POLICY BRIEF

MAKING SAFE AND DURABLE ELECTRIC VEHICLES

ROLE OF BATTERY MANAGEMENT SYSTEMS

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1. Introduction

India's ambition for electrifying its vehicle fleet is growing stronger, with demand incentive programmes catalyzing the electric vehicle (EV) market. Production-linked incentives (PLI) for Advanced Chemistry Cells (ACC) and other supportive interventions are driving the localization of battery manufacturing, which is crucial for reducing costs, achieving scale and minimizing import dependence on EV batteries and components.

To support this growth, a robust local EV ecosystem is emerging. State governments have also started offering incentives to establish local manufacturing hubs for EVs, components and batteries, thus creating opportunities to localize significant parts of the value chain, both upstream and downstream. This is expected to diversify the production base to meet the increasing demand for electric motors, components, and batteries, with specialized production centres focused on various stages of battery development—such as electrode production, cell assembly and battery management systems.

These technological developments must be guided by regulatory standards that ensure performance, durability, reliability, and safety across the product's lifespan. Strong regulations and standards are necessary to build consumer and investor confidence in this growing market.

Even though regulations and standards for product development in India are evolving, continuous feedback on technology performance in the field is pushing for regulatory reforms to fill gaps and strengthen performance metrics. This became especially evident following a series of electric two-wheeler fire incidents in 2022, exposing critical safety gaps. Concerns about discrepancies between the certified range of EVs and their actual on-road performance also highlighted the need for stringent technology standards.

Technology development cannot happen in isolation—it requires standards that enforce strict performance requirements, robust testing protocols and consideration of local climatic conditions. Regulations must set the terms of technology development, ensuring that best manufacturing practices and quality control are followed throughout the process.

As a result, the focus has shifted toward strengthening regulations around battery development—the core of EV technology. Attention is now on improving cell manufacturing quality, implementing diagnostic systems to detect thermal issues early, enhancing battery management systems, and localizing processes to suit Indian conditions.

Policy discussions are increasingly cantered around enabling local development, with emphasis on investments, research and development, and taking innovative products from concept to commercialization. The recent white paper on “Tropical EV Batteries,” published by the Department of Science and Technology in collaboration with the Centre for Science and Environment (CSE) and industry stakeholders, underscores critical pathways for developing an R&D ecosystem tailored to India’s tropical conditions. This white paper highlights the importance of measurable outcomes in technology development projects.

The culture of innovation must be industry-wide, requiring strong multi-stakeholder participation to drive forward safe, durable and efficient EV technologies in India.

From this perspective, CSE has initiated a series of investigations into various aspects of battery technology development. The goal is to understand the current status, opportunities and potential for advancement in this field, while identifying gaps in existing regulations and standards that need to be addressed to guide the way forward. It is important to note that with the rapid increase in EV penetration in India, the demand for batteries is projected to rise significantly, reaching 139 GWh by 2035.[1]

The first in this investigative series is an in-depth look at the battery management system (BMS)—the in-built intelligence of batteries.

1.1 Why this spotlight on battery management systems?

The rapidly evolving regulations surrounding batteries are becoming increasingly complex, requiring battery manufacturers to meet a wide range of performance metrics and fulfil certain obligations. To ensure compliance with these regulations, batteries need an inbuilt intelligence system capable of sensing, monitoring, responding and communicating based on real-world performance.

This intelligence comes in the form of a battery management system, an electronic control circuit integrated within battery packs. The BMS plays a critical role in monitoring and regulating key functions related to safety, performance and optimizing the lifespan of batteries under various charging, discharging and environmental conditions. Its primary goal is to ensure that the battery remains safe, reliable and durable while preventing potential damage.

An effective BMS provides multiple benefits: it protects the battery from harm, ensures operational safety, predicts battery life and maintains efficiency. The system is essential for monitoring charge levels, temperature and overall battery health.

Inside a battery pack, which consists of multiple modules built from individual cells, the BMS acts as the intermediary, communicating vital information about battery status to the external systems of an EV. It is interconnected with all battery-pack components as well as the vehicle's control systems, gathering data through sensors to assess and regulate the battery's condition. This advanced monitoring capability is crucial for achieving optimal battery performance in today's rapidly expanding EV market.

The built-in BMS continuously monitors the behaviour and performance of the battery pack based on a wide range of parameters, including:

- **State of Charge (SOC):** This refers to the amount of charge remaining in the battery, while State of Health (SOH) measures the condition of the battery and how much power it can deliver. The BMS can estimate the battery's range and remaining life by relying on voltage data and coulomb counting to track these parameters.
- **Cell balancing:** To equalize the charge levels across individual cells in the battery, preventing overcharging or undercharging. Battery packs are composed of multiple cells arranged in series or parallel, which can develop inhomogeneities due to production differences or operating conditions. Cell imbalance occurs when there are differences in cell voltage or SOC, with the lowest voltage cell in a series often limiting the battery's capacity.

Passive equalization is a simple, cost-effective technique where excess energy from a cell is dissipated through a parallel resistor.

Active equalization involves transferring charge from a cell with excess energy to one with a deficit, minimizing energy loss and increasing efficiency, though it is more expensive due to the need for additional switching components.

- **Battery cooling system monitoring:** The BMS tracks the battery's temperature during high ambient temperatures, high power discharge and fast charging.

Cooling strategies depend on the application (e.g., two-wheelers vs. four-wheelers), cell chemistry, and cell type. Techniques include air cooling, indirect and direct liquid cooling, immersion cooling, tab cooling and the use of phase-change materials. By monitoring current and voltage, the BMS prevents over-voltage and under-voltage, keeping the battery within a safe operating range.

- **Protection against overcharge, over-discharge, and other hazards:** The BMS safeguards the battery from overcharging, over-discharging, overcurrent, short circuits and extreme temperatures. These protections are crucial for preventing safety hazards and extending battery life.
- **Diagnostics:** The BMS detects faults and abuse conditions, allowing for proactive maintenance and preventing potential failures.
- **Data logging and communication:** A BMS records detailed reports on battery performance and communicates real-time data, enabling informed decision-making and system improvements.
- **Maximizing vehicle range:** By optimizing energy usage, the BMS helps extend the range of electric vehicles, ensuring efficient use of the stored energy.

This multi-sensing approach of the BMS provides comprehensive data on the battery's status, allowing for proactive and effective management to ensure safety, reliability and longevity.

BMS architecture must be custom-designed, developed and calibrated for each type of battery system and vehicle segment, as different applications have varying requirements. This ensures the BMS functions optimally to suit the specific needs of each battery system.

1.2 Why does BMS help?

Consider a battery storage system made up of hundreds or even thousands of lithium-ion cells packed together, with configurations varying according to vehicular application. These systems can have a wide range of voltage ratings, and any technical flaw or imbalance in such high-voltage packs can lead to serious hazards. This makes BMS absolutely critical.

BMS plays a vital role in preventing such incidents by ensuring safe operations, reliable on-road performance, and a durable lifespan despite the wear from charging and discharging cycles, temperature fluctuations and battery ageing. It allows for the optimal utilization of the battery's capacity, which increases both range and overall performance.

Additionally, BMS is essential for diagnostics, data collection, reporting and communication, providing insights into battery status that enable early diagnosis of potential problems. This functionality helps address issues related to performance, functional safety and design, enabling continuous improvement while reducing development time and associated costs.

Advanced tools are available that can quickly generate models based on basic datasheet specifications and measurement curves for various electronic devices and battery chemistries. These tools support more efficient BMS development and calibration, ensuring that systems are tailored to the specific needs of different battery types and vehicle applications.

In summary, the BMS is indispensable in the safe and efficient management of battery storage systems, ensuring they perform optimally while minimizing risks and maintaining longevity.

1.3 The way forward: Next steps

Lithium-ion cells offer high energy density and remarkable power density, but this very feature can also lead to instability under certain conditions, affecting performance if the cells are not operated within safe limits. BMS serves as the first line of defence, responding to temperature, voltage and current anomalies, and preventing potential safety incidents such as thermal runaway. Thus, the BMS not only manages the risk of safety events but also mitigates performance loss caused by high-temperature-related cell degradation.

With rising temperatures across the country, the need for domestically designed and manufactured BMS for electric vehicle batteries has become crucial. These systems must be resilient and responsive, tailored to the unique demands of the battery vehicle in terms of cell chemistry, weather, geography and durability.

As India continues to localize battery manufacturing, regulatory frameworks and standards must address several key issues. Going forward, policies, regulations, and innovation pathways will need to focus on the following strategies:

1. **Estimation of the SOC and SOH of batteries:** Accurate estimation of the SOC and SOH of batteries is crucial, especially under real-world driving conditions where operating environments vary, and long resting or parking periods lead to calendar aging. Incorporating field data and seasonality into laboratory testing will enable the development of robust SOH estimation models. Sharing India-specific data generated at local labs with Original Equipment Manufacturers

(OEMs), battery makers, and BMS developers is essential. Creating feedback loops and fostering data sharing within the ecosystem is imperative for continuous improvement.

2. **Thermal runaway prediction:** Thermal runaway prediction should be a key focus area. Leveraging emerging hardware and software BMS capabilities to provide timely warnings is essential. Development efforts should prioritize modelling thermal runaway within a broader system context, simultaneously simulating micro-scale internal cell mechanisms and macro-scale system effects.

3. **Battery ageing:** Additionally, a stronger focus on battery ageing data is needed to assess the residual value of batteries at different points in their lifecycle, aiding in decisions about repurposing and recycling. Publicly available battery ageing datasets are critical for accelerating the development of probabilistic diagnostic and prognostic models.

4. **Enhancing diagnostic capabilities of BMS:** To enhance BMS diagnostic capabilities, early detection and resolution of potential battery safety and performance issues should be prioritized. Strengthening the diagnostic functions of BMS will lead to more reliable operations and timely interventions.

5. **Developing a battery passport:** India's version of a battery passport must include SOH data for scalable digital solutions across the battery value chain, enabling more robust battery reuse and recycling initiatives. This approach can help standardize data requirements for batteries, ensuring consistency and transparency across the industry.

6. **Enabling battery/product co-design:** Developing thermal, electrical, mechanical and ageing models will optimize all aspects of cell design. The goal is to enable battery/product co-design where the battery's form factor, packaging, cooling, and control algorithms are optimized within unified engineering constraints such as cost, volume, weight, energy and operating conditions, considering regional climate and driving habits.

7. **Building technical and regulatory capacity:** It is crucial for developing expertise in BMS hardware design, testing and software integration. Proficiency in SOC and SOH estimation techniques, advanced supervisory algorithms, fault detection, cell knowledge, EV use cases and temperature management

techniques is essential. Competence in electronic assembly will also play a significant role.

8. **Open-source BMS templates:** An open-source BMS template could be a game-changer for the light EV sector. Many new entrants in India lack the capability to develop BMS systems and rely on pre-made solutions. A generic but functional open-source BMS platform would allow companies to customize the system to their vehicle specifications. This template could also include pre-certified hardware and software function blocks, effectively reducing time to market and simplifying certification according to AIS norms.

9. **Integrating BMS technology into corporate strategies:** Finally, vehicle manufacturers need to integrate robust BMS technology pathways into their corporate and manufacturing strategies to ensure long-term competitiveness and sustainability in the EV market.

2. BMS: An evolving technology

BMS technology continues to evolve to meet both global regulatory and performance requirements. For a detailed understanding of how BMS works, its functions, and the technical scope of its application, refer to Annexure.

However, even as research advances to improve the performance and safety of lithium-ion batteries (LIBs), several challenges persist, which BMS technology must address. LIBs exposed to stresses, particularly mechanical and thermal abuse, tend to exhibit safety risks. When the rate of heat generation within the battery exceeds its dissipation, temperature distribution (TD) across the cell can shift, leading to potential safety hazards.

Innovation in BMS technology in India needs to continually tackle these issues, and some key challenges are highlighted here:

1.1 Battery state estimation

Current algorithms and physics-based models deployed in BMS are limited by the on-board computing power and data storage available. The microprocessors typically used in BMS have constraints, preventing more sophisticated historical data analysis and long-term performance insights. Equivalent circuit models (ECMs), traditionally employed by BMS, often lack accuracy and depth in long-term analysis.

- To address this, cloud-based or edge-based architectures could be introduced. In such systems, sensor data from the BMS is relayed to external servers, where more advanced machine-learning algorithms, physics-based modelling, and digital twins can be used to generate more accurate estimations.
- A digital twin is a real-time virtual representation of a physical battery deployed in an EV. However, cloud-based systems face challenges such as data privacy/ security and latency, which could delay information transmission.

1.2 Temperature measurement

Surface-mounted temperature sensors (e.g., thermistors or thermocouples) measure the temperature within a battery pack but are affected by heat transfer delays due to the thermal mass and conductivity of the cells. As a result, these sensors may transmit incomplete or delayed temperature information.

As noted in the DST white paper on tropical EV batteries, certain operating conditions like fast charging or high ambient temperatures can cause significant differences between internal and surface temperatures. Hotspots within the cell may reach temperatures of up to 80–90°C, even when the measured surface temperature is 60°C–high enough to trigger ignition. These internal temperature variations, especially in larger format LIBs, can go undetected and compromise safety, performance and battery lifespan.

1.3 Communication interface

The BMS communicates vital information about battery status to external systems, such as the vehicle control unit (VCU), charger controllers and test equipment. This interface also facilitates the modification of BMS control parameters and supports diagnostic information retrieval, enabling the early detection and resolution of battery issues.

1.4 Improved SOC and SOH estimation

While current BMS systems typically rely on simplistic equivalent circuit models for SOC and SOH estimation, more advanced methods are required. These include:

- Electrochemical impedance spectroscopy (EIS), a technique to measure cell degradation.
- Kalman filters, which use data-based modelling for estimation.
- Physics-based models that consider the electrochemical and thermodynamic behaviours of the battery.

1.5 Incremental ageing data

Tracking the incremental ageing of batteries is critical for various predictive purposes. This data is particularly useful for financiers, banks and insurers to assess the residual value of batteries at different points in time. It can also help in determining whether a battery should be discarded or repurposed for secondary storage.

India needs a regulatory framework similar to Europe's evolving battery passport system, which is expected to be implemented by 2027. The battery passport is an electronic record for each battery, containing important supplier and usage information. Data collected during the battery's first life, collected via the BMS, can assist in evaluating the battery's end-of-life options. This framework will be crucial for improving the understanding of EV batteries while also guiding the development of safer battery designs in the future.

3. Setting higher benchmarks for BMS

As regulations in India and other countries are making stronger demands on the performance, durability, lifespan, safety, range and reliability of EVs and batteries, more complex and advanced BMS systems are evolving for in-built oversight. It is necessary to understand how evolving regulations and standards are shaping the technologies.

3.1. Global battery safety regulations and implications for BMS

Global battery safety regulations for electric vehicles have evolved significantly and have a strong impact on BMS development. These regulations fall under the World Forum for Harmonisation of Vehicles, a permanent working group (WP 29) that operates within the Transport Division of the United Nations Economic Commission for Europe (UNECE). Signatory countries agree to mutual recognition of type approvals and adherence to a common set of technical specifications and requirements. Currently, 64 countries are signatories to this agreement.

India has thus far refrained from joining the UNECE 1958 Agreement, citing reservations about certain restrictive provisions. Additionally, two major vehicle markets, the United States and China, have also not signed the agreement.[2]

However, both the United States and China are signatories to the UN's parallel 1998 Agreement, which publishes the Global Technical Regulations (GTR). Unlike the 1958 Agreement, this parallel framework does not mandate mutual recognition of approvals between countries based on global technical regulations. Instead, it allows for independent regulatory practices while adhering to common global standards.[3]

UNECE published Regulation no. 100 in 1996, which outlines certification requirements for electric powertrains and other EV components. This was later followed in the US by the United Nations Global Technical Regulation (UN GTR) no. 20, which addresses safety, and UN GTR no. 22, which covers battery durability and thermal management, along with mandating the inclusion of a BMS in EV batteries. These regulations apply to most major EV manufacturing and purchasing countries worldwide.[4]

In addition, international standards serve as voluntary practices (considered recommended guidelines) that aim to enhance the engineering behind vehicular mobility. For instance, the SAE J2990/2_202011, titled Hybrid and Electric Vehicle Safety Systems Information Report, outlines isolation requirements similar to those found in FMVSS No. 305, but also addresses enclosures, labels and identifications. Given the safety risks associated with high-voltage electric propulsion systems, it is essential to have clearly labelled manual switches that can disconnect and de-energize the high-voltage system, reducing complete reliance on software.

SAE International introduced the "Electric Vehicle Battery Abuse Testing" standard in 1999. The latest version, updated in August 2021, is now titled Electric and Hybrid Electric Vehicle Rechargeable Energy Storage System (RESS) Safety and Abuse Testing.[5]

These electric vehicle standards and guidelines are designed to ensure that the complex components and subsystems within a vehicle not only function according to their design intent but also have a low probability of failure when integrated. Vehicles consist of large systems made up of smaller subsystems, and each must operate cooperatively to ensure the overall system functions reliably.

Despite the advancements in EV safety performance globally following the introduction of UN GTR No. 20, the residual value of a battery after its first life remains unclear, presenting challenges for financiers, banks and insurers in assessing an EV's end-of-life value.

These challenges are addressed by UN GTR No. 22, which includes a requirement for minimum durability of batteries installed in full-electric and plug-in hybrid vehicles. Established in the Global Registry in March 2022, this regulation represents the first international effort to address battery degradation. Countries subscribing to the regulation are required to incorporate it into their national or regional legislation.[6]

UN GTR No. 22 recommends that battery manufacturers use their proprietary algorithms for estimating battery parameters and conducting diagnostics. However, the regulation does not mandate a specific algorithm due to the wide variability in battery chemistries, sizes and other factors.

The regulation requires manufacturers to certify that the batteries in their EVs will retain at least 80 per cent of their initial capacity over 5 years or 100,000 km, and at least 70 per cent over 8 years or 160,000 km. This is intended to prevent the use of low-quality batteries, ensuring that only durable batteries are used in electric vehicles. Additionally, the regulation emphasizes that battery warranties offered by EV manufacturers should not rely solely on technical performance, but should also take into account commercial and customer satisfaction factors.

This approach is crucial for increasing consumer trust in EVs and enhancing their environmental performance beyond zero-emission features. Ensuring that batteries last longer helps reduce the strain on critical raw material reserves needed for battery production and minimizes waste generated by used batteries.[7]

UN GTR No. 22 further emphasizes the critical role of optimized BMS and BTMS in achieving the durability and performance goals outlined in the regulation. It allows automakers the flexibility to install proprietary and unique BMS solutions, fostering innovation through an iterative, learning-by-doing approach.

The regulation highlights the importance of BMS in cooling the battery and managing its BTMS, ensuring optimal thermal conditions to maintain battery health. Additionally, BMS is instrumental in transmitting battery health data to national or regional authorities, as required by the standard, using locally mandated data transmission methods.

Recording essential battery health data will also support the sale of vehicles in the second-hand market, providing buyers with valuable insights into battery performance and lifespan, thereby improving transparency and consumer confidence.

3.2. USA: Evolving regulations and BMS

Battery testing in the US gained significant attention following a fire incident involving the Chevrolet Volt, a range-extended electric vehicle by General Motors, in 2011. The fire led to a series of investigations by the US Highway Traffic Safety Administration (NHTSA) to understand the events leading to cell venting, shorting of the battery's negative bus bar, and battery coolant leakage. One of the key findings from these investigations was that NHTSA was unable to replicate the fire event through vehicle or battery component testing.

As a result of the Volt investigations, in November 2011, the US, Japan and the European Union jointly proposed the formation of two working groups to address safety and environmental concerns related to electric vehicles. The goal was to develop a globally harmonized regulation under the framework of the 1998 agreement. These efforts culminated in the establishment of Global Technical Regulation (GTR) No. 20 for electric vehicles, which was added to the Global Registry on 14 March 2018.[8]

The NHTSA governs the Federal Motor Vehicle Safety Standards (FMVSS), which establish regulations focused on the design, performance and durability of vehicles. For instance, FMVSS No. 305 specifies performance requirements for battery packs, including addressing electrolyte spillage and ensuring isolation of high-voltage batteries from low-voltage components, particularly in the event of a crash. The standard mandates that the high-voltage system must be deactivated within a specific timeframe after a crash to protect first responders from electrical hazards while assisting victims. Understanding the shock hazards of high-voltage systems is crucial for crash detection and automatic shutdowns.

In 2021, the US NHTSA launched its Battery Safety Initiative, aimed at collecting and analysing data to better understand battery behaviour and potentially prevent fire incidents. In 2023, when the EU adopted its Battery Regulation (EU 2023/1542), it mandated the inclusion of a BMS to enhance safety and performance standards.

The urgency of addressing battery safety is underscored by incidents such as the 200 fires caused by lithium-ion batteries in New York City alone in 2022. These incidents highlight the critical need for stringent regulations and safety measures related to battery technologies in electric vehicles.[9] The US NHTSA is working on developing standards for safety issues related to battery thermal runaway, water immersion and vibration resistance.[10]

3.3. Europe: Evolving regulations and BMS

Europe has framed battery regulations that have included several rules for battery management.[11] The Battery Regulation EU 2023/1542 mandates that starting in May 2024, all batteries must include a BMS. This BMS must be capable of estimating the SOC and SOH, performing cell balancing to extend battery life, and storing data related to the battery's health and expected lifespan.

Before July 2023, EU battery regulations, including the Battery Directive 2006/66/EC (on batteries and waste) and Directive 2007/46/EC (on motor vehicle approval), did not mention BMS requirements. However, with the repeal of the Battery Directive and the introduction of Battery Regulation EU 2023/1542, a significant shift occurred. The new regulation explicitly defines the role of a BMS and mandates that key information, such as the battery's state of health and expected lifetime, must be stored within the BMS. This information must also be accessible to both the end-user and any third party acting on their behalf.

Moreover, the regulation requires that the BMS must include a software reset function to allow operators to upload different BMS software when necessary, ensuring flexibility and adaptability in battery management.[12]

The regulations have also mandated that the information captured by the BMS must be made accessible to natural and juridical persons who legally purchase batteries or to third parties. It further states that the BMS data must be better defined “to limit the operating scope of those having access to the data.”[13] This is to avoid safety issues, breaches and conflict of property rights.

Legally, the integration of a BMS is closely tied to the recycling and repurposing of used batteries. The regulations mandate that BMS information must be shared to help evaluate the residual value and SOH of a battery, facilitating its reuse, repurposing, remanufacturing or recycling. This allows the end-user or any third party to assess the battery’s condition and expected lifetime at any time, which supports processes like battery aggregation.

Additionally, the regulations require the implementation of a due diligence policy to assess social and environmental risks in the battery supply chain. This policy establishes a system for control and transparency regarding supply chain traceability, imposing obligations to manage risk across the entire supply chain. Parties involved must report on risk assessments, adopt risk management measures, monitor and track risk mitigation efforts, and design strategies to respond to identified risks.

The EU Regulation also stipulates that if a software reset function is used, the original battery manufacturer will not be held liable for any safety or functionality issues that arise due to battery management system software uploaded after the battery was initially placed on the market.[14]

3.4. China: Evolving regulations and BMS

China has developed its battery safety standards, which are regularly updated to meet evolving requirements. Before 2018, there were several recommended best practices and regulations globally related to batteries, some of which have now become obsolete. For instance, GB/T 31485, adopted in 2015, was a Chinese standard that mandated many of the current tests on EV batteries, such as short circuit tests, drop tests, heating tests, crushing tests, and over-charge and over-discharge tests. This standard has since been discontinued as newer regulations have been introduced to address the advancements in battery technology and safety requirements.[15] It was replaced by GB 38031–2020 on 12 May 2020.[16]

Chinese vehicle battery safety standards classify batteries into four categories: battery cells, battery modules, battery packs and battery systems. One of the key standards, GB 38031–2020 ("Safety Requirements for Power Batteries for Electric Vehicles"), came into effect on 12 May 2020. This is a mandatory national standard addressing safety requirements for EV batteries, covering cells, modules and systems. It not only fills the gaps in earlier standards but also references international standards like IEC 62660–2, IEC 62660–3, ECE R100 and UN GTR20.

To ensure the reliability and safety of battery management systems, China has developed two additional standards: GB/T 38661–2020 and QC/T 897–2011. These standards define mandatory safety requirements, including those for the China Compulsory Certificate (CCC), which is required for vehicles manufactured or imported into China.

3.5. India: Evolving regulations and BMS

Following a series of safety incidents involving two-wheelers in 2022, India has undertaken significant reforms to tighten its battery regulations. Automotive Indian Standards (AIS) 038 (Rev 2), aligned with GTR 20/ECE R100 (Rev 3), was introduced for four-wheelers or M & N category vehicles. Similarly, the AIS 156 standard was formulated for L category vehicles, including two-wheelers and three-wheelers, based on ECE R136. Both standards adopt a system-level approach, integrating high-voltage EV safety and battery safety by setting detailed construction, design, safety and performance requirements.

An official investigation by the Ministry of Road Transport and Highways (MoRTH) into the 2022 fire incidents identified several quality issues, particularly with component sourcing. The committee found that, in addition to the use of low-grade cells, a critical factor in the safety failures was the inadequacy of the BMS. The BMS in the affected EVs was unable to prevent thermal runaways or provide adequate warnings, leading to the incidents. The investigation concluded that these EVs had suboptimal BMS and BTMS, which contributed to the safety lapses.[17]

After the 2022 incidents, MoRTH amended battery safety norms and updated the AIS, specifically AIS 038 and AIS 156, to enhance the safety, reliability and efficiency of EVs in India. These updated regulations, which came into full effect in April 2023, are aligned with EU standards and incorporate a range of tests, including environmental and thermal propagation assessments.

Key certification requirements under these regulations include tests for electrical safety, thermal propagation, mechanical strength, water protection, braking performance and electromagnetic compatibility. These tests are critical in ensuring that EVs meet the necessary safety and environmental standards, providing due diligence for the industry.

The rules have also placed new demands on original equipment manufacturers (OEMs), requiring the use of BMS that meet a minimum level of technical rigour. For two- and three-wheelers, testing now includes vibration tests, thermal shock tests, cycle tests, mechanical drop tests (for removable and rechargeable batteries), fire resistance tests, external short circuit protection tests, and overcharging/over-discharging/over-temperature protection tests.

AIS 156 mandates a minimum of four thermal sensors in the battery pack, and it requires audio-visual alarms and an automatic power cut-off when temperatures exceed 60 degrees. The vehicle must provide warnings, even when parked. Additionally, the BMS is required to log and maintain data on critical battery parameters (see *Table 1: Key requirements of AIS 038 Rev 2 and AIS 156 as per latest amendments*).

For four-wheelers and larger vehicles, the regulations also include thermal propagation tests, hydrogen emission tests and the newly added thermal runaway test. The BMS must detect thermal events by monitoring parameters such as cell voltage drop and battery pack temperature. Notably, the nail penetration test as a cell trigger method has been removed, and manufacturers are now required to provide risk analysis documentation and outline risk mitigation functions in case of a thermal runaway event.

The BMS is also required to offer electromagnetic compatibility (EMC) protection per AIS 004, to prevent electrical malfunctions caused by external interference.

With these updates, battery certification processes have become more demanding and testing standards more rigorous. This is crucial for building consumer confidence in the safety and reliability of electric vehicles.

Table 1: Key requirements of AIS 038 Rev 2 and AIS 156 as per latest amendments

Requirement	AIS 038 Rev 2	AIS 156
Charge-discharge cycle	Cells to undergo minimum 5 cycles of charge-discharge at C/3 current rate	Cells to undergo minimum 1 cycle of charge-discharge at C/3 current rate
BMS circuit	BMS shall be microprocessor/ microcontroller-based circuit	BMS shall be microprocessor/ microcontroller-based circuit
BMS protection programme verification	Over-voltage protection, over-charge protection, over-discharge protection, over-temperature protection, over-current protection, short-circuit protection	Over-charge protection, over-discharge protection, over-temperature protection, over-current protection, short-circuit protection
System circuit breaker	Additional safety fuse or circuit breaker in addition to BMS features	Additional safety fuse or circuit breaker in addition to BMS features
Electromagnetic compatibility	Comply with EMC requirements as per AIS 004 Part 3 or AIS 004 Part 3 Rev 1	Comply with EMC requirements as per AIS 004 Part 3 or AIS 004 Part 3 Rev 1
Onboard or portable charging	Have charge voltage cut-off, time-based charge cut-off function, soft-start function every time REESS is connected for charging, pre-charge function, input supply variation protection, output voltage and current regulation, earth leakage detection, communication with battery	Have charge voltage cut-off, soft-start function every time REESS is connected for charging, pre-charge function to detect deep discharge condition of REESS, input supply variation (230 VAC +/- 10%) protection, communication with battery
Traceability of systems and parts	Each REESS manufactured to have a traceability document to be maintained by the manufacturer	Each REESS manufactured to have a traceability document to be maintained by the manufacturer
Design for kinetic energy recovery	Adequate protection of cells in case of regenerative braking	Adequate protection of cells in case of regenerative braking
BMS data storage	Data logging feature required	Data of critical parameters of battery pack shall be logged by BMS and latest data for at least one month shall be maintained
Thermal propagation test	Evaluate the ability of REESS to withstand thermal propagation which is triggered by an internal short-circuit leading to a single cell thermal runaway and subsequent thermal propagation and shall not result in fire and explosion	Evaluate the ability of REESS to withstand thermal propagation which is triggered by an internal short-circuit leading to a single cell thermal runaway and subsequent thermal propagation and shall not result in fire and explosion
Thermal management	-	Have at least 4 temperature sensors in the battery pack to measure the cells' temperature and decision thereon by BMS. In case the temperature crosses 60 °C an audio-visual alarm shall come as an alert, and if the vehicle is in use, BMS shall gradually cut off the traction battery power supply to the motor.
Circuit design	Active paralleling circuits for the parallel connection of cells and strings to eliminate circulating currents	Active paralleling circuits for the parallel connection of cells and strings to eliminate circulating currents

In India, the Automotive Research Association of India (ARAI) is responsible for testing and certification of EV batteries under AIS 156 and AIS 038.

The incorporation of AIS 156 (for L category powertrain vehicles) and AIS 038 (for M and N category powertrain vehicles) amendments, have the potential to effect a generational shift in BMS approaches in the Indian EV industry.

Lithium-ion batteries, at a minimum, require a BMS with a "simple management" framework. This system uses improved detection circuitry to ensure accurate and reliable measurement of external parameters such as voltage, current and temperature. It also incorporates passive protection features to safeguard the battery.

More advanced BMS configurations go beyond basic monitoring and involve comprehensive battery modelling, SOC and SOH estimation, thermal management, battery cell equalization, charging control and fault diagnosis. These advanced capabilities are achieved through the use of sophisticated optimization algorithms and control strategies, allowing for enhanced performance, safety and efficiency.

3.6. Make regulations more robust—address the gaps

Indian regulations require further development and updates to address existing shortcomings. For example, there is currently a lack of clarity regarding the audio-visual warning requirements. The regulations should specify the exact positioning of LED indicators and establish a standard for the decibel levels of buzzers to ensure consistency and effectiveness. Additionally, there are no specific regulations concerning the monitoring of SOC and SOH to accurately estimate the remaining battery life.

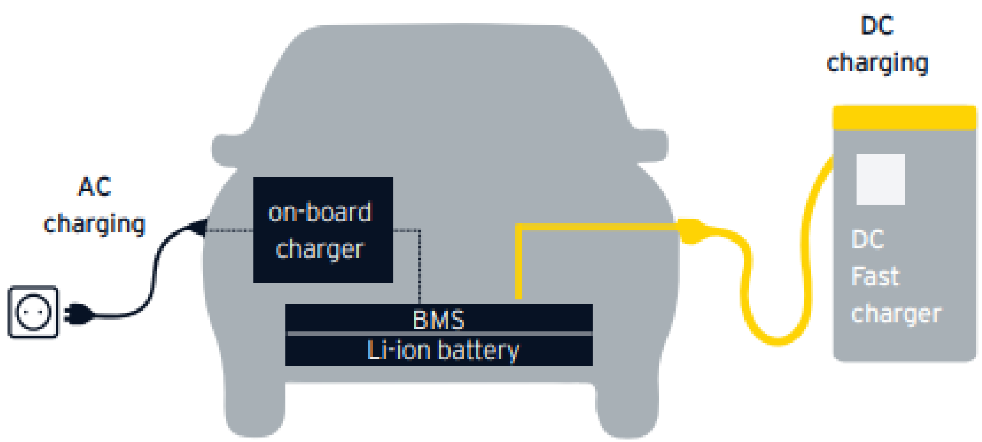
Regulators should also focus on cases of sudden SOC drops and establish calibration requirements to ensure accurate state estimation. Moreover, safety-critical battery parameters should be accessible through OBD port monitoring (similar to internal combustion engine vehicles) for self-diagnostics, maintenance and roadside assistance. There should also be provisions for the development of BMS and vehicle control unit (VCU) firmware updates via over-the-air (OTA) methods to enhance safety and functionality.

4. Role of BMS in EV charging

Establishing communication between an EV and electric vehicle supply equipment (EVSE) is essential to ensure that the vehicle is charged at the optimal rate required by its battery. This is crucial for both safety and preventing accelerated cycle ageing of the battery. Charging communication involves the BMS and the charger (EVSE) agreeing on the vehicle's power requirements, the current and voltage used during charging, and monitoring the charging process to ensure efficiency and safety.

In AC charging, the on-board charger must condition the power by converting it into high-voltage DC before supplying it to the BMS. In DC charging, the off-board charger interfaces directly with the BMS, bypassing the on-board charger (see *Figure 1: Interface between charging and BMS*).

Figure 1: Interface between charging and BMS

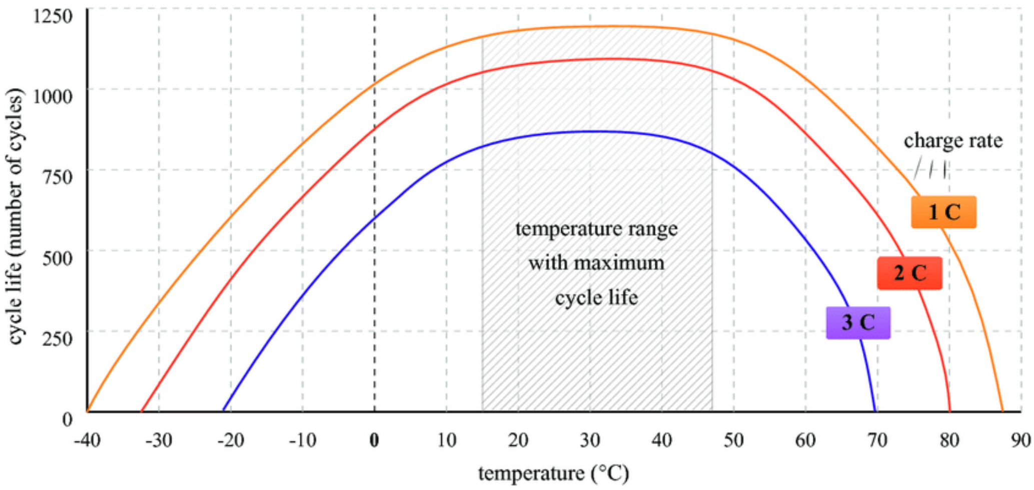


Source: Anon, 2019, "Propelling Electric Vehicles in India", EY, BEE, available at https://beeindia.gov.in/sites/default/files/2019%20-%20EY%20to%20BEE%20-%20Technical%20study%20on%20EVs%20%26%20Charging%20Infrastructure.pdf

Controlling the threshold limits and making decisions to control the required charge/discharge rates is important. Li-ion batteries can undergo degradation faster if charged at higher C rates at higher ambient temperatures.

The cycle life of Li-ion batteries strongly depends on the operating temperature. Ageing is also influenced by the rate of charge/discharge, which is depicted for 1C, 2C and 3C (see *Figure 2: Charging and BMS – operating temperature and ageing*).

Figure 2: Charging and BMS – Operating temperature and ageing



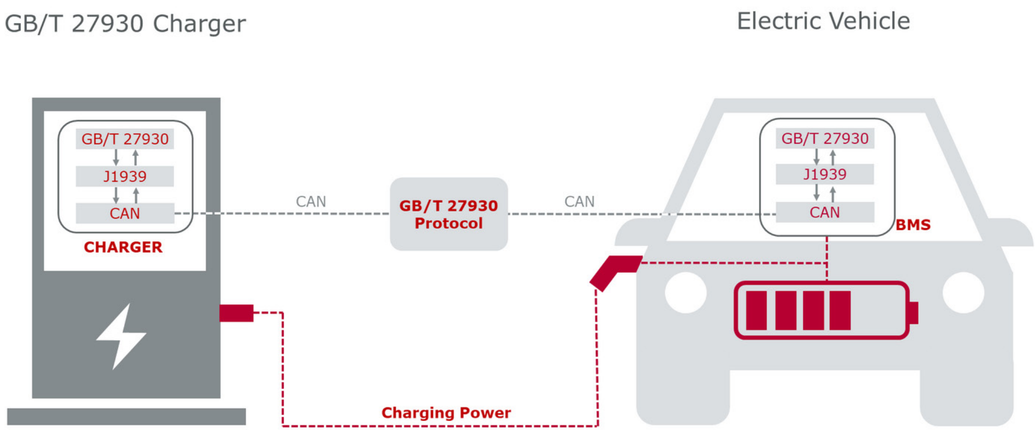
Source: Pichler, Benjamin. (2016). Increasing Electric Vehicle Range with a Recommendation App providing Context Specific Trip Rankings. 10.13140/RG.2.2.33985.76645.

Globally, multiple standards and protocols address communication between the EVSE and the EV. These protocols are defined by the ISO 15118 series of standards, which have been adopted in various regions, such as the US, Europe, China and India, albeit with different standard numbers. For example, IEC 61851-24, GB/T 27930, and IS 17017-24 are functionally equivalent in their requirements, and all adhere to the general specifications provided by the ISO 15118 series. These standards outline the communication protocols necessary for ensuring compatibility and safety during the charging process across different regions and markets.[18]

In India, the DHI standardisation committee decided that “Bharat charger specs for DC-001” will start with GB/T-27930 with additional requirements embedded into it.[19]

The GB/T 27930-2015 standard presents the communication protocol between the off-board charger and the BMS. It is based on the SAE J1939 network protocol and uses the CAN bus with a point-to-point connection between the charger and the BMS (see *Figure 3:*).

Figure 3: Chinese protocol for communication between chargers and EVs



Source: Anon, "Chinese Protocol for Communication Between Chargers and Electric Vehicles", Vector, available at https://www.vector.com/se/en/know-how/protocols/gbt-27930/

The EV charging ecosystem's scope includes various elements such as connector type, charging topology, communication protocols, safety, and security measures. Different charging systems, such as CHAdeMO, CCS-2 and GB/T are employed across the globe for various EVs and Electric Vehicle Charging Stations (EVCS). Based on the charging system in use, the appropriate digital communication protocol between the EVSE and the BMS is selected to ensure compatibility, safety and efficiency during the charging process.

4.1. Battery swapping and BMS

Battery swapping or Battery-as-a-Service (BAAS) is an appealing alternative to public EV charging, as it allows users to exchange depleted batteries for fully charged ones, offering flexibility by charging batteries separately at a swapping station. Querying the BAAS Pack's BMS is essential to evaluate the battery pack's quality every time it is docked at the charging station after use. For swappable batteries, mandatory cell diagnostics are critical. These diagnostics should be run before a new pack is inserted into the vehicle, providing vital information on the battery's health and the likelihood of degradation.

Tracking incremental ageing is also important, as this data can be extremely useful for predictive analysis, enabling financiers, banks and insurers to assess the residual value of the battery at various points in time. It will also guide decisions regarding whether to discard or reuse batteries for secondary storage purposes.

BMS-CHARGER INTERFACE: HIGHLIGHTS OF SOME KEY ISSUES

- **Compatibility:** It is essential to ensure that the BMS and charger are compatible. They should communicate effectively and support the same protocols for data exchange.
- **Communication errors:** If there are communication errors between the BMS and charger, it can lead to incorrect charging profiles or failure to control the charging process properly.
- **Faulty sensors:** The sensors used by the BMS to monitor battery parameters may be faulty, leading to inaccurate readings and improper charging/discharging.
- **Overcharging/Undercharging:** If the BMS fails to control the charging process effectively, it can lead to overcharging, which can damage the battery, or undercharging, which can result in reduced battery performance.
- **Temperature regulation:** Temperature monitoring and regulation are critical for battery safety. If the BMS fails to regulate charging based on temperature readings, it can lead to overheating and battery degradation.
- **Software bugs:** Like any software system, the BMS may have bugs that could affect its performance. Regular testing and debugging are necessary to ensure proper functioning.
- **Insufficient documentation:** Lack of clear documentation for either the BMS or charger can make integration challenging, leading to errors or delays in the integration process.

In 2022, NITI Aayog released a draft battery swapping policy, aimed at introducing battery standardization for interoperability. This policy would necessitate a degree of standardization in the BMS. Some of the key aspects highlighted in the draft policy include:[20]

- Batteries must be BMS-enabled to allow monitoring, data analysis and safety
- The battery's BMS must be self-certified and open for testing to check its compatibility with various systems, and capability to meet safety requirements
- BMS must be IoT-enabled to allow for safety and security monitoring

However, the policy nudge towards standardization has received pushback from the industry and the swapping policy is yet to come into force.

5. BMS and aftermarket and second-life use

A data-driven secondary market will be crucial in driving EV penetration in India. Other markets, such as the US (e.g., Autotrader, CarMax) and China (e.g., Uxin, Guazi, Alibaba), have already established secondary markets for EVs, which are supported by detailed data on vehicle performance. This data typically includes battery capacity and health, total distance travelled, and well-defined heuristics for price discovery of used batteries.[21] Improving access to metrics such as battery health and usage history will enhance the credibility of the aftermarket and drive greater EV penetration.

In India, the lack of reliable testing frameworks, combined with OEMs' proprietary data protection, which restricts access to BMS data, could undermine confidence in the second-life market for EV batteries. Currently, there is no standardized method for determining the SOH of batteries for second-life applications. Since OEMs have control over the BMS and battery data during its use, they may be hesitant to share this data for subsequent life cycle stages.

A potential solution is to extend the OBD-II standard, which is mandatory in internal combustion engine vehicles, to EVs. This would facilitate the collection of diagnostics and usage history data for post-processing and analysis, helping to assess battery health more transparently and accurately.

Such an approach is already being adopted in the US, where California has introduced regulations requiring car manufacturers to phase in a standard EV diagnostic system under the state's Advanced Clean Cars II program. Implementing similar standards in India could boost the development of a robust second-life market, fostering trust and accelerating EV adoption.[22]

Decoding the communication protocol to extract relevant data from the BMS is often challenging. A Controller Area Network (CAN) matrix is essential to decode the messages sent to and from the battery. However, OEMs are typically reluctant to provide access to this CAN matrix, as it would expose internal messages and confidential battery information. Additionally, it introduces the potential risk of parameter manipulations, which could affect the performance, safety and warranty of the battery systems. This reluctance creates barriers to obtaining

THE SET OF DESCRIPTORS OF THE LIFE OF THE BATTERY WHICH MAY BE RETRIEVED FROM THE BMS TO ASSESS THE SOH ARE AS FOLLOWS:

- BMS specifications
- Remaining capacity for each module in the battery pack, and for each individual cell (if feasible)
- History of storage conditions (temperature/duration)
- Overall kilometres in e-mobility or overall cycles in stationary applications (system level)
- Total number of charges and discharges (system level)
- Information on battery use, including load charge and discharge profiles or the time spent at certain SOC (system level)
- Internal resistance increases for each module in a pack/system
- Remaining power or power fade in a pack/system
- Remaining round-trip efficiency or efficiency fade in a pack/system
- Actual cooling demand
- Self-discharge rates
- Negative events during lifetime (below/above temperature limit, voltage spikes, overcharge and over-discharge, previous repairs)
- Any error messages and faults occurring in the BMS itself

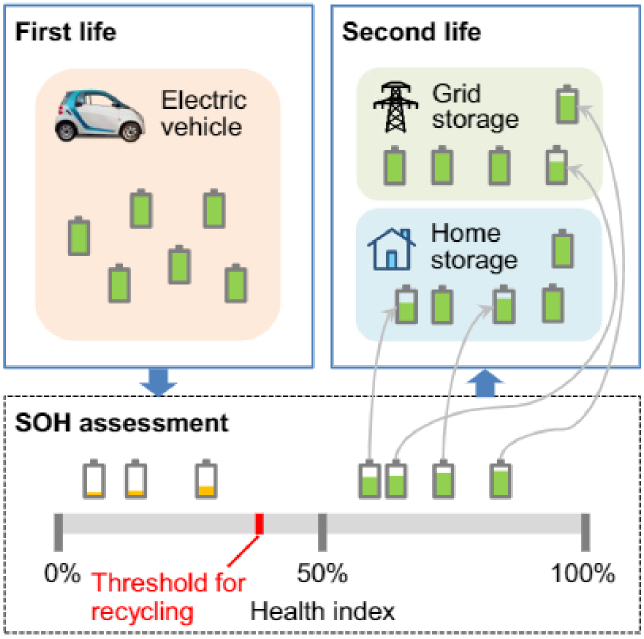
necessary battery data, limiting transparency and hindering efforts to develop robust second-life applications or independent diagnostics.[23]

Additionally, the actual depletion of EV batteries has been slower than OEMs originally estimated. This enhances the potential for higher tradability in the secondary market, particularly for 2W EVs.[24] A secondary market for EVs presents a significant opportunity in India, either through OEM buy-back schemes, OEM-led secondary marketplaces, or third-party platforms like Spinny or Cars24 in the 4W segment. Establishing such a market can help determine a credible salvage value for EVs, which in turn could reduce financing costs for customers by providing more predictable resale values.

End-of-life (EoL) automotive battery packs must be disassembled and processed before they can be used in second-life applications. Without access to BMS data, accurately determining the SOH is difficult, often requiring battery disassembly. The planned introduction of a battery passport in the EU could simplify the identification and evaluation of EoL batteries. By making first-life battery data available, the BMS could assist in accurately assessing battery usage history, facilitating second-life applications.[25]

Another challenge of the repurposing process is the development of a new BMS, which might be necessary if access to the existing BMS is not possible. OEMs often refrain from providing the appropriate communication interface due to the resulting disclosure of sensitive data. It should be considered that the development of a new BMS leads to significant additional effort and higher rededication costs.

Figure 4: Cell SOH assessment for second-life applications



Source: A Thelen et al, 2024, "Probabilistic machine learning for battery health diagnostics and prognostics— review and perspectives", Nature, available at https://rdcu.be/dXXGf

The regulatory push towards the 'right to repair' and the need to recycle could push for access to the current digital information locked within the BMS, with marginal additional cost to manufacture. Without a compelling need to share information, this is likely to be restricted to the minimum information possible.

Article 14 of the EU Battery regulation requires that the BMS of EV batteries must contain up-to-date SOH and expected lifetime data based on specified parameters. The information will be accessible in a read-only format and must be provided to those who legally purchase the battery. Further, the European Commission has requested harmonized European standards to describe procedures for the determination of the SOH of batteries by June 2027.[26]

The battery passport concept presents a valuable opportunity for India as it builds its domestic battery value chain. Drawing from the recent EU battery passport regulations, India could develop its version of the battery passport, incorporating key elements such as the SOH provided by the BMS as a core data field. By doing so, India can take advantage of its expertise in deploying scalable digital solutions across various stakeholders in the battery value chain. This would help establish a more robust system for reusing and recycling batteries, ultimately enhancing the sustainability and longevity of the battery ecosystem.

6. BMS and user experience

The telematics functions of the BMS are vital to improve the ownership experience of an EV. The BMS transmits battery status information to external systems like VCU, charger controller and test equipment using a communication interface. This interface is also used to modify the BMS control parameters and for diagnostic information retrieval. BMS offers diagnostic capabilities that enable early detection and resolution of potential battery issues.

CAN (controller area network) is the most common communications bus in automotive applications including EVs. CAN networks come in various implementations and can include a range of higher-level "application layer" protocols like unified diagnostic services, OBD II, J1939, etc.[27] The BMS utilizes these protocols to provide data on a range of parameters like temperature, pack voltage, cell voltage, current, errors, SOC and SOH. This data is shown on the vehicle display unit to the driver and it can be extracted using a data logger during maintenance or troubleshooting.

Fleets can use this feature to minimize downtime and reduce maintenance costs by addressing battery problems before they escalate. BMS data can empower OEMs to efficiently manage warranty claims by identifying when repairs or replacements are necessary, thus reducing warranty-related costs.

7. Global and national market in BMS

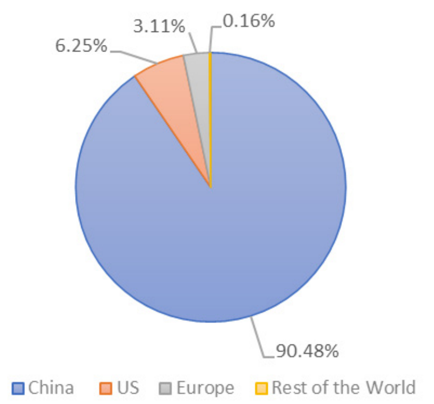
7.1 Global BMS demand

With the rapid growth of vehicle electrification, the demand for BMS is expected to surge. As the market diversifies and expands across different geographies, the production base for BMS is also growing. This trend is reflected in the analysis of vehicle demand data from the International Energy Agency's Global EV Outlook 2024, reviewed by CSE. It is assumed that one BMS is required for each vehicle, allowing BMS demand to be calculated based on EV demand.

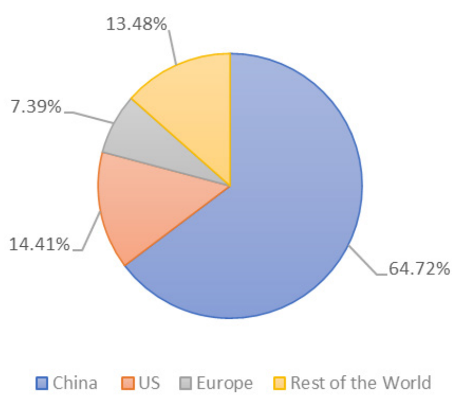
The data shows a shift in the global distribution of BMS demand. China's share of global BMS demand has decreased from 90.48 per cent in 2015 to 64.72 per cent in 2023. In contrast, the rest of the world (countries other than China, USA and EU) has seen an increase, with its share rising from 0.16 per cent to 13.48 per cent over the same period. This increase is primarily driven by the expanding two-wheeler and three-wheeler markets in India and Southeast Asia (see *Graph 1: Trend in region-wise demand for battery management systems*).

Graph 1: Trend region-wise demand for battery management systems

BMS Demand – 2015



BMS Demand – 2023



Source: CSE analysis of IEA data

7.2. Global BMS market segmentation and trends

The global BMS market is composed of three key types of players: automotive OEMs (e.g., Tesla and BYD), battery manufacturers (e.g., CATL and LG), and third-party BMS providers (e.g., Denso, Lithium Balance, and Guochuang).

Typically, vertically integrated OEMs such as Tesla and BYD produce their BMS in-house, while legacy ICE automotive OEMs tend to source their BMS from battery manufacturers or third-party providers. However, as competition intensifies in the automotive BMS market, some BMS manufacturers are diversifying into the battery energy storage market.

According to the IEA Global EV Outlook 2024, venture capital investments and leading EV start-ups are concentrated in China, USA and Europe. There is notable variability in start-up ecosystems across different EV technology areas. Between 2018 and 2023, the US attracted around 75 per cent of venture capital investment in BMS technology, followed by Europe and China.

Advancements in BMS hardware configurations and software strategies for battery state estimation have led to a significant increase in scientific publications and patents in 2023. The Volta Foundation reports that more than a quarter of total publications in the battery space are related to BMS, while BMS patents account for 32 per cent of total battery-related patents.

The BMS market is further classified by unit size or vehicle segment. The Asia-Pacific region, including India, China and ASEAN countries, is the largest market for two- and three-wheeler electric vehicles, which typically use a simpler centralized BMS architecture due to smaller battery pack sizes. In contrast, larger vehicles, such as four-wheelers and heavy-duty vehicles, require more complex distributed or decentralized BMS architectures to manage their larger battery packs. These architectures introduce challenges such as cell balancing, increased temperature monitoring precision, and higher risks of electromagnetic interference.

A notable trend since 2020 is the growing demand for analogue front-end integrated circuits (AFE ICs), which sense and collect data such as cell voltage and temperature. This increased demand is driven by the shift toward higher battery voltages in electric vehicles.

The global EV BMS market continues to evolve, with automotive OEMs, battery manufacturers, and third-party providers all playing critical roles in driving innovation and meeting the demands of an expanding EV industry.

Typically, BMS development and deployment in an EV involves the following activities:

- Battery cell modelling
- Battery pack design
- Electrical and thermal battery pack components
- BMS algorithms and components
- Closed-loop simulation and testing of the BMS algorithm
- Implementation of the BMS algorithm on a hardware
- Real-time testing / HIL validation

While third-party BMS makers are restricted to the design, simulation and testing of hardware and software, battery manufacturers are involved in the entire process from cell modelling to pack design and BMS integration. However, it is EV OEMs that can perform vehicle integration and carry out real-time testing of the BMS. Thus, depending upon R&D costs, supply chain and manufacturing strategy, EV OEMs either develop BMS in-house or source it from battery manufacturers or third-party suppliers (see *Table 2: Global battery industry structure*).

Legacy ICE OEMs rely on battery manufacturers or third-party BMS providers to source BMS technology specialization. OEMs that lack in-house capabilities would typically require a budget to set up a development unit to design and manufacture the BMS. In comparison, sourcing it offers competitive costs and access to efficiency improvements.

Although most large battery manufacturers also produce BMS, not all OEMs source their BMS from battery suppliers. For example, CATL has the largest share in the cell market. However, CATL's BMS market share is significantly lower than its battery market share because OEMs deploy a diversified battery component supply strategy and source the BMS from other players.[28]

The evolution of such industry trends will not only affect the supply of traction batteries, but also affect the reshaping of the competitive landscape of the supply chain of core vehicle components such as BMS.

According to Shenzhen Gaogong Industry Research Company (GGII), the BMS market structure is changing. In the past few years, due to dual market squeezes from EV OEMs and battery manufacturers, the market share of third-party BMS

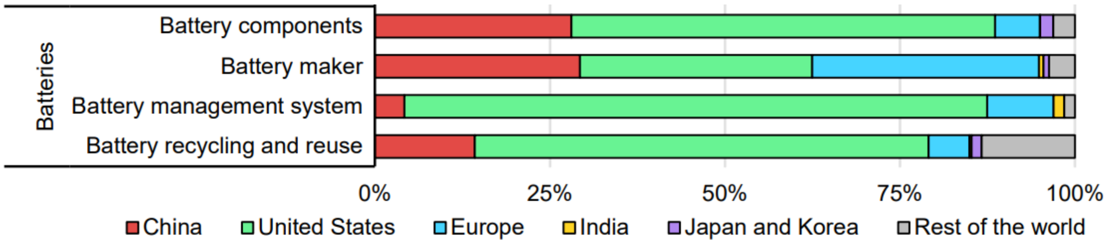
Table 2: Global battery industry structure

	Country	Name
EV OEM	USA	Tesla
		Rivian
		Lucid
	China	BYD
		SAIC
		BAIC BJEV
Battery manufacturer	China	CATL
		SVolt
		Sunvoda
		Gotion
	Korea	LG
	Japan	Panasonic
Third-party manufacturer	China	Guochuang
		DALY
		Huizhou E-power Electronics
		Shanghai G-Pulse
		Neusoft Reach Automotive Technology (Shanghai)
	Japan	Denso
		Mitsubishi Electric
		Marelli
	Canada	Eberspaecher Vecture
	Denmark	Lithium Balance
	Croatia	Rimac

manufacturers has fluctuated downwards. GGII data shows that in the 2023 BMS installed list in the Chinese passenger car market, OEMs accounted for 52.9 per cent, battery manufacturers accounted for 22.7 per cent, and third-party BMS manufacturers accounted for 24.4 per cent of the market share of battery manufacturers.

Under increasing market competition, some third-party BMS manufacturers have diversified from the automotive BMS market to the energy storage battery BMS market (see *Graph 2: Cumulative venture capital investment, by technology, country or region, 2018–23*).

Graph 2: Cumulative venture capital investment, by technology, country or region, 2018–23



Source: Anon 2024, "Global EV Outlook 2024", IEA, available at https://iea.blob.core.windows.net/assets/4b9758a7-543c-4c6a-b749-f53deffc5c4b/GlobalEVOutlook2024.pdf

The trend towards higher battery voltage platforms necessitates a proportionate increase in the number of battery cells connected in series, leading to the requirement of more Analog Front End Integrated Circuits (AFE ICs). A resultant surge in demand for AFE ICs in BMS is reshaping the automotive PMIC (power management integrated circuits) market.

Since the start of the early 2020s, the global automotive industry has witnessed a significant supply gap and subsequent push for BMS AFE ICs.[29] AFE ICs hold particular importance within BMS, as they are pivotal in collecting critical data, such as voltage and temperature of battery cells. They also employ specialized algorithms to estimate vital battery parameters such as SOC and SOH, relaying this information to the control chip for decision-making and monitoring.

7.3. Vehicle segmentation

EVs incorporate powertrains of different voltage architectures depending upon the vehicle segment.

Table 3:

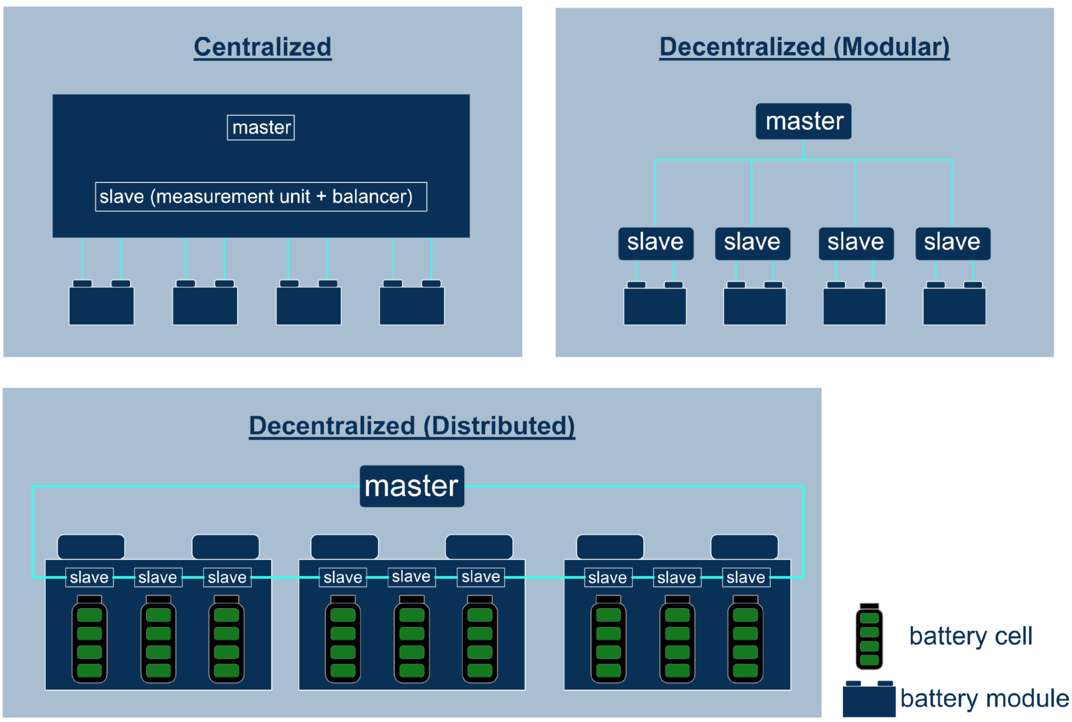
Segment	Battery capacity	Battery voltage
2w	1.2-3.3 kWh	48-72 V
3w	3.6-8 kWh	48-60 V
4w passenger (1st gen)	21 kWh	72 V
4w passenger (2nd gen)	30-80 kWh	350-500 V
HDV		800 V

The BMS covers three basic functions—sensing, protection and control algorithms. While the basic principles and the functions of the BMS remain the same across all vehicle segments, the voltage architecture dictates the electrical specification and mechanical design of the battery pack.

To achieve the desired voltage levels, a battery typically consists of a combination of cells strung in series and parallel. This configuration has a significant impact on the performance, thermal management, degradation and complexity of the BMS.

The two-wheeler and three-wheeler segments use battery packs in the range of 48 to 72 V. The centralized BMS topology stands as the most prevalent choice for 2- and 3-wheeler solutions. In this configuration, a single controller oversees all battery cells within the pack. The simplicity of architecture enhances cost-effectiveness, making it an ideal solution for low-voltage batteries commonly found in LEVs. The absence of an active cooling system due to space and cost constraints in most light EVs requires innovative BMS strategies in cell balancing and temperature control to maintain optimal battery operation. Using temperature data from cell characterization for building BMS models will aid with robust pack design and thermal management.

Figure 5: BMS topologies: Centralized, decentralized (modular) and decentralized (distributed)



Source: Schärtel, Lukas, Benedikt Reick, Markus Pfeil, and Ralf Stetter. 2022. "Analysis and Synthesis of Architectures for Automotive Battery Management Systems" *Applied Sciences* 12, no. 21: 10756. Available at https://doi.org/10.3390/app122110756

In response to the increasing need for longer range and enhanced charging efficiency, automakers are shifting from the traditional 400V platform to the emerging 800V platform, particularly in electric four-wheelers. This trend is especially prominent in vehicles requiring larger battery packs, such as e-buses and e-trucks, where the complexity of the BMS grows significantly due to the number of cells and their arrangement in series and parallel configurations.

As the number of cells increases, the BMS must monitor more voltage, temperature and current control points. A distributed BMS architecture, with slave (module-level) and master (system-level) BMS components, works together to ensure the safety and performance of the battery pack. However, the complexity of distributed systems introduces challenges such as increased wiring, the need for precise communication protocols, and advanced algorithms for cell monitoring and balancing. It also raises the risk of failures, such as wire breaks or poor connector contact, which are exacerbated by vehicle vibrations.

In higher-voltage systems, such as the 800V platform, cells connected in series present additional challenges. Voltage imbalances between cells are more likely, which can lead to inefficient capacity utilization and accelerated degradation due to inconsistent cycling. To mitigate these effects, the BMS must employ sophisticated balancing algorithms and active balancing systems, increasing both the system's complexity and cost.

Temperature variation sensitivity is another critical issue, as cells in a series configuration may not heat or cool evenly, leading to localized hotspots that accelerate degradation. Active cooling strategies and advanced thermal models must be integrated into the BMS to ensure uniform temperature distribution across the battery pack.

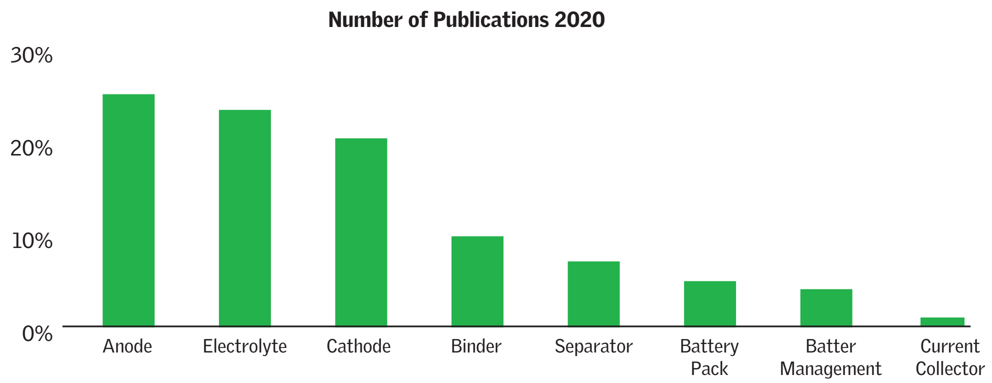
The shift to 800V systems also necessitates high-voltage galvanic isolation to detect faults quickly and prevent system failures. Additionally, the higher voltages introduce more electromagnetic interference issues, increasing the potential for disturbances from radio-frequency emissions and the creation of parallel current paths through cable loops.

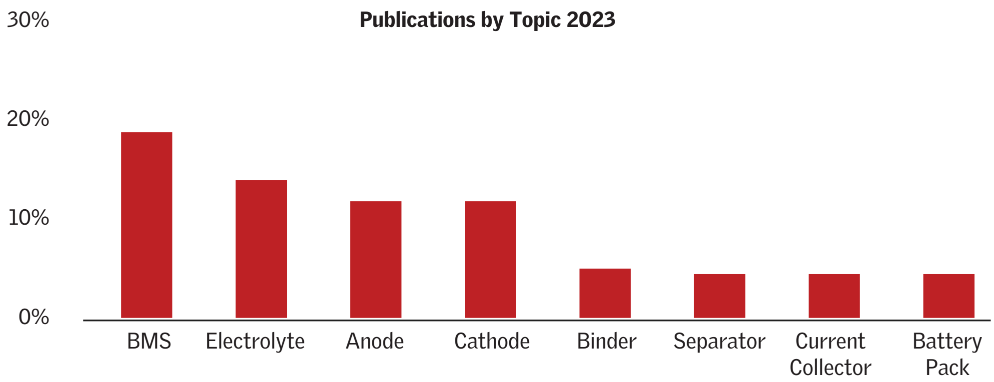
The BMS also plays a pivotal role in regenerative braking, where it determines the battery's charge acceptance rate. If the battery is near full capacity or outside the recommended temperature range, the BMS may restrict energy recovery, affecting both braking performance and overall energy efficiency.

BMS research has gained significant attention in recent years, reflecting its growing importance. According to a report by Volta Foundation, publications related to BMS accounted for more than a quarter of all battery-related research in 2023, while BMS and battery pack patents comprised 32 per cent of total battery patents. Research topics include improving hardware configurations, optimizing system efficiency, and enhancing BMS software to provide accurate state indicators (SOX), while ensuring the computational power needed for seamless integration with BMS microprocessors or cloud-based communication.

Interest in BMS research has surged since 2020. In 2020, only about 5 per cent of battery-related publications focused on BMS, but by 2023, this figure had increased to approximately 25 per cent (see *Graph 5: Trends in BMS research publications*). Similarly, there has been a notable rise in patents related to BMS technology (see *Graph 6: Patent issued in different sub-segments including battery management systems, 2023*).

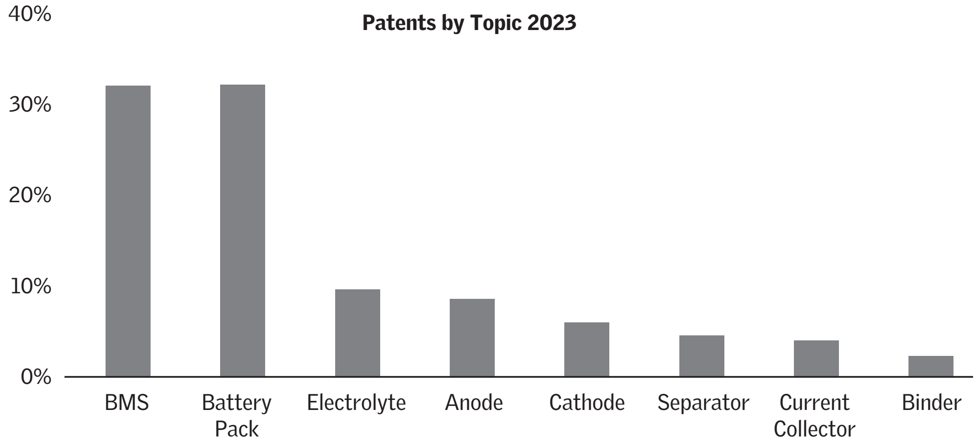
Graph 5: Trends in BMS research publications





source: Anon 2023, "Battery Report", Volta foundation, available at https://volta.foundation/battery-report/

Graph 6: Patent issued in different sub-segments including battery management systems, 2023



Source: Anon 2023, "Battery Report", Volta foundation, available at https://volta.foundation/battery-report/

8. Localization of BMS manufacturing in India

Currently, India relies heavily on imports to fulfil the demand for auto-electronic products, such as the BMS, which falls under power electronics and safety control electronics of an EV. Around 64 per cent of the total demand is imported.[30]

With the growing proliferation of EVs in India, the government is increasingly focused on boosting indigenization at all levels. The phased manufacturing programme mandates that EV OEMs progressively increase their domestic value addition in the vehicle. However, indigenization has yet to achieve significant scale. This is largely due to the availability of various imported BMS options, which offer different levels of reliability at competitive prices. The cost of development and time-to-market are critical factors influencing the design considerations for BMS, particularly in the cost-sensitive two- and three-wheeler markets. Each new EV has unique parameters in terms of performance and safety, making development iterations time-consuming and requiring a designated budget.

Currently, most OEMs rely on imported child parts and assemblies, including key components like thin wall casings, heat exchangers, thermoplastics and PCBs. India already has a reasonable manufacturing base for these products in non-automotive sectors. To increase local value addition in BMS manufacturing, these components will need to be redesigned to meet the standards of the automotive industry. Additionally, the heavy reliance on imported automotive electronics presents potential cybersecurity risks.

As outlined in the DST white paper on tropical EV batteries, India could consider developing a common BMS platform. Since certain functional blocks are consistent across most battery systems, reusing these blocks and the related documentation required for certification could streamline the process. Certification-ready hardware and software functional blocks would help reduce time-to-market, including the certification process according to AIS norms.

The urgency for domestic production of electric vehicle cells and batteries has never been greater. India currently imports all its lithium-ion cells, but these imports have shown manufacturing defects, substandard quality, and low resilience to the typical abuse and operating conditions of India's tropical climate. Many of these cells are prone to catching fire, endangering the lives of drivers and passengers. Thus, India must develop and manufacture cells and batteries tailored to the Indian climate, road conditions and consumer charging habits. A robust, India-specific BMS is central to achieving this indigenization of the battery value chain.

India's diverse vehicle market includes small and light two- and three-wheelers, four-wheelers, and heavy-duty electric buses and trucks. The risks of thermal runaway and battery degradation vary by vehicle segment, geography (particularly tropical conditions) and usage. Therefore, it is essential to develop BMS algorithms tailored to Indian driving cycles for optimized EV battery usage.

Additionally, material security can be improved by promoting recycling and working toward a circular economy. As the number of used batteries rises over time, accurate SOH estimation and EoL prediction enabled by the BMS will be key to facilitating second-life applications and recycling.

The revised AIS safety regulations have significantly driven the localization of BMS design and customization. However, much of India's EV industry still relies on imported BMS. While imported options offer reliability at competitive costs, the challenge lies in achieving significant local production. The breadth of available imported BMS components presents competitive cost advantages, but development costs and time-to-market constraints are substantial, especially in the two- and three-wheeler segments. Each EV model requires unique performance and safety adjustments, adding to development costs and time.

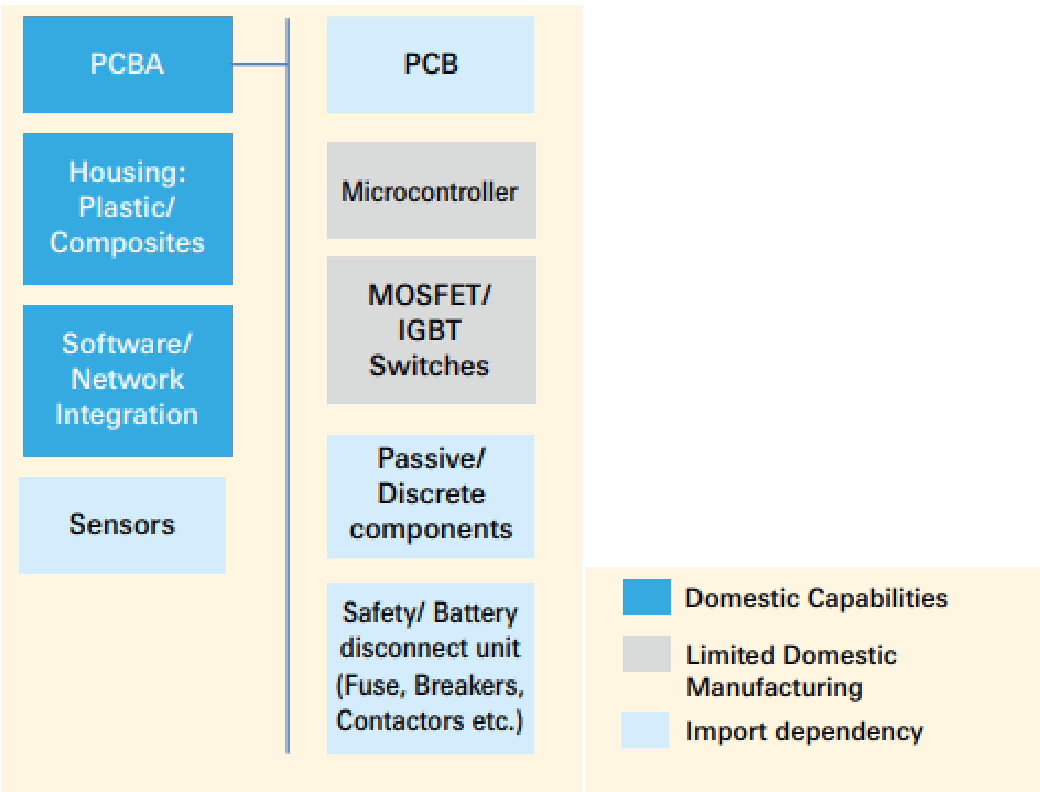
However, to reduce costs, new market entrants face the risk of sourcing cheaper, lower-quality products (B or C grade) that fail to pass Quality Control tests during manufacturing. These substandard components are often available on third-party commerce platforms, a risk that could be mitigated by purchasing directly from reputable manufacturers.

The semiconductor powertrain content in an EV is 6–10 times more than that in an ICE vehicle.[31] There is a significant dependence on BMS sub-components that are not manufactured in India: IC (semiconductor chips) for microcontrollers, sensors, transistor switches, etc. A global shortage of electronic child parts in 2022 led to production shortfalls. Most OEMs import the child parts and assemblies of the products, which often include components such as thin wall casing, heat exchangers, thermoplastics and PCBs.[32] India already has a reasonable manufacturing base in these product categories for non-automotive applications.

The industry will need to upgrade the product design of these components to meet automotive industry standards which can increase local value addition in the BMS.

When the AIS amendments were introduced, local BMS manufacturers found it challenging to source new components to adhere to the standards within the mandated time frame. Meanwhile, AIS-compliant Chinese-made BMS already started to flood the market due to control over supply chains. While the imported BMS can meet AIS requirements, their reliability during on-road operation is sometimes a matter of concern (see *Figure 6: Localization status of BMS components*).

Figure 6: Localization status of BMS components



Source: Anon, 2021, "EV Landscape: Opportunities for India's Auto Component Industry", ACMA, availbale at https://www.acma.in/uploads/otherdocmanager/ACMA_YES_Bank_Report_EV_Landscape_Opportunities_for_Indias_Auto_Component_Industry.pdf as accessed on June 2024

Import dependence on automotive electronics can also present a potential cybersecurity threat. Software modification or hardware Trojans during manufacture could lead to loss of data integrity from sensors, calculations for state estimations, scheduling routines and the lack of optimization for cell balancing.[33]

These can result in accelerated battery degradation, unexpected shutdowns and thermal runaways. The BMS can be used as a tool to transmit sensitive user information.

To strengthen the BMS supply chain, OEMs should build a resilient vendor base to ensure access to the latest advancements in SOC technology. Locally designed and assembled BMS printed circuit boards, using contract manufacturing, could be tailored to suit Indian environmental conditions. Developing BMS competencies requires building expertise in hardware design, testing, software integration, SOC and SOH estimation, advanced fault detection algorithms, cell chemistry knowledge, EV applications and temperature management—areas with relatively low capital requirements compared to cell manufacturing.

India's strong software and electronics ecosystem provides an advantage for developing scalable BMS solutions suitable for both domestic and export markets. However, a significant hurdle for start-ups remains the lack of accessible, cost-effective testing facilities. Global standards for BMS product development often employ "Hardware-in-Loop Simulators" (HILS), which simulate external conditions for comprehensive testing but require substantial investment, estimated between Rs 30–50 crore. HILS can accelerate development cycles, allowing start-ups and manufacturers to conduct rapid, in-depth testing of BMS products to ensure quality and cost competitiveness in the global market.[34] It offers simulation of the real-world environment in which the BMS will be used, assisting in discovery and rectification of potential faults.

Although there are standards for determining battery parameters, such as ISO 12405-1 or USABC electric vehicle battery test procedures, they are time-consuming (up to 75 hours) and therefore not suitable for mass rededication. This is why the realization and standardization of rapid test procedures are of particular interest to the battery industry.[35]

8.1 Can standardized and open-source BMS be developed?

An open-source BMS provides a repository of hardware platform files and software code freely available for use, modification and sharing under an open-source license. FoxBMS, developed by Germany's Fraunhofer Society in 2016, is a prime example, supporting developers, engineers and researchers worldwide.

NITI Aayog proposed a similar open-source BMS platform for India in 2020, aimed at ensuring high-quality, safe battery packs for light electric vehicles, particularly suited to India's operating conditions. This initiative would offer a generic but functional platform that companies could then customize to create tailored, value-added products. New entrants, especially in India's light EV segment, may lack the resources to develop their own BMS, relying instead on ready-made solutions. This platform could enable them to utilize a generic BMS as a foundation for their vehicles.

At first, a multi-segment development platform may appear to challenge functional safety principles. However, a common BMS platform makes sense, as many functional blocks are consistent across battery systems, allowing reuse of these components and related certification documentation. This approach can streamline the time-to-market, reducing certification timelines under AIS norms. Additionally, modularity and reusability in code and hardware components would be key, influencing architectural design and hardware selection decisions.

Some key considerations in this context are:

- Currently, voltage sensing is the basis for estimating the state of charge and state of health, etc.; we have to envisage the potential for additional inputs in the future.
- The hardware selected must be available from multiple vendors.
- The architecture must provide for data logging and forensic abilities.
- The BMS must also be able to address new battery systems that may arise with different state characteristics from the existing ones.

FoxBMS employs 48-volt modules stacked to reach pack voltages of approximately 500 V or higher. A similar modular approach in India could initially focus on low-voltage platforms, such as two- and three-wheelers, and gradually expand to larger EV platforms. Generic protection and control algorithms could be adapted across these platforms, ensuring a scalable and flexible development framework.

One of the main challenges in EV BMS development is efficiently transitioning advanced algorithms from development stages into the embedded BMS environment. FoxBMS facilitates this by allowing developers to easily share battery-related data from the battery system with algorithms running on connected devices, supporting a streamlined integration process and promoting collaborative development.[36]

Open-source software for battery data management and physics-based modelling offers opportunities for broader collaboration between OEMs and academic institutions by establishing a feedback loop between real-world data and experimental research. Such a project has distinct requirements, calling for a unique organizational structure. One approach could be to leverage an existing entity at one of the IITs, registered as a Section 8 company, to oversee and manage the platform.

To balance openness with intellectual property (IP), IP registration should protect core innovations while maintaining transparency for third-party audits. Select components could be licensed at no cost to foster widespread adoption, while other aspects of the platform might be suitable for monetization, enabling the project to sustain itself financially while remaining open and accessible.

9. Way forward

Lithium-ion cells offer high energy density, providing exceptional power output, but this same feature can make them prone to instability under certain conditions, affecting performance if they operate outside safe limits. A BMS acts as the first line of defence, responding to temperature, voltage and current anomalies to prevent safety events, such as thermal runaways.

The BMS's role extends beyond safety; it also mitigates performance loss due to high temperature-induced cell degradation. Given rising temperatures across the country, the demand for domestically designed and manufactured BMSs for electric vehicle batteries has become critical. This requires resilience built into BMS designs to ensure batteries operate efficiently under varying conditions of cell chemistry, climate, geography and durability.

Localization of battery manufacturing and the associated regulation and standards development need to address the following issues.

9.1 Accuracy of SOC and SOH estimation

BMS design must account for cell ageing effects, adjusting protective and state estimation parameters as cells age. Initially calibrated on fresh batteries, BMS algorithms become less accurate over time as the cell's current-voltage profile shifts with calendar and cycle ageing, leading to potential inaccuracies in SOC estimation and range projections. Regular BMS calibration is, therefore, essential.

Diagnostics that encompass all ageing factors, especially within specific EV applications, remain challenging, with the key issue being an optimal balance across on-board, edge or cloud-based methods. India must prioritize advanced SOC and SOH estimation techniques, such as Electrochemical Impedance Spectroscopy (EIS) for cell degradation characterization, Kalman filters for data-driven modelling, and physics-based models that reflect the battery's electrochemical and thermodynamic properties.

To support these advancements, India will need to establish capabilities to manage and analyse battery data, utilizing 5G-connected vehicle technologies and edge computing. This will enable the creation of digital twins—real-time virtual representations of physical EV batteries—providing a comprehensive framework for accurate battery management and predictive maintenance.

9.2 Prediction of thermal runaways

Strengthening thermal runaway prediction is essential, with an emphasis on harnessing advanced hardware and software BMS capabilities for early warnings. Developing predictive models for thermal runaway is key, focusing on both micro-scale internal cell mechanisms and macro-scale system effects to offer a comprehensive safety framework.

BMS design, development and calibration must align with specific cell chemistries and applications. Each battery chemistry exhibits a unique charge-discharge curve with specific voltage levels, safety limits and SOC profiles. For instance, materials like LFP cathodes and Silicon anodes show significant hysteresis, where the voltage profile during charging differs from that during discharging, a factor that the BMS must incorporate to maintain accuracy and safety.

9.3 Significance of battery ageing data

Incremental ageing data holds significant value for downstream stakeholders, including financiers, banks and insurers, as it helps assess a battery's residual value over time. This information is crucial for informed decisions on battery redeployment or recycling. Frequent quality assessments of the battery pack, especially at each docking point in a swapping station, are indispensable. These evaluations are critical for maintaining safety and for accurately predicting the battery's remaining useful life (RuL). For swappable batteries, mandatory cell diagnostics would provide an essential safeguard, ensuring ongoing performance, safety and viability for extended use.

9.4 Enabling early detection and resolution of potential battery issues through diagnostic capabilities of the BMS

In India, the lack of reliable testing frameworks and the restrictive access to BMS data due to OEMs' proprietary data policies hampers trust in the second-life battery market. Currently, there is no standardized approach for assessing the SOH of batteries intended for second-life applications, limiting their repurposing potential. Expanding the BEV sector to include OBD-II standards—mandated in internal combustion vehicles for diagnostics and usage history—could address this gap. Such a standard could facilitate comprehensive data collection, enabling more effective analysis and processing for extended battery life applications.

9.5 Inclusion of SOH data in Indian battery passport

BMS data presents an opportunity to establish a battery passport initiative in India. As the country develops a domestic battery value chain, it would be strategic to adopt regulations for an indigenous battery passport akin to the EU's model. This Indian battery passport should include SOH data from the BMS, making critical health and lifecycle information accessible to stakeholders across the battery ecosystem. Leveraging India's experience with scalable digital solutions, this initiative can enhance battery reuse and recycling. To support such a programme, India should create guidelines for a standardized BMS public data structure, enabling shared access to key SOX data. This would facilitate accurate Remaining Useful Life (RuL) assessments and promote sustainable second-life applications.

9.6 Importance of publicly available battery ageing datasets for accelerating the development of probabilistic battery diagnostic and prognostic models

Existing datasets have played a critical role in advancing battery research, though they are mostly limited to cell-level aging data collected in controlled lab settings. This approach often overlooks the impact of real-world factors like packaging, cooling systems, and fluctuating operating conditions on battery ageing. To drive meaningful advancements, industry and academia must collaborate to compile and share high-quality data on aging across cells, modules, and packs. This comprehensive data will be essential to support future research and optimize battery performance in practical applications.[37]

This approach could establish a consensus on a minimum set of data requirements, with clear justifications for each. The battery industry would then be positioned to define the optimal procedure for supplying this data and validate it through the battery passport framework. This validation process would help ensure consistency and reliability across the battery value chain, enhancing transparency and supporting the reuse and recycling of batteries in second-life applications.

9.7 Role of coupled thermal, electrical, mechanical, and ageing models in optimizing all aspects of cell design

These models facilitate battery and product co-design, where battery form factor, packaging, cooling and control algorithms are jointly optimized under unified engineering constraints such as cost, volume, weight, energy requirements and specific operating conditions, including regional climate and driving patterns. Interdisciplinary collaboration will be essential to successfully develop integrated digital twin models, which will provide a dynamic, real-time representation of battery performance and support robust design and operational efficiencies in the future.

9.8 Use of battery data to strengthen circular economy

To enhance battery material security, it is crucial to encourage recycling and build a circular economy around battery use. As the volume of spent and used batteries rises, precise State of Health assessment and end-of-life prediction via BMS will be essential for enabling reuse and recycling. India's EV market spans diverse vehicle categories, from light two- and three-wheelers to heavy-duty electric buses and trucks. Given the varied thermal runaway and degradation risks influenced by vehicle type, regional climate (tropical in this case), and usage patterns, it's vital to employ BMS algorithms tailored to Indian driving conditions to optimize battery life and performance across this range of vehicles.

9.9 Build technical and regulatory capacity

Building competency in BMS requires targeted capacity-building efforts across hardware design, testing and software integration. Key skills include proficiency in developing estimation techniques for State of Charge and State of Health, advanced algorithms for supervision and fault detection, expertise in EV cell chemistry and use cases, temperature management, and electronic assembly. Unlike cell manufacturing, these activities demand relatively low investment, making it feasible to develop specialized skills domestically. By capitalizing on India's robust software and electronics expertise, the sector can create scalable BMS solutions suitable for both domestic and export markets, enhancing India's position in the global EV value chain.

9.10 Need for open-source BMS template and platform

The goal of an open source BMS effort is to develop a generic but functional platform that can then be customized by companies to provide value-added products. Many new entrants to the sector in the light EV segment in India often do not have the ability to develop the BMS and have to depend on ready-made solutions. Such candidates could utilize the generic open-source BMS and customize it according to their vehicle specifications. Such a product could also have pre-certified hardware and software function blocks that can effectively reduce time to market, which includes the certification process according to AIS norms.

9.11 Change required in the perspective of manufacturers towards BMS

In 2022, numerous vehicle fires were attributed to the absence or inadequate performance of BMS in electric vehicles, as per investigations by MoRTH. These incidents prompted critical amendments to EV safety standards (AIS156 and AIS038), marking a shift from viewing BMS as a mere commodity to emphasizing its engineering significance. Although AIS standards cover many essential BMS functions, the reliability of these systems demands further attention within India's regulatory framework.

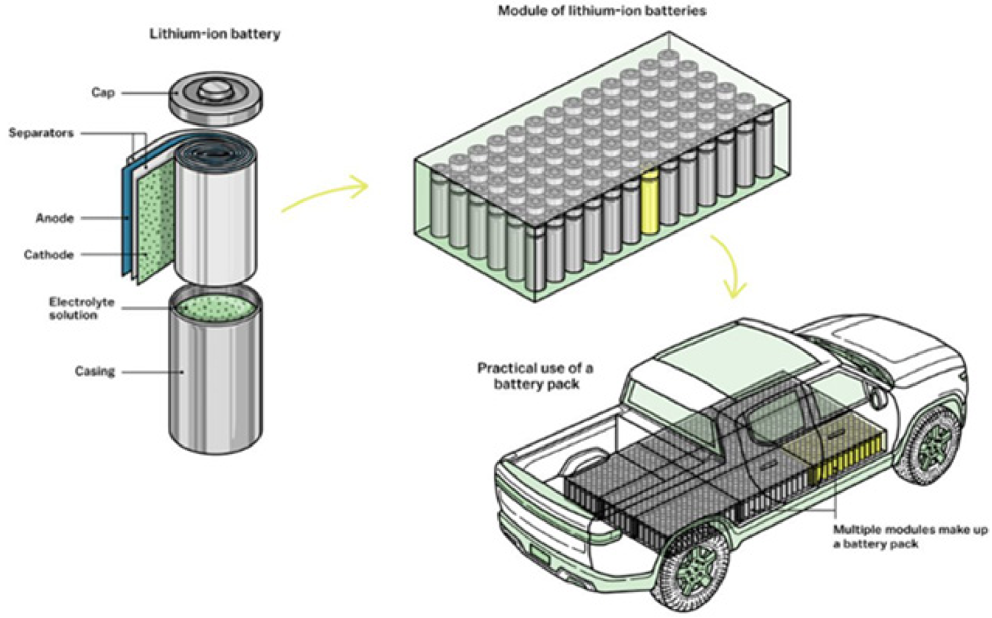
BMS systems represent a new frontier of increased software integration in automobiles, where advancements largely rely on software. As BMS hardware and software configurations grow more intricate, the risks of software glitches and sensor faults also escalate, underscoring the need for OEMs to align BMS development with functional safety standards.

Real-world driving conditions in India—such as diverse driving styles, partial charging and discharging, seasonal climate impacts and prolonged parking—add layers of complexity to battery ageing. To develop accurate SOH estimation models, it's crucial to incorporate these real-world conditions into lab testing. Sharing India-specific data from local labs with OEMs, battery manufacturers and BMS developers, coupled with feedback loops and data sharing, is essential for building a resilient ecosystem.

10. Annexure: What does a BMS do?

The Battery Management System (BMS) is an essential electronic system that ensures the safe and efficient functioning of an electric vehicle (EV) battery. Within an EV, the battery pack comprises modules containing multiple individual cells, and the BMS plays a critical role in overseeing these cells. It monitors and regulates cell operation to maintain optimal performance and safety, while also communicating the battery's status to the vehicle's external systems, making it integral to the overall function of an EV.

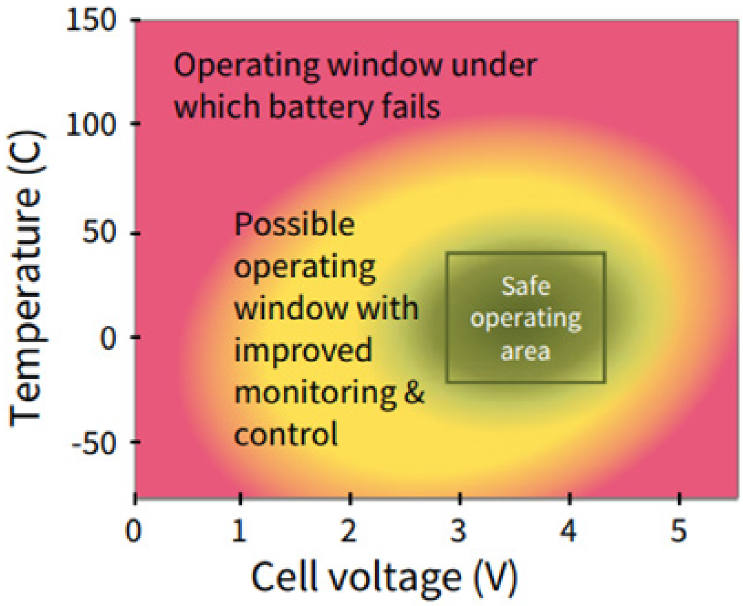
Figure 1: An EV powered by a lithium-ion battery



Source: Rebecca Heilweil 2022. *How to build a better battery*, Vox, available at https://www.vox.com/recode/23027110/solid-state-lithium-battery-tesla-gm-ford

While the high energy and power density provided by lithium-ion batteries has enabled the proliferation of electric mobility, lithium-based chemistry also brings risks associated with the battery being operated outside its 'Safe Operating Area' (see *Figure 2: The operating window of a Li-ion battery cell*).

Figure 2: The operating window of a Li-ion battery cell



Source: https://www.infineon.com/dgdl/Infineon-INF1197_ART_BMS_Whitepaper_d08-Whitepaper-v01_00-EN.pdf?fileId=8ac78c8c7f2a768a017f8da0f4ff7734&da=t

Currently, EV battery packs in India rely on cells primarily manufactured in China or South Korea, which are not tailored to withstand India's specific driving conditions, including high temperatures, heavy rains, dust, road vibrations and high humidity. To enhance EV safety, range and performance, it is crucial to adapt BMS for these local conditions, making their development and ownership essential for long-term success in the Indian market.

Additionally, the battery supply chain's dependence on critical materials, alongside the insufficient infrastructure for battery recycling, calls for a focus on safely maximizing battery potential. This approach not only extends battery life but also minimizes environmental impacts by reducing the need for raw material extraction.

The BMS plays a vital role in managing a battery's charge and discharge processes, setting and maintaining safety limits, optimizing operating conditions, and executing algorithms for battery health and charge management. It continuously monitors each cell, facilitates cell balancing to keep them at uniform states of charge, and communicates essential data with other system components. A robust BMS safeguards the battery from damage, ensures operational safety, predicts battery lifespan and maintains efficiency throughout its lifecycle.

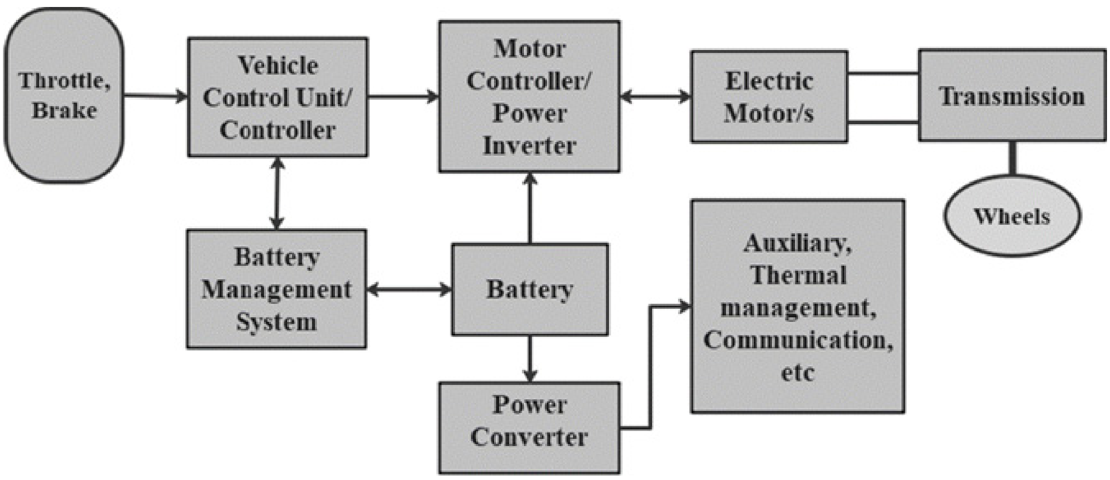
Table 1: Functions of BMS

Key parameter monitoring	Current monitoring Voltage monitoring Temperature monitoring High voltage interlock and isolation monitoring (for high voltage applications)
Battery state analysis	State of Charge (SOC) evaluation State of Health (SOH) evaluation State of Function (SOF) evaluation
Energy control management	Charging control Discharging control Balancing control
Safety management	Over-current protection Overcharge and over-discharge protection Over-temperature protection
Information management	Display Store historical information

Source: Xiaojun Tan 2022, et al. 2022, Battery Management System and its Applications, Wiley

As part of the larger vehicle system, the BMS also interfaces with the Vehicle Control Unit (VCU), which manages power delivery to the motor (see *Figure 3: Electric vehicle sub-systems and BMS*). The VCU ensures that the battery can safely supply the required energy when the car needs additional power, such as during acceleration. State of Charge and battery temperature information from the BMS are needed for this.

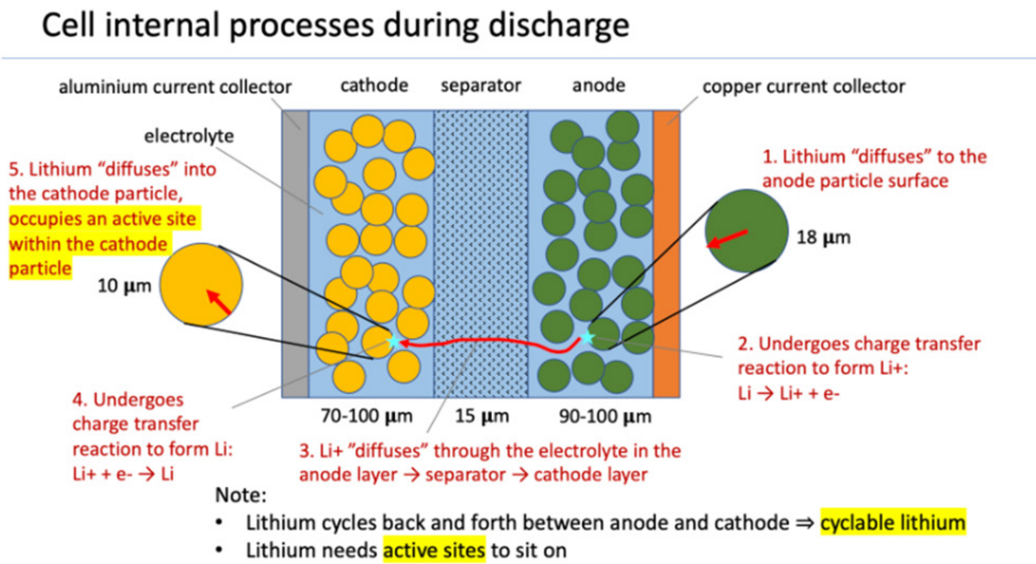
Figure 3: Electric vehicle sub-systems and BMS



Source: K W See et al, May 2022, "Critical review and functional safety of a battery management system for large-scale lithium-ion battery pack technologies", International Journal of Coal Science & Technology, Springer, available at https://link.springer.com/article/10.1007/s40789-022-00494-0/figures/1 as accessed on June 2024

A typical lithium-ion cell functions through electrochemical reactions where lithium ions undergo intercalation (the reversible insertion of ions into layered materials) and de-intercalation within the cell's electrodes. This process generates a flow of electrons in the outer circuit, producing current. The dynamics of these internal reactions are influenced by temperature, charge/discharge rates, and the electrical load applied. To ensure safe and efficient operation, electronic circuits monitor these interconnected cells in a battery pack, managing and optimizing performance in real-time.

Figure 4: Electrochemical reactions inside a lithium-ion cell

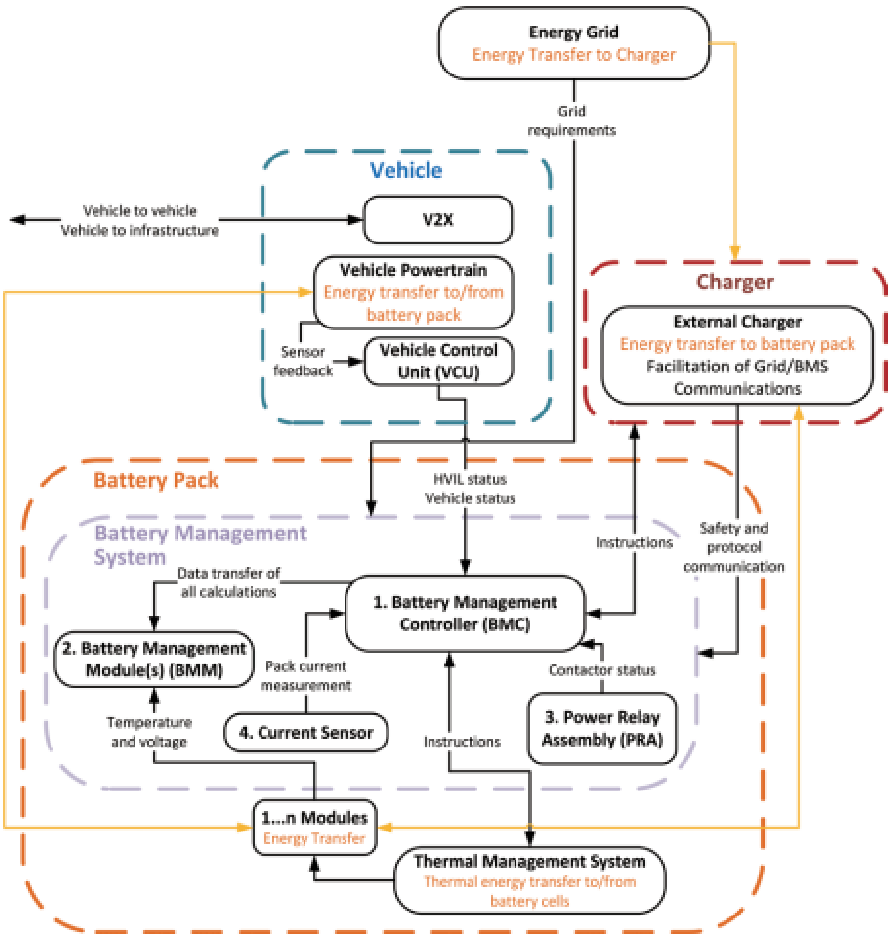


Source: CSE

The BMS gathers critical battery data through sensors measuring physical parameters like temperature, voltage and current, collectively known as the Analog Front End (AFE). This data forms the basis for estimating battery state, cell balancing, controlling charge/discharge and managing thermal conditions. The BMS uses the AFE to determine if measurements exceed safe thresholds, prompting the control unit to disconnect the battery from the external circuit via relays or power contactors if needed. Effective BMS functionality depends heavily on precise measurements—accuracy, sampling speed, pre-filtering and data integrity are key factors.

Expanding beyond standard metrics, experimental sensors like pressure and gas sensors are being tested, providing deeper insights into battery health. This multi-sensing approach enhances the BMS's ability to manage batteries proactively and effectively, optimizing safety and performance.

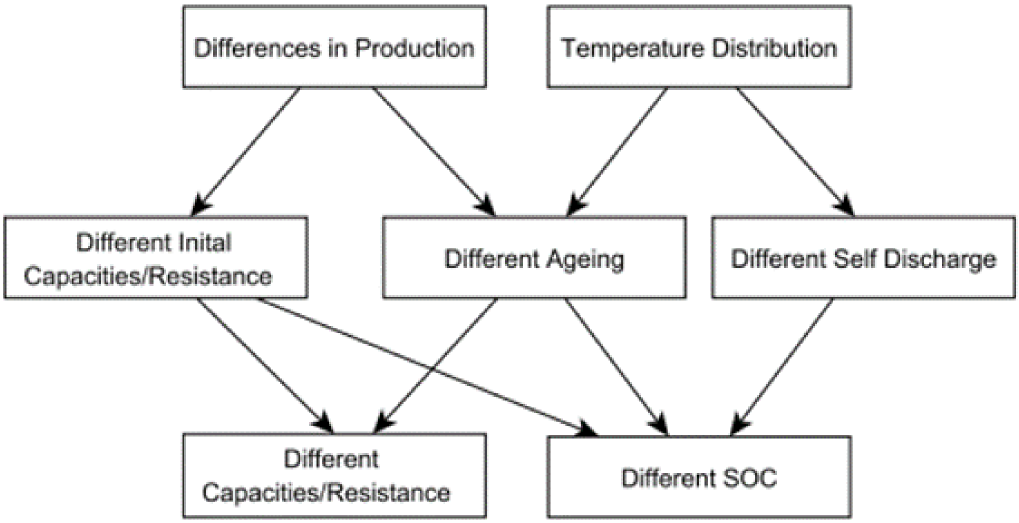
Figure 5: Architecture of a generic BMS and its relationship to the wider vehicular system



Source: M Cheah and R Stocker, "Cybersecurity of Battery Management Systems", Horiba Mira, available at https://static.horiba.com/fileadmin/Horiba/Company/Readout/E53/R53E_18_082.pdf as accessed on June 2024

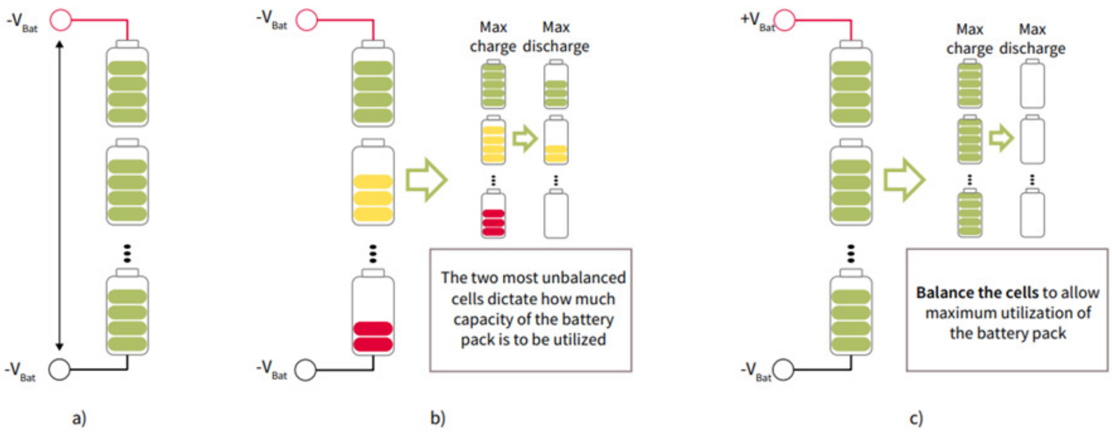
A battery pack comprises multiple cells connected in series and parallel, which can lead to inconsistencies among cells due to variations in production or differing operational conditions (see *Figure 6: Causes for cell imbalance*). These inconsistencies may create varying initial conditions, uneven ageing and differing self-discharge rates, causing cells to have divergent SOC, capacity and internal resistance values. To counter this, the BMS performs cell balancing, ensuring that all cells maintain an even SOC. Without balancing, a single faulty cell can trigger an early power cut-off, leading to a sudden loss in range (see *Figure 7: Showing the charging and discharging behaviour of (a) cells in series when (b) unbalanced and (c) balanced*).

Figure 6: Causes for cell imbalance



Source: Battery Management System Hardware Concepts: An Overview

Figure 7: Showing the charging and discharging behaviour of (a) cells in series when (b) unbalanced and (c) balanced



Source: https://www.infineon.com/dgdl/Infineon-INF1197_ART_BMS_Whitepaper_d08-Whitepaper-v01_00-EN.pdf?fileId=8ac78c8c7f2a768a017f8da0f4ff7734&da=t

Cell balancing in a BMS can be achieved via passive or active equalization. The passive method is straightforward and low-cost, dissipating excess energy from a cell through a parallel resistor as heat. Active equalization, on the other hand, transfers charge from a cell with excess to one with a deficit, reducing energy loss and boosting efficiency, though it is more costly due to the added circuit-switching components.

Accurately estimating SOC and SOH is crucial for effective battery management. SOC reflects the battery's remaining charge capacity, essential for calculating an EV's remaining range and for avoiding overcharge or deep discharge, which could harm the battery. SOH indicates the battery's capacity loss and ageing, defined as the ratio of current maximum capacity to its original rated capacity. SOH degradation is influenced by factors such as power fade, solid electrolyte interphase (SEI) growth and capacity loss, all impacting battery longevity and efficiency.[38] Battery degradation levels and variations among cells are highly influenced by operating conditions, charge-discharge cycles and usage schedules. Accurate SOH prediction is crucial for optimizing battery cycle efficiency and assessing battery viability for secondary applications or recycling.

Because SOC and SOH lack direct physical measurement equivalents, they must be estimated indirectly using measurable properties like temperature, voltage, current, impedance and C rate (charge/discharge time). Estimating these states of charge and health reliably is among the most essential functions of a BMS software system, enabling efficient battery management and extending the battery's lifespan.

MODELS FOR SOH ESTIMATION

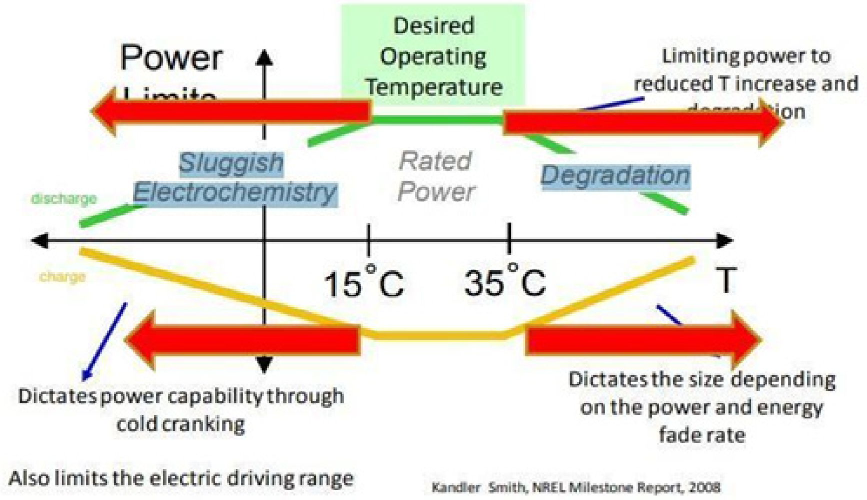
There are two main approaches to model cell degradation: physics-based and data-based.39 Physics-based models utilize electrochemical and thermodynamic equations to map the interactions between current, voltage and various design parameters, such as electrolyte type and electrode porosity. Data-based models, conversely, rely on observed battery behaviour across different conditions (C-rate and temperature) to create empirical models, often using equivalent circuits. While pure physics-based simulations can face challenges due to limited real-world data and unknown variables, a hybrid modelling approach is emerging. This combines physics-based modelling with data-driven machine learning, optimizing accuracy and adaptability.

Electrochemical Impedance Spectroscopy (EIS) is a valuable tool for assessing battery health. By applying a small signal across a frequency range and measuring the response, EIS identifies impedance changes, which often signal cell degradation. Characterizing impedance is essential for setting operational limits, predicting performance and tracking SOH. EIS serves as both a diagnostic and prognostic tool throughout the battery lifecycle—ranging from quality assurance and state estimation to internal temperature monitoring and assessment for second-life applications.

Tracking of safety

While research efforts focus on improving lithium-ion battery performance, achieving these targets with high safety standards remains challenging. Lithium-ion batteries subjected to stressors become increasingly vulnerable to mechanical and thermal risks. Factors like excessive vibration, high temperatures and inconsistent charging patterns can lead to safety incidents. Ultra-fast charging, which often surpasses recommended charge rates, also accelerates battery wear. Moreover, high temperatures combined with a full charge exert significant stress on these batteries, inducing faster degradation than standard charging cycles (see *Figure 8: Ideal temperature for lithium-ion batteries*).

Figure 8: Ideal temperature for lithium-ion batteries

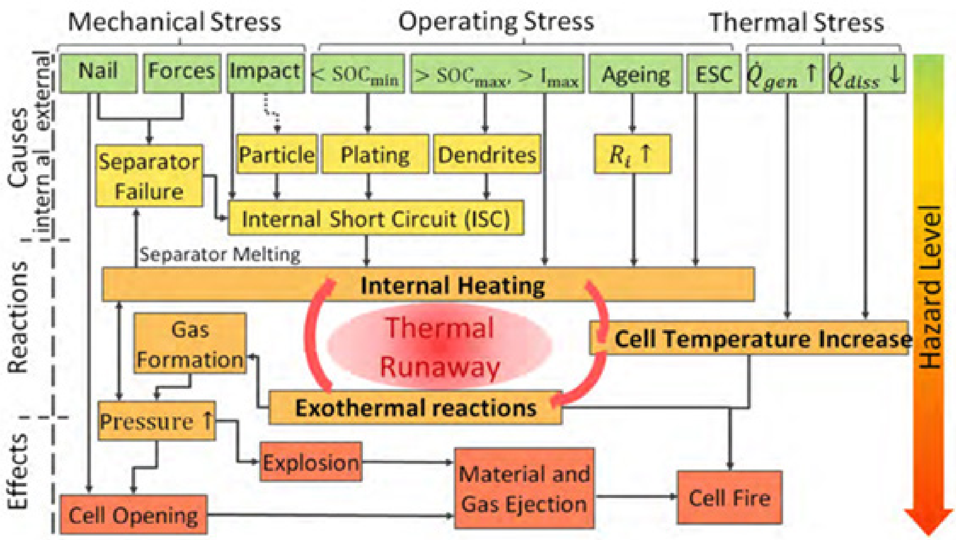


Source: National Renewable Energy Laboratory, US[13]

Battery fires can stem from various failure modes, including unexpected stochastic events. When mechanical, electrical or thermal tolerance levels are compromised, internal heating can occur, potentially triggering a thermal runaway. This runaway effect is a self-sustaining reaction that escalates temperatures within the battery, potentially leading to fire or even explosion if not managed effectively. Robust battery management systems play a crucial role in monitoring and mitigating these risks, ensuring the battery remains within safe operational limits (see *Figure 9: Abuse conditions and failure modes of Li-ion cells*).

Lithium-ion cells are prone to safety risks when the rate of heat generation surpasses heat dissipation, causing uneven temperature distribution (TD) across the cell. While understanding TD within a cell is crucial for assessing safety risks, detecting it in real-time is challenging. Battery scientists often create models to simulate thermal properties like internal conduction and convection, along with external heat dissipation under stress conditions. These models, coupled with electrochemical reactions, provide insight into temperature evolution within the cell and predict battery behaviour under various operating conditions.

Figure 9: Abuse conditions and failure modes of Li-ion cells

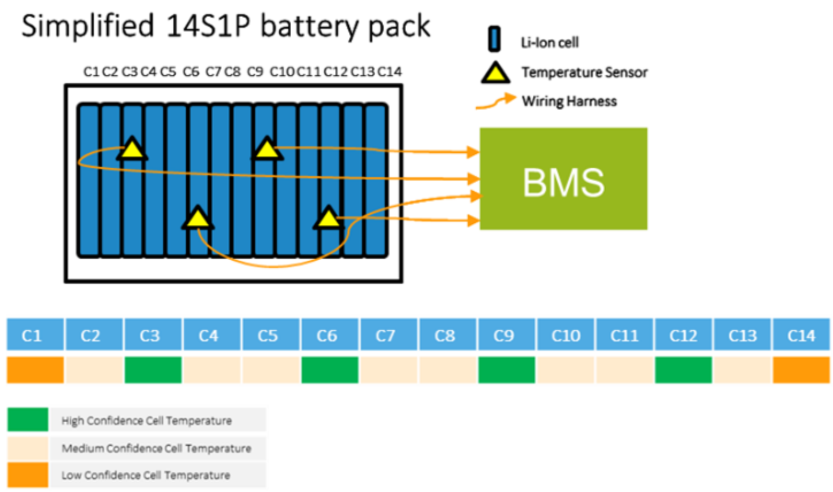


Source: C. Ziebert, et al. 2021, How Calorimetry can help in Battery Research, KIT

However, theoretical simulations need validation through real-world testing across multiple batteries to deepen our understanding of lithium-ion behaviour. Predicting thermal runaway—a key area of current research—aims to leverage BMS hardware and software to deliver early warnings. Thermal runaway, or uncontrolled heating, poses significant risks, including fire and explosion. A rise in temperature in just one cell can trigger ignition in neighbouring cells, potentially leading to fire propagation across the battery.

Temperature sensors, such as thermistors or thermocouples, are often mounted on the battery surface to gauge temperatures within a pack. While these sensors provide an approximation of the cell's internal temperature, they encounter delays due to the thermal mass and conductivity of the battery, resulting in incomplete and slightly delayed readings. This lag underscores the need for improved sensing and prediction methods to enhance battery safety.

Figure 10: Traditional BMS hardware has limitations with providing visibility into individual cell temperatures

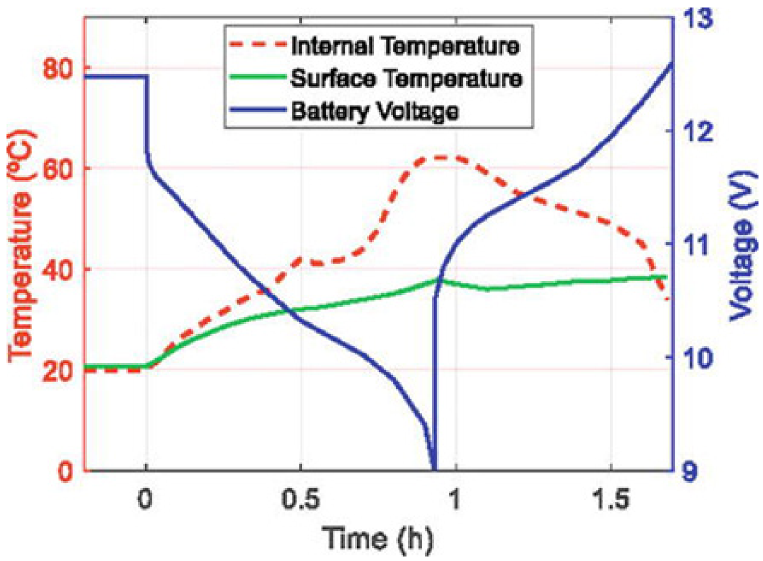


Source: N Kamath and V Dravid, November 2023, "Combining edge ML on BMS microcontroller with high-fidelity training data for EV batteries", EV reporter, available at https://evreporter.com/oorja-heat-app-nxp-eiq-auto-can-enable-efficient-thermal-management/ as accessed on June 2024

In specific operating scenarios, such as fast charging, high ambient temperatures or demanding load conditions, internal temperatures within a lithium-ion battery can vary significantly from surface measurements (see *Figure 11: Internal and superficial temperature during fast charging and discharging*). Since cells are not homogenous, localized hotspots may develop, potentially reaching temperatures of 80–90°C, even when surface readings indicate around 60°C. Such hotspots can reach ignition thresholds, posing severe safety risks.

These internal temperature variations, particularly in larger LIB formats, may remain undetected with surface-only temperature measurements, adversely impacting performance, ageing and safety. To address this, researchers have developed advanced temperature estimation methods to capture internal temperatures more accurately. Often utilizing EIS, these methods detect specific impedance features that correlate with temperature, providing insights beyond superficial readings. Depending on the technique, the estimated temperature may represent electrode-specific, core/internal or average values, and even the internal temperature distribution across the cell.

Figure 11: Internal and superficial temperature during fast charging and discharging



Source: Lalinde, I., Berrueta, A., José Valera, J., Arza, J., Sanchis, P., & Ursúa, A. (2022). Perspective Chapter: Thermal Runaway in Lithium-Ion Batteries. IntechOpen. doi: 10.5772/intechopen.106539

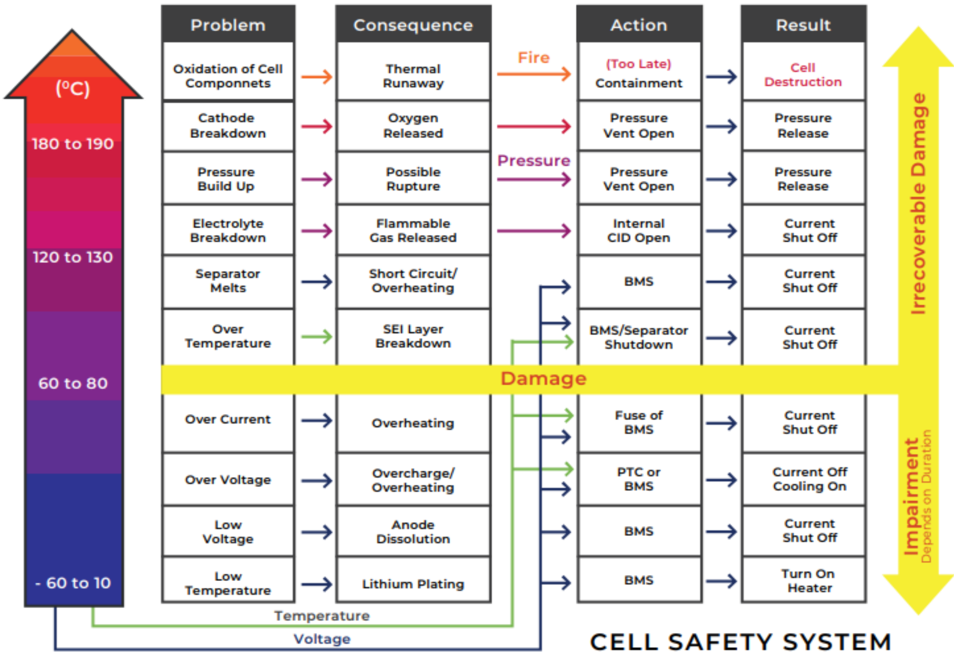
Predicting thermal runaway is particularly challenging due to the interplay of multiple battery degradation mechanisms, including SEI layer growth, lithium plating, and particle stress and cracking. While the SEI layer alone is not typically associated with catastrophic failure, it can decompose at elevated temperatures, contributing to thermal runaway. SEI growth consumes electrolyte solvents, reducing both electrolyte volume and conductivity, while lithium plating on the anode is uneven, exacerbating localized stress. These degradation processes work in combination, creating complex conditions that can lead to rapid temperature increases and, ultimately, a thermal event. [40]

Examples of anomalies which the BMS should detect are[41]:

- Excessive self-discharge or drop in block voltage during rest periods
- Long taper current charging times
- Noisy voltage profiles during charge and discharge
- Excessive cell heating near the end of charging
- Charge capacity being higher than discharge capacity, beyond typical losses
- Change in efficiency of charge/discharge over a short period

As discussed in the Tropical EV Battery paper, there is a need for advanced research on the mechanism to initiate and propagate a thermal runaway condition in a cell within a pack. A key area of development is the model of thermal runaway in a cell in a wider system context, simulating both the micro-scale cell internal mechanisms at the same time as the macro-scale system effects.

Figure 12: BMS provides the first line of defence as a response to temperature, voltage and current anomalies, pre-empting a thermal runaway



Source: Anon, 2022, "A GUIDANCE DOCUMENT ON ACCELERATING ELECTRIC MOBILITY IN INDIA",IIT Madras (CBEEV) & WRI India available at https://shaktifoundation.in/wp-content/uploads/2022/01/Accelerating-electric-mobility-in-India.pdf as accessed on June 2024

Performance requirements

Managing increased temperature is about more than just preventing safety risks; the BMS must also address performance degradation linked to high temperatures. Cycle ageing is directly tied to cell usage, influenced by charge and discharge currents, C-Rate, Depth of Discharge (DoD), cycle count and temperature. Additionally, factors like charging mode (fast or extreme temperature charging) and driving behaviour (such as acceleration and braking) significantly impact cycle ageing.

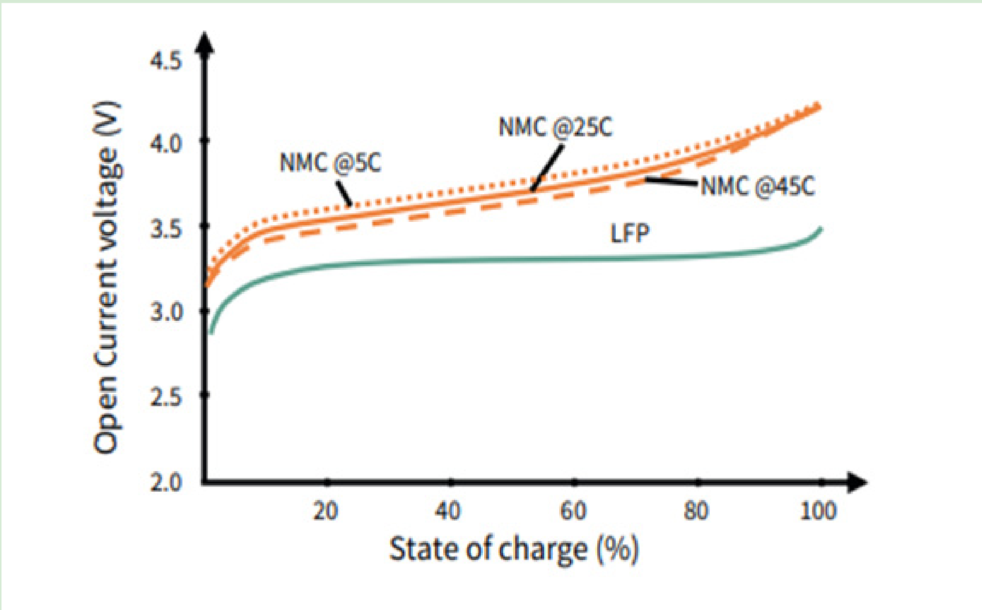
Calendar ageing, in contrast, occurs independently of charge-discharge cycles, related instead to the average SOC during storage, storage time and temperature. Cells experience ageing as a combination of both cycle and calendar effects.

CASE: CHALLENGES WITH LFP SOC ESTIMATION

Estimating the SOC in Lithium Iron Phosphate (LFP) batteries is more challenging than in Nickel Manganese Cobalt (NMC) batteries due to LFP's flat voltage characteristics. In an LFP battery, a small variation in measured voltage can signify a large change in SOC, unlike in NMC batteries where the voltage varies more significantly across the SOC range. This minimal voltage variation across the SOC band in LFP batteries complicates accurate SOC estimation.

While the flat voltage profile of LFP batteries supports precise voltage measurement for non-destructive assessments, it becomes difficult to implement using low-precision voltmeters. Consequently, SOC estimation for LFP batteries cannot rely solely on voltage measurements and requires the integration of techniques like coulomb counting or physics-based modelling to improve accuracy. Deploying sophisticated tools and customizing them according to specific cell chemistries and material proportions is essential for reliable SOC estimation in LFP batteries.

Figure 13: Open Circuit Voltage vs SOC curve of NMC and LFP cell



Source: Mahmoud Ismail, et al. 2022, Understanding and overcoming the challenges of building high voltage automotive battery management systems, Infineon Technologies AG

BMS design should account for cell ageing by adjusting its protective and state estimation parameters accordingly. While algorithms are initially calibrated for new batteries, the current-voltage profile of cells shifts as they age through calendar and cycle ageing, causing SOC estimation inaccuracies that may lead to incorrect range predictions. Regular BMS calibration is thus essential.

The BMS should be specifically designed, developed and calibrated for the underlying cell chemistry, as each type has unique charge-discharge curves, voltage levels, safety limits and SOC profiles. Additionally, materials like LFP cathodes and silicon anodes display significant hysteresis (charge-discharge voltage profile differences), which the BMS must accommodate.

Beyond chemistry configurations, the BMS must account for cell manufacturing variability and local operating conditions. It also needs to adapt to the specific arrangement of cells in a module, particularly when strung in series. A customized BMS is essential, tailored to the vehicle dynamics and expected peak loads, as it governs peak discharge rates for optimal performance and safety.

Battery models in BMS

Equivalent Circuit Models (ECM) are the most widely used for real-time battery status estimation due to their simplicity and reasonable accuracy in capturing voltage and temperature-lumped dynamics when batteries are well characterized.[42] A simple ECM is easy to execute on a traditional BMS microprocessor. However, ECM's lack of physical insight restricts the model's ability to capture complex electrochemical dynamics and provide deeper insights into SOX.[43]

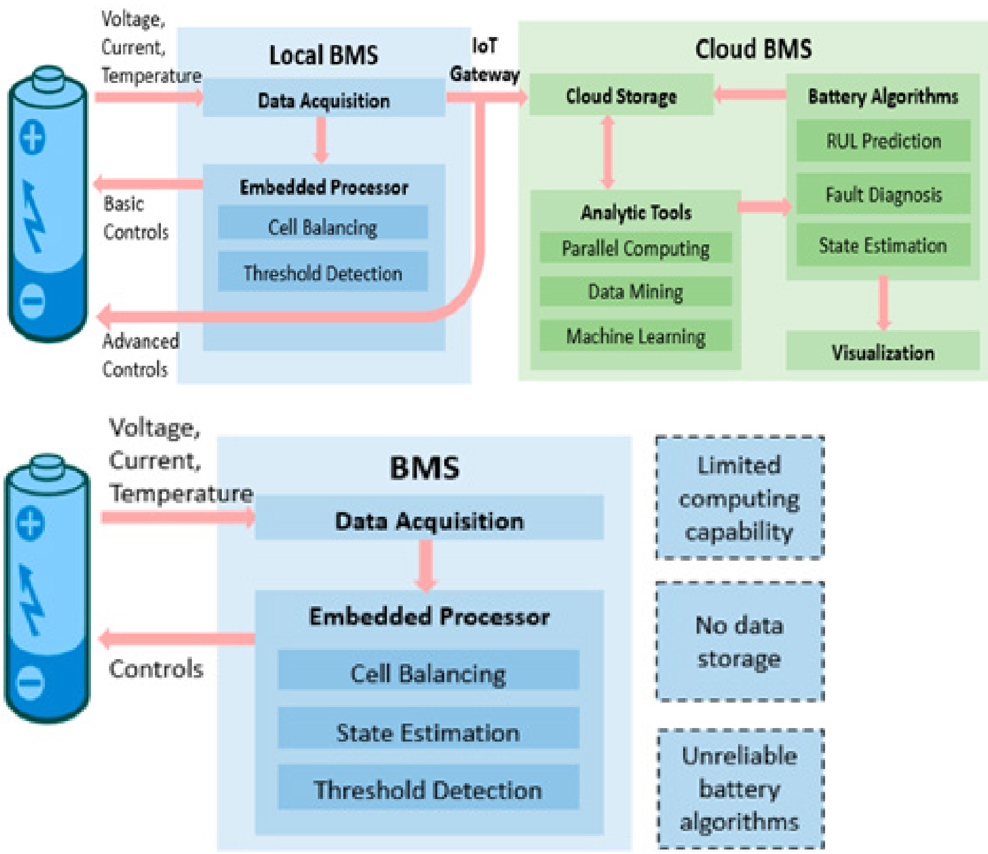
Data-driven machine learning algorithms like Artificial Neural Networks (ANNs), Support Vector Machines (SVMs), and Fuzzy Logic (FL) enhance model adaptability and significantly improve the accuracy of SOX estimations (State of Charge, State of Health). These algorithms complement physics-based models, grounded in electrochemistry, transport phenomena, and thermodynamics to simulate lithium-ion battery (LIB) behaviour. However, these advanced approaches demand high processing speeds, parallel computing capabilities, and substantial memory to store the extensive datasets required for ML algorithms.

Advances in microprocessor technology are making it increasingly feasible to incorporate such complex models into battery management systems. The automotive industry, for instance, is adopting multi-core 32-bit microprocessors capable of handling these demands, with up to tens of megabytes of flash memory and speeds reaching 500 MHz. This technological progression enables battery management systems to support more sophisticated algorithms, allowing for improved precision in monitoring and managing battery health.[44]

The total memory requirement for BMS models largely depends on the desired detail and accuracy in tracking parameter variations. With more data, models can better identify and adapt to degradation parameters, improving insights into battery health. However, scaling memory and computation within the constraints of locally embedded microprocessors in current BMS hardware remains a significant challenge.

Advancements in 5G-connected vehicle technology and edge computing are paving new paths for BMS development. Cloud-based architectures, especially through the development of Digital Twins (DTs), offer a promising alternative. A DT provides a real-time virtual representation of the physical battery used in an EV, allowing for continuous monitoring and analysis. By employing a cloud-based BMS with DT capabilities, much of the local computational burden can be offloaded to external servers, enabling more sophisticated data processing and insights without overwhelming the BMS hardware.

Figure 14: a) BMS design with on-board data processing only; b) BMS design with cloud-based data processing



Source: Tran et al, 2022. "Concept Review of a Cloud-Based Smart Battery Management System for Lithium-Ion Batteries: Feasibility, Logistics, and Functionality" Batteries 8, no. 2: 19 available at https://doi.org/10.3390/batteries8020019 as accessed on June 2024

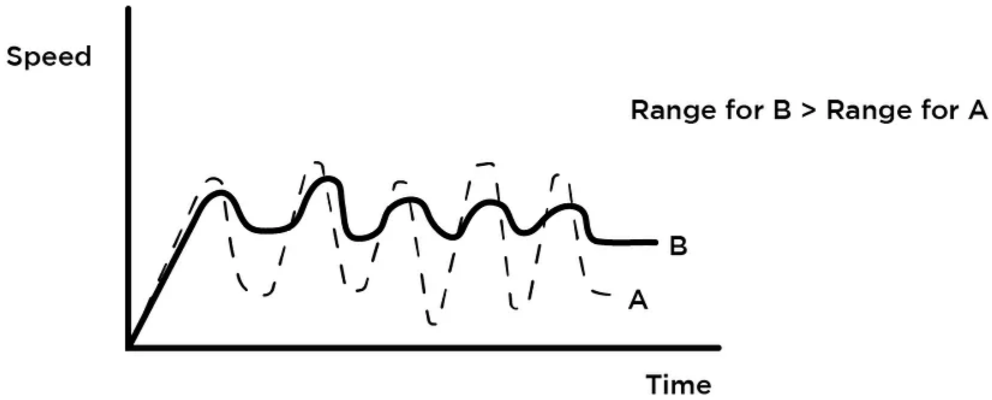
Obtaining holistic battery state diagnostics considering every ageing factor and compatibility with an EV application remains a major challenge. Currently, the key issue for ageing estimation is finding the ideal compromise between various methods: on-board, edge and cloud-based; considering their applications in EVs.[45]

Energy management: Range calculation

Estimating whether an EV has sufficient energy to complete a trip is more complex than for an ICE vehicle. Energy management in an EV is assessed at four levels: (a) at the instantaneous level, (b) over the next 10 meters, (c) throughout the trip, and (d) across the battery's life cycle. In this process, SOC alone is insufficient, as the amount of charge the battery can deliver depends on the discharge rate. As an EV moves, it draws different current levels at varying speeds, which affects the battery's output.

SOE is used to address this challenge. SOE is defined as the ratio of the remaining battery energy under specific operating conditions (such as variable load and temperature) to the total available battery energy.[46] SOE prediction is closely linked to the drive cycle, specifically the velocity-versus-time curve, which encompasses various acceleration and deceleration phases. Optimizing battery range, therefore, significantly depends on driving habits—minimizing aggressive acceleration and braking helps extend the battery's effective range.

Figure 15: Drive cycle comparing gradual versus aggressive acceleration and deceleration



Source: Pugulia, March 2019, "All about the range of an EV, in flat 9 minutes", Ather energy, available at https://blog.atherenergy.com/all-about-the-range-in-an-ev-in-flat-8-minutes-e31f815b64cd as accessed on June 2024

Therefore, adequate data on important drive cycle parameters from the VCU must be available along with inputs such as vehicle weight and tyre pressure for accurate SOE calculation. The BMS should be able to influence the driver to drive appropriately in view of the objectives and priorities for battery longevity.

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The recent white paper on "Tropical EV Batteries," published by the Department of Science and Technology in collaboration with the Centre for Science and Environment (CSE) and industry stakeholders, underscores critical pathways for developing an R&D ecosystem tailored to India's tropical conditions. This white paper highlights the importance of measurable outcomes in technology development projects.

The culture of innovation must be industry-wide, requiring strong multi-stakeholder participation to drive forward safe, durable and efficient EV technologies in India.From this perspective, CSE has initiated a series of investigations into various aspects of battery technology development starting with the Battery Management System (BMS). The goal is to understand the current status, opportunities and potential for advancement in this field, while identifying gaps in existing regulations and standards that need to be addressed to guide the way forward.

The battery management system (BMS) is an electronic control circuit integrated within battery packs. The BMS plays a critical role in monitoring and regulating key functions related to safety, performance and optimizing the lifespan of batteries under various charging, discharging and environmental conditions. Its primary goal is to ensure that the battery remains safe, reliable and durable while preventing potential damage.With rising temperatures across the country, the need for domestically designed and manufactured BMS for electric vehicle batteries has become crucial. These systems must be resilient and responsive, tailored to the unique demands of the battery vehicle in terms of cell chemistry, weather, geography and durability.

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