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BATTERY MANAGEMENT SYSTEMS FOR ELECTRIC VEHICLES: A REVIEW OF STATE-OF-THE-ART TECHNOLOGIES

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Abstract

Battery management systems (BMS) play a crucial role in safety, performance and life span of the electric vehicle (EV) batteries. The paper will give a detailed overview of the current state of art BMS technologies, and also determine the gaps in innovation that are preventing further development. The paper explores the latest trends in estimation of SOC/SOH, cooling, the integration of AI and IoT, as well as sustainability based on the evidence of literature, large-scale databases (EVBattery, PulseBat, CALCE, VED), and recent patent studies. Results indicate that the current designs of BMS are technically advanced, but they have drawbacks regarding dynamic accuracy, predictive thermal control, secure deployment of IoT, and integration of sustainability concepts. The study suggests an original framework that integrates an estimation model based on hybrid AI, predictive thermal management, cloud analytics based on the IoT, and a sustainability module to overcome these problems. This model embraces systematic innovation principles in solving contradictions between safety, cost, performance, and environmental responsibility. It guarantees adaptive decisions, greater safety, and eco-friendly design to meet the demands of the new industry and regulatory trends. The paper covers the implications that this framework has on a variety of aspects of technology, including the possibility to revolutionize BMS technologies and highlight the challenges that the framework faces in regards to cybersecurity, data needs, and mass adoption. The suggested method provides a clear path to the development of next-generation BMS both as academically important work and an industrial product in the developing area of electric mobility.

Keywords: Battery Management System, Electric Vehicles, SOC/SOH Estimation, Predictive Thermal Management, Artificial Intelligence, Sustainability.

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1. Introduction

The global push towards sustainable transportation has accelerated the adoption of electric vehicles (EVs), positioning the battery management system (BMS) as a pivotal technology in ensuring the efficiency, safety, and longevity of lithium-ion batteries. Some of the important parameters that are monitored and controlled by the BMS include state of charge (SOC), state of health (SOH), cell temperature, and cell voltage to avoid failure and to maximize battery performance (Xing et al., 2011; Tie & Tan, 2013). With the automotive sector on its way to advanced electrification, the need to have smarter and more innovative BMS solutions is increasing (Rahimi-Eichi et al., 2013; Ehsani et al., 2021). In the past, there has been a considerable improvement in the BMS technologies, and these advancements include enhanced SOC/SOH estimation algorithms, smart thermal management and energy optimization systems (Park et al., 2020; Hannan et al., 2018). However, current systems still face persistent challenges. They are low accuracy of estimations in dynamic driving conditions, high sensitivity to parameter changes, and absence of robust predictive thermal models, as well as low scalability of AI-based control solutions (Ali & Söffker, 2018; Laadjal & Cardoso, 2021). Also, the use of second-life batteries and sustainability are still underdeveloped in the current designs (Tao et al., 2025; Biswas & Emadi, 2019). These challenges also present an urgent demand to methods that not only enhance the current technologies, but also bring systematic innovation to discover and overcome inherent contradictions in the development of BMS.

Several studies have reviewed different aspects of BMS. Most of the SOC estimation methods were analyzed by Hannan et al. (2018) and Ali et al. (2019), whereas Chemali et al. (2016) and Hossain Lipu et al. (2022) concentrated on thermal management. The study by Dehury & Samal (2025) and Xiong & Shen (2019) considered how artificial intelligence can improve the decision-making process of BMS. Simultaneously, patent studies conducted by Wan et al. (2025) and Tong & Zhu (2025) have identified new trends and gaps in the existing technologies, which can be seen as the opportunities to develop innovative solutions. Although the extant literature is vast, majority of reviews are descriptive and fail to systematically determine the opportunities of innovation that can be used in future.

This paper aims to critically evaluate the current state of the art BMS technologies and determine gaps in innovation that can be used to design the next generation of solutions. This research will specifically seek to: (1) review the current BMS technologies and their shortcomings, (2) evaluate the trend of innovations by carrying out patent search and new research and (3) develop a framework of how technological advancements can be matched with organized innovation strategies.

This combination strategy will guarantee that the paper not only remains a cumulation of what has been known before but also offers practical information on the development of BMS in electric cars. To pursue these goals, the paper relies on various sources of evidence, including big-data, including databases of EVBattery (He et al., 2022), PulseBat (Tao et al., 2025), CALCE Battery Data Repository (Pecht et al., 2025), and Vehicle Energy Dataset (Oh et al., 2020), as well as on recent patent studies (Van Mierlo et al., 2021; Camargos et al., 2022). These sources give empirical basis of assessing the existing trends and future innovation opportunities. This extensive review has provided the basis of a new insight on BMS research and the insights illustrated are useful to both academic researchers and industrial practitioners who are seeking the development of efficient, safe, and sustainable EV technologies.

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2. Literature Review

The study of battery management systems (BMS) of electric vehicles (EVs) has been developing in the past twenty years due to the growing demand in the improvement of performance, safety, and sustainability. The initial efforts were tailored to simple monitoring and control of battery variables including voltage, current, and temperature (Conte, 2006; Xing et al., 2011). These early BMS designs offered crude SOC estimation and could not do the advanced diagnostics and prognostics needed in contemporary EVs. With the passage of time, the growth of computational intelligence and the use of sensors have made it possible to produce sophisticated methods of SOC and SOH estimation. The review by Rahimi-Eichi et al. (2013) and Ali et al. (2019) compared several model-based and data-driven estimation techniques of SOC and pointed out the trade-offs between estimation accuracy and computational complexity. Hannan et al. (2018) and Park et al. (2020) gave broad evaluations of state estimation algorithms, with challenges on parameter sensitivity, nonlinear battery behaviour, and performance degradation in dynamic situations. All these reviews point to the fact that although better estimates of SOC/SOH are obtained, real-time accuracy at different load conditions is still a big challenge.

The BMS research has also been of particular concern in terms of thermal management. Poor thermal control may result in an increased rate of battery degradation and safety risks. According to Chemali et al. (2016) and Laadjal & Cardoso (2021), the development of integrated thermal models that incorporate both electrochemical and thermal processes to avoid thermal runaway, is important. The more recent methods such as bio-inspired cooling and AI predictive models appear as a promising solution (Hossain Lipu et al., 2022). Parallel to that, the combination of AI and IoT in BMS has created new opportunities. Dehury & Samal (2025) introduced the overview of smart algorithms and control strategies that rely on the use of machine learning predictive diagnostics, anomaly detection, and adaptive energy management. Xiong & Shen (2019) addressed the benefits of AI-based BMS to decision-making, yet they emphasized the problems of explainability and robustness. According to recent surveys conducted by Skouras et al. (2019) and Iqbal et al. (2023), the gap remains in finding applications of AI that are capable of reliable operation in real-life driving scenarios despite these improvements.

Sustainability and the use of second-life batteries has also been a topic of interest. The PulseBat dataset presented by Tao et al. (2025) offers valuable data to the understanding of second-life diagnostics via rapid pulse testing. The Tong & Zhu (2025) patent analyses indicated the emergence of the recycling and repurposing technologies of battery electrodes, which proved the connection between sustainability and innovation in the field of BMS. Moreover, Barbosa et al. (2022) employed bibliometric research to derive the latest trends in the EV research scenario, which implies the increasing popularity of a circular economy. Patent-driven innovation is becoming increasingly relevant. To illustrate the patent analysis of EV BMS technologies, Wan et al. (2025) considered the trend of innovations in the field of safety, fast charging, and compact design. These results back the significance of the systematic methods to find contradictions and possibilities of breakthrough innovations, namely, TRIZ and entropy-based methods. These discussions are in line with the goal of this paper to inculcate systematic innovation in the evaluation of BMS technologies. The results of the previous research and to demonstrate the connection between contributions in the study and the gaps, Table 1 provides an overview of the existing literature. This table organizes the studies into focus areas, highlights the major contributions made by the studies and also points at the unsolved problems that this paper seeks to solve.

Received: August 07, 2025

Table 1. Summary of Key Literature on BMS Technologies and

Focus Area	Key References	Main Contributions	Identified Gaps
SOC/SOH Estimation Techniques	Rahimi-Eichi et al. (2013); Ali et al. (2019); Hannan et al. (2018)	Compared model-based vs. data-driven methods; identified performance trade-offs	Limited accuracy under dynamic conditions and parameter variations
Thermal Management	Chemali et al. (2016); Laadjal & Cardoso (2021); Hossain Lipu et al. (2022)	Developed models for thermal regulation; explored AI/bio-inspired cooling	Lack of robust predictive models preventing thermal runaway
AI and Smart Algorithms	Dehury & Samal (2025); Xiong & Shen (2019)	Applied AI for predictive diagnostics and adaptive energy control	Scalability, explainability, and robustness issues
Sustainability & Second-Life Use	Tao et al. (2025); Tong & Zhu (2025); Barbosa et al. (2022)	Analyzed second-life batteries; patent analysis on recycling technologies	Insufficient integration with BMS innovation frameworks
Patent and Innovation Analysis	Wan et al. (2025); Garg et al. (2016)	Applied AHP/entropy methods; identified innovation trends in BMS	Lack of TRIZ-based systematic innovation applications

3. Methodology

This section explains the systematic methodology followed in order to critically examine the prevailing position of battery management systems (BMS), detect the gaps in innovation, and suggest an innovation-based framework. The approach combines three main components, including a thorough analysis of the literature, empirical data analysis, and an evaluation of patent landscapes, which result in the creation of an organized innovation map. The methodology allows the consideration of a multi-dimensional analysis of BMS technologies due to an extensive review of academic literature, empirical datasets, and patent evidence. The comprehensive strategy is not only able to capture the state-of-the-art, but also determines the innovation gaps necessary to advance the next generation of BMS solutions.

3.1. Literature Collection and Evaluation

It was followed by the collection and analysis of the existing research on BMS technologies in extensive sources, such as journal articles, conference proceedings, and technical reports. The chosen 30 sources of the presented research were divided into four thematic topics: the methods of estimating SOC/SOH, thermal management strategies, AI and IoT integration into BMS, and innovation trends such as sustainability and patent analyses. All the references were evaluated in terms of their technological contribution, limitations and relevance to realization of opportunities in systematic innovation. To ensure quality, only peer-reviewed works and credible patent studies were included. The choice made it possible to make the review as extensive as possible, including not only those articles that formed the basis of research, like Conte (2006), but also new and significant works, such as Dehury & Samal (2025). The inclusion criteria included in this process are summarized in Table 2.

Table 2. Criteria for Literature Inclusion and Evaluation

Criteria	Description	Outcome
Relevance	Focus on BMS technologies, SOC/SOH estimation, thermal management, AI, IoT, and innovation strategies.	30 high-quality studies selected.
Publication Quality	Indexed journals, conferences, and credible patent reports.	Ensured reliability and depth of analysis.

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Innovation Insight	Evidence of gaps, contradictions, or emerging trends.	Guided innovation-focused evaluation.
Time Frame	Studies published between 2006–2025.	Captured historical and current advancements.

3.2. Dataset Selection and Utilization

In addition to the literature review, this work included open-access databases which provide practical evidence to examine BMS performance and innovation opportunity. Four datasets were chosen according to the scope of coverage SOC/SOH estimation, diagnostics, and vehicle energy patterns:

- EVBattery (He et al., 2022) - Big-data of EVs, which allows defining shortcomings in the accuracy of SOC/SOH estimation.
- PulseBat (Tao et al., 2025) - The data of retired batteries in pulse conditions, which can be used to inform about second-life battery diagnostics.
- CALCE Battery Data Repository (Pecht et al., 2025) - Annotated experimental cycling data to test techniques of estimating SOC.
- Vehicle Energy Dataset (VED) (Oh et al., 2020) Vehicle Energy Dataset (VED) is a large-scale data that helps to learn more about the energy consumption of vehicles and its interaction with BMS.

The datasets were analyzed in terms of their parameters and their suitability towards the study of innovation and their compatibility with the objectives of BMS research. They were not put under experimental testing but as a yardstick to determine the current shortcomings and technological gaps. Table 3 summarizes the datasets and their relevance to the study.

Table 3. Selected Datasets and Their Relevance

Dataset	Key Features	Application in this Study
EVBattery	Real-world EV battery charge/discharge data	Highlights gaps in SOC/SOH estimation and AI-based control.
PulseBat	Second-life battery diagnostic data	Supports development of repurposing and diagnostic innovations.
CALCE Repository	Annotated experimental cycling data	Serves as a benchmark for validating SOC estimation algorithms.
Vehicle Energy Dataset (VED)	Energy consumption data across EVs	Links BMS development to vehicle-level energy optimization.

3.3. Patent Landscape Analysis

The next step involved analyzing the patent landscape to uncover innovation trends and emerging opportunities in BMS technology. Patents by Wan et al. (2025) and Tong & Zhu (2025) were considered, and the innovations concerned technology in safety improvement, energy use, and recycling. These examinations were cross-checked with the information provided in publicly available patent databases such as Google Patents and Lens.org to be comprehensive. This analysis has identified major gaps that are less identified in the academic literature by sorting patents into categories (safety, charging efficiency, compactness and sustainability). The synthesis of scholarly and patent data allowed to get the more comprehensive picture of the innovation potential in BMS.

3.4. Innovation Mapping and Synthesis

The last step was to synthesize the information of literature, datasets, and patents into a complete innovation map. This procedure found areas of contradiction in existing technologies, including the

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safety versus energy density of batteries or the fast charging versus long-term life example. These inconsistencies were associated with possible innovation strategies, which are explained in more details in the following sections.

- The mapping process followed three steps:
- Categorizing technologies by maturity and limitations.
- Linking evidence from datasets and patents to innovation opportunities.
- Identifying innovation-driven directions that align with future BMS requirements.

Table 4 illustrates the mapping between identified gaps, evidence sources, and potential innovation directions.

Table 4. Mapping of Gaps, Evidence Sources, and Innovation Opportunities

Gap Identified	Evidence Source	Innovation Opportunity
Limited SOC/SOH accuracy under dynamic conditions	Literature (Hannan et al., 2018); EVBattery dataset	Adaptive AI algorithms and hybrid estimation models
Ineffective second-life battery diagnostics	PulseBat dataset; Tao et al. (2025)	Systematic diagnostic frameworks for repurposing
Risks of thermal runaway	Chemali et al. (2016); patent data (Wan et al., 2025)	Predictive thermal control and bio-inspired cooling
Poor AI/IoT integration in real BMS	Dehury & Samal (2025); Xiong & Shen (2019)	Scalable IoT-BMS and explainable AI implementations
Lack of sustainability focus	Tong & Zhu (2025); Barbosa et al. (2022)	Recycling-aware and circular BMS innovations

4. State-of-the-Art in Battery Management Systems

Recent advancements in SOC/SOH estimation accuracy, thermal management efficiency, and AI integration illustrate the shift from conventional methods to intelligent, data-driven BMS designs. Such technological advances are not consistent, but in the past 10 years, they have been increasing at a very fast pace, particularly with the emergence of large datasets like EVBattery (He et al., 2022) and PulseBat (Tao et al., 2025). The Figure 1 illustrates this development, showing that the estimation of SOC/SOH and thermal management and the use of AI have been developing steadily, especially since 2016 when AI and IoT technologies started to be implemented in the research on BMS as well.

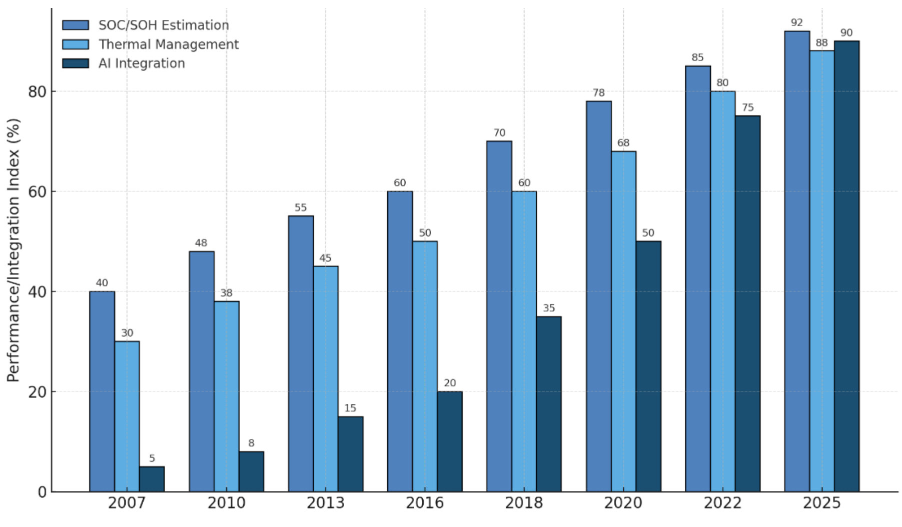

Figure 1: Advancements in BMS technologies over time.

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4.1 Overview of BMS Functions

BMSs ensure optimal battery operation by monitoring voltage, current, and temperature while managing SOC, SOH, cell balancing, charge–discharge cycles, and communication with vehicle control units (Xing et al., 2011; Tie & Tan, 2013). All these functions preserve the battery state of charge, prolong service life and increase the reliability of the whole vehicle.

4.2 Developments in SOC/SOH Estimation

The basic task of BMS is estimation of SOC and SOH. The model-based approaches like the Kalman filters and the equivalent circuit models have the merits of interpretability and efficiency (Rahimi-Eichi et al., 2013). Nevertheless, they lack accuracy when there is dynamic driving. Large datasets have enabled data-driven approaches, which include machine learning algorithms, such as EVBattery (He et al., 2022), to advance the accuracy of prediction considerably. Nevertheless, such progress does not allow generalization to a wide variety of operating conditions, which is why adaptive and hybrid estimation models are required (Ali et al., 2019; Hannan et al., 2018).

4.3 Advances in Thermal Management

Thermal management is the process that keeps battery safe by ensuring that temperature fluctuations do not induce degradation or thermal runaway. Standard passive cooling methods are inexpensive and easy to accomplish, but they are inadequate during high demand situations. Predictive algorithms are being incorporated into active thermal control systems to keep the temperatures safe (Chemali et al., 2016; Laadjal & Cardoso, 2021). More recently, bio-inspired and AI-based techniques with the aim to increase cooling efficiency have been provided (Hossain Lipu et al., 2022), but energy consumption and cost remain a barrier to massive adoption.

4.4 AI and IoT Integration

Artificial intelligence and IoT are reshaping BMS capabilities. With the help of AI algorithms, predictive diagnostics, anomaly detection, dynamic energy management, remote monitoring, and data analytics are possible with the help of IoT connectivity (Dehury & Samal, 2025; Xiong & Shen, 2019). The energy data at a vehicle level in VED (Oh et al., 2020) proves the effectiveness of IoT connected systems in optimizing energy consumption. Nevertheless, the issue of cybersecurity threats and scalability still has to be resolved in order to be able to utilize these technologies to the fullest.

4.5 Sustainability and Second-Life Battery Use

Sustainability considerations are increasingly influencing BMS research. Diagnostic insights based on PulseBat (Tao et al., 2025) are useful to repurpose batteries to second-life applications, whereas patent studies (Tong & Zhu, 2025) offer insights on the trend of innovation in recycling and material recovery. The level of sustainability is not fully integrated into BMS yet, which creates a chance to use environment-friendly design strategies.

4.6 Current Limitations and Gaps

Despite significant progress, BMS technologies face unresolved issues. the SOC/SOH estimation is not robust at different loads, the predictive thermal control necessitates an energy-efficient design and the AI-based IoT frameworks require more robust scalability and cybersecurity. On top of this, sustainability elements are not yet deeply integrated into the mainstream BMS solutions. These gaps

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are supported by patent analyses (Thangavel et al., 2023), which proves the necessity of organized innovation.

A comparative study of the two technologies indicates that they have strengths and shortcomings. To give an example, model-based estimation is computationally easy, but in an actual situation, it is inaccurate, whereas AI-driven estimation is more accurate yet requires big data. Proactive thermal management increases safety at the expense of complexity and cost and sustainable BMS concepts, though promising, are at an early stage of development (Rahimi-Eichi et al., 2013; He et al., 2022; Tao et al., 2025). These insights are summarized in Table 5 and are based on consolidation of literature findings, datasets and patents.

Table 5. Comparison of major BMS technologies.

Technology Category	Strengths	Limitations	Key References
Model-Based Estimation	Simple, interpretable, efficient.	Inaccurate under dynamic conditions.	Rahimi-Eichi et al. (2013); Ali et al. (2019)
Data-Driven AI Estimation	High accuracy, adaptive to patterns.	Requires large datasets, limited generalization.	He et al. (2022); Dehury & Samal (2025)
Active/Predictive Thermal Control	Enhanced safety, predictive management.	High complexity, energy overhead.	Laadjal & Cardoso (2021); Hossain Lipu et al. (2022)
IoT-Integrated BMS	Supports remote analytics, connected decision-making.	Scalability and cybersecurity challenges.	Xiong & Shen (2019); Oh et al. (2020)
Sustainability-Oriented BMS	Enables recycling and second-life usage.	Early adoption stage, limited frameworks.	Tao et al. (2025); Tong & Zhu (2025)

5. Innovation Opportunities for Battery Management Systems

BMS technologies innovations are essential to address the shortcomings pointed out in the previous section. In this section, the identification of existing gaps is performed, along with matching them with opportunities in innovation, and their discussion regarding their possibilities based on systematic analysis using the evidence of datasets and patents.

5.1 Identified Innovation Gaps

Existing BMS designs, while advanced, still face unresolved issues. The estimation of SOC/SOH is not consistent in a variable driving condition as the traditional models cannot adjust to nonlinear battery dynamics. Thermal management is faced by the challenge of estimating and avoiding thermal runaway without unnecessarily using a lot of energy. Scalability and the risk of cybersecurity limit the potential of integrating AI and IoT. Also, there is a lack of commercial systems with sustainability integration, like second-life battery diagnostics and recycling-based designs. These gaps are confirmed by patent analyses (Sarda et al., 2023; Mishra et al., 2021), which indicate that there are no frameworks integrating the concepts of safety, performance, and environmental responsibility.

5.2 Systematic Innovation Opportunities

Opportunities for innovation emerge directly from these gaps. Estimation of SOC/SOH AI-powered has the transformative potential with the help of hybrid models that can be implemented with machine learning and physics-based techniques, along with the use of datasets such as EVBattery and CALCE (He et al., 2022; Pecht et al., 2025). A combination of real-time monitoring and bio-inspired cooling can be used, respectively, in predictive thermal control to stop thermal events effectively (Chemali et

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al., 2016; Hossain Lipu et al., 2022). Smart BMS architectures that use IoT to enable connected analytics require secure communication protocols to reinforce them (Xiong & Shen, 2019). Lastly, the designs that are sustainability-focused will be able to use the diagnostic data of PulseBat (Tao et al., 2025) to enhance battery reuse and recycling plans. Figure 2 illustrates how the innovation impact varies across these opportunities, with AI-driven estimation having the highest transformative effect, while sustainability, although crucial, has a slower adoption rate.

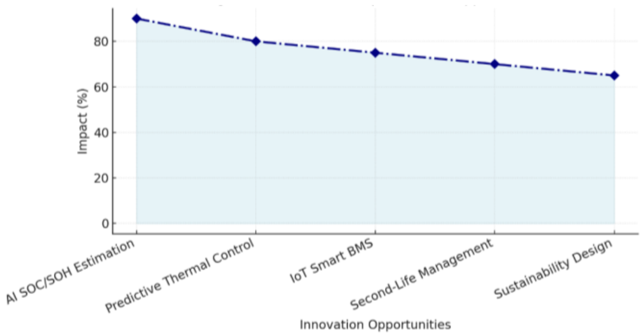

Figure 2: Innovation impact across BMS opportunities.

5.3 Future Directions

The future studies should be directed on incorporating these innovations into the logical frames. Artificial intelligence models should be explainable to take hold in industry. The IoT solutions ought to incorporate robust security and remain responsive in real-time. Sustainability needs to become a practical issue, rather than a theoretical one, and it has to become a design principle based in every BMS operation. Patent research (Wan et al., 2025) indicates that it is also possible to use TRIZ-based analysis to solve the contradiction between safety, cost, and performance. These guidelines open the path to a new era of BMS which is smarter as well as environmentally responsible. According to Figure 3, the level of readiness of these innovations represents that although the AI-based estimation is the most advanced, sustainability-oriented designs are at the initial stage of development.

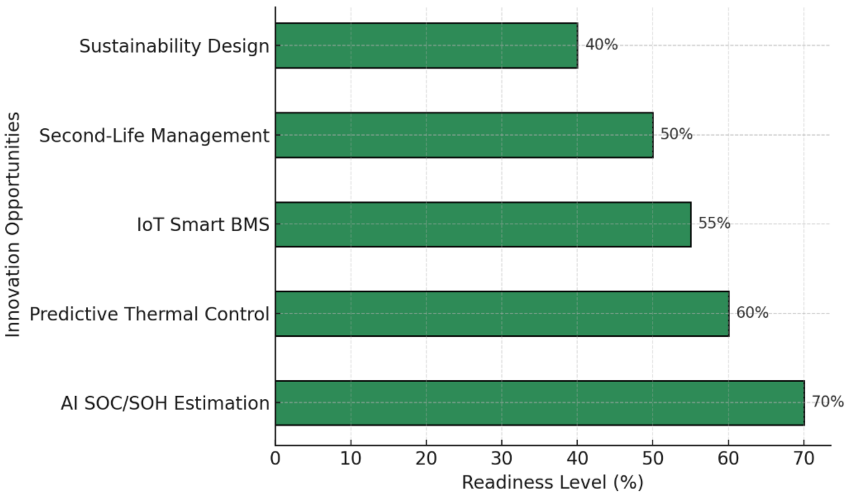

Figure 3: Readiness levels of BMS innovations.

5.4 Mapping Gaps to Opportunities

The correlation between existing gaps and new solutions is summed up in the below analysis. In case of SOC/SOH estimation, it is suggested to use a hybrid AI method to address dynamic conditions. The energy-efficient models may be integrated into predictive thermal control with real-time

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analytics. IoT frameworks should evolve into cloud-integrated and secure ecosystems. Sustainability demands diagnostic tools that would allow the second-life use and recycling of materials. Patent studies highlight these directions as strategically significant. To consolidate the findings, 6 maps current gaps to innovation opportunities and supporting evidence (Table 6).

Table 6. Gaps and corresponding innovation opportunities in BMS.

Gap	Innovation Opportunity	Supporting Evidence
Inconsistent SOC/SOH estimation	AI-driven hybrid algorithms	He et al. (2022); Dehury & Samal (2025)
Thermal safety risks	Predictive thermal control, bio-inspired cooling	Chemali et al. (2016); Hossain Lipu et al. (2022)
Limited AI/IoT scalability	Secure, cloud-integrated IoT-BMS	Xiong & Shen (2019); Oh et al. (2020)
Weak sustainability integration	Recycling-aware, second-life oriented BMS	Tao et al. (2025); Tong & Zhu (2025)
Lack of innovation frameworks	TRIZ-based contradiction analysis	Wan et al. (2025); Garg et al. (2016)

6. Proposed Innovative Framework for Battery Management Systems

To address the gaps identified in Section 5, this section presents a comprehensive framework that integrates AI-based estimation, predictive thermal management, IoT-enabled analytics, and sustainability modules into a single decision-oriented architecture. The structure has been designed in the way that the battery performance can be enhanced, the battery is made safer, and the battery is improved in terms of environmental sustainability.

6.1 Framework Overview

The proposed framework combines data-driven intelligence, real-time monitoring, and sustainability considerations into a unified BMS structure. It leverages datasets such as EVBattery and CALCE for model training, applies predictive algorithms for thermal management, and integrates IoT connectivity for remote analytics. This integration will make decision-making flexible, foreseeing, and climate-sensitive. The framework is made up of four functional modules namely: AI SOC/SOH Estimation, Predictive Thermal Management, IoT Integration with Cloud Analytics, and a Sustainability Module, and centrally controlled by a Control and Decision Layer as shown in Figure 4.

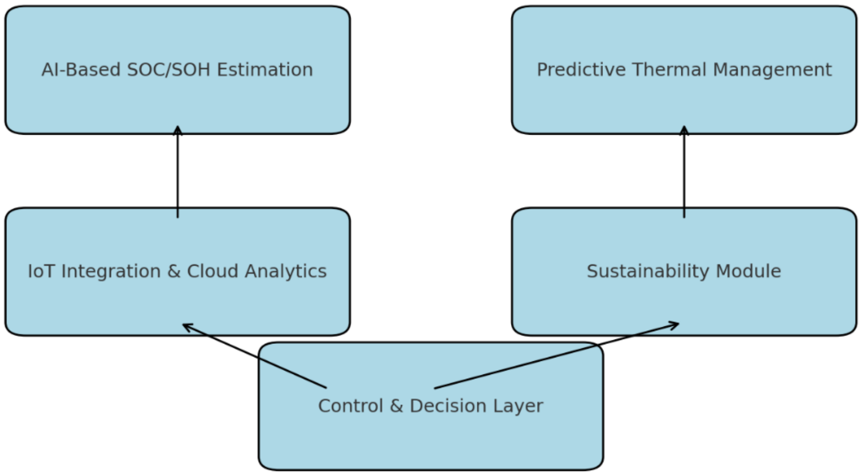

Figure 4: Innovative BMS framework design.

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6.2 Key Components

AI-Based SOC/SOH Estimation: This module employs hybrid AI models that combine machine learning with physical battery parameters. It enhances the accuracy of estimation in dynamic driving situations based on the datasets such as EVBattery (He et al., 2022) and PulseBat (Tao et al., 2025).

Predictive Thermal Management: Uses real time thermal monitoring and predictive algorithms and bio-inspired cooling. This will not only be safe but also reduce the energy use, which is a problem that has been noted in the patent studies (Wan et al., 2025).

IoT Integration & Cloud Analytics: Enables real-time data transmission and processing via secure cloud-based platforms. IoT allows carrying out distant diagnostics and predictive maintenance, yet there must be excellent cybersecurity to avoid vulnerabilities (Xiong & Shen, 2019).

Sustainability Module: It is centered on battery diagnostics at the end of life, second-life applications, and recycling integration. It applies diagnostic information to increase sustainability, which is consistent with patent analyses (Tong & Zhu, 2025).

6.3 Functional Workflow

The modules are dynamically connected with each other via the Control and Decision Layer. The AI estimation is used to estimate SOC/SOH to make optimal control decisions, predictive thermal management is used to make sure everything is safe, IoT analytics enable external monitoring, and the sustainability module provides information that feeds recycling and repurposing strategies. This process will also result in a smooth blend of performance, safety, and environmental aspects.

6.4 Expected Benefits

This framework eliminates the main contradictions that have been mentioned above by enhancing accuracy, increasing safety, and incorporating sustainability. It also creates a path towards industry adoption due to the scalable IoT architecture and explainable AI which means it is ready to meet future requirements of EV. In order to summarize the components of the framework and their contribution the functional role and the expected output of each module is tabulated in Table 7.

Table 7. Framework components and roles.

Component	Role in Framework	Expected Outcome
AI SOC/SOH Estimation	Predict battery state under dynamic conditions	Higher accuracy, adaptive estimation
Predictive Thermal Management	Monitor and control thermal risks	Enhanced safety, energy-efficient thermal control
IoT & Cloud Analytics	Enable remote monitoring and big-data analytics	Smarter decision-making, real-time diagnostics
Sustainability Module	Support second-life and recycling diagnostics	Environmentally responsible BMS design
Control & Decision Layer	Integrate data from all modules to guide actions	Coordinated, optimized battery performance

Discussion

The proposed new model of battery management systems is a big leap towards solving the shortcomings of the existing technologies. This discussion is a critical appraisal of its implications, benefits, the possible hurdles, and its fit with industry trends and research directions. A large part of

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the problem with SOC/SOH estimation in BMS technology has always been accurate state prediction in dynamic driving conditions, and the very inclusion of AI-based SOC/SOH estimation into the framework solves this issue. The conventional model-based approaches have the drawback that they are not flexible to adapt to different environmental and load conditions whereas the pure data-driven approaches have a drawback that they cannot generalize. The framework is improved in terms of prediction accuracy and flexibility by using a hybrid AI method based on the use of large-scale datasets like EVBattery (He et al., 2022) and CALCE (Pecht et al., 2025). Moreover, explainable AI techniques make it possible to be transparent, which enables its use in industry and compliance with regulations.

Predictive thermal management is yet another pillar of this framework. The risk of thermal runaway is one of the key concerns to safety, which is also highlighted in literature (Chemali et al., 2016; Hossain Lipu et al., 2022) and patent research (He et al., 20252The suggested module will utilize in-time sensors, AI-based estimations and bio-inspired cooling mechanisms to actively avoid overheating and reduce energy overhead to a minimum. Such proactive measures enhance safety as well as increasing battery life, which is one of the most important considerations by manufacturers and end-users. The usage of IoT and cloud analytics adds functionality to the intelligence of the BMS operations by providing uninterrupted remote control, predictive diagnostics, and over-the-air updates. The real-time connectivity enables fast faults detection, performance analysis of the fleet, and decision-making based on data. But, this kind of integration poses threat to data privacy and cyber security to a large extent. The use of IoT allows allowing the BMS to be exposed to cyber-attacks, which should be minimized with the help of research and industry-standard security protocols unless it is secured with a strong encryption and secure communication protocols (Xiong & Shen, 2019).

The key distinguishing feature of this framework is its Sustainability Module that incorporates second-life battery diagnostics and recycling into the design of the BMS. Although sustainability has regularly been addressed as a secondary activity, this strategy makes it a fundamental operation, which is associated with the concept of the circular economy presented by Tong & Zhu (2025) and backed by the statistics of PulseBat (Tao et al., 2025). With early detection of the degradation patterns and end-of-life conditions, the framework can facilitate repurposing of batteries to less demanding applications, minimize waste and encourage environmentally sustainable practices. The suggested framework also meets the principles of systematic innovation, especially those based on TRIZ, that can be used to address the contradiction as improving safety without sacrificing energy density or fast charging without degrading battery life. The analysis of patents also proves that the innovations aimed at solving these contradictions are becoming more appreciated in the industry (Wan et al., 2025). In this way, the framework does not only fill the existing gaps, but it also sets up as a guideline to future research and development. Although the framework has very great strengths, it is not devoid of difficulties. The application of hybrid AI models necessitates substantial data with high quality and impressive computing power. In practice, it is necessary to test thoroughly in a variety of conditions to make it reliable. IoT integration must balance connectivity with cybersecurity. Moreover, sustainability characteristics require regulatory favor and market inducement to make sure they are adopted. These issues are the areas of future research and partnership between academia, industry and policymakers.

Various comparative advantages of the proposed innovative framework are also available when compared to the conventional BMS designs. It combines intelligence, predictive ability and environmental responsibility in a manner that is not only technologically superior but also in tandem

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with the future market trends. The anticipated results consist of increased battery performance, safety, reduced lifecycle cost and adherence to sustainability objectives. Besides, using data sets, patent knowledge, and systematic innovation tools, this framework establishes a systematized roadmap to next-generation solutions. The discussion highlights that the effective operation of this framework relies on the joint opportunities. It requires improving the AI algorithms of researchers, engineers should create scalable infrastructures of IoT, and policymakers should promote sustainable models by providing regulations and incentives. Integrating these efforts, the new framework described in this paper may become the basis of the future progress in the sphere of electric vehicle battery management.

Conclusion

The development of the electric vehicle is core to battery management systems, which are directly related to safety, performance, and sustainability. The review of the state-of-the-art in BMS technologies provided in the paper demonstrated that there are still gaps in SOC/SOH estimation and thermal management, integration of AI and IoT, and sustainability. The literature review was based on a large literature review, empirical data like EVBattery, PulseBat, CALCE, and VED, and patent analysis, which illuminated innovation hotspots and the trends that could be expected in the future. The analysis has shown that, though the current designs of BMS have improved significantly, they are not up to the requirements of the next-generation electric mobility. To fill these gaps, a new framework was suggested, which would combine AI-based SOC/SOH estimation, predictive thermal management, IoT-driven cloud analytics, and sustainability module. The framework provides greater accuracy, safety and environmental responsibility through systematic innovation principles and TRIZ-based resolution of contradiction. This will provide a clear guideline on coming up with smarter safer and greener BMS solutions. The discussion showed the potential advantages of the framework, such as better precision of predictions, active safety control, better decision-making, and facilitation of a circular economy practice. Nevertheless, the issues of cybersecurity threats, data demands, and the necessity of industrial cooperation should be overcome to facilitate the implementation. The framework proposed is not only consistent with the focus of the International Journal of Systematic Innovation on innovative problem solving but is also practically helpful to the researchers, engineers, and policymakers that are currently engaged in the process of designing the future of battery management in electric vehicles.

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