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EV Battery Technologies and Battery Management in India: Evolution and the Way to a Solid-State Future

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ABSTRACT

The technological development of electric vehicle batteries has deeply influenced the course of sustainable mobility. LIBs have traditionally been the main energy source within the EV industry due to their favourable energy density, reliability, and manufacturing maturity. However, limitations such as thermal instability, resource dependency, and safety concerns have driven the development of SSBs. SSBs, which use solid electrolytes rather than liquid ones, offer better safety, longer lifespans, and higher energy densities. This review provides an overall analysis of EV battery evolution from LIBs to SSBs, highlighting the key factors for consideration: electrochemical characteristics, materials development, interface engineering, and control integration via advanced Battery Management Systems. Further, the paper discusses India's strategic role in the global transition to electric mobility, with an emphasis on national policies and industrial development, as well as localised research initiatives. Such a synthesis of global and Indian perspectives identifies how India can emerge as a major stakeholder in solid-state innovation through industrial localization, policy incentives, and research-driven manufacturing.

Keywords: *Electric Vehicles, Lithium-ion Battery, Solid-state Battery, Battery Management System, Energy Storage, India, Sustainable Mobility, Policy Framework.*

1 Introduction

The electrification of transportation is one of the most profound technological changes of the twenty-first century. The rapid exhaustion of fossil fuels, in conjunction with growing concerns about greenhouse gas emissions, has accelerated the shift towards electric vehicles. At the heart of this transition is the battery-its chemistry, capacity, and control systems determining the fundamental vehicle efficiency, range, and economy. Lithium-ion batteries have been the linchpin of EV power trains for over three decades, thanks to their high energy density, reasonable costs, and an established supply chain from cell manufacturing to recycling in place, with energy densities in the range of 150-250 Wh/kg [1], [2].

LIBs, although successful, still have several critical challenges. Since liquid electrolytes are employed, thermal runaway, leakage, and fire hazards cannot be ruled out. Its poor recyclability and dependency on rare metals like cobalt and nickel raise serious concerns about its long-term sustainability and supply chain. In this regard, the scientific community moved to SSBs that use nonflammable solid electrolytes. "The systems demonstrate an energy density of up to 800 Wh/kg, improved safety, and superior cycle stability" [3]. Their large-scale commercialization has been greatly hindered due to interface instability and high manufacturing costs, brought about by complex fabrication requirements.

The EV revolution thus presents both a technological opportunity and an economic imperative in the Indian context. National initiatives like FAME-II and PLI for the manufacturing of ACC have accelerated local battery production, reduced import dependence, and attracted foreign investment [5]. The Indian EV market, driven by two- and three-wheelers, is likely to reach a sales figure of over 10 million annually by 2030 [6]. However, full localization is restricted due to technological dependence, limited raw material availability, and below-par investments in R&D.

The paper provides a detailed assessment of global and Indian developments in EV battery technology.

The objectives are fourfold:

1. To trace the scientific and industrial evolution from LIBs to SSBs.
2. Analyze material innovations and improvements in electrochemical performance.
3. Assess the integration of BMS for improved safety and efficiency.
4. To place India's policy, industrial, and research progress in perspective in the global electrification scenario.

2 Research Methodology

Review: A systematic, evidence-based framework combining literature synthesis with comparative analysis has been followed. Publications were collected from open-access journals and official government reports from 2018 to 2025. The data selection emphasized peer-reviewed studies on EV battery chemistry, electrochemical modeling, and BMS integration, together with policy and industrial reports describing the EV ecosystem in India.

2.1 Data Sources

The literature set was divided into two analytical clusters:

Cluster A - Global Technical Research:

The studies included are from Batteries, published by MDPI; Heliyon; Energy Procedia; Interdisciplinary Materials; Journal of Industrial Ecology, covering electrochemical improvements, interface design, and lifecycle analysis of LIBs and SSBs [7]–[10].

Cluster B – Indian Contextual Studies:

Included were reports such as NITI Aayog’s Electric Vehicles in India: Unlocking a $200 Billion Opportunity (2025), Dhairiyasamy et al. (2024) on India’s EV supply chain, Mohamed et al. (2018) regarding EV challenges, and Rajendran et al. (2025) regarding industrial competitiveness [11]–[14].

2.2 Selection Criteria

Papers were included based on:

- Quantitative data on battery performance (energy density, cycle life, conductivity).
- Qualitative insights on policy, manufacturing, and sustainability.
- Relevance to India’s EV industry and national electrification objectives.

2.3 Analytical Approach

The study uses a model of comparative integration that:

1. Aligns global advances in materials and electrochemistry with India's industrial adaptation capacity.
2. Correlates electrochemical parameters with BMS control strategies.
3. Correlates the Lifecycle Assessment data with sustainability goals under India's EV Mission.

2.4 Research Objectives

The key goals of this review are:

- To identify performance trends across LIB and SSB technologies.
- To assess BMS integration for intelligent monitoring and fault prediction.
- To assess India's preparedness for large-scale solid-state manufacturing.
- To propose a structured roadmap linking research, manufacturing, and policy.

3 Theory and Calculation

The electrochemical functionality of EV batteries is controlled by ion transportation and redox reactions in closed electrochemical cells. In this regard, shifting from conventional LIBs to SSBs is highly driven by the demand for high energy density, safety, and longer life cycles by integrating solid electrolytes.

3.1 Lithium-Ion Battery Chemistry

A typical LIB consists of a graphite anode, a transition-metal oxide cathode (such as $LiCoO_2$, NMC, or NCA), a porous separator, and a liquid electrolyte with dissolved lithium salts such as $LiPF_6$ in organic solvents. In the course of discharge, lithium ions migrate through the electrolyte from the anode to the cathode, while electrons pass through the outer circuit and deliver useful electrical energy. The reactions can be described as:

$$Anode\colon LiC6 \rightarrow C6 + Li + +e -$$

$$\textit{Cathode: } Li_{1-x}CoO_2 + xLi^{+} + xe^{-} \rightarrow LiCoO_2$$

The theoretical voltage of a lithium-ion cell falls between 3.6 V and 4.2 V. Depending on the cathode material, general values of specific capacity are 372 mAh g^{-1} for graphite anodes and 180–220 mAh g^{-1} for NMC or NCA cathodes. Energy densities for state-of-the-art high-nickel NMC chemistries are around 250 Wh kg^{-1}, but they tend to be prone to thermal degradation at temperatures over 60 °C.

3.2. Solid-State Battery Mechanism

Solid-state systems replace liquid electrolytes with inorganic or polymeric solid electrolytes that conduct lithium ions sans volatile solvents. This structural change eliminates electrolyte leakage and mitigates thermal runaway. Solid-state batteries could allow direct pairing with metallic lithium anodes, providing theoretical specific capacities as high as 3860 mAh g^{-1}.

Common Electrolyte Families:

- **Sulfide-based** $Li_{10}GeP_2S_{12}$, Li_6PS_5Cl. These exhibit high ionic conductivity of $\sim10^{-2}$ S cm^{-1} and good interfacial wetting.
- **Oxide-based** for example, $Li_7La_3Zr_2O_{12}$; chemically stable yet dense, needs sintering >1000 °C.
- **Polymer-based** for example, polyethylene oxide complexes: flexible and cheap but show lower conductivity ($\sim10^{-5}$ S cm^{-1}).

The theoretical gravimetric energy density for SSBs could exceed 800 Wh kg^{-1} depending on electrolyte thickness and active-material utilization. Safety advantages arise from the nonflammable nature of solid electrolytes as shown in the table 1.

3.3 Comparative Electrochemical Parameters

Parameter	Lithium-Ion Battery	Solid-State Battery
Energy Density (Wh kg^{-1})	150–250	300–800
Cycle Life (cycles)	1000–3000	3000–10000
Operating Temperature (°C)	−20 to 60	−40 to 100
Electrolyte Type	Liquid ($LiPF_6$ in EC/DMC)	Solid (sulfide/oxide/polymer)
Safety	Moderate (flammable)	High (non-flammable)

Parameter	**Lithium-Ion Battery**	**Solid-State Battery**
Cost (USD kWh^{-1})	120–150	300–400 (declining)

Table 1: Comparative Properties of LIBs and SSBs [10].

3.4 Degradation and Thermal Behaviour

Capacity degradation follows a semi-empirical relation:

$$Qt = Q0(1 - kct1/2) - kst$$

where $Q_t$is the remaining capacity at time t, $k_c$represents diffusion-limited degradation, and $k_s$accounts for side reactions such as solid-electrolyte-interphase (SEI) growth. Thermal stability is critical for BMS control; heat generation rate $Q$is described by:

$$Q = I2R + I(TdTdE)$$

with Ibeing current, Rinternal resistance, and $dE/dT$the entropic coefficient. These relationships underpin temperature-aware BMS algorithms for cell balancing and fault prediction.

4 Results and Discussion

4.1 Evolution of Battery Materials

The improvement in cathode and electrolyte chemistry has gradually increased the performance of batteries. The early $LiCoO_2$ systems had high voltage, but they were essentially burdened by cobalt cost and instability. Transition to nickel-rich NMC 811 and NCA formulations increased the energy density further while reducing cobalt consumption. Research in [7] [10] illustrates that sulfide and oxide solid electrolytes such as $Li_{10}GeP_2S_{12}$ (LGPS) and $Li_7La_3Zr_2O_{12}$ (LLZO) exhibit ionic conductivities of up to 10^{-2} S cm^{-1}, reaching the values of liquid electrolytes without compromising safety [7],[8].Changes in the interface by thin coatings of $LiNbO_3$ or Li_3PO_4 significantly reduce interfacial impedance and improve cyclic stability as shwon in the Figure 1[9].

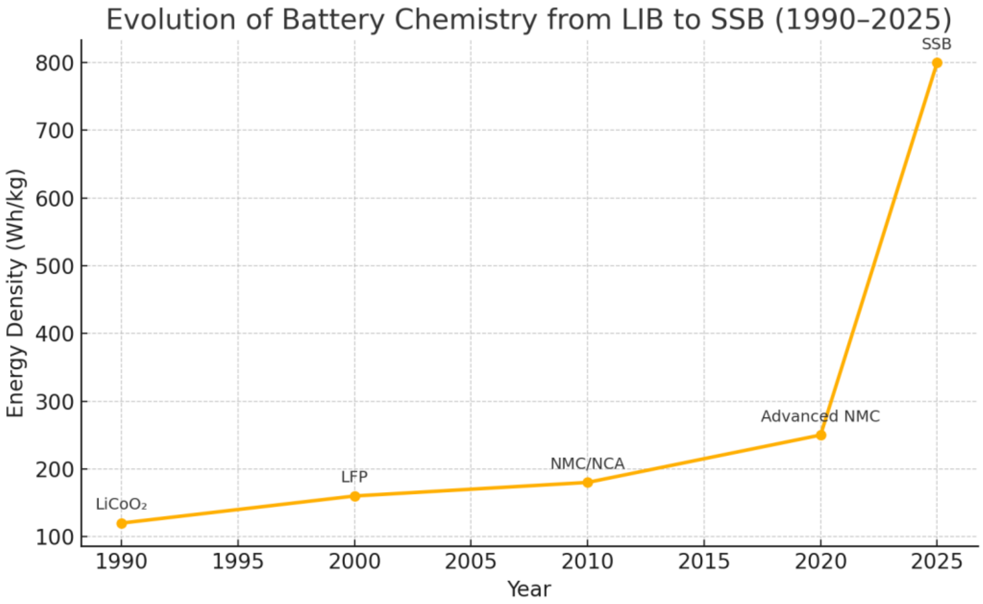

Figure 1: Evolution of Battery Chemistry from LIB to SSB (1990–2025) [7] [10].

4.2 Performance and Environmental Comparison

Combined data from [10] reveal that SSBs roughly double the gravimetric energy density while offering greater intrinsic safety compared to LIBs. Manufacturing, however, requires high-temperature densification processes, which increase initial embodied energy. Degen et al. [10] reported production emissions of 60–90 kg CO_2-eq kWh^{-1} for LIBs and 90–130 kg CO_2-eq kWh^{-1} for SSBs. This environmental penalty is offset by the extended life span of the SSBs (>6000 cycles). Lithium-iron-phosphate (LFP) cells remain a transition technology option for India, balancing safety, cost, and sustainability as shown in the table 2.

Chemistry	**Energy Density (Wh kg^{-1})**	**Life Span (cycles)**	**GHG Emissions (kg CO_2-eq kWh^{-1})**	**Key Advantage**
LFP	170	> 3 000	≈ 60	Safe and cost-effective
NMC 811	250	2 000	≈ 90	High capacity
SSB (LGPS/LLZO)	400–800	> 6 000	≈ 100	High safety and longevity

Table 2: Comparative Environmental Impact of Battery Chemistries.

4.3 Integration of Battery Management Systems

BMS units ensure operational safety and optimize performance. Modern BMS architectures feature layered control involving pack-level monitoring and cell-level microcontrollers. Techniques such as the Extended Kalman Filter and neural-network regression enable accurate State-of-Charge and State-of-Health estimation with errors below 2 % [11].Machine learning-based fault detection systems identify internal short-circuit precursors well in advance of thermal escalation [12]. Distributed active balancing minimizes cell voltage deviation and extends battery life by 10–15 %. Cloud integration may also provide diagnostic capabilities in real-time, enable over-the-air firmware updates, and offer V2G capability. Pilot projects at Delhi and Bengaluru have shown that a coordinating BMS–grid communication can help shave peaks on load demand by roughly 7% [13].

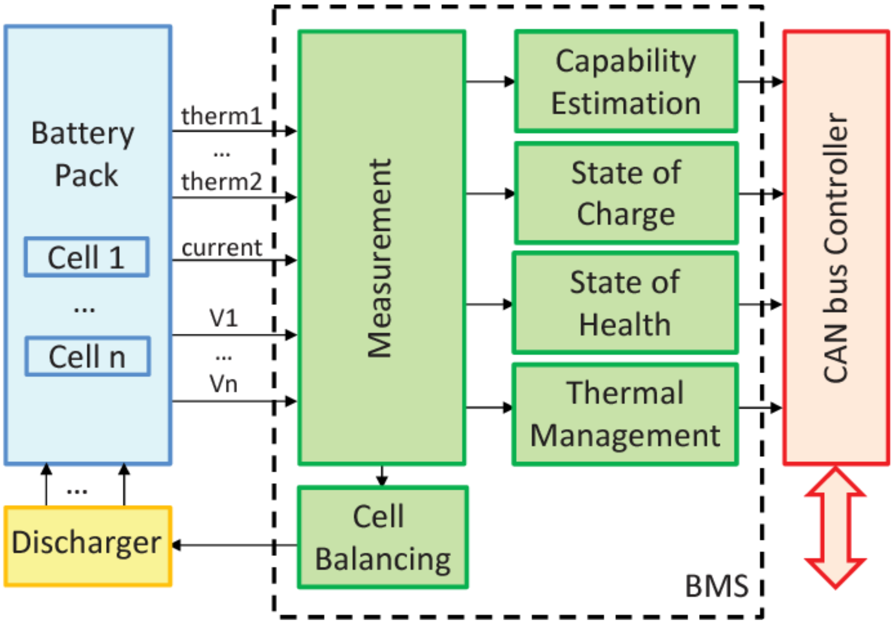

Figure 2: Smart BMS Architecture for AI-assisted Monitoring and Control [21].

4.4 India’s Policy and Industrial Progress

India's EV transformation is based on strong governmental support. NITI Aayog (2025) opines that the local EV market may yield a revenue opportunity of approximately $200 billion by 2030 [4]. However, the country, to date, locally meets only ≈ 20 % of its battery requirements [14]. The PLI scheme targets creating 50 GWh per year of cell manufacturing capacity by 2027, which has received investments from Tata Chemicals, Ola Electric, and Suzuki [15]. Rajendran et al. (2025) demonstrate that implementation of advanced manufacturing (robotics, Industry 4.0, automated assembly) cuts down production time by 30 % and improves consistency by 25 %. Incentives to purchase, charging infrastructure, and collaborations on R&D between academia and industry are given by national initiatives like FAME-II and state EV policies. Such partnerships-gap workforce and technology gaps, including Ashok Leyland's BMS development with IIT Madras.

Figure 3: Structure of India’s EV and Battery Manufacturing Ecosystem [4].

4.5 Persistent Challenges

Despite strong policy momentum, India faces critical constraints:

Key Challenge	Impact	Recommended Measure
Limited raw-material reserves	Supply-chain vulnerability	Domestic mining, recycling, and strategic imports
Solid-state fabrication complexity	High cost and interface issues	Development of hybrid solid-electrolyte composites
BMS standardization	Limited interoperability	Creation of national BMS protocol standards
Skill and R&D deficits	Slower innovation	Targeted technical training and academic–industry clusters
Recycling inefficiency	Environmental burden	Implementation of 2022 Battery Waste Management Rules

Table 3: Key Challenges and Proposed Solutions for India’s EV Battery Ecosystem [6]

Present recycling rates are below 25 % in India, compared with the EU average of 70 %, hence the framing of circular economy frameworks is critical for sustainable growth as shwon in the table 3.[18].

4.6 Global–National Synthesis

Samsung, and QuantumScape globally target commercial solid-state EVs by 2030. India's trajectory is laggard technologically but benefits from fast-track policy and investment alignment. Accomplishing the planned 50 GWh domestic capacity and deploying intelligent BMS frameworks may reduce import dependence by ≈ 40 % and create almost two million jobs by the end of the decade.

5 Conclusions

The global transition from lithium-ion batteries to solid-state batteries represents the next transformative phase in EV energy storage. While lithium-ion technology is commercially dominant, it has inherent safety risks, material scarcity, and limited energy density, which constrain sustainability in the long term. Solid-state batteries address such issues through solid electrolytes, improved thermal stability, and compatibility with high-capacity lithium-metal anodes, offering twofold increases in energy density and significantly extended cycle life. However, large-scale manufacturing, interface stability, and cost reduction remain unresolved barriers.

In India, the development of batteries aligns with the national priorities of clean mobility and industrial self-reliance. Government initiatives such as FAME-II, PLI-ACC Manufacturing, and the Battery Waste Management Rules of 2022 stand out as structured commitments to nationwide EV and battery development. Private investment by companies such as Tata, Ola Electric, and Suzuki, along with collaborations with academic institutions, began filling the technology and skills gaps. The integration of AI-driven BMS further enhances operational reliability through predictive control, energy optimization, and V2G participation.

Going forward, India's competitiveness will be influenced by three converging factors:

1. Localization of advanced chemistry cell production and secure access to critical raw materials.

2. Adoption of hybrid electrolyte designs will help ease the transition from LIBs to SSBs and maintain manufacturability.

3. Institutionalized R&D collaboration between universities, public labs, and industry for accelerating indigenous innovation.

If done well, India can transition from a fast-growing EV market to one of the world's key producers of sustainable, high-performance batteries. The combination of solid-state innovation and intelligent energy management systems provides the cornerstone for such a transition, one in which science, policy, and manufacturing come together to pave the way toward a safer, more sustainable mobility future.

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