

A Comprehensive Review of Electric Vehicles: Technologies, Challenges, Recent Developments, and Future Perspectives

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Abstract - Electric vehicles (EVs) are an important pathway toward reducing dependence on petroleum-based road transport. However, their performance and sustainability depend on the combined operation of vehicle architecture, energy storage, power conversion, charging systems, control strategies, and electricity supply. This review critically examines five review papers covering a broad range of EV technologies and related challenges. Lithium-ion batteries remain the main type of battery used in electric vehicles, although selecting the right battery chemistry involves trade-offs among energy density, cost, cycle life, safety, and material availability. Battery management systems (BMSs) play an essential role in ensuring reliable operation by monitoring battery conditions, estimating battery states, detecting faults, and controlling battery performance to improve safety and efficiency. Charging convenience depends on the interaction of charging power, battery charging capacity, power electronics, charging infrastructure, communication protocols, and grid conditions. Therefore, no single charging solution can overcome all existing challenges. Battery-supercapacitor hybrid energy storage systems can help manage sudden changes in power demand, although their benefits depend on proper system sizing, converter losses, and coordinated control. Regenerative braking can improve energy efficiency, but its effectiveness also depends on suitable component selection and control strategies.

Keywords: Electric vehicles; battery technologies; battery management systems; charging infrastructure; power electronics; hybrid energy storage; artificial intelligence; grid integration.

1. INTRODUCTION

1.1. Definition and Importance of Electric Vehicles

The electrification of road transport is an important step towards reducing dependence on petroleum-based fuels and developing more sustainable transportation systems. Electric vehicles (EVs) have gained considerable attention because of their energy efficiency and potential to reduce tailpipe emissions. However, their overall performance depends on several factors, including battery technology,

power electronics, charging infrastructure, and energy management. Understanding these technologies is essential for addressing the challenges associated with EV development and adoption.

Battery technology is one of the most important aspects of EV performance because it affects driving range, charging time, cost, safety, and vehicle lifetime. Although lithium-ion batteries are widely used because of their favourable energy density and performance, selecting a suitable battery involves trade-offs among cost, power capability, cycle life, and thermal stability. Battery management systems (BMSs) help monitor battery conditions, estimate battery states, detect faults, and maintain safe operation. Similarly, charging systems, power converters, regenerative braking, and energy management strategies contribute to improving EV efficiency. Battery-supercapacitor hybrid energy storage systems and artificial intelligence (AI)-based techniques also offer opportunities to improve power management, battery monitoring, and system reliability. However, challenges related to cost, safety, charging infrastructure, and system integration remain.

The research papers selected for this review examine different aspects of EV technology. Sanguesa et al. [1] provide an overview of EV technologies, batteries, charging methods, and energy management. Al Tahtawi et al. [2] focus on the modelling and control of battery-supercapacitor hybrid systems. Liu et al. [3] examine battery technologies, battery management, state estimation, and fault diagnosis. Amer et al. [4] discuss battery technologies, charging standards, AI applications, and vehicle communication systems. Keramati and Maghanaki [5] review battery technologies used in commercial battery electric vehicles, including battery chemistry, cell formats, and battery-pack architecture.

Although these studies share the objective of improving electric mobility, they differ in their technical focus. Collectively, they provide useful insights into battery performance, charging systems, power conversion, and energy management. However, topics such as traction motor technologies, lifecycle environmental assessment, total cost of ownership, and the impact of EV adoption on electricity networks receive comparatively less attention

across this selected collection. Comparing these studies can therefore help identify connections between existing technologies and areas that require further investigation.

The main objective of this review is to critically analyse and synthesize the findings of the selected papers to understand the major EV technologies, their technical challenges, recent developments, and future research opportunities. The review also examines the relationships between battery technology, battery management, charging systems, and energy management

To achieve this aim, the review examines the interconnections among EV architecture, battery technologies, battery management, charging systems, and control strategies based on the selected literature. It also analyses the common technical challenges and performance trade-offs that influence EV efficiency, reliability, safety, and practical deployment. Furthermore, the review identifies potential future research opportunities by comparing and synthesizing the findings and limitations of the five selected papers.

1.2 Development of Electric Mobility

The development of electric mobility has increasingly focused on improving vehicle performance, energy storage, charging convenience, and environmental sustainability.

Early electric vehicle technologies included lead-acid and nickel-based batteries. Although these technologies provided electrical energy storage, their relatively low specific energy limited their suitability for applications requiring longer driving ranges.

Lithium-ion batteries subsequently became a major technology for electric vehicles because of their comparatively high energy density, useful power capability, and potential for long service life. Continuing developments have focused on improving battery chemistry, reducing manufacturing costs, increasing charging performance, and enhancing safety.

Battery development has also expanded beyond improvements in electrochemical materials. Modern research considers battery management systems, thermal management, advanced manufacturing, battery-pack integration, and intelligent monitoring.

Charging technology is another important aspect of electric mobility. Conductive charging systems, different charging standards, wireless power transfer, and intelligent charging approaches are being investigated to improve charging convenience and energy management.

Recent research also examines emerging battery technologies, including sodium-ion, lithium-metal, solid-state, and lithium-sulphur batteries. These technologies offer potential advantages but face different technical and commercial challenges.

Furthermore, the integration of artificial intelligence, data-driven battery monitoring, and advanced control strategies provides opportunities to improve battery-state

estimation, fault diagnosis, thermal management, and energy utilization.

Overall, electric mobility is developing through the combined advancement of vehicle architecture, energy storage, charging infrastructure, control systems, and manufacturing technologies.

1.3 Importance of Battery Technology in Electric Vehicles

Battery technology directly influences several important electric vehicle characteristics:

1. **Driving range:** The amount of usable stored energy affects the distance a vehicle can travel between charging sessions.
2. **Vehicle weight:** Battery mass influences vehicle design and energy consumption.
3. **Charging performance:** Battery chemistry and operating conditions influence acceptable charging rates.
4. **Power delivery:** Battery power capability affects acceleration and the ability to meet changing driving demands.
5. **Safety:** Temperature, voltage, material characteristics, and operating conditions influence battery safety.
6. **Service life:** Repeated charging and discharging, operating temperature, and usage patterns affect battery degradation.
7. **Cost:** Battery materials, manufacturing processes, and pack architecture contribute to overall vehicle cost.
8. **Environmental impact:** Material extraction, battery production, electricity generation, and recycling influence lifecycle sustainability.

Battery performance therefore cannot be evaluated using energy density alone. A suitable battery must balance energy storage, power delivery, cost, safety, durability, and application requirements.

2. TYPES OF ELECTRIC VEHICLES

Electric vehicles can be classified according to their propulsion systems and the sources used to supply electrical energy.

2.1 Battery Electric Vehicles (BEVs)

Battery electric vehicles operate entirely using electric power stored in rechargeable battery packs. They do not use an internal combustion engine for propulsion.

The battery supplies electrical energy to the vehicle's electric drive system, which converts the stored energy into mechanical power.

Main characteristics:

- Operate using rechargeable battery packs.
- Do not require liquid fuel for vehicle propulsion.
- Require external charging to replenish battery energy.
- Produce no tailpipe emissions during operation.
- Depend on battery capacity, energy consumption, and driving conditions for their driving range.
- Battery electric vehicles are particularly associated with developments in lithium-ion batteries, charging infrastructure, electric drives, and battery management systems.
- However, their performance is influenced by battery cost, charging time, battery degradation, temperature, and the availability of charging facilities.

2.2 Hybrid Electric Vehicles (HEVs)

Hybrid electric vehicles combine an internal combustion engine with an electric motor and an electrical energy storage system.

The vehicle can use both power sources according to its operating conditions. Electrical energy may be recovered during braking and used to support vehicle propulsion.

Conventional HEVs generally do not require external charging because their batteries are charged through the vehicle's powertrain and regenerative braking system.

Main characteristics:

- Combine electrical propulsion assistance with conventional engine operation.
- Recover part of the vehicle's kinetic energy during braking.
- Reduce dependence on fuel compared with conventional vehicles under suitable operating conditions.
- Use relatively small batteries compared with many battery electric vehicles.
- Continue to depend on conventional fuel.
- HEVs provide a way to combine electric propulsion with an established fuel-based powertrain, although their environmental performance depends on vehicle design, fuel consumption, and operating conditions.

2.3 Plug-in Hybrid Electric Vehicles (PHEVs)

Plug-in hybrid electric vehicles combine an electric motor, rechargeable battery, and internal combustion engine. Unlike conventional HEVs, their batteries can be charged using an external electrical source.

PHEVs can operate electrically for a limited distance before relying more heavily on their combustion engine, depending on vehicle design and operating conditions.

Main characteristics:

- Combine electric and combustion-engine propulsion.
- Support external battery charging.
- Can complete suitable journeys using stored electrical energy.
- Retain a conventional engine for operation when required.
- Require both charging access and fuel availability.
- Their fuel consumption and emissions depend on the frequency of charging, the distance travelled electrically, driving conditions, and the efficiency of the combustion engine.

2.4 Fuel Cell Electric Vehicles (FCEVs)

Fuel cell electric vehicles use an electric motor for propulsion, with electrical energy generated through a fuel-cell system. Hydrogen is commonly used as the fuel.

In a hydrogen fuel-cell system, hydrogen reacts electrochemically with oxygen to produce electrical energy. Water is produced by the fuel-cell reaction.

Main characteristics:

- Use an electric motor for propulsion.
- Generate electricity using a fuel-cell system.
- Require a supply of hydrogen.
- Produce water as the principal product of the fuel-cell reaction.
- Depend on hydrogen storage, fuel-cell performance, and refuelling infrastructure.
- Although FCEVs do not produce conventional combustion exhaust during fuel-cell operation, their overall environmental impact depends on hydrogen production, processing, transportation, and distribution.
- The availability of hydrogen refuelling infrastructure is an important factor affecting their adoption.

2.5 Extended-Range Electric Vehicles (ER-EVs)

Extended-range electric vehicles use an electric propulsion system and include an additional combustion engine that can generate electrical energy when required. In this configuration, the range-extending engine supplies energy to the electrical system rather than directly driving the wheels.

Main characteristics:

- Use electric propulsion.
- Include a battery for electrical energy storage.
- Incorporate a combustion engine as a range extender.
- Can extend driving range when stored battery energy is insufficient.
- Require additional space and weight for the range-extending system.
- Their architecture differs from that of conventional hybrids because the additional engine primarily supports electrical energy generation.

- Their relatively low-specific energy makes them less suitable for many modern electric vehicles requiring long driving ranges.

3.2 Nickel-Metal Hydride (NiMH) Batteries

Nickel-metal hydride batteries use nickel-based positive electrodes and a hydrogen-absorbing alloy as the negative electrode.

They have been used in hybrid electric vehicles because of their ability to provide electrical power under repeated operating cycles.

Characteristics:

- Suitable for applications requiring repeated charge and discharge.
- Provide useful power capability.
- Have lower specific energy than many lithium-ion battery technologies.
- Their performance depends on operating conditions and battery design.
- Are less widely used than lithium-ion batteries in modern battery electric vehicles.
- NiMH batteries remain relevant when comparing established battery technologies, particularly in hybrid vehicle applications.

2.6 Comparison of Electric Vehicle Types

Parameter	Battery Electric Vehicle (BEV)	Hybrid Electric Vehicle (HEV)	Plug-in Hybrid Electric Vehicle (PHEV)	Fuel Cell Electric Vehicle (FCEV)	Extended-Range Electric Vehicle (ER-EV)
Vehicle illustration (schematic)					
Primary propulsion	Electric motor	Electric motor and combustion engine	Electric motor and combustion engine	Electric motor	Electric motor
Main energy source	Rechargeable battery	Fuel and electrical energy	Fuel and rechargeable battery	Hydrogen (converted to electricity by fuel cell)	Battery and fuel (used by range extender)
External charging	Required	Generally not required	Supported	Not normally used to replenish hydrogen	Required to replenish the traction battery
Combustion engine	No	Yes	Yes	No	Yes (used as a range extender)
Tailpipe emissions during operation	None	Present during engine operation	Present during engine operation	None (water is the main product of the fuel-cell reaction)	Present when the range extender operates
Typical battery size	Large	Small	Medium	None (uses hydrogen and fuel cell)	Medium
Driving range dependency	Depends on battery capacity and energy consumption	Depends on fuel tank and hybrid system efficiency	Depends on battery capacity, charging frequency, and fuel tank	Depends on hydrogen storage and fuel-cell performance	Depends on battery capacity and range-extender fuel supply
Main advantages	No tailpipe emissions, high energy efficiency	Improved fuel efficiency, regenerative braking	Electric driving with fuel backup	Fuel refuelling, no tailpipe emissions during operation	Extended driving range with electric propulsion
Main technical considerations	Battery performance, charging infrastructure, cost, degradation	Engine efficiency, energy recovery, system complexity	Battery charging, combined powertrain efficiency	Hydrogen storage, fuel-cell performance, refuelling infrastructure	Battery performance, range-extender design, system complexity

3. TYPES OF BATTERIES USED IN ELECTRIC VEHICLES

Different battery technologies have been investigated or used in electric vehicles. Their suitability depends on energy density, power density, cycle life, charging characteristics, cost, operating temperature, and safety.

3.1 Lead-Acid Batteries

Lead-acid batteries use lead-based electrodes and electrolytes to store and release electrical energy. They are an established rechargeable battery technology and have been used in automotive electrical systems and earlier electric vehicle applications.

Characteristics:

- Established and familiar battery technology.
- Relatively low-specific energy compared with lithium-ion batteries.
- Limited suitability for applications requiring high energy storage with minimal mass.
- Require consideration of battery weight and volume.
- Have established recycling processes, although environmental management remains necessary.

3.3 Lithium-Ion Batteries

Lithium-ion batteries are widely used in modern electric vehicles because of their comparatively high energy density, useful power capability, and potential for long service life.

They operate through the movement of lithium ions between electrodes during charging and discharging.

Characteristics:

- Comparatively high energy density.
- Suitable for vehicle applications requiring substantial stored energy.
- Available in different electrode chemistries.
- Support a wide range of battery pack designs.
- Require battery management and thermal protection.
- Are sensitive to operating temperature and voltage conditions.
- Experience degradation with use and ageing.
- Lithium-ion batteries are not a single uniform technology. Their characteristics depend on electrode chemistry, cell design, operating conditions, and battery-pack engineering.

3.4 Lithium Iron Phosphate (LFP) Batteries

Lithium iron phosphate is a lithium-ion battery chemistry that uses lithium iron phosphate as the cathode material. LFP batteries have attracted attention because of their material cost characteristics, cycle-life potential, and thermal stability.

Characteristics:

- Generally offer favourable thermal stability.
- Can provide long cycle life under suitable conditions.
- Use iron and phosphate in the cathode material.
- Are suitable for applications where durability and cost are important.
- Generally have lower gravimetric energy density than nickel-rich lithium-ion chemistries.
- LFP batteries are increasingly relevant to electric vehicle designs that prioritize cost, durability, and safety-related characteristics.
- However, their actual performance depends on cell design, operating conditions, and pack integration.

3.5 Nickel Manganese Cobalt (NMC) Batteries

- Nickel manganese cobalt batteries are lithium-ion batteries that use nickel, manganese, and cobalt in their cathode material.
- Their composition can be adjusted to influence energy density, stability, cost, and other performance characteristics.

Characteristics:

- Can provide comparatively high energy density.
- Are suitable for applications where driving range and battery mass are important.
- Require careful thermal and electrical management.
- Depend partly on the availability and cost of their constituent materials.
- Have performance characteristics that vary with cathode composition and cell design.
- NMC batteries are used in electric vehicle applications where a balance between energy density, power capability, and other design requirements is needed.

3.6 Sodium-Ion Batteries

Sodium-ion batteries use sodium ions as the charge-carrying species rather than lithium ions.

They are being investigated as an alternative rechargeable battery technology.

Characteristics:

- Use sodium-based electrochemistry.
- Offer an alternative to lithium-based battery materials.
- Have potential advantages related to material availability and cost.
- Require further development to meet different electric vehicle performance requirements.
- Must be evaluated in terms of energy density, cycle life, charging performance, and safety.
- Sodium-ion batteries represent a possible alternative for applications in which their cost and performance characteristics are suitable. Their suitability should not be assumed to be identical to that of lithium-ion batteries.

3.7 Solid-State Batteries

- Solid-state batteries use a solid electrolyte rather than a conventional liquid or gel electrolyte.
- They are being investigated as a possible next-generation energy storage technology.

Characteristics:

- Have the potential for improved energy density.
- May enable changes in electrode design.
- Could offer improved safety characteristics depending on the materials and cell architecture.
- Face challenges related to manufacturing, interfaces, materials, and practical performance.
- Require further evaluation of durability, cost, and large-scale production.
- Although solid-state batteries are promising, their potential advantages should be distinguished from performance demonstrated in commercially deployed battery systems.

3.8 Lithium-Sulfur Batteries

Lithium-sulfur batteries use lithium-based negative electrodes and sulfur-containing positive electrodes. They are investigated because of their potential for high-specific energy.

Characteristics:

- Offer potential for high-specific energy.
- Use sulfur as a cathode material.
- Face challenges related to cycle life and degradation.
- Require further development of electrode materials and cell design.
- Must address practical performance and manufacturing requirements.
- Lithium-sulfur batteries remain in an important research direction, but their potential advantages

must be assessed alongside their durability and implementation challenges.

4. COMPARATIVE ANALYSIS OF BATTERY TECHNOLOGIES

Battery technologies should be compared using several performance parameters rather than relying on a single characteristic.

Energy density, power density, cycle life, charging time, cost, efficiency, safety, and environmental impact are related but distinct measures.

4.1. Comparative Table

Table 4.1 Comparative Analysis of Battery Technologies for Electric Vehicles

Battery Technology	Energy Density (Wh/kg)	Power Density (W/kg)	Cycle Life (Cycles)	Charging Time (80% charge)	Cost (Relative)	Efficiency (%)	Safety (General)	Environmental Impact (General)
Lead-Acid (LA)	30 – 50	150 – 250	200 – 500	8 – 12 hours (slow)	Low	70 – 85	Moderate (requires ventilation)	Moderate (lead recovery and recycling requirements)
Nickel-Metal Hydride (NiMH)	60 – 120	250 – 1,000	500 – 1,500	4 – 6 hours (moderate)	Medium	75 – 90	Good (reliable in operation)	Moderate (nickel and rare elements management)
Lithium-Ion (Li-ion)	150 – 250	250 – 3,400	1,000 – 3,000	0.5 – 3 hours (fast to moderate)	Medium to High	90 – 95	Moderate (requires BMS and thermal control)	Moderate (material sourcing and recycling needed)
Lithium Iron Phosphate (LFP)	90 – 160	300 – 2,000	2,000 – 6,000	1 – 4 hours (moderate)	Medium to Low	90 – 95	High (good thermal stability)	Lower (more abundant and less toxic materials)
Nickel Manganese Cobalt (NMC)	150 – 250	400 – 3,000	1,000 – 3,000	0.5 – 3 hours (fast to moderate)	Medium to High	90 – 95	Moderate (requires careful thermal control)	Moderate (nickel and cobalt resource concerns)
Sodium-Ion (Na-ion)	100 – 160	200 – 2,000	1,000 – 3,000	0.5 – 3 hours (moderate)	Low to Medium	85 – 92	Moderate (requires BMS and thermal control)	Lower (medium abundance and lower toxicity)
Solid-State (SSB)	250 – 400 (potential)	500 – 3,000 (potential)	1,000 – 5,000 (potential)	0.5 – 2 hours (potential fast)	High (current stage)	90 – 97 (potential)	High (potentially safer)	Lower (potentially better life-cycle impact)
Lithium-Sulfur (Li-S)	300 – 500 (potential)	300 – 2,000 (potential)	500 – 1,500	0.5 – 3 hours (potential)	Medium (potential)	85 – 93 (potential)	Moderate (requires further development)	Lower (sulfur abundance and lower toxicity)

Note: The values represent typical ranges reported in the reviewed literature. Actual performance depends on specific cell design, operating conditions, and battery pack configuration.

4.2 Energy Density

- Energy density describes the amount of energy stored per unit volume, generally expressed in watt-hours per liter (Wh/L).
- Specific energy describes the amount of energy stored per unit mass, generally expressed in watt-hours per kilogram (Wh/kg).
- These parameters influence battery-pack size, vehicle mass, and driving range.
- Lithium-ion batteries generally provide higher energy density than lead-acid and nickel-metal hydride batteries. Within lithium-ion technology, nickel-rich chemistries such as NMC and nickel cobalt aluminium (NCA) can provide higher gravimetric energy density than LFP, although actual performance depends on the specific cell and pack design.
- Emerging technologies such as solid-state and lithium-sulfur batteries are being investigated for their potential to improve energy storage performance.

4.3 Power Density

- Power density describes the power that a battery can deliver per unit volume, while specific power expresses power per unit mass.

- These parameters influence a battery's ability to meet short-duration power demands.
- Battery power capability depends on internal resistance, electrode characteristics, temperature, and operating limits.
- Hybrid energy storage systems that combine batteries with supercapacitors offer a different approach to meeting high power demands. Supercapacitors can provide rapid charge and discharge, while batteries provide principal energy storage.

4.4 Cycle Life

- Cycle life refers to the number of charge-discharge cycles a battery can undergo before reaching a defined end-of-life criterion.
- Cycle life depends on chemistry, temperature, charging and discharging rates, depth of discharge, and other operating conditions.
- LFP batteries can offer favorable cycle-life characteristics under suitable conditions. Other lithium-ion chemistries, nickel-based batteries, and emerging technologies have different durability profiles.
- Cycle-life figures should not be compared directly unless the test conditions and end-of-life definitions are consistent.

4.5 Charging Time

- Charging time depends on battery capacity, charging power, charging-system efficiency, temperature, battery condition, and the charging limits imposed by the battery management system.
- Higher charging power can reduce the time required to replenish stored energy, but the relationship is not simply proportional throughout the charging process.
- Fast charging can increase thermal and electrochemical stresses if the battery is operated outside its recommended limits.
- Charging performance therefore depends on the combined design of the battery cells, battery pack, thermal management system, charger, and charging-control strategy.

4.6 Cost

- Battery cost depends on the materials used, cell chemistry, manufacturing processes, production scale, pack architecture, and quality-control requirements.
- LFP batteries can provide cost advantages associated with their cathode materials, while

nickel-rich chemistries may be selected when higher energy density is important.

- Emerging battery technologies must be evaluated not only in terms of their potential material advantages but also in terms of manufacturing complexity, durability, and commercial scalability.

4.7 Efficiency

- Battery efficiency describes the relationship between energy supplied during charging and energy recovered during discharging, using a defined measurement boundary.
- Efficiency varies with chemistry, temperature, current, and operating conditions.
- At the vehicle level, overall energy efficiency also depends on the electric motor, power electronics, auxiliaries, drivetrain, and energy-management strategy.
- Hybrid battery-supercapacitor systems require effective control to distribute current between the two energy sources while maintaining system efficiency.

4.8 Safety

- Battery safety depends on electrochemical materials, cell construction, operating temperature, voltage, current, manufacturing quality, and protection systems.
- Lithium-ion batteries require effective monitoring and control because operation outside permitted temperature or voltage limits can cause degradation and hazardous conditions.
- LFP chemistry generally offers favourable thermal stability compared with some other lithium-ion chemistries. However, no battery chemistry should be considered completely free from safety risks.
- Solid-state batteries may offer safety advantages, but their practical safety depends on the electrolyte, electrode interfaces, manufacturing quality, and overall cell architecture.

4.9 Environmental Impact

- Battery environmental impact is influenced by raw-material extraction, material processing, manufacturing energy, transportation, battery lifespan, electricity generation, and end-of-life treatment.
- Battery recycling and material recovery are important for reducing waste and supporting the reuse of valuable materials.
- Battery technologies should therefore be evaluated across their lifecycle rather than only

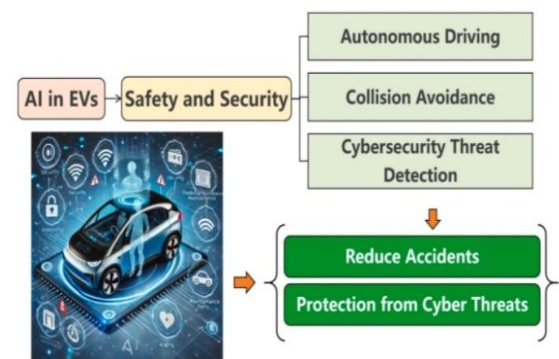
according to their performance during vehicle operation.

- The environmental benefits of electric vehicles also depend on the electricity supply used for charging and the processes involved in manufacturing and disposing of their batteries.

5. INTEGRATED TECHNICAL REVIEW

5.1. EV architectures and system boundaries

The reviewed literature distinguishes battery electric vehicles (BEVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and fuel-cell electric vehicles (FCEVs) [1,3,4]. Their energy pathways differ: BEVs rely on stored electrical energy and external charging; HEVs combine electric drive with an onboard combustion engine; PHEVs add external charging to a hybrid architecture; and FCEVs generate electricity onboard from hydrogen through a fuel cell. These categories should not be compared as if their energy-conversion, refueling, and emissions boundaries were identical. The supplied papers do not provide a harmonized lifecycle dataset for ranking all architectures.



5.2. Battery Chemistry, Formats and Pack Engineering

Battery performance depends on several factors. Liu et al. [3] identify energy, power, lifetime, safety and cost as key performance indicators. Keramati and Maghanaki [5] further highlight the importance of cell format, pack architecture, voltage class, battery placement, and vehicle integration. Although battery chemistry influences cell-level characteristics, the way these characteristics affect overall vehicle performance also depends on pack structure, thermal design, usable capacity, control systems, and packaging.

Lithium-ion batteries are the main traction-battery technology discussed in the reviewed literature, but their different chemistries have distinct characteristics. The papers examine lithium iron phosphate (LFP), nickel-rich chemistries such as nickel manganese cobalt (NMC) and nickel cobalt aluminum (NCA), as well as emerging

technologies, including lithium-metal and solid-state batteries, sodium-ion batteries and other post-lithium alternatives [3–5]. LFP is commonly associated with lower cost, longer cycle life, and better thermal stability, whereas nickel-rich chemistries are often preferred when higher gravimetric energy density is required. However, the actual trade-offs depend on cell design, operating conditions, pack integration, and the intended application. As the reviewed papers do not provide a common dataset obtained under identical testing conditions, this review does not assign specific quantitative energy-density or lifetime values to individual chemistries.

Battery cell formats, including cylindrical, prismatic and pouch cells, along with module-based and cell-to-pack architectures, influence packaging, manufacturing, serviceability and structural integration [5]. Integrated pack designs can reduce packaging overhead, but their benefits should not be assumed without considering other factors, such as repairability, crashworthiness, thermal propagation, manufacturing yield, and end-of-life disassembly.

5.3. Battery Management and Thermal Safety

A battery management system (BMS) monitors battery operation and ensures that it remains within permitted electrical and thermal limits. The reviewed literature examines battery modelling, state estimation, fault diagnosis and safety, along with data-driven electrothermal models, artificial intelligence (AI) and cloud-supported battery management approaches [3,4]. State of charge (SOC) estimates the remaining charge according to a defined reference convention, while state of health (SOH) indicates battery degradation or condition relative to a reference state. Both parameters are estimated rather than measured directly, and their accuracy depends on sensor quality, model assumptions, battery chemistry, temperature, ageing and operating history.

The different BMS functions are closely interconnected. State estimation helps determine permissible power limits, while thermal monitoring influences charging and discharging limits.

Fault detection enables appropriate protective actions, and cell balancing helps manage differences between individual cells. Data-driven methods can identify complex nonlinear patterns in battery behaviour, but their reliability depends on the representativeness of the training data, validation across different temperatures and ageing conditions, computational constraints and the availability of safe fallback mechanisms. The reviewed sources identify these methods as promising research directions; however, they do not establish that AI-based approaches consistently outperform all conventional methods.

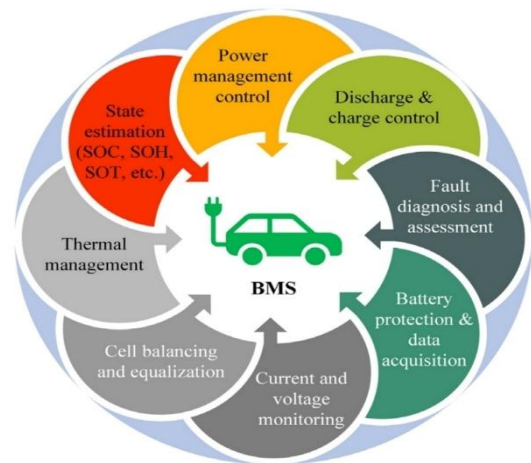


Fig - 1: Advanced Battery Management System

5.4. Charging Standards, Infrastructure and Communication

Charging performance depends on several factors beyond a station's rated power. These include the vehicle's power-conversion pathway, battery voltage and temperature, state of charge, charge-acceptance limits, connector and communication compatibility, and the charging curve. Kilowatts (kW) measure power, whereas kilowatt-hours (kWh) measure energy. Since charging power can vary throughout a charging session, a station's rated power is not necessarily maintained continuously. The reviewed papers examine charging methods, standards and connectors [1,4], but do not identify a single standard as the best choice for every region and vehicle class.

Conductive AC charging generally relies on an onboard AC-to-DC converter, while DC fast charging supplies controlled direct current through offboard power conversion. Wireless power transfer can improve convenience in specific applications. Dynamic or move-and-charge concepts may also reduce the need for large onboard energy-storage systems, but they introduce challenges related to alignment, infrastructure requirements, conversion efficiency, interoperability and cost [3,4]. Stationary wireless charging, dynamic charging and conductive charging also differ in their technological maturity and deployment requirements.

Smart charging and vehicle-to-grid (V2G) technologies can coordinate charging activities with grid conditions and potentially support bidirectional energy exchange between vehicles and the electricity grid. However, their implementation requires compatible hardware, reliable communication systems, suitable control strategies, appropriate tariff arrangements and consideration of battery degradation. The reviewed literature does not establish that V2G is economically beneficial across all markets and usage patterns [3,4].

5.5. Power Electronics and Hybrid Energy Storage

Power electronic converters manage energy transfer between batteries, supercapacitors, the DC bus and the traction drive. Their performance affects overall system efficiency through converter losses, switching and conduction constraints, thermal limits and control stability. Al Tahtawi et al. [2] distinguish between high-fidelity, control-oriented and integrated dynamic models. High-fidelity models are useful for detailed simulations, whereas control-oriented models may be more suitable for real-time design, depending on computational requirements and validation.

A battery-supercapacitor hybrid energy source combines the battery's high energy-storage capacity with the supercapacitor's ability to deliver high power. This configuration can meet short-term power peaks, capture energy during regenerative braking and reduce rapid fluctuations in battery current. However, additional components increase system mass, cost and complexity while introducing further conversion losses. The overall benefits depend on the driving cycle, component sizing, system topology, battery operating limits and control strategy. The reviewed literature identifies integrated vehicle dynamics, unified high- and low-level control, and nonlinear optimal-adaptive strategies as important areas for future research [2].

5.6. AI, Connected Vehicles and Cybersecurity

Artificial intelligence (AI) and data-driven methods can support state of charge (SOC) and state of health (SOH) estimation, thermal prediction, fault diagnosis, charging coordination and vehicle communication [3,4]. Their effectiveness should be evaluated against established baseline methods using independent test data and realistic variations in operating conditions. However, the inclusion of an AI-based method in a review does not establish that it is ready for safety-critical applications. Connected battery management systems (BMSs) and charging services also rely on reliable communication, data integrity, secure software updates and effective cybersecurity measures. Compared with battery technology, the reviewed literature provides less detailed coverage of cybersecurity validation.

5.7. Environmental and Economic Considerations

The environmental performance of electric vehicles (EVs) cannot be assessed solely on the basis of tailpipe emissions. A reliable comparison requires clearly defined system boundaries and consideration of electricity generation, vehicle and battery manufacturing, maintenance, battery lifetime and end-of-life processing. Similarly, cost comparisons depend on several factors, including purchase price, energy prices, charging access,

maintenance, financing, residual value and vehicle usage. The reviewed papers discuss sustainability, recycling and material availability [1,3–5], but do not provide a harmonized lifecycle assessment or total-cost model covering all EV architectures. Therefore, lifecycle analysis remains an essential part of EV evaluation rather than a basis for making universal numerical claims about environmental or economic performance.

6. CONCLUSION

The reviews show that EV progress depends on connected engineering decisions across storage, management, charging, power conversion, and vehicle integration. Lithium-ion batteries remain central in the reviewed literature, but chemistry and pack choices involve trade-offs among energy, power, cost, lifetime, safety and manufacturability. BMS functions support state estimation, operating limits, and fault diagnosis. Charging performance depends on the full vehicle-charger-grid interface rather than charger rating alone. Battery-super capacitor systems may manage transient power, yet net benefits depend on modelling, converter efficiency, sizing and control. AI and connected energy concepts offer opportunities but require validation and cybersecurity attention. Priority research opportunities include integrated validated models, standardized commercial battery data, robust BMS evaluation, interoperable grid-aware charging, and transparent lifecycle analysis. Since the evidence base is small and battery-heavy, broader literature verification and venue-specific editing remain necessary before submission

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