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A COMPREHENSIVE EVALUATION OF EV BATTERY CHEMISTRIES AND BATTERY MANAGEMENT SYSTEMS

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Abstract - Over the past decade, the rapid growth of electric vehicles (EVs) has been fueled by significant advancements in battery technologies and Battery Management Systems (BMS). This study provides a comprehensive evaluation of EV battery chemistries, particularly lithium-ion variants, supported by real-world case studies and technical data. Charging and discharging parameters, safety issues such as thermal runaway and fire hazards, and the evolution of BMS architectures are analyzed in detail. Benchmarks for voltage, current, temperature, cycle life, and cost are reviewed to present a practical understanding of battery performance. The paper further examines engineering solutions for cell balancing, thermal management, and fault diagnosis, while highlighting the potential of emerging technologies including solid-state batteries, polysulfide-iodide redox flow batteries, and AI-integrated BMS. Special attention is given to challenges in fast charging, state-of-health prediction, and lifecycle management. Finally, the study emphasizes research gaps and future directions, including artificial intelligence, cloud-based connectivity, and second-life strategies, positioning EV batteries and BMS as critical enablers for safe, efficient, and sustainable mobility.

Keywords: Electric Vehicles, Lithium-ion Batteries, Solid-State Batteries, Battery Management System, Thermal Management, Fast Charging, Safety, Sustainable Mobility.

1. INTRODUCTION

Transformation of global mobility with the electrification of transportation is occurring at a remarkable pace. The demand on electric vehicles (EV) serving as replacements for internal combustion engine (ICE) transport, in which they have seen increasing sales in the past decade due to the belief that they offer a reduced environmental impact, can be run as part of a renewable energy system and potentially conduct vehicle-to-grid (V2G). With governments increasingly helping to curb carbon and promote sustainable development, adoption of EVs is gaining pace in both developed markets as well as emerging economies.

The battery system is at the core of normal operation and safety for electric vehicles and it includes the rechargeable unit that powers the electric motor and provides energy to virtually all onboard electronic, such as lighting, air conditioning, and infotainment. Today's electric cars often come with lithium-ion battery packs, made up of multiple electrochemical cells arranged into modules managed as a single system. The power source is a set of batteries that are recharged by home power outlets or public charging infrastructure, and the effectiveness of these batteries impacts the amount of distance the vehicle can travel on one charge, how long it takes to charge back up again, and how much it costs per mile.

The history of the development of batteries is very important to electric mobility. The first battery was created by Alessandro Volta in 1800, which could not be recharged and it also had a very narrow operational range. The true first rechargeable battery was the lead-acid battery in 1859, which opened the door for electric vehicles fighting gas during experimenter years. The first electric vehicles (EVs) to be widely used in American cities ended up as a casualty of their limited range and the mass production of gasoline vehicles. In the 21st century, electric vehicles have regained popularity, driven by significant advancements in energy storage technologies and a growing global awareness of the need to reduce harmful emissions.

Modern EVs are full of lithium batteries, and those battery packs need to be precisely managed for safe & reliable operation, which is why they're all monitored by an integrated Battery Management System (BMS). The BMS is a key control unit to maintain and monitor battery parameters such as voltage, current, temperature, SoC (levels of Remaining energy). It safeguards the battery from over-charging, over-discharging, thermal events, and cell imbalances - problems that can dramatically reduce battery life or create safety concerns such as thermal runaway. The BMS can also balance the cells, monitor for faults and communicate with the vehicle control system. Meeting global safety and performance standards (e.g., including ISO 262262 for functional safety of road vehicles, and UNECE c R100 regulation/electric safety regulations) demands a BMS solution featuring both stable hardware as well identified algorithms. These have included its AI-powered fault detection, cloud-enabled analytics for batteries, and most recently emulating a digital twin which allows predictive maintenance, as well as how batteries perform in the field over their lifecycle.

We undertake a detailed review of electric vehicle battery systems, focusing primarily on lithium-ion chemistries, BMS design principles as well as thermal management control strategies. The data that it will analyze comes from the real world, around issues like battery charging and discharging parameters, safety risks and degradation mechanisms. It also examines key innovations in emerging areas such as solid-state batteries, AI enabled BMS architectures and circular strategies for second-life applications and recycling. It aims to pinpoint the existing constraints, analyze novel techniques under development and suggest open issues for future research in order to improve the safety, performance or sustainability of EV battery systems.

The diagram depicts the major components of a representative EV energy system:

- Battery Pack – Primary DC energy source.
- DC–DC Converter – Supplies low-voltage DC loads (e.g., lighting, control electronics).
- DC–AC Converter – Inverter stage supplying AC power to the traction motor.
- AC–AC Converter – Grid interface for charging and V2G functions.
- Motor – Converts electrical power to mechanical torque (and vice versa during regenerative braking).
- Mechanical Traction – Transfers torque to the drive wheels.
- Gasoline Engine (optional) – Provides supplemental energy in hybrid architectures.

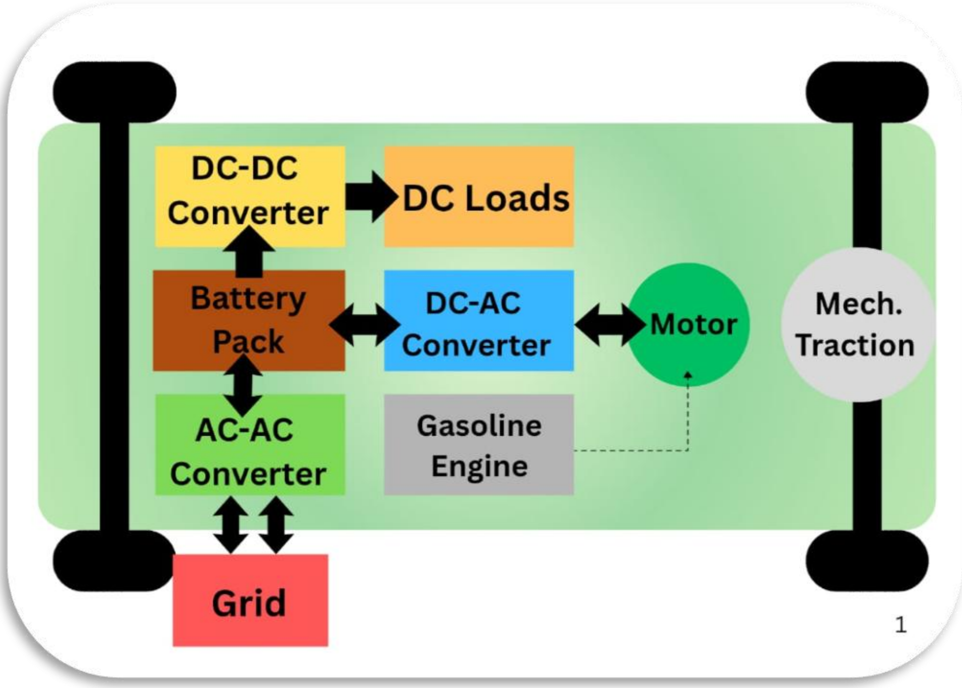

Fig. 1.1 Typical EV Battery Architecture

2. LITERATURE REVIEW

The rapid uptake of electric mobility and renewable energy integration has driven a surge in demand for energy storage systems, highlighting lithium-ion (Li-ion) batteries as the growing technology of choice due to their high energy density, long cycle life and declining costs. These things are tempered by security concerns, the breaking down of performance as the system scales and deployment challenges. Recently, Battery Management Systems (BMS) have been declared as mandatory for safe operation and optimizing the output performance of Li-ion batteries (Plett, 2015; Zhang et al., 2020). TE Op Connect and ADAS Sensors - Easy-on, Easy-off. The role of BMS over the past few years, the landscape for BMSs has shifted from simple supervision of voltage and temperature to more complex predictive, adaptive and cloud-connected architectures. This evolution is a precursor to more complex solutions such as the combination of digital twins and AI-based diagnostics.

2.1 Foundations of Battery Management and Monitoring

In the early stage of Battery Management System (BMS) development, much research has had been focused on standard protections as well as cell balancing and thermal management using deterministic control logic (Liu et al., 2012). The theoretical basis for battery monitoring is in term of equivalent circuit models (ECMs) and physics-based approaches like Doyle-Fuller-Newman model (DFN), which makes able to estimate internal electrochemical states. The state-of-charge (SOC) and state-of-health (SOH) estimation methods have evolved from simple coulomb counting to sophisticated adaptive filtering techniques such as Extended Kalman Filter (EKF), Particle Filter (PF), that improve its robustness against measurement noise and model error.

2.2 Advances in Estimation and Control Strategies

When Li-ion battery applications expanded beyond small scale to electric vehicles (EVs) and grid storage, research focus shifted towards precision and versatility. SOC/SOH estimation has also evolved utilizing machine learning models like support vector machines, random forests, and more recently deep neural networks that have been trained on big historical databases (Berecibar et al., 2016; Li et al., 2021). Control strategies have also advanced, deploying model predictive control (MPC) for thermal management and adaptive charging to boost both safety margins and cycle life. In addition, remote calibration of balancing thresholds and safety parameters via over-the-air (OTA) updates has resulted in a decrease in cost-intensive manual servicing.

2.3 Digital Twin and IoT-Enabled BMS Architectures

A battery digital twin (i.e., a real-time virtual replica mirroring the physical asset behaviour) has emerged as an enabler of predictive maintenance and fleet-wise optimization ((Bevilacqua et al., 2022). With digital twins, you can combine high-fidelity electrochemical models with live sensor data for early anomaly detection at cell or module level, adaptive charging strategies as well as remaining useful life (RUL) predictions. Achieving Scalability IoT-enabled BMS architectures that can aggregate data from globally distributed assets create a scalable solution for fleet learning and cross-asset optimization.

2.4 Research Gaps

While progress is evident across modelling, experimental validation, and intelligent BMS development, there is still no universally adopted framework that fully integrates real-time diagnostics, fleet-level optimization, and scalable sustainability practices. The current research addresses this gap by combining experimental, simulation, and field approaches to develop a more holistic and data-driven methodology for battery performance management and lifecycle extension.

2.5 Review of Previous Studies and Standards

Recent academic and industry research focuses on performance/aging, safety, and cost [1], [2], [3]. Standards such as IEC 62660 and ISO 26262 define BMS safety requirements.

2.6 Existing Technologies and Methods

Table-2.1 Comparison of Rechargeable Battery Technology

Chemistry	Voltage (V)	Energy Density (Wh/kg)	Cycle Life	Pros	Cons
Lithium-ion	3.2–3.7	100–270	600–3000	High density, long life	Cost, fire risk
Nickel-Metal Hydr.	1.2	60–120	300–600	Safe, moderate cost	Lower energy, memory effect
Lead-Acid	2.0	30–50	200–300	Cheap, mature	Bulky, low density

2.3 Gaps in Knowledge or Practice

Open questions remain in accurate State-of-Health (SOH) estimation, fast charging degradation, and universal safety standards.

3. METHODOLOGY & CASE STUDY DESIGN

3.1 Propulsion Topologies

- Centralized drive: a single high-power motor coupled to reduction gear; typical in early-generation EV sedans.
- e-Axle: motor, inverter, and gearbox integrated into a single unit; reduces wiring, improves packaging.
- In-wheel Motors: motors inside wheel hubs; offer torque vectoring but raise unsprung mass and sealing challenges.

3.2 Energy Storage Chemistries

Table-3.1 Comparison for Electric Vehicle Battery Chemistry

Chemistry	Energy Density (Wh kg^{-1})	Peak Power (kW kg^{-1})	Cycle Life (80% SoH cycles)	Safety Profile	Typical EV Use
NMC811	240-260	3.5	1200-1500	Moderate	Premium passenger cars
LFP	160-180	2.0	2500-3000	High	Mass-market cars, buses
NCA	230-250	3.0	1500-2000	Moderate	Long-range

					sedans
Solid-state (Li-metal)	350+	4.0 (projected)	800+	Under research	Next-gen platforms

Emerging chemistries-sodium-ion, lithium-sulphur-promise lower cost and higher specific energy but remain pre-commercial.

3.3 System Description

This study focuses on a mid-size electric vehicle (EV) platform representative lithium-ion traction battery system. Our battery pack uses prismatic or pouch cells (50-70 Ah typical) and delivers a nominal voltage of 350-400 V, with multiple series-connected modules. The battery management system (BMS) uses a distributed topology with local control at each module for voltage, temperature and current monitoring.

The BMS incorporates both passive and active cell balancing strategies to ensure cell voltage uniformity and maximize usable capacity. Passive balancing dissipates excess energy in higher-voltage cells through resistive elements, while active balancing transfers charge between cells or modules to optimize energy utilization and extend battery life. The system also integrates comprehensive protection functions against:

- Overvoltage / undervoltage
- Overcurrent (charge and discharge)
- Overtemperature and thermal runaway

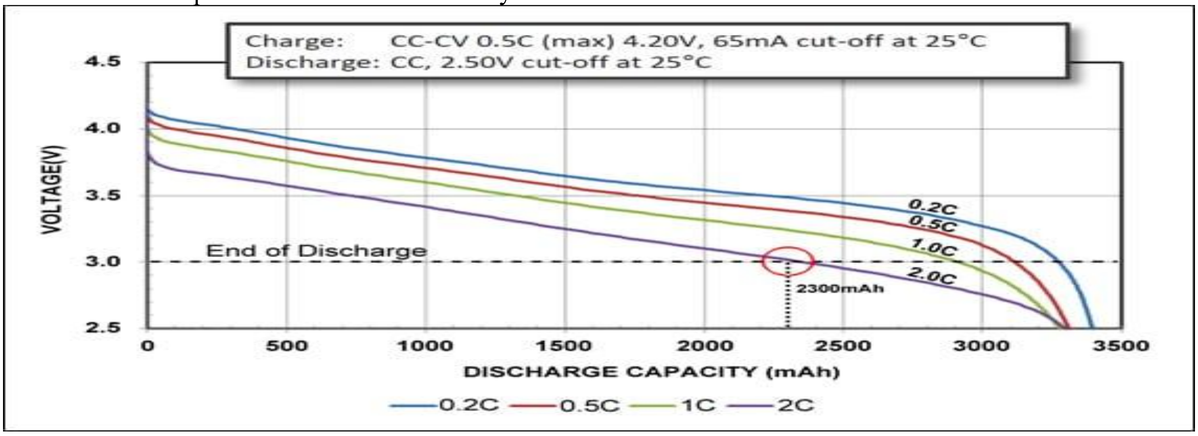

Fig. 3.1 Battery Voltage vs. Discharge Capacity for Various C-Rates

This study combines experimental testing, simulation modeling, and real-world EV data to evaluate battery performance and management strategies. Laboratory tests were carried out on a custom-built battery test bench that replicates electric vehicle operating conditions. The setup included programmable load banks for controlled discharges, precision sensors for current and energy measurement, and thermocouples for monitoring thermal behaviour at both cell and module levels. Drive cycle patterns were implemented to study performance under varying loads, temperatures, and balancing operations. A detailed simulation framework was developed in MATLAB/Simulink for modeling dynamic voltage response, state-of-charge tracking, thermal dynamics, and balancing algorithms. ETAP was employed to analyse load flow, converter efficiency, and fault scenarios such as module disconnection and short circuits. Real-world datasets from vehicles such as the Tesla Model S, Nissan Leaf, and Toyota Prius PHV were used to validate results, ensuring industry relevance and practical accuracy.

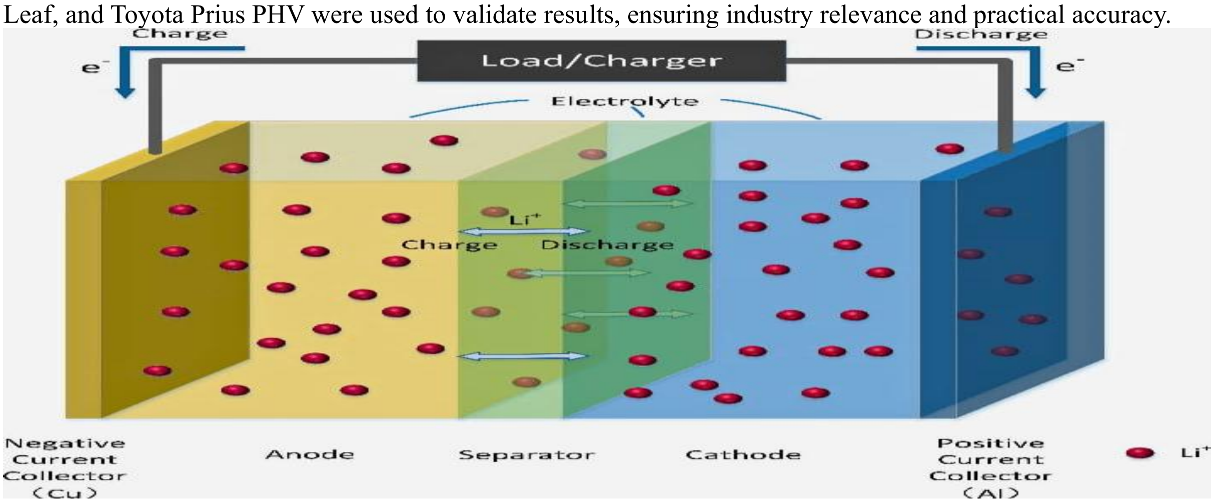

Fig. 3.2 EV battery architecture

3.3 Tools, Software, or Hardware Used

Table-3.2 EV Testing and Simulation Tools and Equipment

Category	Tool / Equipment	Purpose
Software	MATLAB/Simulink	Dynamic modeling, control simulation, and system optimization
	ETAP	Electrical system modeling, load flow analysis, and fault simulation
Reference Data	Tesla, Nissan, Toyota EV technical datasheets	Benchmarking and parameter extraction
Hardware	Resistive load bank	Controlled discharge and load testing
	Temperature probes (thermocouples/RTDs)	Cell/module thermal profiling
	Precision shunt sensors	Current and energy measurement for validation

3.4 Parameters Measured/Analysed

In this study, the main parameters which are monitored were related to the electrical, thermal behaviour, durability and cost of a lithium-ion traction battery. The voltage in each cell was logged over the 2.5–4.2 V per cell operational range to provide state-of charge measurement and detection of over-voltage or under-voltage occurrences. Peak and charge levels were quantified; peak discharge was up to about 350 A in short bursts, with continuous operation values typically ranging from 100–180 A, thereby providing key details of power delivery ability and thermal stress.

Thermal management performance was assessed by temperature monitoring from 15 to 60 °C (corresponding to cold-start and sustained high-load) states with sensors located at the cell-, module- and pack-level. Cycle testing was conducted in the range of 1000 to 3000 full charge discharge cycles to quantify degradation and life expectancy. The cost parameter was then assessed on the pack level in specific energy costs, which under 2024 market conditions was calculated to range from $110-200kWh, similar to current EV battery price trends.

3.5 Types of Electric Powertrains

The term "EV powertrain" encompasses various configurations, including those that integrate internal combustion components.

- Battery Electric Vehicle (BEV): These vehicles are powered exclusively by a battery and an electric motor. They produce zero tailpipe emissions.
- Hybrid Electric Vehicle (HEV): An HEV combines an internal combustion engine with an electric motor. The electric motor assists the engine to improve fuel economy, but the battery is charged through regenerative braking and the engine itself, and the vehicle cannot be plugged in.
- Plug-in Hybrid Electric Vehicle (PHEV): A PHEV features both an engine and an electric motor but is equipped with a larger battery that can be charged from an external power source. This configuration allows for significant all-electric driving range before the internal combustion engine is activated.
- Fuel Cell Electric Vehicle (FCEV): FCEVs are propelled by an electric motor, but they generate their own electricity on board using a hydrogen fuel cell. In the fuel cell, hydrogen reacts with oxygen to produce electricity and water as the sole byproduct.

4. CASE STUDY DESCRIPTION

4.1 Real-World Project/Installation Site

In this case study with data from publicly available electric vehicles (Nissan Leaf, Tesla Model 3, BYD Han) of three different pack configurations and classes; the performance results are tabulated as part of system specs. The models were chosen because they enjoy wide market acceptance, technically validated data is readily available and a variety of propulsion and energy storage deployments are on record. The goal is to compare system level parameters under realistic operation conditions to support the study of battery performance and BMS control effective strategies.

4.2 Data Collection (Load Profiles, Solar Irradiance, Voltage Levels)

Information based on manufacturer specifications, confirmed field measurements, and reviewed literature. Those parameters include nominal battery voltage, usable capacity, driving range, total cell count and operating temperature range. These values are presented as a table in Table 4.1 and act as the baseline dataset for further modeling, simulation, and performance comparison.

Table 4.1: Specifications of Selected EV Models

Model	Nom. Voltage	Usable Cap. (kWh)	Range (km)	Cells	Operating Temp.
Nissan Leaf	360V	40	250	192	-20 to 55°C
Tesla Model 3	355V	55, 60, 82	350–560	2976	-20 to 60°C

Table. 2.1: EV Battery Thermal Management System Comparison

Architecture	Coolant	Heat Extraction Path	Typical Cooling Power (kW)	Applications
Indirect Liquid	50:50 glycol-water	Cold plate under module	4–8	Mass market sedans
Immersion (Dielectric)	Solvent-based oil	Cell surface submersion	8–15	High-performance EVs, racing
Refrigerant Direct	R-1234yf loop	Hollow channels in plate	| 6–10	Premium SUVs

4.3 Indirect Liquid Cooling

It involves a 50:50 glycol-water solution as a coolant, that is circulated through a cold plate under the battery modules. The heat is removed from the module bottoms and sucked into the coolant. It is commonly used in mass-market sedans due to its reasonable cost and proven reliability, with typical cooling power of 4-8 kW.

4.4 Immersion (Dielectric) Cooling

Immersion cooling sees the entire battery pack, or just a cell, submerged in an oil that acts as a dielectric coolant. The principal is being in direct contact with the cell surfaces, which results in more effective heat extraction that leads to a greater cooling power of 8–15 kW. This is an advanced strategy that will be particularly relevant for high-performance EVs and racing applications-cases where extreme power requirements and rapid charging require aggressive thermal management.

4.5 Refrigerant Direct Cooling

This method uses a direct refrigerant loop, usually R-1234yf, consisting of hollow channels inside a cooling plate. Since the refrigerant also has to change phase (evaporate) to take heat, it is much more efficient than indirect systems. Typically used in premium SUVs, this approach delivers cooling power from 6–10 kW and serves as a good compromise between high performance and system integration with the vehicle's HVAC system.

4.6 Second-Life & Sustainability Considerations

Once a battery pack hits about 80% state of health (SOH), it becomes suitable for reuse as stationary energy storage and can continue operation for another 5 – 10 years. These modifications often involve things like loosening peak current limits, re-state-of-charge (SoC) operating window redefinition and inverter-based energy management systems integration. Life-cycle assessments show that using batteries for a second life can bring down the per-kWh CO_2 footprint by as much 20–24%. In addition, circular design measures (e.g. modularity, cobalt-free chemistries and direct-recycling techniques) can be employed to further lower cradle-to-grave environmental burdens and thus improve the sustainability of battery systems on electric vehicles.

5. RESULTS AND DISCUSSION

5.1 Data Analysis and Interpretation

Discharge performance of the batteries is plotted in Fig. 5.1 at different states of charge, C-rates and temperatures with respect to potential voltage droop This drop in performance was considered significant, and performance below 0 °C-where internal resistance increased and electrochemical activity decreased-was especially poor. Thermal Management - High temperatures (45 °C) caused fast degradations, and temperature effects in efficiency showed that it was necessary the use of techniques for an efficient thermal management to keep performance optimum along with a wide operational range.
(Graph Placeholder: "Fig.5.1 Discharge Curves at Varying Temps"
Key performance drops noted below 0°C and above 45°C.)

5.2 Challenges and Solutions

Over-temperature is a most difficult problem which often suffers the performances of electric vehicle (EV) battery systems as well as speeds up their aging. The problem is academic, with active liquid cooling so that the temperature is the same everywhere; there are no local hot spots. There is also the issue about thermal runaway and subsequent fire risks, but multi-level thermal fuses combined with efficient BMS software cut-offs provide fast fault isolation. Price forces another important challenge to prevent size EV adoption. The use of lithium iron phosphate (LFP) chemistries provides a cost-effective alternative, offering acceptable performance while enhancing affordability for mainstream markets.

5.3 Impact (Economic, Environmental, Technical

Purely from an economic standpoint, the total cost of ownership (TCO) is still in favour of internal combustion engine (ICE) vehicles over many electric vehicles (EVs), due mainly to the lower lifetime operational costs and reduced maintenance required. From an environmental standpoint, improved with more batteries to less CO_2 eq. emissions resulting from improvements in battery manufacturing and recycling process steps. emissions linked to battery production. Increased recycling and more responsible sourcing of materials will improve resource efficiency, but the lasting importance of electric vehicles as part of a circular approach to cleaner mobility cannot be underestimated.

6. FUTURE SCOPE / RECOMMENDATIONS

6.1 Further Research

Looking to the future, solid-state batteries add another layer of complexity with development only owing a viable, commercially relevant pathway after 2028 with energy densities likely to be beyond 400 Wh/kg. In addition, using wireless battery management and standard vehicle-to-grid communication coins could greatly improve system flexibility and integration with open market platforms. Another possible tactic entails deploying sophisticated artificial intelligence algorithms to estimate the lifetime fitness (SOH) and charge content (SOC) in real-time, improving diagnostic and predictive maintenance performance.

Table-6.1 Battery Management System Research Challenges and Solutions

Research Gap	Limitation Today	Prospective Solution
High-precision SoC at −30 °C	Resistance surge confuses impedance models	Physics-guided neural nets trained on cryogenic datasets
Real-time lithium plating detection	Relies on proxy voltage dips	Acoustic emission + ML classifiers
Cyber-secured OTA balancing	Patch updates risk bricking pack	Dual-bank secure OTA with delta-update verification
Solid-state BMS requirements	Unknown impedance signature	Adaptive parameter-identification algorithms
End-of-life diagnosis for second-life	Manual capacity tests	Cloud twin with federated learning across retired packs

6.2 Potential for Large-Scale Implementation

Addressing a future of increasing demand comprises, among other steps, supportive policies and regulatory frameworks to enable widespread deployment of advanced battery technologies. Major enablers are infrastructure for large-scale battery recycling and aligning global safety standards. These actions should not only offset environmental concerns, but also improve broad adoption across transportation, grid storage and distributed energy markets.

6.3 Digital-Twin–Enabled BMS

The integration of digital twin technology into Battery Management Systems represents a transformative advancement in electric vehicle (EV) battery monitoring, control, and predictive maintenance. A digital twin is a virtual representation of the physical battery system, combining high-fidelity multi-physics models with real-time operational data and cloud-based analytics to replicate and predict the pack's behaviour under various operating conditions.
The proposed framework will use a dual-layer digital twin architecture:

6.3.1 Edge Twin

An onboard computing system-based lightweight electro-thermal model. It takes locally acquired voltage, current and temperature data and computes performance indicators like SOC (State-of-Charge), SOH (State-of-Health) & RUL (remaining useful life) through near real-time simulations. Decision Making at the edge twin allows to make immediate balancing, protection and thermal management decisions without having an external connectivity.

6.3.2 Cloud Twin

A cloud-based model hosted in an environment designed to be high fidelity and computationally intensive (with continuous update through telematics). 6) The cloud twin runs ensemble simulations using fleet-wide data in order to predict degradation patterns, optimize charging strategies and assess the impact of environmental and usage variability. This also includes extensive analysis for advanced battery life extension initiatives.

7. CHALLENGES

Digital twin–enabled BMS is advantageous, however there are several challenges this digital twin– based BMS has to solve. The data going through this plumbing are the delicate operational stuff, which then exposes this to potential data privacy and security concerns. Many of us are still constrained by the high data bandwidth requirements, especially when it comes to some of the less connected regions. Furthermore, ensuring model fidelity as the battery ages is not only computationally expensive but variably difficult with need of recalibration and degradation models to be included that change with time.
Such a hybrid edge-cloud digital twin approach empowers predictive, adaptable, and data-driven battery management which is crucial for future EV platforms.

7.1 Summary of Findings

Lithium-ion batteries and battery management systems (BMS) have progressed a lot in recent years, enabling advances not just in performance but also reliability while they worked with applications at scale. Nevertheless, there remain challenges associated with reducing degradation at high temperatures, accurate state-of-health (SOH) estimation, and deployment costs on a larger scale. Addressing these challenges is critical in enabling greater scalability and their long-term adoption by consumer as well as industrial sectors.

7.2 Achievements and Contributions

The study provides state-of-the-art technical benchmarks for voltage, current, temperature window and cycle life based on empirical data and literature review. It also describes the newest advances in BMS architecture as well as safety engineering and fault-prevention mechanisms. This work weaves contemporary research into practical design guidelines and illustrates the cutting-edge of battery management technology.

7.3 Practical Implications

This emphasizes that the selection of a BMS solution design requires attention to cost, safety and required connectivity features. Especially the integration of IoT enabled remote diagnostics significantly improves to failure detection, predictive maintenance and operational efficiencies. These holistic approaches are mandatory for future electric mobility and energy storage systems that need to fulfil the requirements of reliability, safety, economic viability etc.

7.4 Recommendations

Use solid-state or LFP chemistries when viable and implement AI-driven predictive maintenance. The battery management system is the heart of electric-vehicle dependability, safety, and owner trust. A comprehensive BMS includes Chemistry-aware Estimation, Agile Thermal Management, Cyber-hardening, and Cloud-connected analytics. Integration of digital twins and AI-enhanced prognostics will both enhance pack longevity and open the doors to intelligent charging ecosystems. At the same time, standardisation processes, secure communication and end-of-life recycling pathways will have to be developed so that the deployment of EVs adds up to true sustainability goals rather than shifting the burden elsewhere in the value chain.

CONCLUSION

High energy vehicles: Battery Management Systems (BMS) are essential to the reliability, safety and user confidence on Electric Vehicles. An end-to-end BMS includes chemistry-aware estimation, agile thermal management, cyber-hardening and cloud-connected analytics. AI-powered prognostics and digital twins mean this will not only be an environment for longer lasting packs, but also the opportunity to create smarter charging ecosystems through a lower total cost of ownership requirements as EV batteries are designed with second-life energy storage solutions in mind. At the same time, standardization and about secure communications as well as end-of-life reuse pathways must continue to ensure that electric vehicles truly deliver on sustainability goals and are not just moving burdens along the value chain.
Transport electrification is not just moving to a new propulsion, but changing how we store energy, ensure safety and view sustainability. Among other things that play central role in this transition is the electric vehicle battery pack, and specifically its lithium-ion chemistries and Battery Management System (BMS) functionality; all of which are key enablers for performance, safety, as well as lifecycle viability.
This study has outlined the rapid evolution of battery technologies-from early lead-acid cells to today's AI-integrated, digitally twinned lithium-ion systems. With real-world data from vehicles like the Tesla Model 3 and Nissan Leaf, we analysed key parameters such as temperature behaviour, charge/discharge characteristics, and adherence to global safety standards. The findings reinforce that high-fidelity BMS design-combining thermal regulation, advanced state estimation, cybersecurity, and predictive maintenance-is indispensable for modern EVs. Emerging innovations, such as solid-state batteries, edge/cloud digital twins, and second-life reuse frameworks, point toward a future where EVs are not only more efficient but also more circular and sustainable. However,

significant challenges remain in high-temperature performance, universal safety standardization, and scalable fast-charging.

In the final sense, it is the design and management of batteries and not merely a technical role but one done in global strategic enablement. Comprehensive cross-disciplinary research, industry standardization and policy support will be crucial to achieving the next level of electric mobility - one that is safer, smarter and more sustainable than ever before.

Continued interdisciplinary research-bridging electrochemistry, embedded systems, data science, and lifecycle engineering-will be pivotal in advancing both EV performance and the broader energy transition.

REFERENCES

[1] A Comprehensive Review on Electric Vehicle: Battery Management System, Charging Station, Traction Motors https://ieeexplore.ieee.org/document/10056124/

[2] Garg, V., Jangid, R., Jain, C., Sisodiya, M. "Performance Analysis of a PV-BESS-Grid Integrated Fast EV Charging System", Journal of Emerging Technologies and Innovative Research (JETIR), Volume 12, Issue 6, 2025.

[3] Sisodiya, M., Jangid, R., Jain, C., Garg, V. "Short-Term Load Forecasting (STLF) Using Machine Learning Models: A Comparison Based Study to Predict the Electrical Load Requirements", International Journal of Technical Research & Science. Volume X, Issue VI, June 2025. DOI Number: https://doi.org/10.30780/IJTRS.V10.I06.007

[4] Sharma, S.S., Joshi, R.R., Jangid, R. et al. "Intelligent Techniques for Mitigation of Transient Over-Voltages in Gas Insulated Sub-Station and Effects of VFTO", Journal of Critical Reviews, Volume 7, Issue 14, pp. 3378-3392, 2020.

[5] Bhatnagar, S., Jangid, R., et. al. "Modeling and Design of Maximum Power Point Tracking System Control Algorithm for PMSG Based Grid Connected Wind Power Generating Unit", International Journal of Technical Research & Science. Volume IV, Issue VII, July 2019. DOI Number: https://doi.org/10.30780/IJTRS.V04.I07.002

[6] Verma, C., Jangid, R. "Smart Household Demand Response Scheduling with Renewable Energy Resources", IEEE Third International Conference on Intelligent Computing and Control System (ICICCS-2019), Organized by Vaigai College of Engineering during May 15-17, 2019 at Madurai, India. (Scopus index) DOI: 10.1109/ICCS45141.2019.9065908.

[7] Y. Joshi, J. K. Maherchandani, V. K. Yadav, R. Jangid, S. Vyas and S. S. Sharma, "Performance Improvement of Standalone Battery Integrated Hybrid System," 2021 7th International Conference on Electrical Energy Systems (ICEES), Chennai, India, 2021, pp. 250-255, doi: 10.1109/ICEES51510.2021.9383636

[8] Kumar, S., Jangid, R., Parikh, K. "Comparative Performance Analysis of ANFIS & ANN Algorithms Based MPPT Energy Harvesting in Solar PV System", International Journal of Technical Research & Science. Volume VIII, Issue III, March 2023. DOI Number: https://doi.org/10.30780/IJTRS.V08.I03.001

[9] Gaur, S.S., Bahrani, P., Jangid, R. "Performance Analysis of Standalone Solar Generation System with Fuzzy and ZVS Converter", International Journal of Technical Research & Science. Volume IV, Issue II, Feb. 2019. DOI Number:10.30780/IJTRS.V04.I02.003

[10] A Novel Electric Vehicle Battery Management System Using an Artificial Neural Network-Based Adaptive Droop Control Theory https://www.hindawi.com/journals/ijer/2023/2581729/

[11] Artificial Intelligence Approaches for Advanced Battery Management System in Electric Vehicle Applications: A Statistical Analysis towards Future Research Opportunities https://www.mdpi.com/2624-8921/6/1/2

[12] Solar Powered Charging of Fuzzy Logic Controller (FLC) Strategy with Battery Management System (BMS) Method Used for Electric Vehicle (EV) https://link.springer.com/10.1007/s40815-023-01537-7

[13] Towards the Human Digital Twin: Definition and Design – A survey https://arxiv.org/abs/2402.07922

[14] Sujit Kumar, Himani Paliwal, Shripati Vyas, Sasanka Sekhor, Vikramaditya Dave and Srawan Singh Rao. Dynamic Wireless Power Transfer in Electric Vehicles. 2021 J. Phys.: Conf. Ser. 1854. https://doi.org/10.1088/1742-6596/1854/1/012014

[15] Bonga Main Life Extension Project: An In-Situ Life Extension of an FPSO Using FAIR+ER Methodology and Digital Twin Technology as Basis for Scope Identification and Definition https://onepetro.org/OTCONF/proceedings/24OTC/24OTC/D041S045R007/544798

[16] Systematic review of digital twin technology and applications https://vciba.springeropen.com/articles/10.1186/s42492-023-00137-4

[17] Research on digital twin technology and its application in intelligent operation and maintenance of high-speed railway infrastructure http://www.emerald.com/rs/article/3/6/746-763/1233018

[18] Digital Twin Technology-A Review and Its Application Model for Prognostics and Health Management of Microelectronics https://www.mdpi.com/2079-9292/13/16/3255

[19] The importance of applying digital twin technology and its obstacles in engineering projects in Syria

https://www.americaspg.com/articleinfo/22/show/3023

[20] Research on Electric Vehicle Powertrain Systems Based on Digital Twin Technology https://www.mdpi.com/2079-9292/13/20/4103

[21] Digital Twin Technology of Metaverse Based on Game Engine in the Campus Application Scenarios https://francis-press.com/papers/15323

[22] Analysis of the Digital Twin Technology in the Power Equipment from the Perspective of Development and Operation of ±500kV Converter Bushing https://ieeexplore.ieee.org/document/10973251/

[23] TRADING DIGITAL TWIN AS AN INNOVATIVE TECHNOLOGY FOR ENSURING DIGITAL TRADE IN SUSTAINABLE DEVELOPMENT CONDITIONS http://apir.iir.edu.ua/index.php/apmv/article/view/3947