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Recent Trends, Challenges, and Future Prospects of Battery Technologies and Battery Management Systems for EVs

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الاتجاهات الحديثة والتحديات والآفاق المستقبلية لتقنيات البطاريات وأنظمة إدارة البطاريات للسيارات الكهربائية

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Abstract:

This article presents a comprehensive invistigation of battery technologies and battery management system (BMS) functionality for electric vehicles (EVs), synthesizing the current status, key challenges, and future perspectives. The study highlights that lithium-ion chemistries, particularly NMC, LFP, and NCA, remain the dominant solutions due to their technological maturity and balanced trade-offs among energy density, power capability, cycle life, safety, and cost. Emerging alternatives, including solid-state, lithium–sulfur, and sodium-ion batteries, are examined as prospective pathways to enhance safety, sustainability, and resource security, although they face limitations in readiness level, durability, and scalable integration. The article further analyzes the functional architecture of BMS, emphasizing critical subsystems for sensing and data acquisition, state estimation (SOC, SOH, SOP), cell balancing, and thermal coordination. It demonstrates a transition from classical model-based approaches toward hybrid and data-driven methods, including adaptive observers and machine-learning-assisted estimation, to improve robustness under aging and uncertain operating conditions. Key challenges identified include electrochemical degradation, thermal runaway risk, fast-charging stress, sensor drift, model uncertainty, cybersecurity vulnerabilities, and system-level issues related to high-voltage architectures, pack scalability, and vehicle-to-grid compatibility. Finally, future directions are outlined, focusing on next-generation materials, ultra-fast-charging-compatible designs, intelligent connected BMS platforms, digital twins, cloud diagnostics, and predictive health management. The article concludes that battery–BMS co-design, aligned with safety standards and lifecycle sustainability, is essential to enable next-generation electric mobility and accelerate transportation decarbonization.

Keywords: Electric vehicles; Battery technologies; Battery management systems; State estimation; Intelligent energy storage.

الملخص:

تقدم هذه المقالة دراسة شاملة لتقنيات البطاريات ووظائف نظام إدارة البطارية (BMS) في المركبات الكهربائية(EVs) ، مع تلخيص الوضع الحالي والتحديات الرئيسية والآفاق المستقبلية. وتوضح الدراسة أن كيميائيات بطاريات الليثيوم-أيون، ولا سيما NMC و LFPو NCA، لا تزال تمثل الحلول المهيمنة بفضل نضجها التقني والتوازن المناسب بين كثافة الطاقة، وقدرة القدرة، والعمر التشغيلي، والسلامة، والتكلفة. كما تستعرض بدائل ناشئة، بما في ذلك بطاريات الحالة الصلبة، والليثيوم–الكبريت، والصوديوم-أيون، باعتبارها مسارات واعدة لتعزيز السلامة والاستدامة وأمن الموارد، رغم أنها لا

تزال تواجه قيودًا تتعلق بمستوى الجاهزية، والمتانة، وإمكانية التكامل على نطاق واسع. وتحلل المقالة كذلك البنية الوظيفية لنظام إدارة البطارية، مع التركيز على الأنظمة الفرعية الأساسية الخاصة بالاستشعار وجمع البيانات، وتقدير الحالة (SOC، SOH، SOP) ، وموازنة الخلايا، والتنسيق الحراري. كما تُظهر الدراسة وجود تحول من الأساليب التقليدية المعتمدة على النماذج نحو الأساليب الهجينة والمدفوعة بالبيانات، بما في ذلك المراقبين التكيفيين وتقنيات التقدير المدعومة بالتعلم الآلي، بهدف تحسين الموثوقية في ظل تقادم البطارية وظروف التشغيل غير المؤكدة. وتشمل التحديات الرئيسية المحددة التدهور الكهروكيميائي، ومخاطر الانفلات الحراري، والإجهاد الناتج عن الشحن السريع، وانحراف الحساسات، وعدم يقين النماذج، والثغرات السيبرانية، إضافة إلى القضايا النظامية المرتبطة بهياكل الجهد العالي، وقابلية توسع حزم البطاريات، والتوافق مع أنظمة المركبة إلى الشبكة(V2G) . وأخيرًا، تستعرض المقالة الاتجاهات المستقبلية التي تركز على المواد المتقدمة من الجيل القادم، والتصاميم المتوافقة مع الشحن فائق السرعة، ومنصات أنظمة إدارة البطارية الذكية والمتصلة، والتوائم الرقمية، والتشخيص السحابي، والإدارة التنبؤية للحالة الصحية. وتخلص الدراسة إلى أن التصميم التكاملي المشترك بين البطارية ونظام إدارتها، المتوافق مع معايير السلامة واستدامة دورة الحياة، يعد أمرًا أساسيًا لتمكين الجيل القادم من التنقل الكهربائي وتسريع إزالة الكربون من قطاع النقل.

الكلمات المفتاحية: المركبات الكهربائية؛ تقنيات البطاريات؛ أنظمة إدارة البطاريات؛ تقدير الحالة؛ تخزين الطاقة الذكي.

1. Introduction

The rapid growth of electric vehicles (EVs) has intensified global research and industrial efforts toward improving battery technologies and their associated battery management systems (BMS) [1]. Batteries represent the most critical and costly component of EV powertrains, directly influencing vehicle range, safety, charging behavior, and total cost of ownership as presented in Figure 1. Recent trends in EV battery development are characterized by the pursuit of higher energy density, enhanced safety, longer cycle life, and reduced reliance on critical raw materials. In parallel, BMS functionality has evolved from basic protection mechanisms into sophisticated control platforms that actively optimize battery performance under diverse and highly dynamic operating conditions [2].

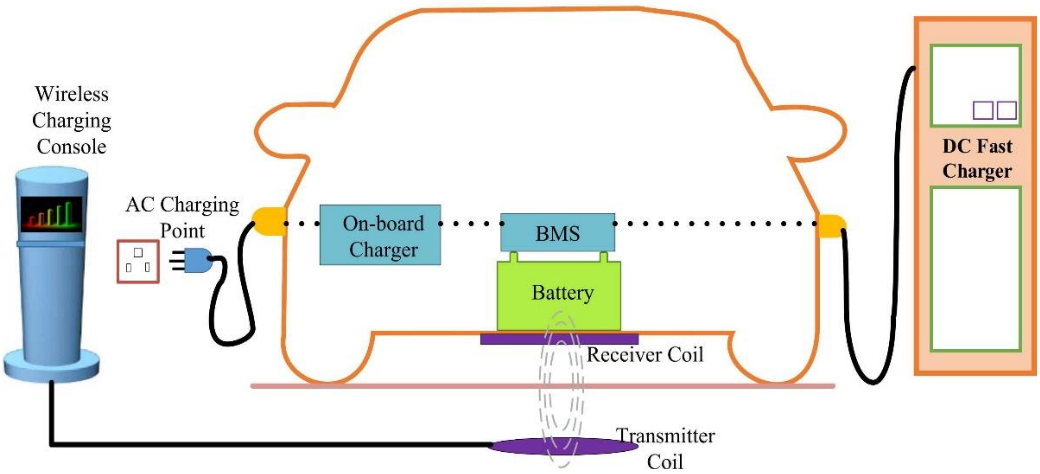

Figure 1. Configuration of the charging system for electric vehicle applications [3].

In thid direction, Lithium-ion battery technologies continue to dominate the EV market, with nickel-manganese-cobalt (NMC), lithium iron phosphate (LFP), and nickel-cobalt-aluminum (NCA) chemistries representing the most widely deployed solutions. Current research trends focus on increasing nickel content to improve energy density, optimizing cathode and anode materials to mitigate degradation, and enhancing electrolyte formulations to support fast charging [4,5]. At the same time, growing interest in LFP chemistry reflects a strategic shift toward safer, longer-life, and lower-cost solutions, particularly for mass-market and fleet applications. These developments demonstrate that battery chemistry selection increasingly depends on application-specific performance requirements rather than a single optimization metric [6,7]. Figure 2 demonstrates several crucial applications of Battery Management Systems in electric vehicle technology.

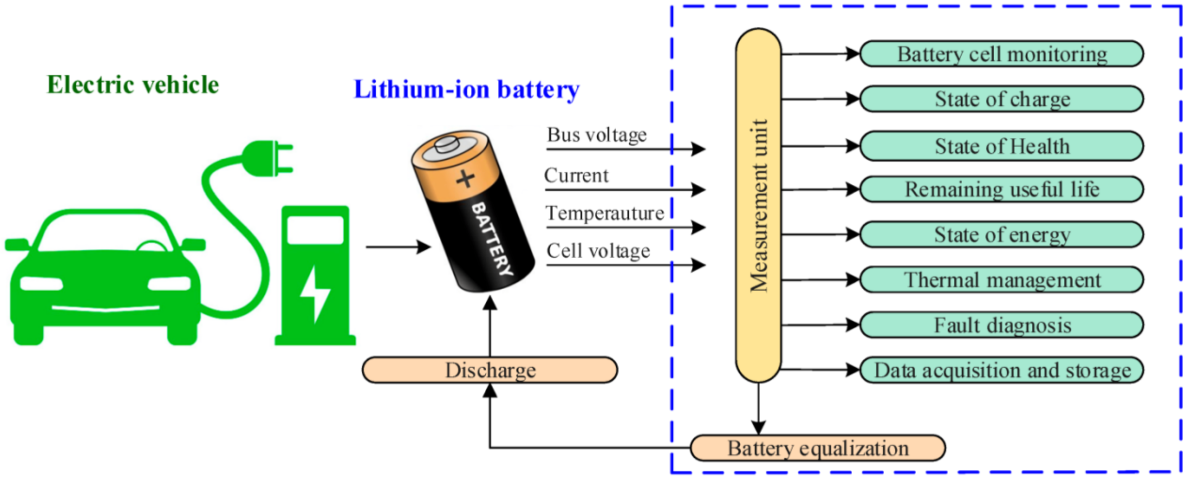

Figure 2. Several crucial applications of Battery Management Systems in electric vehicle technology.

Beyond conventional lithium-ion systems, emerging battery technologies are gaining momentum as potential enablers of next-generation EVs. Solid-state batteries promise improved safety and higher theoretical energy density by replacing flammable liquid electrolytes with solid alternatives, while lithium-sulfur and sodium-ion batteries offer pathways toward material abundance and sustainability. However, challenges related to interfacial stability, limited cycle life, manufacturability, and system integration remain significant barriers to commercialization [8,9]. Recent advances in BMS design reflect a shift toward intelligent and adaptive architectures capable of managing increasingly complex battery systems [10,11]. Core BMS functions-including sensing and data acquisition, state estimation of charge, health, and power, cell balancing, and thermal management, are now augmented by advanced algorithms such as adaptive observers, model predictive control, and machine-learning-assisted estimation [12,13]. These approaches aim to improve robustness against sensor inaccuracies, aging-induced parameter drift, and nonlinear battery behavior. As a result, the BMS has become a central enabler of safety, performance optimization, and battery longevity in modern EVs.

Despite technological progress, several critical challenges continue to constrain the widespread deployment of advanced EV battery systems [14-16]. Electrochemical degradation, thermal runaway risks, and fast-charging-induced stress remain key safety and durability concerns. Additionally, operational challenges such as sensor drift, model uncertainty, and cybersecurity vulnerabilities complicate BMS implementation in connected and high-voltage EV architectures [17-20]. System-level issues related to battery pack scalability, vehicle-to-grid (V2G) compatibility, and heterogeneous battery chemistries further highlight the need for robust, fault-tolerant, and scalable BMS designs [21-24].

In this direction, the future of EV battery systems will be shaped by the co-development of next-generation battery materials and intelligent BMS platforms. Research directions increasingly emphasize battery-BMS co-design, ultra-fast-charging-compatible architectures, and the integration of artificial intelligence, digital twins, and cloud-based diagnostics for predictive health management. In parallel, regulatory frameworks, standardization efforts, and sustainability considerations will play an expanding role in guiding technology adoption [25-27]. Collectively, these trends position advanced battery technologies and intelligent BMS functionality as foundational pillars of EV and global transportation decarbonization.

Several studies have addressed battery technologies and battery management systems for electric vehicles, as summarized below. According to [28], the battery constitutes the primary energy source of an electric vehicle (EV). A variety of storage technologies have been adopted in EV applications, including lithium-ion (Li-ion), nickel-metal hydride, lead-acid, and solid-state batteries, as well as ultracapacitors for high-power buffering. Because EV performance is fundamentally constrained by the onboard energy storage system, deficiencies in battery management system (BMS) design and operation can lead to critical user-level challenges, most notably extended charging durations and limited driving range. Efforts to shorten charging time typically rely on fast-charging strategies that increase charging current, which elevates cell temperature and accelerates degradation, thereby reducing battery lifespan. Moreover, frequent high-rate charge/discharge events-particularly when coupled with regenerative braking can intensify electrochemical and thermal stresses that further exacerbate aging.

In [29], battery management systems (BMS) are identified as essential for maintaining the performance, reliability, and safety of battery packs, largely through accurate estimation of the battery state of charge (SOC). Because onboard SOC estimation, together with other BMS functions can increase design complexity, cost, and energy consumption, the study investigates a data-driven SOC estimation framework for lithium batteries during discharge. Specifically, it evaluates simple linear regression, ensemble learning methods, and neural networks to achieve accurate SOC prediction with reduced computational burden compared with conventional approaches. The models are trained and validated using a large benchmark dataset comprising 835,248 records derived from a $Li[NiMnCo]O_2$ (H-NMC) / Graphite + SiO cell, enabling a systematic comparison to identify the best-performing method in terms of accuracy and time complexity.

In [30], a three-variable control framework integrating both an energy management system (EMS) and a thermal management system (TMS) for a fuel cell/battery hybrid electric vehicle was developed and optimized using particle swarm optimization (PSO). The proposed strategy aims to improve thermal behavior by enhancing temperature stability and shortening temperature rise time, while simultaneously minimizing the total energy consumption of the dual energy sources. To achieve this, the EMS-TMS control policies were formulated as a PSO-based optimization problem and implemented using a model structure with five inputs and three outputs. The control model was informed and validated using prior experimental data, enabling the optimization to be grounded in realistic operating conditions and system dynamics.

This article contributes a unified, system-level synthesis of EV battery technologies and battery management system (BMS) functionality by jointly evaluating the performance trade-offs of dominant lithium-ion chemistries (NMC, LFP, NCA) and emerging candidates (solid-state, lithium-sulfur, sodium-ion) alongside the core BMS architecture and algorithms required to operate these batteries safely and efficiently. It clarifies how chemistry selection governs EV range, charging behavior, thermal requirements, and lifecycle sustainability, while demonstrating that modern BMS platforms, through sensing, SOC/SOH/SOP estimation, balancing, and thermal coordination, are essential to maximizing usable energy and extending service life. The article further consolidates the most critical barriers to deployment, including degradation, thermal runaway, fast-charging stress, sensor/model uncertainty, cybersecurity exposure, and integration challenges associated with high-voltage packs and V2G operation. Finally, it delineates actionable future research directions centered on battery-BMS co-design, intelligent and connected BMS (AI, digital twins, cloud diagnostics), and standards-aligned sustainability pathways, positioning these developments as foundational to scalable electric mobility and transportation decarbonization.

2. State-of-the-Art Battery Technologies for Electric Vehicles

Lithium-ion batteries currently dominate the electric vehicle (EV) market due to their balanced performance in terms of energy density, power capability, efficiency, and commercial maturity. Among the various lithium-ion chemistries, nickel-manganese-cobalt (NMC), lithium iron phosphate (LFP), and nickel-cobalt-aluminum (NCA) systems are the most widely adopted [31,32]. These chemistries underpin the majority of modern EV platforms, enabling competitive driving ranges, acceptable charging times, and declining costs through large-scale manufacturing and supply-chain optimization. Their widespread deployment has positioned lithium-ion technology as the benchmark against which emerging battery systems are evaluated.

NMC batteries offer a flexible design space by adjusting the relative proportions of nickel, manganese, and cobalt, allowing manufacturers to tailor energy density, thermal stability, and cost. High-nickel NMC variants provide superior gravimetric energy density, making them attractive for long-range passenger EVs, while lower-nickel formulations enhance safety and cycle life [33,34]. However, concerns related to cobalt supply risks, thermal runaway under abuse conditions, and degradation during fast charging remain active research challenges. These factors necessitate advanced thermal management and battery management system (BMS) strategies to ensure safe and reliable operation [35,36].

LFP batteries have gained renewed attention due to their intrinsic safety, long cycle life, and reduced reliance on critical raw materials. Although their lower energy density compared to NMC and NCA limits driving range, LFP systems exhibit excellent thermal stability and tolerance to high charge-discharge rates. These characteristics make them particularly suitable for urban EVs, electric buses, and fleet applications where safety, durability, and cost effectiveness outweigh range considerations [37-39]. The growing adoption of LFP technology reflects a broader industry trend toward chemistry selection based on application-specific requirements rather than maximum energy density alone.

NCA batteries are characterized by very high energy density and strong power performance, which have supported their use in premium and high-performance EV segments [40,41]. Nevertheless, their relatively lower thermal stability and higher sensitivity to operating conditions demand sophisticated BMS algorithms and stringent cooling strategies. Material cost and long-term degradation under aggressive driving and fast-charging scenarios also present limitations. As a result, NCA systems highlight the inherent trade-offs between performance optimization and system complexity in advanced EV battery design.

Beyond conventional lithium-ion technologies, several emerging battery chemistries are under intensive investigation. Solid-state batteries promise substantial improvements in energy density and safety by replacing flammable liquid electrolytes with solid electrolytes, potentially enabling higher-voltage operation and compact pack designs. Lithium-sulfur batteries offer exceptionally high theoretical energy density and material abundance, but they face unresolved challenges related to polysulfide shuttling, limited cycle life, and poor rate capability. Sodium-ion batteries, while offering lower energy density, present a cost-effective and resource-secure alternative, particularly for entry-level EVs and energy-intensive mobility applications [42,43].

Collectively, the state of battery technology development underscores the importance of chemistry selection in shaping EV performance, charging behavior, thermal requirements, and environmental impact. High-energy-density chemistries extend driving range but impose stricter safety and cooling demands, whereas safer and more durable systems support longer lifetimes and lower total cost of ownership. As EV adoption accelerates, comparative evaluation of battery chemistries within a lifecycle sustainability framework, encompassing raw material sourcing, manufacturability, recyclability, and second-life potential, can be central to guiding future battery innovation and deployment strategies.

3. Functional Architecture and Core Algorithms of Battery Management Systems

The rapid electrification of the transportation sector has positioned battery management systems (BMS) as a critical enabler of electric vehicle (EV) performance, safety, and reliability as showing in Figure 3. As EV battery packs increase in capacity, voltage level, and architectural complexity, the role of the BMS has expanded beyond basic protection functions toward intelligent supervision and optimization of electrochemical energy storage systems. Modern BMS architectures must operate under highly dynamic driving conditions, variable environmental temperatures, and aggressive charging regimes, all while ensuring compliance with stringent safety and durability requirements [44,45].

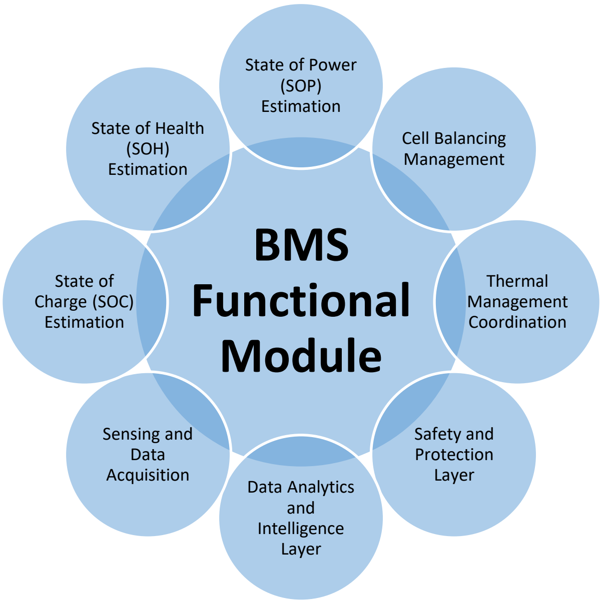

Figure 3. BMS Functional Module.

At the core of a BMS lies a layered functional architecture that integrates sensing and data acquisition, state estimation, cell balancing, thermal management, and safety protection. Accurate measurement of voltage, current, and temperature forms the foundation upon which higher-level algorithms estimate key battery states, including state of charge (SOC), state of health (SOH), and state of power (SOP). These estimated states directly influence vehicle range prediction, power availability, and operational decision-making, thereby linking battery electrochemistry with vehicle-level control strategies [45,46].

Recent advances in BMS design have seen a transition from purely rule-based and equivalent-circuit-model approaches toward hybrid frameworks that incorporate adaptive observers, model predictive control, and machine-learning-assisted estimation. These developments aim to address limitations associated with parameter uncertainty, aging effects, and non-linear battery behavior under real-world conditions. Consequently, the functional architecture of contemporary BMS has evolved into an intelligent, data-driven system capable of predictive diagnostics, fault tolerance, and performance optimization [47,48]. In this context, Table 1 systematically summarizes the functional architecture and core algorithms of EV battery management systems, highlighting the interactions between key subsystems and their impact on vehicle safety, efficiency, and battery longevity. By providing a structured overview of both classical and emerging algorithmic approaches, the table establishes a comprehensive reference framework for understanding current BMS capabilities and identifying future research directions.

Table 1. Functional architecture and core algorithms of battery management systems for EVs [49-69]

BMS Functional Module	Primary Functions	Key Algorithms / Methods	Inputs & Outputs	Impact on EV Performance and Safety
Sensing and Data Acquisition	Real-time monitoring of battery operating conditions	Signal conditioning, sensor fusion, fault detection logic	Inputs: Cell voltage, current, temperature Outputs: Filtered data	Accurate system awareness and early fault detection
State of Charge (SOC) Estimation	Estimation of remaining battery capacity	Coulomb counting, OCV, EKF, adaptive observers, ML models	Inputs: Current, voltage, temperature Outputs: SOC (%)	Reliable range prediction and charging control
State of Health (SOH) Estimation	Assessment of battery aging and degradation	Capacity fade models, impedance analysis, neural networks	Inputs: Cycling data, resistance Outputs: SOH (%)	Predictive maintenance and lifecycle management
State of Power (SOP) Estimation	Determination of available charge/discharge power	Equivalent circuit models, thermal constraints, AI prediction	Inputs: SOC, SOH, temperature Outputs: Power limits	Safe acceleration and regenerative braking
Cell Balancing Management	Equalization of cell voltages and capacities	Passive and active balancing, optimization strategies	Inputs: Cell voltages Outputs: Balancing signals	Extended battery life and usable capacity
Thermal Management Coordination	Control of battery temperature distribution	Rule-based control, MPC, AI thermal optimization	Inputs: Cell temperature, ambient data Outputs: Cooling/heating commands	Prevention of thermal runaway and efficiency improvement
Safety and Protection Layer	Fault detection and emergency response	Threshold logic, anomaly detection, ML fault classification	Inputs: Diagnostic data Outputs: Shutdown or derating	Operational safety and standards compliance
Data Analytics and Intelligence Layer	Advanced diagnostics and prognostics	Machine learning, digital twins, cloud analytics	Inputs: Long-term operational data Outputs: Predictive insights	Adaptive control and intelligent EV services

Table 1 provides a comprehensive overview of the functional architecture and core algorithms that constitute modern battery management systems (BMS) for electric vehicles (EVs), illustrating how multiple subsystems operate in a coordinated manner to ensure safe, efficient, and durable battery operation. The table 1 highlights the hierarchical structure of the BMS, starting from low-level sensing and data acquisition and extending to higher-level intelligence and analytics, thereby reflecting the increasing complexity and functional integration required in contemporary EV platforms.

The sensing and data acquisition module forms the foundation of the BMS architecture, as all subsequent control and estimation functions depend critically on the accuracy and reliability of measured voltage, current, and temperature signals. The inclusion of signal conditioning and sensor fusion techniques underscores the need to mitigate noise, sensor drift, and measurement uncertainties, which can otherwise propagate errors into higher-level state estimation algorithms. Reliable sensing is therefore indispensable for early fault detection and for maintaining battery operation within safe electrochemical and thermal limits.

State estimation functions specifically state of charge (SOC), state of health (SOH), and state of power (SOP), represent the analytical core of the BMS. As summarized in the table 1, a wide spectrum of algorithms is employed, ranging from classical coulomb counting and equivalent circuit models to advanced adaptive observers and machine-learning-based methods. This diversity reflects the inherent trade-off between model transparency and estimation accuracy. While traditional approaches remain attractive due to their low computational burden, data-driven techniques offer enhanced robustness against nonlinear behavior, aging effects, and variable operating conditions, which are increasingly prominent in real-world EV usage.

Cell balancing and thermal management modules directly address the spatial non-uniformities that arise within large battery packs. The table 1 highlights both passive and active balancing strategies, emphasizing their role in mitigating cell-to-cell voltage and capacity mismatches that accelerate degradation. Similarly, thermal management coordination, often integrated with predictive or AI-assisted control, plays a critical role in preventing thermal runaway, reducing temperature gradients, and stabilizing degradation rates. Together, these functions contribute significantly to extending battery lifespan and improving overall system reliability.

The safety and protection layer, as detailed in the table 1, represents a non-negotiable component of BMS architecture, tasked with fault detection, isolation, and emergency response. The increasing adoption of anomaly detection and machine-learning-based fault classification reflects growing concerns over cyber-physical security, sensor failures, and complex fault modes in high-voltage EV systems. These advanced safety mechanisms are essential for meeting stringent regulatory standards and for maintaining user trust in electric mobility technologies.

Finally, the data analytics and intelligence layer illustrate the ongoing evolution of BMS from embedded control units toward intelligent, connected platforms. By leveraging long-term operational data, machine learning, and digital twin concepts, this layer enables predictive diagnostics, adaptive control, and integration with cloud-based services. As indicated in the table 1, such capabilities are expected to play a pivotal role in future EV ecosystems, supporting vehicle-to-grid interactions, fleet-level optimization, and sustainable battery lifecycle management. Overall, The study discusses that the effectiveness of a battery management system lies not in individual algorithms but in the seamless integration of functional modules across sensing, control, safety, and intelligence layers. This holistic architectural perspective is essential for addressing the growing performance, safety, and sustainability demands of next-generation electric vehicles.

4. Key Technical, Operational, and Integration Challenges in EV Battery Technologies and BMS

The rapid evolution of electric vehicle (EV) technologies has intensified the technical and operational demands placed on battery systems and their associated battery management systems (BMS). As EV batteries scale toward higher energy densities, faster charging capabilities, and increased system voltages, a wide range of challenges emerge that directly affect safety, reliability, and lifecycle performance [70,73]. These challenges are not limited to electrochemical limitations of battery cells but extend to sensing accuracy, control robustness, system integration, and cyber-physical security within increasingly complex vehicular architectures. From a battery technology perspective, degradation mechanisms such as solid–electrolyte interphase growth, lithium plating, and structural electrode fatigue continue to limit long-term performance, particularly under aggressive fast-charging and high-power operation. Simultaneously, thermal runaway risks and non-uniform temperature distributions pose critical safety concerns in large battery packs. Addressing these issues requires BMS platforms capable of real-time monitoring, predictive thermal regulation, and dynamic power limitation to ensure operation within safe electrochemical and thermal boundaries [74-77].

Operational challenges further complicate BMS implementation, as accurate state estimation is hindered by sensor noise, calibration drift, and model uncertainty arising from aging and environmental variability. Traditional model-based approaches often struggle to maintain estimation fidelity under real-world driving conditions, motivating the integration of adaptive observers and data-driven techniques.

Moreover, the increasing connectivity of EVs exposes BMS architectures to cybersecurity threats, necessitating secure communication protocols and resilient fault-detection mechanisms [78-81]. At the system-integration level, high-voltage architectures, vehicle-to-grid (V2G) functionality, and the scalability of large battery packs introduce additional layers of complexity. Bidirectional power flow and heterogeneous battery chemistries demand flexible, chemistry-aware BMS designs that can adapt to diverse operational profiles without compromising safety or durability. In this context, Table 2 systematically categorizes the key technical, operational, and integration challenges confronting EV battery technologies and BMS implementations, while highlighting the corresponding design requirements needed to achieve robust, fault-tolerant, and future-ready battery management solutions.

Table 2. Key technical, operational, and integration challenges in EV battery technologies and BMS [82-95].

Challenge Category	**Specific Challenge**	**Description and Root Causes**	**Implications for EV Operation**	**BMS Design Requirements / Mitigation Strategies**
Electrochemical and Aging Challenges	Battery degradation mechanisms	Capacity fade and resistance growth due to SEI formation, lithium plating, electrode aging	Reduced driving range and shortened battery lifespan	Advanced SOH estimation, aging-aware control strategies
Electrochemical and Aging Challenges	Fast-charging-induced stress	High C-rates causing thermal stress and lithium plating	Safety risks and accelerated degradation	Dynamic charge control and temperature-aware charging
Thermal and Safety Challenges	Thermal runaway risk	Exothermic reactions from overcharge or internal faults	Fire hazards and catastrophic failure	Redundant sensing and predictive thermal management
Thermal and Safety Challenges	Non-uniform temperature distribution	Thermal gradients within large battery packs	Uneven aging and localized hotspots	Model predictive thermal control and active cooling
Measurement and Modeling Challenges	Sensor inaccuracies and drift	Noise, aging, and calibration errors	Inaccurate state estimation	Sensor fusion and fault detection algorithms
Measurement and Modeling Challenges	Model uncertainty and nonlinearity	Parameter variation with SOC, temperature, and aging	SOC/SOH/SOP estimation errors	Adaptive observers and hybrid models
Control and Balancing Challenges	Cell imbalance in large packs	Manufacturing tolerances and uneven aging	Reduced usable capacity	Active balancing and optimization-based control
Cybersecurity and Reliability Challenges	Cybersecurity vulnerabilities	Increased connectivity exposing cyber-physical attacks	Unsafe control actions	Secure communication and anomaly detection
Cybersecurity and Reliability Challenges	Fault tolerance and robustness	Component failures in harsh environments	Unexpected shutdowns	Redundant and fault-tolerant BMS design
System-Level Integration Challenges	High-voltage architecture complexity	Insulation, isolation, and safety constraints	Increased system cost	Integrated HV protection and standards compliance
System-Level Integration Challenges	Vehicle-to-Grid (V2G) compatibility	Bidirectional power flow increasing cycling stress	Accelerated aging and control complexity	V2G-aware BMS and lifecycle management
System-Level Integration Challenges	Scalability for large battery packs	High cell count increases computation and communication load	Latency and reliability issues	Modular and distributed BMS architectures

Heterogeneity and Real-World Operation	Diverse battery chemistries	Different electrochemical behaviors across chemistries	Limited control generalization	Chemistry-aware and adaptive BMS
Heterogeneity and Real-World Operation	Real-world usage variability	Aggressive driving and extreme climates	Uncertain performance prediction	Data-driven and predictive BMS strategies

Table 2 presents a structured synthesis of the principal challenges affecting electric vehicle (EV) battery technologies and battery management system (BMS) implementation, emphasizing their multifaceted nature across electrochemical, thermal, control, and system-integration domains. The table demonstrates that many of these challenges are deeply interdependent, requiring coordinated mitigation strategies rather than isolated technical solutions. As EV architectures evolve toward higher energy densities and increased system complexity, these challenges become more pronounced and demand increasingly intelligent and resilient BMS designs.

The electrochemical and aging challenges summarized in the table highlight battery degradation as a dominant constraint on EV performance and lifetime. Mechanisms such as solid-electrolyte interphase growth and lithium plating are exacerbated by fast charging and high-power operation, leading to capacity fade and resistance growth. These degradation processes not only reduce driving range but also increase safety risks, underscoring the need for aging-aware control strategies and accurate state-of-health estimation. The table clearly illustrates how BMS functionality must evolve from static protection toward adaptive, degradation-informed management.

Thermal and safety-related challenges form another critical category, particularly in large battery packs where non-uniform temperature distributions are difficult to avoid. As shown in the table, thermal runaway risks and localized hotspots can result from both internal cell failures and external operating conditions. Predictive thermal management, supported by redundant sensing and advanced control algorithms, is therefore essential to maintaining safe operating margins. These findings reinforce the role of the BMS as a safety-critical system rather than a purely supervisory controller.

Measurement and modeling challenges, including sensor inaccuracies and model uncertainty, significantly influence the reliability of BMS decision-making. The table highlights that errors at the sensing level propagate through state estimation algorithms, potentially leading to incorrect SOC, SOH, or SOP values. This issue becomes particularly severe as batteries age or operate under extreme environmental conditions. The increasing adoption of sensor fusion, fault detection and isolation, and hybrid physics-data-driven models reflects a shift toward more robust estimation frameworks capable of handling real-world variability.From a control and integration perspective, the table underscores the complexity introduced by large-scale battery packs, high-voltage architectures, and vehicle-to-grid (V2G) operation. Cell imbalance, communication latency, and bidirectional power flow introduce new stress factors that conventional BMS architectures were not originally designed to address. Modular, distributed, and hierarchical BMS designs emerge as key enablers for scalability and flexibility, allowing effective management of thousands of cells while maintaining system reliability.

Finally, the inclusion of cybersecurity and real-world operational challenges in Table 2 reflects the growing convergence between energy storage, digital control, and connected vehicle ecosystems. Increased connectivity exposes BMS platforms to cyber-physical threats, while diverse battery chemistries and highly variable driving behaviors complicate control generalization. The table clearly indicates that future BMS solutions must be fault-tolerant, chemistry-aware, and intelligent, integrating predictive analytics and secure communication to ensure long-term safety and performance. Overall, The article demonstrates that addressing the challenges of EV battery technologies and BMS implementation requires a holistic, system-level approach. The effectiveness of future EVs will depend not only on advances in battery materials but also on the development of robust, adaptive, and secure BMS architectures capable of managing complexity across the entire battery lifecycle.

5. Future Prospects and Research Directions for Intelligent EV Battery Systems

The continued global transition toward electric mobility places unprecedented demands on battery technologies and battery management systems (BMS), positioning them as central enablers of vehicle performance, safety, and sustainability. As electric vehicles (EVs) evolve toward higher energy densities, ultra-fast charging capability, increased system voltages, and bidirectional grid interaction, conventional battery designs and rule-based BMS architectures are approaching their practical limits [96-100]. Recent advances in materials science, particularly in solid-state electrolytes, lithium-metal anodes, and high-voltage cathodes, offer promising pathways to improve energy density and intrinsic safety [101-104]. However, these next-generation chemistries introduce fundamentally different electrochemical behaviors, thermal sensitivities, and degradation mechanisms that challenge existing BMS models and control strategies. At the same time, consumer demand for ultra-fast charging and extended battery lifetime intensifies the need for predictive control, real-time power limitation, and degradation-aware energy management [105-109].

Parallel to material innovation, the rapid digitalization of EV platforms is driving the evolution of BMS from embedded supervisory controllers to intelligent cyber-physical systems. Artificial intelligence, digital twins, cloud connectivity, and predictive health management are emerging as key tools for enhancing state estimation accuracy, fault prognosis, and lifecycle optimization [110-113]. These technologies enable continuous learning from real-world operation but also raise new challenges related to cybersecurity, data governance, and functional safety. Within this context, this section outlines future prospects and research directions for intelligent EV battery systems, emphasizing the co-development of advanced battery materials and intelligent BMS architectures [114-119]. By integrating technological, regulatory, and sustainability perspectives, the discussion positions intelligent battery systems as a cornerstone of next-generation electric mobility and a critical contributor to transportation decarbonization.

A. Next-Generation Battery Materials and Solid-State Integration

Future EV battery development will increasingly depend on materials innovation that simultaneously improves energy density, safety, and lifecycle durability while reducing exposure to critical-material constraints. Solid-state batteries (SSBs) are a central pathway because they replace flammable liquid electrolytes with solid electrolytes (sulfides, oxides, polymers, or composites), enabling potentially higher-voltage operation and improved thermal stability. In principle, SSBs may facilitate lithium-metal anodes, which can significantly increase specific energy; however, practical deployment remains constrained by interfacial contact loss, dendrite formation, mechanical cracking, and impedance growth at solid-solid interfaces.

A key research direction is interface engineering, including protective coatings, graded interfaces, and mechanically compliant interlayers, to reduce interfacial resistance and suppress short-circuit pathways. Parallel efforts in cathode design focus on high-nickel and high-voltage materials, which demand electrolyte stability and robust cathode–electrolyte interphases. From a systems perspective, SSB integration will require BMS frameworks that can handle different OCV–SOC relationships, temperature sensitivity, and failure modes compared with conventional Li-ion. Therefore, battery materials research must be linked explicitly with BMS co-design to ensure that the controls and diagnostics are compatible with new chemistry behavior.

B. Ultra-Fast Charging and High-Power Battery System Design

Ultra-fast charging (UFC) is a dominant consumer requirement and a practical barrier to mass adoption, but it introduces severe electrochemical and thermal stresses. At high C-rates, batteries are vulnerable to lithium plating, accelerated SEI growth, and internal resistance increase-mechanisms that degrade capacity and elevate safety risks. Thus, research must shift from simply increasing charge power to designing charge protocols and pack architectures that sustain UFC while preserving lifetime.

Promising directions include adaptive charging profiles that respond to real-time battery states (SOC, temperature, internal resistance) rather than fixed current limits. Thermal systems will also move beyond conventional cooling to integrated approaches such as immersion cooling, advanced heat spreaders, and predictive thermal scheduling. In parallel, advanced state-of-power (SOP) estimation must consider electrochemical constraints and thermal margins to prevent operation near unsafe regions. The core challenge is optimizing the triad of charging speed–safety–degradation, which demands integrated models coupling kinetics, aging, and heat generation, implemented through computationally efficient algorithms suitable for onboard controllers.

C. Intelligent and AI-Driven Battery Management Systems

The next generation of BMS will increasingly adopt hybrid intelligence, combining physics-informed models with machine learning (ML) to improve robustness under real-world variability. Classical equivalent circuit and electrochemical models provide interpretability and control stability, but often lose accuracy under aging, manufacturing variability, and temperature extremes. ML can enhance estimation and prediction (SOC, SOH, remaining useful life) when trained on large datasets, but it must be constrained to ensure safety-critical reliability.

Research priorities include physics-informed ML, where learning is bounded by conservation laws and known battery behavior, improving generalization and reducing data requirements. AI can also enable fault prognosis (early detection of internal shorts, thermal anomalies, sensor drift), adaptive balancing, and dynamic power limiting based on predicted risk. However, deployment requires addressing challenges such as dataset bias, lack of labeled failure data, and explainability for safety certification. Consequently, intelligent BMS research must include validation protocols, uncertainty quantification, and safe fallback logic so that the system remains stable even when the AI component is uncertain or wrong.

D. Digital Twins, Connectivity, and Cloud-Based Battery Intelligence

Digital twins represent a major shift from isolated onboard management to continuous lifecycle intelligence. A battery digital twin uses a combination of real-time sensor streams and calibrated models to simulate battery behavior, predict degradation trajectories, and recommend control actions. In EV fleets, this enables remote diagnostics, predictive maintenance, and fleet-level optimization, especially when batteries experience diverse usage patterns and environmental conditions.

A key research direction is the partitioning of intelligence between onboard and cloud: safety-critical functions must remain onboard, while computationally heavy analytics, such as long-horizon degradation forecasting or population-level learning, can be offloaded. This architecture introduces new challenges: communication latency, intermittent connectivity, data integrity, cybersecurity, and privacy. It also requires standardized data pipelines and robust synchronization between the physical battery and its twin. Future systems will likely incorporate federated learning to learn across fleets without transferring raw private data, enabling scalable improvement of models while respecting confidentiality constraints.

E. Standardization, Sustainability, and Battery–BMS Co-Design for Decarbonization

As EV deployment scales globally, future battery systems must meet not only performance targets but also stringent requirements for safety compliance, sustainability, and circular economy integration. Standardization will expand beyond basic safety to include guidelines for fast charging behavior, V2G cycling impacts, diagnostic reporting, and cybersecurity. Intelligent BMS will be central to demonstrating compliance because it governs safe operating boundaries and produces traceable diagnostics for certification and warranty.

Sustainability research priorities include battery design choices that reduce lifecycle emissions, support ethical material sourcing, and enable recycling and second-life deployment (e.g., stationary storage). Battery passports and lifecycle tracking will demand BMS capabilities for traceability, reliable health reporting, and standardized indicators of degradation. Critically, the agenda emphasizes battery–BMS co-design: chemistry selection, pack thermal architecture, sensing strategy, and control algorithms must be optimized together. This integrated approach is essential to minimize degradation under real usage, improve total cost of ownership, and ensure that EV batteries deliver maximum decarbonization benefit across their entire lifecycle. The future of electric vehicle battery systems can be defined not by isolated advances in materials or control algorithms, but by the co-evolution of battery technologies and intelligent battery management systems. As highlighted in this section, next-generation materials such as solid-state electrolytes and lithium-metal anodes offer transformative potential in terms of energy density and safety, yet their successful deployment depends on BMS platforms capable of handling new electrochemical dynamics and failure modes. Similarly, ultra-fast charging, while essential for widespread EV adoption can only be realized sustainably through predictive, degradation-aware control strategies tightly integrated with advanced thermal management.

The transition toward AI-driven, connected BMS architectures represents a fundamental shift in how batteries are monitored, controlled, and optimized throughout their lifecycle. Intelligent estimation, digital twins, and cloud-based analytics enable unprecedented visibility into battery health and usage, supporting predictive maintenance, fleet-level optimization, and second-life applications. However, these benefits must be balanced against challenges related to explainability, cybersecurity, and compliance with safety-critical automotive standards. From a broader perspective, future research must increasingly adopt a systems-level and lifecycle-oriented approach, integrating performance optimization with sustainability, standardization, and circular economy objectives. Battery-BMS co-design emerges as a central principle, ensuring that material selection, pack architecture, sensing strategies, and control algorithms are jointly optimized for safety, durability, and environmental impact. Ultimately, intelligent EV battery systems will play a decisive role in enabling scalable electric mobility, reducing greenhouse gas emissions, and supporting resilient, low-carbon energy systems.

6. Conclusion

This article has provided a comprehensive synthesis of battery technologies and battery management system (BMS) functionality for electric vehicles (EVs), addressing their current status, key challenges, and future perspectives within a unified framework. The review of state-of-the-art battery technologies demonstrates that lithium-ion chemistries, particularly NMC, LFP, and NCA, continue to dominate the

EV market due to their relative maturity and balanced performance in terms of energy density, power capability, safety, and cost. At the same time, emerging alternatives such as solid-state, lithium-sulfur, and sodium-ion batteries highlight promising pathways to overcome material scarcity, safety limitations, and sustainability concerns, albeit with clear trade-offs in technological readiness, durability, and system integration. These findings underscore that battery chemistry selection remains a decisive factor shaping EV range, charging behavior, thermal requirements, and lifecycle environmental impact.

The analysis of BMS functional architecture emphasizes that modern EV batteries cannot operate safely or efficiently without advanced management and control. Core BMS functions, including sensing and data acquisition, state estimation (SOC, SOH, and SOP), cell balancing, and thermal management, form an integrated control hierarchy that links electrochemical behavior to vehicle-level performance. The comparison between classical model-based approaches and emerging data-driven methods reveals a clear trend toward hybrid frameworks, where adaptive observers and machine-learning-assisted algorithms enhance robustness under aging, uncertainty, and highly dynamic operating conditions. Consequently, the BMS is no longer a passive protection layer but an active intelligence layer that maximizes usable energy, extends battery lifespan, and ensures safety across diverse driving and environmental scenarios.

Despite significant progress, the article highlights several unresolved technical, operational, and integration challenges that continue to constrain EV battery systems. Battery degradation, thermal runaway risk, and fast-charging-induced stress remain critical barriers to long-term reliability and user acceptance. These challenges are compounded by sensor inaccuracies, model uncertainty, cybersecurity vulnerabilities, and system-level complexities associated with high-voltage architectures, large-scale battery packs, and vehicle-to-grid (V2G) operation. Addressing these issues requires robust, fault-tolerant, and scalable BMS designs capable of operating across heterogeneous battery chemistries and real-world usage profiles, reinforcing the need for system-level thinking rather than isolated component optimization.

Moreover, the future of EV battery systems lies in the co-evolution of next-generation battery materials and intelligent BMS platforms. Advances in solid-state integration, ultra-fast charging compatibility, and high-energy-density materials must be accompanied by intelligent, connected BMS architectures incorporating artificial intelligence, digital twins, and cloud-based diagnostics. Such systems will enable predictive health management, lifecycle optimization, and compliance with evolving safety and sustainability standards. Ultimately, this review demonstrates that advanced battery–BMS co-design is a cornerstone of next-generation electric mobility, playing a pivotal role in transportation decarbonization, energy system integration, and the realization of sustainable, resilient EV ecosystems.

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