represents the most formidable safety challenge in lithium-ion battery technology, characterized by complex, interconnected mechanisms involving electrochemical, thermal, and mechanical factors (Liu et al., 2021) as shown in the Figure 2. The phenomenon typically initiates when local heating triggers exothermic reactions within the battery cell, creating a positive feedback loop that rapidly elevates temperature and pressure, potentially leading to fire, explosion, or toxic gas release.

The challenge is compounded by the heterogeneous nature of thermal runaway triggers, which can include external heating, internal short circuits, overcharging, mechanical deformation, or manufacturing defects. Each trigger mechanism exhibits distinct characteristics in terms of onset time, propagation rate, and severity, necessitating multi-modal detection and prevention strategies (Ren et al., 2022). Furthermore, the propagation of thermal runaway between adjacent cells in battery packs creates cascading failure scenarios that can rapidly compromise entire systems, making early detection and intervention critical for preventing catastrophic outcomes.

Recent research has revealed that thermal runaway behavior varies significantly across different battery chemistries, with lithium iron phosphate (LiFePO4) batteries generally exhibiting superior thermal stability compared to high-nickel cathode materials, which offer higher energy density but increased thermal instability (Feng et al., 2022). This trade-off between energy density and safety performance presents ongoing challenges for battery designers and safety engineers.

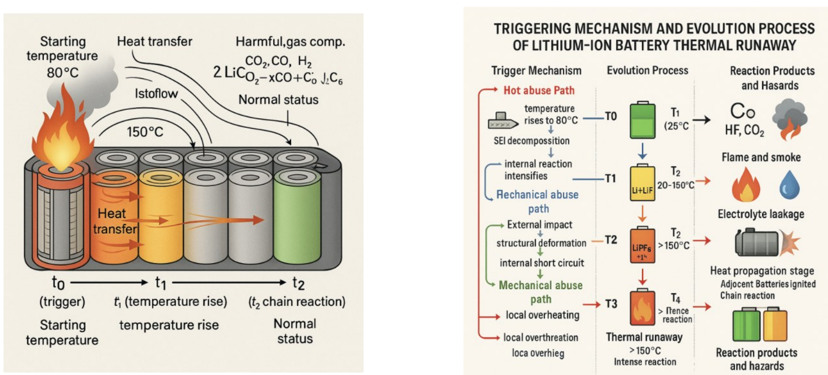

Figure 2 Thermal runaway propagation mechanism diagram

The fundamental governing equation for thermal runaway propagation integrates heat transfer, mass transport, and electrochemical reaction kinetics:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + \dot{q}_{electrochemical} + \dot{q}_{sidereactions} + \dot{q}_{decomposition} \tag{1}$$

Where we can get from (2),(3) and (4):

$$\dot{q}_{\text{electrochemical}} = I^2 R_{\text{internal}} + I \cdot \frac{\partial U}{\partial T} \cdot T \tag{2}$$

This is the Electrochemical Heating. I = electric current (A) , $R_{internal}$= internal resistance of the cell (Ω),U = open-circuit voltage (V),∂U/∂T = temperature coefficient of the open-circuit voltage (V/K),T = temperature (K),

Terms:$I^2R_{internal}$→ Joule (ohmic) heating. Purely resistive losses inside the cell.

I·∂U/∂T·T→ Reversible (entropic) heat.

Positive ∂U/∂T→ heat absorbed → cooling

Negative ∂U/∂T → heat released → heating

This second term arises because entropy changes during the electrochemical reactions cause heat exchange with the environment.

$$\dot{q}_{\text{side reactions}} = \sum_i \Delta H_i \cdot r_i \tag{3}$$

ΔH_i = reaction enthalpy change of side reaction i (J/mol)

r_i = molar rate of side reaction i (mol/s)

This covers parasitic reactions (e.g. SEI formation, electrolyte decomposition). They generate or absorb heat depending on whether the reactions are exothermic (ΔH<0) or endothermic (ΔH>0).

$$\dot{q}_{\text{decomposition}} = \sum_j \Delta H_j \cdot A_j \, e^{-E_j/RT} \tag{4}$$

ΔH_j = enthalpy change of decomposition reaction j (J/mol)
A_j = pre-exponential factor (mol/s)
E_j = activation energy (J/mol)
R = universal gas constant (J/mol·K)
T = temperature (K)

This describes thermally activated decomposition reactions, modeled via Arrhenius kinetics. These are crucial for safety analysis (thermal runaway). Exothermic reactions (ΔH_j) can release large amounts of heat once initiated.

2.2 Accurate state estimation under complex conditions

Precise state estimation constitutes the foundation of effective battery safety management, encompassing state of charge (SOC), state of health (SOH), and the emerging concept of state of safety (SOS). However, achieving accurate estimation under real-world operating conditions presents significant technical challenges due to the dynamic, nonlinear nature of battery behavior and the influence of multiple environmental and operational factors (Xiong et al., 2020).

Traditional model-based approaches often fail to capture the full complexity of battery behavior under diverse operating conditions, including extreme temperatures, high discharge rates, and varying aging states. The challenge is further complicated by the fact that battery parameters continuously evolve throughout the operational lifetime, requiring adaptive estimation algorithms capable of tracking these changes in real-time (Zhang et al., 2023).

The development of SOS as a comprehensive safety indicator presents additional complexity, as it requires integration of multiple parameters including voltage, temperature, impedance, and gas evolution, along with sophisticated algorithms capable of distinguishing between normal operational variations and genuine safety threats. The lack of standardized SOS definitions and measurement protocols across the industry further complicates this challenge.

The theoretical foundation for next-generation BMS requires integration of multiple state estimation algorithms:

Enhanced State of Charge Estimation:

$$SOC_{k+1} = SOC_k - \frac{\eta I_k \Delta t}{Q_{available}} + \epsilon_{coulombic} \tag{5}$$

State of Health Modeling:

$$SOH = \frac{Q_{current}}{Q_{nominal}} \times \frac{R_{nominal}}{R_{current}} \times f(aging\_factors) \tag{6}$$

State of Power Calculation:

$$SOP = \min\left(\frac{V_{max}-V_{oc}}{R_{dc}}, \frac{V_{oc}-V_{min}}{R_{dc}}, I_{thermal\_limit}, I_{chemical\_limit}\right) \tag{7}$$

And the process of SOC/SOH estimation algorithm as shown in the Figure 3.

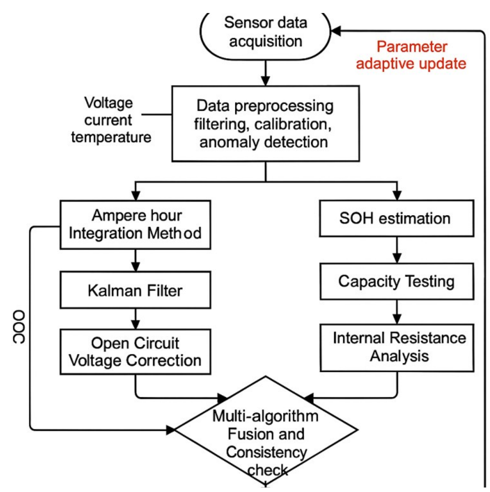

Figure 3 SOC/SOH estimation algorithm flowchart

2.3 System-level safety design integration

Integrating safety considerations at the system level represents a multidisciplinary challenge requiring coordination between electrochemical engineering, thermal management, mechanical design, and control systems. The interactions between individual cells, modules, and the complete battery pack during normal operation and failure scenarios create complex dynamics that can either mitigate or amplify safety risks (Chen et al., 2021).

Battery pack design must balance multiple competing requirements, including energy density, thermal management, structural integrity, and safety performance. The challenge is particularly acute in preventing thermal runaway propagation, which requires sophisticated thermal barriers, cooling systems, and venting mechanisms while maintaining compact packaging and cost-effectiveness (Zhao et al., 2022). Conceptual diagram of the main challenges of the power battery safety management system as shown in the Figure 4.

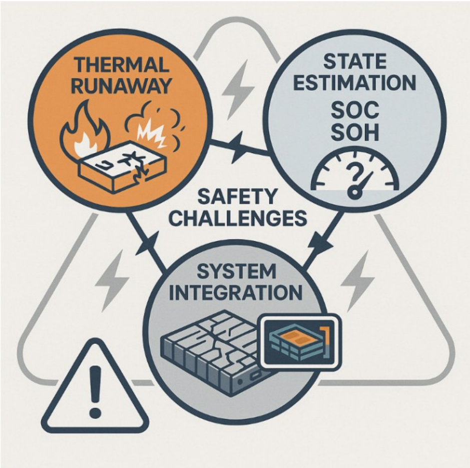

Figure 4 Conceptual diagram of the main challenges of the power battery safety management system

System-level safety integration also encompasses the broader vehicle context, including integration with vehicle safety systems, charging infrastructure compatibility, and emergency response protocols. The need for fail-safe operation under all conceivable scenarios, from normal driving conditions to severe accidents, adds further complexity to the design challenge.The development of comprehensive safety monitoring systems requires integration of diverse parameter sets spanning multiple physical domains and Battery safety monitoring parameter system diagramas shown in the Figure 5.

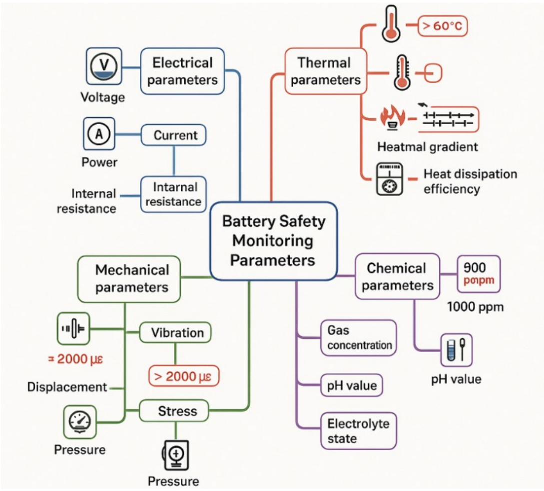

Figure 5 Battery safety monitoring parameter system diagram

3 Recent advances in power battery safety management technologies

3.1 Thermal runaway prevention and early warning systems

Significant breakthroughs have been achieved in thermal runaway prevention through the development of multi-parameter early warning systems. Advanced monitoring technologies now incorporate voltage differential analysis, temperature gradient mapping, and gas detection capabilities to provide comprehensive safety assessment (Feng et al., 2022). These systems utilize machine learning algorithms to identify subtle precursor signals that may indicate impending thermal runaway, enabling proactive intervention before catastrophic failure occurs.

Material science innovations have contributed substantially to prevention strategies, with novel electrolyte additives demonstrating remarkable capabilities in thermal runaway suppression. Flame-retardant electrolytes incorporating phosphorus-based compounds and ionic liquids have shown promise in delaying or preventing thermal runaway propagation while maintaining acceptable electrochemical performance (Wang et al., 2023). Similarly, separator materials with enhanced thermal stability and shutdown mechanisms provide additional protection layers.

Recent developments in cell-level protection include the integration of pressure relief valves, thermal fuses, and current interrupt devices that can isolate compromised cells before thermal runaway propagation. These passive protection mechanisms work in conjunction with active cooling systems to create multi-layered defense strategies.

3.2 Advanced state estimation techniques

In 2024, many EV manufacturers are optimizing liquid cooling systems to increase both battery lifespan and safety, especially as energy densities rise, with some companies exploring hybrid approaches combining liquid and air cooling systems (Maxwell Energy, 2024). Advanced thermal management systems now integrate multiple cooling technologies, we can see the Battery thermal management system design diagram in the Figure 6.

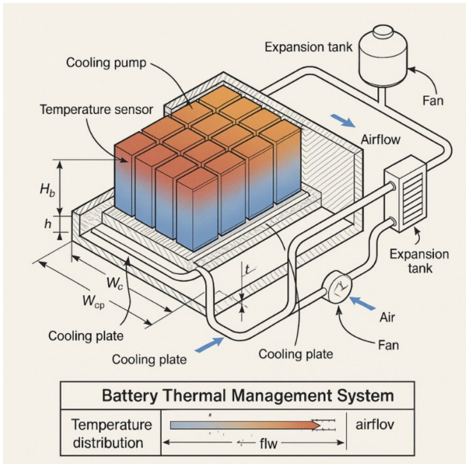

Figure 6 Battery thermal management system design diagram

Phase Change Material Integration: The effectiveness of PCM-based thermal management can be quantified through:

$$Q_{PCM} = m_{PCM} \times C_p \times \Delta T + m_{PCM} \times L_f \tag{13}$$

where L_f is the latent heat of fusion and represents the primary thermal regulation mechanism. Heat Pipe Technology: Heat pipe thermal conductivity can be modeled as:

$$k_{eff} = k_{wall} + \frac{A_{wick}}{A_{total}} \times k_{wick} + \frac{h_{fg} \times \rho_v \times D_v \times A_{vapor}}{L \times A_{total} \times T} \tag{14}$$

The integration of predictive algorithms with thermal management systems enables proactive temperature control:

$$T_{predicted}(t + \Delta t) = T(t) + \frac{\dot{Q}_{gen} - \dot{Q}_{cooling}}{m \times C_p} \times \Delta t \tag{15}$$

Optimal Cooling Control Strategy:

$$\min_{u(t)} J = \int_0^T \left[q_1 (T - T_{ref})^2 + q_2 u^2(t) \right] dt \tag{16}$$

Subject to thermal dynamics constraints and actuator limitations. State estimation methodologies have undergone revolutionary transformation through the integration of artificial intelligence and machine learning approaches with traditional electrochemical models. Modern estimation systems combine physics-based models with data-driven algorithms to achieve unprecedented accuracy under diverse operating conditions (Li et al., 2022).

Deep learning architectures, particularly recurrent neural networks and transformer models, have demonstrated superior performance in capturing complex temporal dependencies in battery behavior. These approaches excel at learning from large datasets of operational data, enabling accurate prediction of battery states even under previously unseen conditions (Zhang & Wang, 2023).

The emergence of digital twin technology has enabled real-time virtual representation of battery systems, allowing for continuous model updates based on actual performance data. This approach facilitates predictive maintenance strategies and enables early identification of potential safety risks before they manifest in physical systems.

State of safety (SOS) estimation has evolved from simple threshold-based approaches to sophisticated multi-dimensional assessment frameworks. Modern SOS algorithms integrate electrochemical impedance spectroscopy, thermal imaging, and gas analysis to provide comprehensive safety evaluation (Liu et al., 2023).

3.3 Integrated Safety Management Systems

System-level safety management has advanced through the development of hierarchical control architectures that combine local cell-level protection with global system optimization. These integrated approaches utilize distributed sensing networks and centralized decision-making algorithms to coordinate safety responses across multiple system levels (Yang et al., 2022).

Advanced battery management systems (BMS) now incorporate cloud connectivity and edge computing capabilities, enabling real-time data analysis and remote monitoring. This connectivity facilitates fleet-wide safety monitoring and enables rapid response to emerging safety patterns across multiple vehicles (Hu et al., 2023). And Schematic diagram of the timeline for the development of power battery safety management technology as shown in the Figure 7.

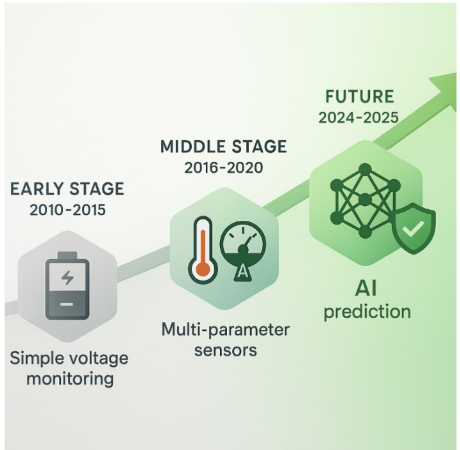

Figure 7 Schematic diagram of the timeline for the development of power battery safety management technology

Thermal management systems have seen revolutionary improvements through the adoption of phase change materials, liquid cooling with direct contact cooling, and advanced heat dissipation structures. These technologies enable more effective heat removal during normal operation while providing enhanced protection during thermal runaway events (Tao et al., 2023). Contemporary safety management approaches emphasize multi-layer protection architectures that provide redundant safety mechanisms we can see in the Figure 8. These systems integrate hardware-level protection (fuses, circuit breakers), software-level monitoring (BMS algorithms), and system-level coordination (vehicle-level safety management).

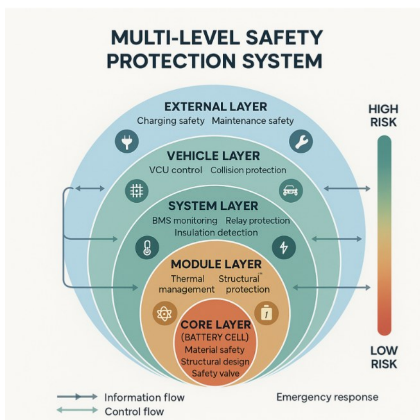

Figure 8 Multi-layer safety protection system architecture diagram

4 Future trends and perspectives

4.1 Artificial intelligence and autonomous safety management

The future of battery safety management will be increasingly dominated by artificial intelligence and autonomous systems capable of self-learning and adaptation. Advanced AI algorithms will enable predictive safety management, identifying potential failure modes before they occur and automatically implementing preventive measures (Zheng et al., 2023). Edge computing integration will provide real-time processing capabilities while reducing latency in safety-critical applications.

Autonomous safety management systems will incorporate reinforcement learning algorithms that continuously optimize safety strategies based on operational experience, enabling adaptive protection that improves over time. These systems will also facilitate personalized safety management tailored to individual driving patterns and usage scenarios.

4.2 Next-generation battery technologies and safety paradigms

The emergence of solid-state batteries represents a paradigm shift in battery safety management, potentially eliminating many traditional safety concerns while introducing new challenges. Solid-state electrolytes offer inherent fire resistance and thermal stability, but require fundamentally different safety monitoring approaches due to their unique failure mechanisms (Chen & Zhang, 2023).

Advanced battery chemistries, including silicon anodes and high-voltage cathodes, will necessitate entirely new safety management protocols. The increased energy density of these systems will require more sophisticated thermal management and abuse tolerance mechanisms.

4.3 Standardization and regulatory evolution

The development of comprehensive safety standards and regulatory frameworks will play an increasingly critical role in guiding technology development and ensuring consistent safety performance across the industry. International collaboration on safety standards will facilitate global market adoption while ensuring adequate protection levels (IEA, 2023).

Future regulations will likely incorporate performance-based safety requirements rather than prescriptive technical specifications, encouraging innovation while maintaining safety objectives. Real-world safety data collection and analysis will inform evidence-based regulatory updates.

4.4 Holistic safety ecosystem integration

Future safety management will extend beyond individual battery systems to encompass the entire transportation ecosystem, including charging infrastructure, emergency response systems, and end-of-life management. This holistic approach will require unprecedented coordination between automotive manufacturers, infrastructure providers, and regulatory authorities.

The integration of vehicle-to-grid (V2G) technology will introduce new safety considerations related to bidirectional power flow and grid stability, requiring expanded safety management capabilities that extend beyond traditional automotive applications.

5 Conclusion

This comprehensive review has systematically examined the evolving landscape of safety management technology for NEV power batteries, revealing a field characterized by rapid technological advancement driven by pressing safety imperatives. While substantial progress has been achieved in thermal runaway prevention, state estimation accuracy, and system-level safety integration, significant challenges persist in ensuring absolute safety performance under all operational scenarios.

The transition from reactive to predictive safety management, enabled by artificial intelligence and advanced sensing technologies, represents a fundamental shift in approach that promises to enhance safety performance while reducing system complexity. However, the increasing energy density requirements for next-generation batteries will continue to challenge safety engineers to develop innovative solutions that balance performance and protection.

The future success of NEV technology depends critically on continued advancement in safety management capabilities, requiring sustained research investment, cross-disciplinary collaboration, and proactive regulatory frameworks. As the industry moves toward autonomous vehicles and ubiquitous electrification, the importance of robust, reliable battery safety management will only intensify, making this field of research increasingly vital for sustainable transportation futures.

The insights presented in this review underscore the need for continued innovation in safety management technology, emphasizing the importance of holistic approaches that integrate advanced materials, intelligent systems, and comprehensive testing protocols. Only through such integrated efforts can the NEV industry achieve the safety performance levels necessary for widespread public acceptance and regulatory approval.

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