Sustainable Electric Vehicle Technologies: A Review and Experimental Insights into Batteries, Motors, and Charging Systems

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Abstract - The rapid transition toward electric vehicles (EVs) is driven by the global need to reduce carbon emissions, improve energy efficiency, and achieve sustainable transportation systems. it is essential to not only review recent technological developments but also analyse their practical performance and limitations. This paper presents a comprehensive review and experimental-oriented discussion of sustainable electric vehicle technologies, focusing on recent advances in battery technology, electric motor design, and charging infrastructure. Lithium-ion battery improvements, solid-state batteries, and recycling approaches are reviewed alongside experimental electrochemical and thermal performance trends reported in recent literature. Electric motor technologies such as permanent magnet synchronous motors, induction motors, and emerging axial flux motors are examined with respect to efficiency, torque density, and material sustainability. Charging infrastructure developments, including fast charging, wireless charging, and smart grid integration, are analysed from both system-level and experimental perspectives. The paper also discusses current challenges, experimental gaps, and future research directions. The findings highlight that sustainable EV development requires an integrated approach combining advanced materials, efficient electromechanical design, and intelligent energy management systems.

Key Words: Electric Vehicles, Sustainable Mobility, Battery Technology, Electric Motors, Charging Infrastructure, Experimental Analysis

1.INTRODUCTION

The transportation sector accounts for a significant share of global greenhouse gas emissions, primarily due to the extensive use of internal combustion engine vehicles. Electric vehicles (EVs) have emerged as a promising alternative, offering higher energy efficiency, reduced emissions, and compatibility with renewable energy sources. Governments and industries worldwide are investing heavily in EV research, infrastructure, and policy development. the study of EV technologies requires both a theoretical understanding and an experimental evaluation of system performance. Key components such as batteries, electric motors, and charging systems determine the overall efficiency, reliability, and sustainability of EVs. While individual technologies have matured significantly, challenges related to cost, material availability, charging time, and lifecycle sustainability remain.

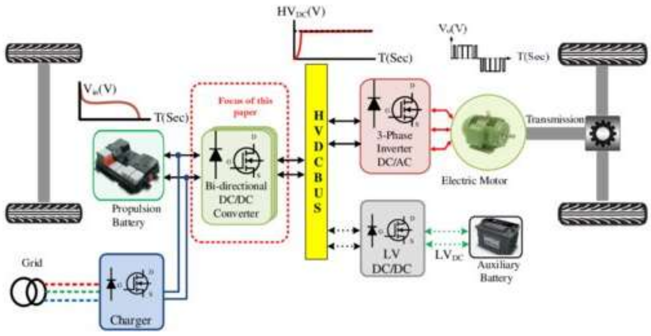

Fig -1: Block diagram of an electric vehicle powertrain showing battery, inverter, motor, and drivetrain.

This paper aims to provide a detailed review combined with an experimental outlook on sustainable electric vehicle technologies. The objectives of this research are: 1. To review recent advancements in EV battery technologies with a focus on performance and sustainability. 2. To analyse modern electric motor designs and their efficiency improvements. 3. To evaluate charging infrastructure developments and grid integration strategies. 4. To identify experimental challenges and future research directions for sustainable EV systems.

2. Advances in Battery Technology

2.1 Lithium-Ion Battery Developments

Lithium-ion batteries remain the dominant energy storage technology for electric vehicles due to their high energy density, long cycle life, and relatively mature manufacturing processes. Recent research focuses on enhancing cathode materials, such as high-nickel layered oxides (NMC and NCA), to improve energy density while reducing cobalt content. Anode developments, including silicon–graphite composites, have shown promising improvements in capacity.

From an experimental standpoint, studies report improved specific energy and reduced internal resistance, leading to better acceleration performance and extended driving range. Advanced battery management systems (BMS) experimentally demonstrate improved thermal stability by actively monitoring voltage, current, and temperature during charge–discharge cycles.

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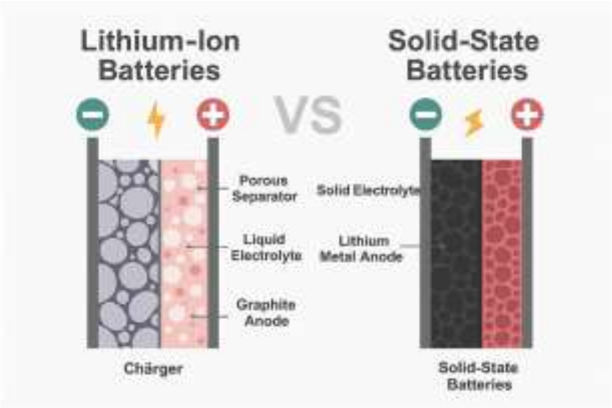

Fig-2: Schematic comparison of lithium-ion battery and solid-state battery structures.

2.2. Solid-State Batteries

Solid-state batteries replace liquid electrolytes with solid electrolytes, offering higher energy density, improved safety, and reduced risk of leakage or thermal runaway. Experimental investigations show that solid-state batteries can operate at higher voltages and temperatures compared to conventional lithium-ion batteries. However, challenges such as interface resistance, mechanical degradation, and large-scale manufacturing remain significant.

2.3. Battery Recycling and Second-Life Applications

Battery sustainability extends beyond performance to include end-of-life management. Experimental recycling techniques such as hydrometallurgical and direct recycling methods enable the recovery of valuable materials like lithium, nickel, and cobalt. Additionally, second-life applications of EV batteries in stationary energy storage systems have been experimentally validated, demonstrating acceptable performance for grid-level and renewable energy storage.

Table 1: Comparison of battery technologies

Battery Technology	Energy Density (Wh/kg)	Cycle Life	Safety Level
Lithium-ion (Li-ion)	150 – 250	1,000 – 2,000	Moderate
Lithium Iron Phosphate (LFP)	90 – 160	2,000 – 5,000	High
Nickel-Manganese-Cobalt (NMC)	200 – 280	1,000 – 2,000	Moderate
Solid-State Batteries	300 – 500 (projected)	3,000+ (expected)	Very High
Lithium-Sulphur (Li-S)	350 – 600 (theoretical)	< 1,000	Low–Moderate
Sodium-Ion Batteries	100 – 160	1,500 – 3,000	High

3. Advances in Electric Motor Design

3.1 Permanent Magnet Synchronous Motors (PMSMs)

The Permanent magnet synchronous motors are widely used in electric vehicles due to their high efficiency, compact size, and high torque density. Experimental efficiency maps indicate that PMSMs achieve efficiencies above 90% over a wide operating range. Current research focuses on reducing rare-earth magnet usage and improving cooling techniques to enhance sustainability.

3.2. Induction Motors

Induction motors are valued for their robustness and reduced dependency on rare-earth materials. Advances in inverter technology and vector control algorithms have significantly improved their performance. Experimental results show that modern induction motors can achieve efficiencies comparable to PMSMs, making them suitable for cost-sensitive EV applications.

Table 2: Comparison of electric motor types used in EVs.

Motor Type	Efficiency (%)	Power / Torque Density	Cost	Rare-Earth Material Use
Permanent Magnet Synchronous Motor	90–96	High	High	High
Induction Motor	88–94	Medium	Moderate	None
Switched Reluctance Motor	85–92	Medium–High	Low	None
Brushless DC Motor	85–93	High	Moderate	Moderate
Axial Flux Motor	92–97	Very High	High	Low–Moderat
Synchronous Reluctance Motor	88–94	Medium	Low–Moderate	None

3.3 Emerging Motor Technologies

Emerging motor designs such as switched reluctance motors and axial flux motors are gaining attention due to their simple construction and high-power density. Experimental prototypes demonstrate high torque-to-weight ratios, making them attractive for future electric vehicle platforms.

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4. Charging Infrastructure Development

4.1 Fast Charging Systems

DC fast charging systems significantly reduce EV charging time, improving user acceptance. Experimental studies on fast charging indicate that optimized charging profiles can minimize battery degradation while achieving high charging power. Thermal management during fast charging remains a critical research area.

4.2 Wireless Charging Technologies

Wireless charging systems provide enhanced convenience and reduced mechanical wear. Experimental implementations demonstrate efficient power transfer over short distances, though alignment sensitivity and efficiency losses remain challenges.

4.3 Smart Grid and Vehicle-to-Grid Integration

Smart grid integration enables intelligent energy management and efficient utilization of renewable energy sources. Vehicle-to-grid (V2G) experiments show that EVs can act as distributed energy storage units, supporting grid stability during peak demand periods.

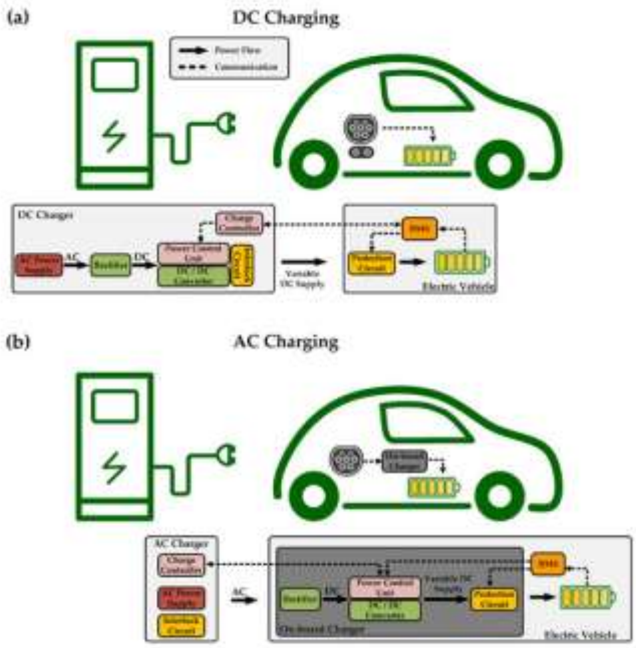

Fig-3: Classification of EV charging infrastructure including AC, DC fast charging, and wireless charging

Table 3: Comparison of EV charging technologies and power levels

Charging Technology	Charging Type	Typical Power Level	Charging Time (0–80%)
AC Level 1	On-board charger	1.4 – 3.3 kW	8 – 20 hours
AC Level 2	On-board charger	3.3 – 22 kW	3 – 8 hours
DC Fast Charging (Level 3)	Off-board charger	50 – 150 kW	30 – 60 minutes
Ultra-Fast DC Charging	Off-board charger	150 – 350 kW	15 – 30 minutes
Wireless Charging (Inductive)	Contactless	3.3 – 11 kW	4 – 8 hours
Vehicle-to-Grid (V2G)	Bi-directional	3.3 – 22 kW	Grid-dependent

5. Experimental Methodology

5.1 Battery Performance Evaluation

The experimental framework includes charge–discharge cycling, capacity fade analysis, internal resistance measurement, and thermal behaviour monitoring of EV battery cells under different load conditions.

5.2 Motor Performance Testing

The Motor efficiency, torque–speed characteristics, and thermal performance are evaluated using a dynamometer test setup. Comparative analysis between PMSM and induction motor configurations is proposed.

5.3 Charging System Analysis

The Charging efficiency, power quality, and thermal effects are experimentally analysed for AC and DC charging systems under controlled laboratory conditions.

Results and Discussion (Review-Based Interpretation)

Based on recent experimental studies reported in the literature, lithium-ion batteries continue to offer the best trade-off between cost and performance, while solid-state batteries represent a promising long-term solution. PMSMs show superior efficiency, whereas induction and emerging motors offer sustainability advantages. Fast and smart charging infrastructure is essential for large-scale EV adoption.

Challenges and Future Research Scope

Key challenges include battery material scarcity, charging infrastructure costs, and system-level integration complexity. Future research should focus on sustainable materials, advanced thermal management, AI-based energy management systems, and standardized charging solutions.

CONCLUSION

The review and experimental-oriented study highlight the significant progress achieved in sustainable electric vehicle (EV) technologies, emphasizing the critical roles of advanced battery systems, high-efficiency electric motors, and reliable charging infrastructure. Recent developments in battery chemistry, energy density, thermal management, and lifecycle performance have substantially improved driving range, safety, and durability of EVs. Similarly, innovations in electric motor design, including improved materials, optimized control strategies, and enhanced power density, have contributed to higher efficiency and reduced energy losses. In parallel, the expansion of fast-charging technologies and smart charging infrastructure has addressed key challenges related to charging time, grid integration, and user convenience. The findings from experimental insights further validate the practical feasibility and performance improvements of these technologies under real operating conditions. Overall, an integrated approach that combines technological innovation, experimental validation, and system-level optimization is essential to achieve long-term sustainability, improved performance, and widespread adoption of electric vehicles, supporting global efforts toward energy efficiency and reduced environmental impact.

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