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A Comprehensive Review of Electric Vehicle Technologies: Batteries, Powertrain, Charging Infrastructure and Sustainable Mobility

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ABSTRACT :

Electric Vehicles (EVs) are becoming an increasingly attractive technology due to their potential to enhance energy efficiency while reducing oil dependence and greenhouse gas emissions. This term paper presents a comprehensive review and synthesis of 30 research papers focused on critical aspects of electric-vehicle technology, such as batteries, electric powertrains, charging, fast-charging, renewable-energy integration, smart charging, vehicle-to-grid (V2G), energy management, environmental impacts, EV adoption. Future developments. The reviewed literature indicates that battery technology is a critical factor influencing the range, performance, charging time, cost, lifetime, and environmental impacts of EVs. While lithium-based batteries are currently dominant, solid-state batteries and post-lithium approaches are being explored to provide higher energy-density and improved safety-profiles while enabling faster-charging, increased longevity. Reduced costs.

The review also explores different EV powertrain technologies and charging systems such as Battery Electric Vehicles (BEVs), Hybrid Electric Vehicles (HEVs), Plug-in Hybrid Electric Vehicles (PHEVs). Other electric vehicles. These require efficient motors, power converters, battery management systems, and appropriate charging infrastructures. Fast charging technologies such as Direct Current (DC) fast charging, ultra-fast charging, inductive charging, bidirectional charging, and battery swapping are being developed to shorten charging time and improve EV usability. However, battery degradation, thermal management, charging infrastructures, standardization, interoperability, and cost are significant challenges associated with EVs.

Keywords: *Electric Vehicles (EVs) Battery Technology, Electric Powertrain, EV Charging Infrastructure, Fast Charging, Renewable Energy, Smart Grid, Vehicle-to-Grid (V2G)*

1. INTRODUCTION

It has been noted that electric vehicles (EVs) will become essential components of future sustainable transportation systems and contribute to energy efficiency, decreasing reliance on fossil fuels. Cutting greenhouse-gas emissions. EVs employ electric propulsion with energy-storage systems, primarily batteries, and their performance characteristics are of utmost importance for driving range, efficiency, cost, safety, and charging time. The state-of-the-art lithium-based batteries, while dominant, are actively being pursued for alternative chemistries and designs such as solid-state and post-lithium variants to offer higher specific energy, power density, cycle life. Safety while enabling accelerated charging.Their powertrain components such as traction machines, power electronics, and battery-management systems along with advanced thermal-control subsystems are also critical to achieving high-performance EVs.

On the other hand, the charging infrastructure, comprising alternating current (AC) charging, direct current (DC) fast and ultra-fast charging, wireless and battery-swapping technologies, constitutes another vital area of R&D to meet the diverse needs of throughput, interoperability. Standardization.

Transportation electrification creates links between the transport and power sectors and smart EV charging at critical points in time can benefit both systems by leveraging renewables, smart grids, vehicle-to-grid (V2G). Vehicle-to-home (V2H) technologies. Advanced algorithms employing artificial intelligence (AI), machine learning, predictive analytics, and optimization techniques are being explored for enhanced control and management of V2G and V2H systems.

This term paper, therefore, amalgamates research papers on EVs, batteries, powertrains, charging infrastructure, renewable energy, smart grids, environmental impact. EV adoption and presents key findings, research gaps, and future directions.

2. LITERATURE REVIEW

Fesli and Ozdemir's study offers a comprehensive review of electric vehicles (EV) with a specific focus on EV technologies and charging modes and standards. The article also examines the use of different methods to integrate EV with the grid, including smart approaches such as V1G and Vehicle-to-Grid (V2G). In addition, the impact of key factors on the adoption of EVs is discussed. These factors include charging infrastructure, cost-

effectiveness, governmental policies, and business models. The research findings highlight the technical challenges related to the high losses on the grid, the problems caused by the EVs to the power quality. The issues of standardized charging coordination. The authors emphasize the need for a multi-objective optimization approach and a number of recommendations related to smart-grid technologies, communication infrastructure, and grid upgrade initiatives.[1]

Hossain et al. (2022) conducted an extensive research study on electric vehicle technologies and their future prospects. The article included a discussion of the worldwide EV demand and growth, electricity and battery requirements, energy-storage technologies, and different charging strategies. Furthermore, researchers explored emerging trends and opportunities, such as wireless power transfer and EVs' role in smart cities. The article concluded with a note that advancements in battery technologies, charging infrastructure, cost, and policies are critical for EV development and adoption in the future. This publication is an excellent source for gaining insight into contemporary trends and the potential of electric vehicles in the future.[2]

Deepak et al. (2023) reviewed in-wheel motor drive systems used in electric vehicles. The paper discusses different types of electric motors, their applications, power electronics, control methods, and cooling systems. It also compares conventional electric vehicle drive systems with in-wheel motor drives. The review identifies major advantages of in-wheel motors, while also discussing challenges related to motor design, unsprung mass, thermal management, control, and reliability. The authors also examined the current industrial state of the technology and highlighted future research requirements. The study provides an overview of how in-wheel motor systems can contribute to the development of advanced electric vehicles.[3]

Ullah et al. (2024) conducted a review of the integration of wind power and energy-storage technologies for modern power-grid frequency regulation. The researchers identified challenges associated with the variable nature of wind generation and the low inertia of renewable-based power systems. Different energy-storage systems and control techniques for maintaining grid frequency were evaluated. Technical barriers and future research opportunities for improving grid stability were identified. The authors emphasized the importance of suitable energy-storage technologies and advanced control strategies for managing fluctuating renewable power generation. The study provided valuable background information on the integration of renewable energy into future electric-vehicle charging and power systems. [4]

He et al. (2024) conducted a study that involved a comprehensive review of lithium-ion battery recycling technologies and industrial market trends. The study analyzed the main methods of battery recycling, such as pyrometallurgy, hydrometallurgy, and direct recycling. Moreover, the authors evaluated the growing impact of lithium-ion batteries in electric vehicles and the need for sustainable recycling approaches. The study is a valuable source of information on the latest technological developments, market trends, and commercialization strategies in the field of lithium-ion battery recycling. The study offers critical insights into the importance of recycling valuable materials from lithium-ion batteries, and various environmental concerns related to the recycling process. The research findings also highlight the current barriers in developing cost-effective and large-scale battery recycling methods to meet the emerging demand for electric vehicles. [5]

Almutairi et al. (2024) conducted a study that provides a review of Internet of Things (IoT) simulators applicable in transportation, energy, and vehicular contexts. The researchers adopted the PRISMA framework to identify the leading studies in the field through a systematic search of bibliographic databases. The initial list of 204 articles was reduced to 58 after applying the screening process. Each work was analyzed in terms of attributes of mobility, energy, scalability, heterogeneity, Software Defined Networking (SDN), and renewable energy. The authors found that IoT simulators are limited in terms of integration with VanetSim and traffic simulations and note that there is a need for a generic simulator capable of addressing a variety of cases. It is recommended to enhance the features related to mobility, security, renewable energy and VanetSim in the new generation of smart transport simulators. [6]

The Celadon et al. (2024) performed an in-depth analysis of battery technologies for electric vehicles. The researchers focused on technical, environmental, market-related and futuristic aspects of the technological progress in batteries. Among the reviewed battery types were lithium-ion and lithium-metal, as well as post-lithium sodium-, aluminum- and magnesium-ion batteries. In addition, the authors evaluated the potential of solid-state batteries in terms of energy density, safety, charging speed, and calendar life. According to the article, batteries comprise 30-40% of the cost and 20-30% of the weight of electric vehicles. Finally, the reviewed article discusses battery reuse, remanufacturing, and recycling. [7]

Ombela et al. (2023) conducted a study that entailed the review of the battery electric vehicle (BEV) drive-circuit technology, with the emphasis on the battery, electric motor, vehicle configurations, charging. Future prospects. The researchers generated a comprehensive comparison of various battery technologies in terms of energy density, efficiency, lifecycle, and cost-benefit. Moreover, induction, permanent-magnet synchronous, brushless DC, and switched reluctance motors were evaluated based on power density, efficiency, reliability, torque, and cost-benefit. The study also discussed BEV, HEV, and PHEV configurations, charging infrastructure, smart charging, battery performance, and grid integration. The authors concluded by identifying battery improvement, fast-charging capabilities, government regulations, and power-market development as the key areas of future work in the field of BEV. [8]

Mohammed et al. (2025) review the powertrain technology of electric vehicles (EV) comprising powertrain classification, motor drives, power converters, and charging systems, and look at future prospects. The main challenges of EVs, according to the authors, are battery energy density, capacity fade, charging speed, charging infrastructure, costs, and battery mineral sustainability. The article presents information on silicon carbide and gallium nitride switching technologies; solid-state and silicon-anode batteries; and advanced thermal management. Upgrades in EV charging infrastructure and renewable energy utilization are also considered opportunities to make EVs more sustainable. [9]

The present paper includes a review of electric-vehicle architectures and configurations. The article covers the basic types of electric vehicles, including battery, hybrid, plug-in hybrid, and fuel cell electric vehicles. The review also concentrates on the main elements of these vehicles, such as sources of energy, propulsion systems, electric motors, power converters, batteries, and ancillary equipment. The key points discussed in the article are the likely impact of electric vehicles on energy consumption and carbon emission, the technical challenges posed by the vehicles. Possible ways of addressing them. the main benefit of the electric vehicle is the reduction of dependence on petroleum and the decreased emissions from tailpipes. [10]

Teimoori and Latta (2026) conducted a survey of electric vehicles, including EV technologies, the EV market situation, charging infrastructure, energy management, performance analysis. Smart-grid, artificial intelligence, machine learning, and quantum computing. The survey was based on a narrative review of the literature retrieved from IEEE Xplore, ScienceDirect, SpringerLink, MDPI, and Google Scholar in 2016--2026. Both AI/ML and quantum computing were discussed as approaches to address various EV-related issues. In particular, the application of AI/ML was suggested for forecasting, charging. Energy prediction and management, while quantum computing was considered to solve such complex problems as routing, charging scheduling, and grid coordination. The research concluded with a recommendation to adopt hybrid quantum-classical approaches to analyze realistic system-level EV-grid challenges. [11]

Gnanavendan et al. (2024) conducted a review of the main challenges, directions for development, and future trends in electric-vehicle technology. The study highlights economic, technological, environmental, and policy aspects of sustainable EV transportation and power system development. Among the main issues are the improvement of battery technologies, the characteristics and development of charging infrastructure, and the impact of these aspects on the economy and environment. The review also emphasizes the importance of addressing EV transportation challenges and directions for technological development that can lead to sustainable and affordable transport. Overall, the study provides a brief overview of the current issues in EV development and directions for future research. [12]

Elkelawy et al. (2025) present a study that includes a state-of-the-art analysis of the technologies and challenges associated with retrofitting internal-combustion-engine vehicles into electric ones. The research involves electric motors, battery packs, power-management systems, and conversion methods, including full and partial conversion processes. The review also considers the main factors associated with retrofitting, such as driving ranges, vehicle compatibility, battery densities, fast charging, cost-effectiveness, and performance improvements. The study also highlights the importance of using renewable energy and comparing the energetic and emission performance of retrofitted electric vehicles with conventionally driven ones. Overall, the authors emphasize the importance of creating a regulatory framework, advanced batteries, and sustainable mobility concepts that would increase the rate of EV conversions. [13]

The literature review conducted for this study examined electricity storage within electric-vehicle (EV) technology, covering EV energy flow, charging and traction circuits, V2G (Vehicle-to-Grid), the integration of renewable energy, and associated technologies. This research examined how EVs interact with energy systems powered by renewable sources. The document explored various scenarios for adding renewable energy, among them wind and solar sources, to supply power systems whose share of electric vehicles keeps growing. In one scenario, the impact of wind and solar additions of 30.86% and 26.45%, respectively, was calculated; measured against 2.36% and 1.78% in the business-as-usual scenario, these additions lowered carbon dioxide emissions and energy costs. The document surveyed various facets of EV technology and power systems, stressing how vital EV charging coordination, renewable energy incorporation, and V2G are for sustainable transportation. [14]

This paper reviews electric-vehicle (EV) charging technologies, focusing on charging methods, power-conversion systems, and the infrastructure needed to support EV operation. Conductive, inductive or wireless, and battery swapping charging systems are examined. Both on-board and off-board chargers are reviewed. A range of converter topologies and charging configurations are presented and assessed for their viability in EV charging. The review offers insight into the key factors relevant to EV charging, such as charging efficiency, charging time, power levels, and infrastructure development needed for large-scale EV integration. The paper emphasizes the need for better EV charging technologies and more advanced power-electronic systems, and indicates that developing charging systems is a significant research area for future EVs. [15]

This paper offers a technical overview of electric-vehicle structures, charging infrastructures, battery chargers, charging strategies, power management, control methods, and grid impacts. The study examines off-grid, grid-connected, and hybrid charging systems, charging powers, and microgrid-based EV charging. It also addresses adaptive and robust control approaches and their role in boosting energy efficiency and overall performance. The paper examines grid impacts caused by EV charging and sets out challenges related to infrastructure development, ultra-fast charging strategies, battery second-life, safety, and cost. The authors emphasize the importance of coordinated control and power management of EVs, along with the need to integrate them into renewable energy systems and the existing power infrastructure for future developments. [16]

Zentani, Almaktoof, and Kahn (2024) carried out a review of fast charging technologies for electric vehicles. The study addressed DC fast charging, ultra-fast charging, inductive charging, Tesla superchargers, bidirectional charging, and battery swapping. It also covered charging standards, connectors, charging communication protocols, and power levels, along with onboard and offboard chargers. The article centers on DC--DC power converters and control strategies aimed at optimizing performance, safety, and efficiency. The study suggests future research on fast charging technologies, infrastructure development, and standardization, in addition to progress in batteries, wireless charging, battery swapping, and smart-grid integration. The authors point out the existing limitations in infrastructure, standardization, battery technology, and energy optimization. [17]

This paper aims to present an overview of the key progress in electric-vehicle technology and its role in sustainable transportation development. The article describes progress in batteries, electric motors, vehicle configurations, charging systems, autonomous-driving technology, battery recycling, and second-life battery applications. It explains that advances in battery technology are critical to improving the driving ranges of electric vehicles, safety, charger performance, and battery lifespan. The article also addresses renewable-energy integration, battery management systems, advanced technologies such as artificial intelligence, and autonomous-driving sensors. The authors also discuss battery recycling and second-life applications, which are key battery recovery areas. The review highlights cost, battery lifespan, charging infrastructure, safety, and technological advancement as battery-related challenges in promoting sustainable transportation. [18]

Zaino et al. (2024) carried out a systematic review of electric-vehicle adoption along with its technological, environmental, organizational, and policy-related implications. In total, 88 articles were analyzed and synthesized to provide insight into global trends in EV adoption. The review covers the analysis of technological advances in batteries and energy storage, environmental impact and life cycle-greenhouse gas emissions, organizational influences and implications. Policy considerations including incentives, regulations, and charging infrastructure. Furthermore, the study examines battery recycling, grid stabilization, and long-term economic implications as key topics for research on EV adoption. The authors conclude that EV

adoption is a multifaceted phenomenon that should be considered from these perspectives in combination. [19]

Performed a systematic review of electric-vehicle studies in 2024. The researchers analyzed 88 articles in the field. The focus of the authors was on the processes of vehicle adoption from technological, environmental, organizational, and policy perspectives. The review covers topics related to battery and energy storage technological advances, lifecycle greenhouse-gas emissions, fleet operations, logistics, government incentives, regulations, and charging infrastructure. Moreover, the authors assessed battery recycling, the impact of vehicles on the grid, and economic issues. The review identified multiple factors affecting vehicle adoption and emphasized technological, environmental, organizational, and policy dimensions. The authors recommend further investigation of recycling, impact, and economic issues. [20]

Munsi and Chaoui (2024) offer a review of Energy Management Systems (EMS) for electric and hybrid electric vehicles. They examined a range of powertrain configurations, such as series, parallel, series-parallel, and complex hybrid systems. The scholars also surveyed numerous EMS approaches, including rule-based, fuzzy-logic, dynamic programming, equivalent consumption minimization, linear programming, and real-time optimization. They assessed the advantages and disadvantages of each method, along with its computational complexity and applications. The researchers determined that optimized energy-management strategies could lead to better fuel consumption, battery usage, and overall system efficiency. Munsi and Chaoui stress the importance of advanced optimization and intelligent control methods for EVs, and propose that these techniques can enhance performance, energy efficiency, and sustainability. [21]

This article examined how electric vehicles have evolved and what part they play in the smart-city transportation systems of tomorrow. The review centered on EV batteries, charging technologies and standards, EV adoption, integration with renewable energy, Vehicle-to-Grid (V2G), communications, and Artificial Intelligence. The article drew comparisons among the SAE-J1772, IEC-62196, and GB/T-20234 charging standards and the power levels they support. It explored how AI is used for energy-aware route planning, smart EV charging, EV load forecasting, and battery thermal management. The article pointed to the shortage of public charging stations, lengthy charging times, battery constraints, and standardization problems as key barriers to EV adoption. Finally, it emphasized communication technologies and AI as means of improving the smart EV charging system. [22]

Mohan et al. carried out a study that shed light on multiple facets of infrastructure for charging electric vehicles. The research examined various charging types that had been investigated from 2015 to 2025. The article centered on AC, DC, wireless, and ultra-fast charging methods, along with standards like CCS, CHAdeMO, GB/T, and Type-2. Furthermore, the study addressed the integration of renewable energy with electric vehicles, vehicle-to-grid (V2G), vehicle-to-home (V2H), smart charging load, and charging station location technology. Artificial intelligence and machine learning were likewise explored for optimizing charging schedules, forecasting demand, and diagnosing system faults. The authors pointed out the technical obstacles facing EV charging infrastructure, such as the absence of interoperability, insufficient charging facilities in rural regions, battery degradation, and cybersecurity concerns. The study called for the development of sustainable, secure, smart, and dependable charging infrastructure to serve future electric vehicles. [23]

This study offers a comprehensive overview of cutting-edge electric vehicle and sustainable transportation technologies, covering solar-powered vehicles, vehicle design, battery technologies, autonomous electric vehicles, battery recycling. Second-life batteries. The articles included in this study show that photovoltaics can provide a new source of renewable energy for vehicles. The works demonstrate that various EV architectures can make use of batteries, electric machines, power electronics, charging systems, and regeneration. The research examines advanced battery concepts capable of enhancing the range, safety, and lifespan of EVs, such as solid-state, sodium-ion, lithium-sulfur, and metal-air batteries. Lastly, the manuscripts examine the impact of AI, machine learning, and Battery Management Systems on battery performance, along with recycling and second-life. The works mentioned above highlight the importance of sustainable transportation and point out the major battery issues tied to the widespread adoption of electric vehicles, including battery limitations, charging infrastructure, degradation, safety, cybersecurity. Cost-effectiveness.[24]

The reviewed article concentrates on electric vehicle (EV) technologies and battery management systems (BMS). The authors address vehicle topologies, battery technologies, charging processes, electric motors, power converters, and control systems. Particular attention is paid to BMSs due to their critical role in battery condition monitoring, which ensures EV safety and efficiency. The study also provides considerations on different charging levels and standards, as well as possibilities of regenerative braking. Modern innovations in EVs such as the Internet of Things (IoT), Machine Learning. Artificial Intelligence are viewed as effective tools for creating smart BMS, monitoring, and managing energy. At the same time, cybersecurity and interoperability issues are highlighted as major concerns in the EV industry. In general, the study underlines active R&D activities in batteries, BMS, charging infrastructure, power electronics, and intelligent technologies. [25]

This study provides an overview of the state-of-the-art and emerging fast-charging techniques for electric vehicles. The paper categorizes and describes various approaches that allow a reduction in the charging time of EV batteries while ensuring their reliability. The main directions of development and research include DC fast charging, ultra-fast charging, inductive charging, battery swapping, charging standards, connectors, power converters, and charging control techniques. The EV charging bidirectional power flow and smart grid concepts are also reviewed since they can considerably improve the efficiency of transportation systems and make them more sustainable. The study concludes that the development of innovative battery cells, charging infrastructures, power electronics, and standardized charging protocols is vital for future EVs. The authors also identified critical research areas related to batteries degradation, thermal management, infrastructure installation, and standardization issues. [26]

The reviewed article examines the idea of autonomous electric vehicles along with the technologies that allow them to run safely and efficiently. It covers the pertinent features of these vehicles, such as energy storage, battery management systems, charging technologies, motors, brakes, and regenerative braking. The research also points out that autonomous vehicles need sensors, cameras, and other hardware, including LiDAR, GPS, Artificial Intelligence. Control systems, in order to carry out the required calculations, perceive their surroundings, and make decisions. This study determines that building such technology demands a focus on energy storage, sensors, and control systems. Regenerative braking technology in autonomous vehicles can make it possible to recover energy while braking. As a result, the study identifies numerous opportunities for applying electric vehicles. [27]

The article under review examines the possibilities for giving spent electric-vehicle (EV) batteries a second life. Even after being discharged, these batteries may still hold 70-80% of their original capacity, which can be put to use in energy storage systems and other applications that demand less than propulsion. The authors thus explore how such batteries might be reused, focusing on assessing battery pack condition, screening, grading and other pertinent factors. The study also pinpoints the key performance characteristics of spent batteries that data-driven or physics-based models can predict. It emphasizes testing, refurbishing, transportation, installation, safety and balancing as the primary elements of battery reuse. [28]

The article under review provides an overview of electric vehicle (EV) technologies along with Battery Management Systems (BMS). It offers a general outline of the various EV configurations, battery technologies, charging methods, electric motors, power converters, and associated systems. The principles of BMS are especially noteworthy and are examined in considerable detail, since the battery's proper operation is essential for ensuring that an EV runs reliably and safely. The article further presents details on the different levels of vehicle charging, the relevant standards, and regenerative braking. Lastly, it discusses engineering solutions for monitoring and managing EVs, such as the use of IoT, ML, and AI. Consequently, the authors conclude that enhancements in batteries, BMS. Charging infrastructure, as well as in power electronics and advanced Internet of Things technologies, constitute the primary directions for EV development. [29]

The reviewed article brings together research on electric vehicles and solar cars, batteries, and alternative energy, autonomous driving, battery recycling, and second-life applications. The work examines the architectural designs of EVs, along with battery, motor. Power electronic hardware, as well as their related power control and management systems, charging and fueling infrastructures, integration with renewable energy sources, and vehicle-to-grid systems. The article also looks at advanced battery technologies (solid-state, sodium-ion, lithium-sulfur, metal-air), along with AI, machine learning, and digital twins for battery management. In addition, it notes that battery recycling helps recover valuable materials, while second-life batteries can be repurposed in other fields. The study indicates that battery degradation, charging infrastructures, safety, battery recycling, cybersecurity, interoperability, and cost are key aspects for EVs and sustainable transportation. [30]

Iqbal et al. carried out a study involving electric vehicle (EV) components, charging systems, batteries, electric motors, power converters, and energy-management systems. The work outlines the design of various EV configurations and examines the key components required for the vehicles to function efficiently. The study offers an overview of batteries, including their energy-storage classes, and provides considerations for their use in EVs. The authors also present various traction electric motors and examine their characteristics. The work examines power-electronic converters and control methods required to convert battery power into mechanical energy for the motor. Lastly, the research paper presents a range of EV charging methods and equipment and examines the challenges tied to building EV charging infrastructures. Iqbal et al. conclude that EV range, charging time, weight, and cost are major issues in EV development.authors have outlined the key technologies involved in creating electric vehicles. [31]

This study offers a review of battery-management systems, EV charging stations, and electric traction motors. The authors stress how important batteries are as the primary energy-storage devices in electric vehicles, and they explain what battery-management systems do. The authors examine the various power-electronic converter topologies that EVs require. They also examine several traction motor technologies appropriate for EVs, among them induction and permanent-magnet motors. The authors describe various configurations of charging stations as well as fast-charging technologies for EVs. The study underscores how important power conversion is in EVs for achieving better performance. The authors conclude that batteries, power converters, traction motors, and charging stations ought to be viewed as one integrated system. Hence, this study offers an integrated technical overview of the essential components of EVs. [32]

This paper reviews different battery-charging topologies, charging standards, and power-electronic converters used in electric vehicles. The authors classify EV charging systems according to voltage, current, power level, charging speed, and converter configuration. Various AC-DC and DC-DC converter topologies are discussed for transferring energy efficiently to the EV battery. The study also examines different control and modulation techniques used in charging systems. On-board chargers are considered suitable for applications where compactness and lower cost are important, while off-board chargers can provide higher charging power. Different charging levels and infrastructure requirements are also discussed. The review emphasizes that charger efficiency, reliability, power quality, and charging time are important factors in EV development. The study is useful for understanding the relationship between EV batteries, power converters, and charging infrastructure. [33]

This review investigates advanced charging technologies for electric vehicles, with particular emphasis on charging topologies, control methods, and charging power levels. The authors discuss conventional and advanced converter configurations used for EV charging applications. Charging time and driving range are identified as important factors influencing the wider adoption of electric vehicles. Different onboard-charger configurations and power-factor-correction techniques are examined to improve charging efficiency and power quality. The study also discusses fast-charging technologies and their importance for reducing the time required to recharge EV batteries. The interaction between EV charging systems and the electrical grid is considered as an important technical issue. The authors highlight the need for efficient, reliable, and high-power charging infrastructure. Overall, the review presents important research directions for improving EV charging performance. [34]

This study reviews energy-management systems and battery-management systems used in electric vehicles. The authors discuss the importance of battery management for maintaining battery safety, performance, and operating life. Different energy-management and control approaches are considered for improving the utilization of electrical energy within the vehicle. The study also examines the role of power-electronic converters in controlling energy flow between the battery, motor, and other vehicle components. Charging-management techniques are discussed in relation to battery performance and efficient energy utilization. Effective control of the battery and powertrain is identified as an important requirement for improving overall EV efficiency. The review also highlights challenges associated with battery operation and energy management. Overall, the study provides useful information about the integration of battery, power electronics, charging, and energy-management technologies in electric vehicles. [35]

3. MATERIALS AND METHODOLOGY

This study is based on a review of 30 research works, including research articles and technical papers related to electric vehicles, solar-powered vehicles, battery technologies, autonomous electric vehicles, battery recycling, and second-life battery applications. The selected papers were carefully reviewed to understand the current developments, major challenges, and future scope of electric vehicle technology. Information was collected from review articles, research papers, and technical publications that focused on different aspects of electric mobility.

3.1 Solar-Powered Electric Vehicle

Solar powered electric cars are equipped with photovoltaic panels that convert solar energy into electricity. This electricity can be used to power the car's battery and onboard systems. Solar power reduces the reliance on fossil fuels and lowers greenhouse gas emissions from tailpipes. The effectiveness of solar-powered cars is influenced by factors such as sunlight exposure, the efficiency of the panels, and the design of the vehicle. Contemporary solar cars are designed with aerodynamic structures and utilize lightweight materials to maximize energy output and performance. A Vehicle-Integrated Photovoltaic the solar cells are placed into the structure of the vehicle such as the roof, hood, and windows. This design improves the aesthetics of the vehicle while reducing extra weight. The VIPV provides an alternative source of power for the vehicle and increases the overall efficiency of the vehicle. This design is one of the focuses of solar vehicle research today.



Fig. 1: Solar-powered electric vehicle

In a Vehicle-Integrated Photovoltaic the solar cells are placed into the structure of the vehicle such as the roof, hood, and windows. This design improves the aesthetics of the vehicle while reducing extra weight. The VIPV provides an alternative source of power for the vehicle and increases the overall efficiency of the vehicle. This design is one of the focuses of solar vehicle research today.

3.2 Vehicle-Integrated Photovoltaic (VIPV) System

A Vehicle-Integrated Photovoltaic (VIPV) system is a promising technology in which photovoltaic panels are integrated into different parts of cars. Such parts may include the roof, hood, doors, rear surface, and windows. It is different from traditional solar panels attached to the vehicles. In VIPV systems, solar cells become a structural part of the vehicles, which makes them more attractive and eliminates additional weight and drag. The energy generated by photovoltaic panels can be stored in batteries and used to power other vehicle equipment. Vehicle-Integrated Photovoltaic (VIPV) system is a promising and advanced technology in which photovoltaic (solar) panels are integrated into different parts of cars, such as the roof, hood, doors, rear surface, and windows. Unlike traditional solar panels that are separately attached to vehicles, VIPV systems integrate solar cells directly into the body structure of the vehicle. This makes the vehicle more attractive and reduces the need for additional mounting structures, extra weight, and air resistance (drag). The solar cells convert sunlight directly into electrical energy, which can be stored in the vehicle's battery for later use. The generated energy can be used to operate various vehicle components, such as lighting systems, air conditioning, ventilation, infotainment systems, and other electrical equipment. It can also reduce the load on the main battery and improve the overall energy efficiency of electric vehicles. VIPV technology helps increase the use of renewable energy, reduce electricity consumption, and decrease carbon emissions. Therefore, it is an important technology for developing sustainable, energy-efficient, and environmentally friendly vehicles.

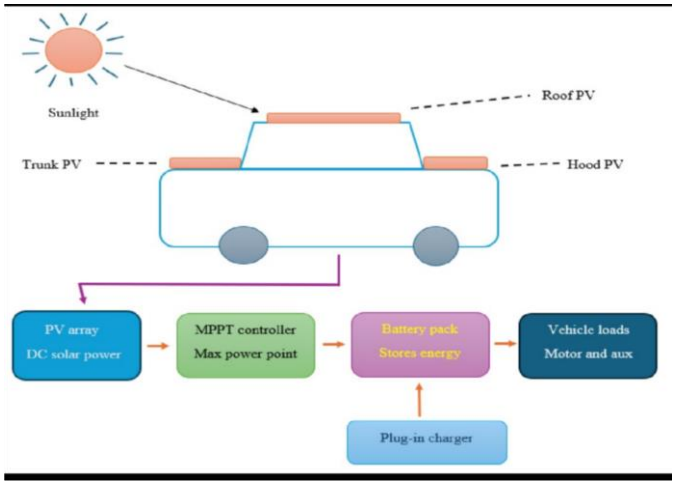


Fig. 2: Vehicle-integrated photovoltaic (VIPV) system

3.3 Basic Electric Vehicle Architecture

The architecture of an electric vehicle can be described in terms of major components and their interaction. The major components of an electric vehicle are the battery, motor controller, power electronic converter (inverter), motor, charger, DC-DC converter, transmission system, and regenerative braking system. The battery stores electric energy in the form of electricity. The motor converts the electrical energy to mechanical energy that powers the wheels. The power electronic converter, or the inverter, facilitates the conversion of direct current (DC) to alternating current (AC) that runs the motor. The power electronic converter, or inverter, converts direct current (DC) from the battery into alternating current (AC) required to operate the motor. The motor controller regulates the speed and torque of the motor according to the driver's requirements. The charger is used to charge the battery from an external power source, while the DC-DC converter reduces the high battery voltage to a lower voltage to operate auxiliary electrical components.

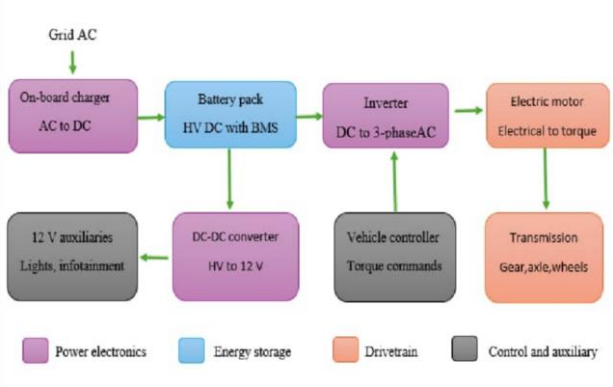


Fig. 3: Basic electric vehicle architecture

3.4 Electric Vehicle Powertrain Components

The electric vehicle powertrain is the energy conversion module that produces and delivers power to the wheels. It comprises several critical components, including the battery pack, power electronic converter (inverter), electric motor, reduction gearbox, differential, drive shaft, and wheels. Together, these parts provide mechanical power to the wheels in the form of torque while meeting performance and reliability expectations. This paper discusses the key features of the electric vehicle powertrain.

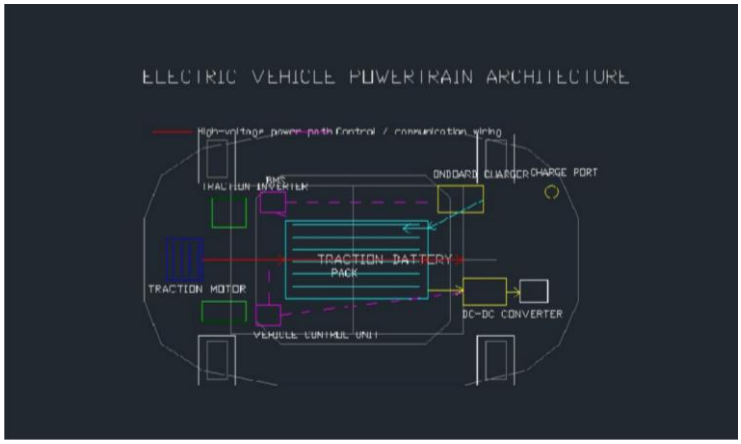


Fig. 4: Electric vehicle powertrain components

3.5 Lithium-Ion Battery Structure

The lithium-ion battery is the most common type of battery in terms of energy storage in electric vehicles due to its high energy density, long cycle life, low weight, and exceptional charging efficiency. The lithium-ion battery cell is comprised of four major components, including the cathode, the anode, the electrolyte, and the separator. The lithium-ion battery works on the principle of energy storage and release between the cathode and anode through the use of an electrolyte. One of the critical attributes of the electric vehicle powertrain is that its brake system captures energy normally lost during deceleration or braking and stores it in the battery pack. This process is called regeneration, facilitates improved energy efficiency and enhances range during driving. Consequently, this feature also reduces the amount of energy.

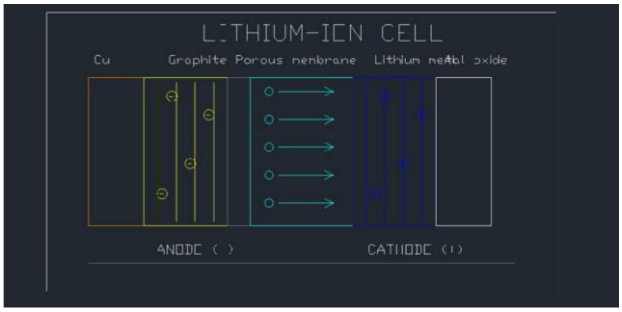


Fig. 5: Lithium-ion battery structure

3.6 Battery Management System (BMS)

The Battery Management System is most crucial and important among the electronic systems of an electric vehicle because of its main role of managing and protecting the battery pack while operating the vehicle. The battery pack of a modern EV consists of hundreds and thousands of battery cells connected together in parallel and series. A battery management system manages and safeguards the battery pack while operating. It acquires data from the battery pack and uses it to maintain and protect the battery performance. This paper highlights the importance of battery management system in an electric vehicle and its functions. The management of the battery state is the most primary function of a battery management system. The BMS supervises the battery voltage and current, temperature, state of charge, state of health, and remaining useful life. The battery management system checks individual battery voltages to prevent overcharging or deep discharging of the battery cells as it has the main role of managing the power of the battery pack. It keeps track of the temperature of the battery cell and safeguards them against extreme hot and cold temperatures; hence, avoiding thermal runaway of the battery. The state of health of a battery is determined by monitoring its temperature as it significantly affects a battery's performance and safety.

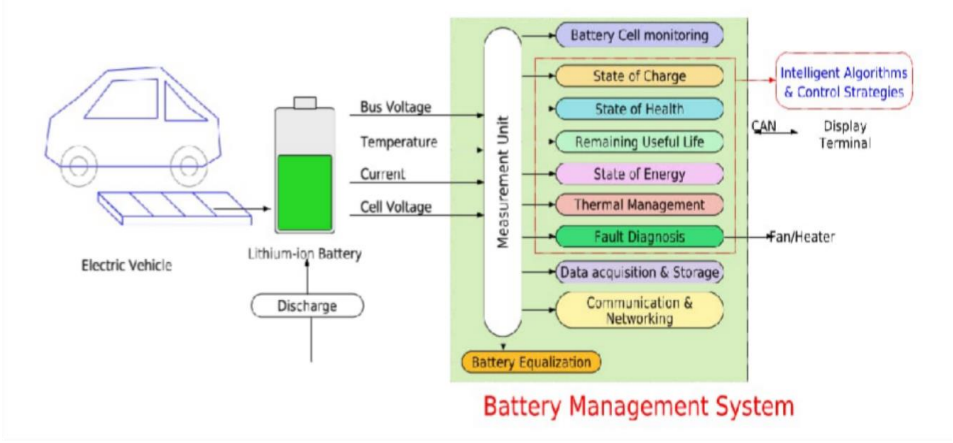


Fig. 6: Battery management system (BMS)

3.7 EV Charging Infrastructure

Electric vehicle (EV) charging infrastructure is a collective term used to describe charging stations, power supplies, charging equipment, communication components, and other structures involved in supplying electricity to electric vehicles. Having reliable and easily accessible EV charging infrastructure plays a critical role in the development and widespread adoption of electric vehicles. This is because the availability of a sufficient number of charging stations increases the convenience level of EV ownership.

Moreover, having proper EV charging infrastructure eliminates range anxiety and facilitates the transition from internal combustion engine vehicles to zero-emission vehicles. The EV charging infrastructure has an essential role to play in supporting private and commercial transport and is a vital component of sustainable transportation systems.

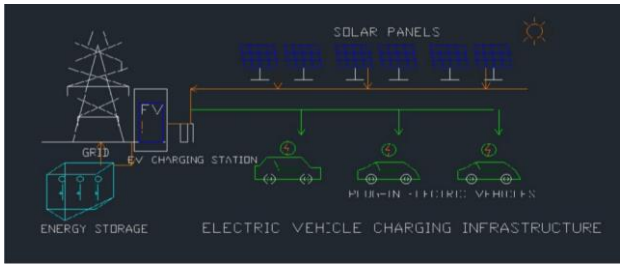


Fig. 7: Electric vehicle charging infrastructure

3.8 Autonomous Electric Vehicle Sensors

Autonomous cars (electric) sensors provide the necessary means for the car to gather information about its environment, including potential obstacles,

and the vehicle's surroundings. Sensors relay this information to the electric vehicle's control and intelligence systems, which provide the car's electronic control unit and artificial intelligence capabilities with the information needed to operate autonomously. The electric vehicle's control and artificial intelligence systems process this information, enabling the car to function without requiring constant human monitoring.

Many different sensors are used in driverless cars because individual sensors cannot fulfill all of these tasks. Autonomous electric car sensors rely on multiple forms of sensing to ensure maximal or better precision, safety, and performance. The most common autonomous car sensors are cameras, Light Detection and Ranging (LiDAR), radar, ultrasonic sensors, Global Positioning System (GPS), and Inertial Measurement Units (IMUs).

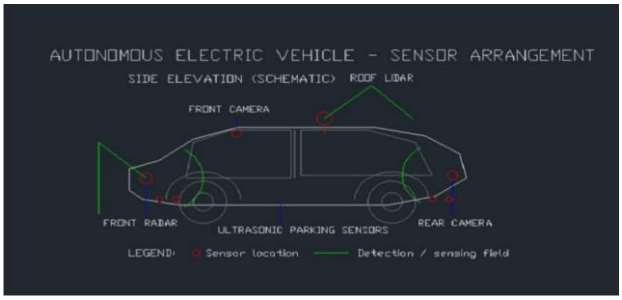


Fig. 8: Autonomous electric vehicle sensors

3.9 Second-Life Battery Energy Storage System

A Second-Life Battery Energy Storage System (SLBESS) refers to a system that repurposes spent traction batteries that were originally used in electric vehicles but were retired due to reduced capacity. In most cases, electric vehicle (EV) traction batteries are terminated when their capacity drops by approximately 70-80% of their initial capacity. Although such batteries can no longer meet the energy density requirements for EVs, they may still possess valuable energy storage capacity.

Therefore, instead of being disposed of immediately, such batteries can be reused in other fields that do not require such a high level of performance. Second-life batteries can provide an extended lifespan of the battery while at the same time promoting sustainability.

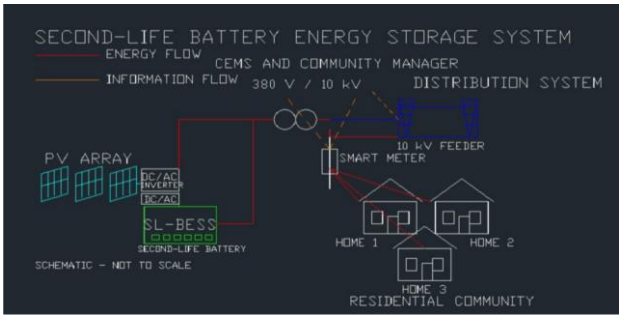


Fig. 9: Second-life battery energy storage system

4. GRAPHS AND COMPARISON

4.1 Comparison of EV Battery Technologies

Table 1: Specific energy, energy density and specific power of EV battery technologies

Battery technology	Specific energy (Wh/kg)	Energy density (Wh/L)	Specific power (W/kg)	Norm. specific energy (%)	Norm. energy density (%)	Norm. specific power (%)
Pb-PbO_2	60	100	100	21.8	13.6	3.3
Ni-Cd	80	150	150	29.1	20.4	5
Ni-MH	120	300	1000	43.6	40.8	33.3
Zn-Br_2	140	70	100	50.9	9.5	3.3
Na-NiCl	160	120	200	58.2	16.3	6.7
Li-ion	275	735	3000	100	100	100

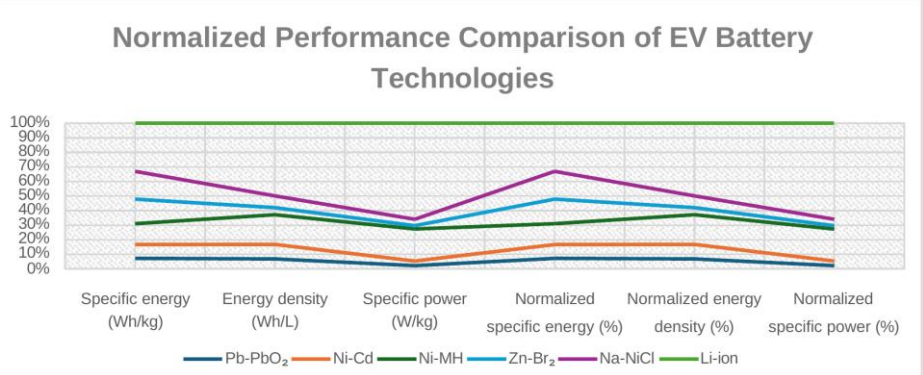


Fig. 10: Normalized performance comparison of EV battery technologies

The graph presents a comparison of six distinct battery technologies that are used, or could be used, in electric vehicles. This comparison relies on various power-related characteristics, including specific energy, energy density, and specific power. As the graph shows, lithium-ion batteries deliver the best performance of all, whereas zinc-bromine batteries perform the poorest. Nickel-metal hydride and nickel-cadmium batteries show a moderate level of performance, while lead-acid batteries rank low compared with the others. Therefore, given their outstanding characteristics, lithium-ion batteries are the most suitable option for electric cars.

4.2 Second-Life Battery Applications

Table 2: Distribution of second-life battery applications

S. No	Battery application	Distribution
1.	Backup power	10%
2.	Renewable energy storage	27%
3.	Micro-grid support	18%
4.	Commercial storage	20%
5.	Residential storage	25%

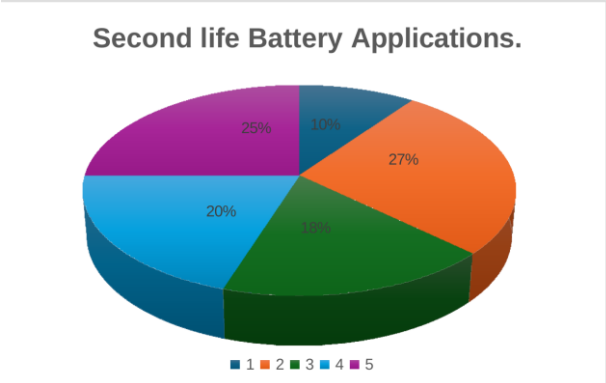


Fig. 11: Second-life battery applications

The diagram provided illustrates the main applications of these batteries. According to the diagram below, second-life batteries are mainly employed to supply energy storage in residential, commercial, microgrid, renewable energy, and backup energy settings. The largest portion of battery usage is in renewable energy, at 27%, with residential storage coming next at 25%. These different uses of batteries offer added value for batteries that would otherwise be discarded once they finish their original role as EV batteries.

4.3 Comparison of Electric Motor Technologies

Table 3: Comparison of electric motor technologies used in EVs

Motor	Power density (100 kW/m²)	Volume (m³)	Efficiency (%)	Power density (norm.)	Effic. (norm.)	Compact. (norm.)
IM	0.26	0.8	96.37	61.9	98.71	70
PMSM	0.42	0.56	97.62	100	100	100
SRM	0.22	0.97	87	52.38	89.12	57.73
SyncRM	0.2	0.65	80	47.61	81.95	86.15
BLDC	0.3	0.7	85	71.42	87.07	80

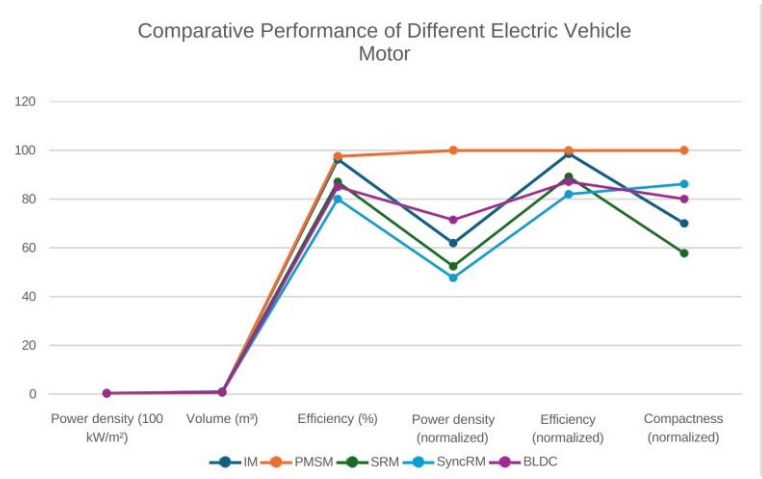


Fig. 12: Comparative performance of different electric vehicle motor technologies

It examines how five major electric motor technologies used in EVs operate: IM, PMSM, SRM, SyncRM, and BLDC. By comparing characteristics such as power density, efficiency. Motor compactness, one can conclude that PMSM delivers high efficiency and high power density, making it well suited for high-performance EVs. IM provides high efficiency and, thanks to its rugged construction, enjoys widespread use. SRM and SyncRM benefit from simpler constructions and reduced reliance on permanent magnets, whereas BLDC motors deliver excellent performance for compact EVs.

4.4 Multi-Parameter Comparison of Energy Storage Technologies

Table 4: Normalized multi-parameter comparison of energy storage technologies

S. No	Storage technology	Life cycles	Energy density	Power density	Energy cost	Power cost
1.	Lead acid	0.125	0.040	0.300	0.214	0.250
2.	Lithium-ion	1.000	0.190	1.000	0.714	1.000
3.	Sodium sulphur	0.333	0.195	0.200	0.286	0.750
4.	Metal air	0.125	1.000	0.100	0.107	0.086
5.	Flow battery	1.000	0.020	0.166	0.429	0.523
6.	Nickel-Cd	0.250	0.060	0.150	1.000	0.500

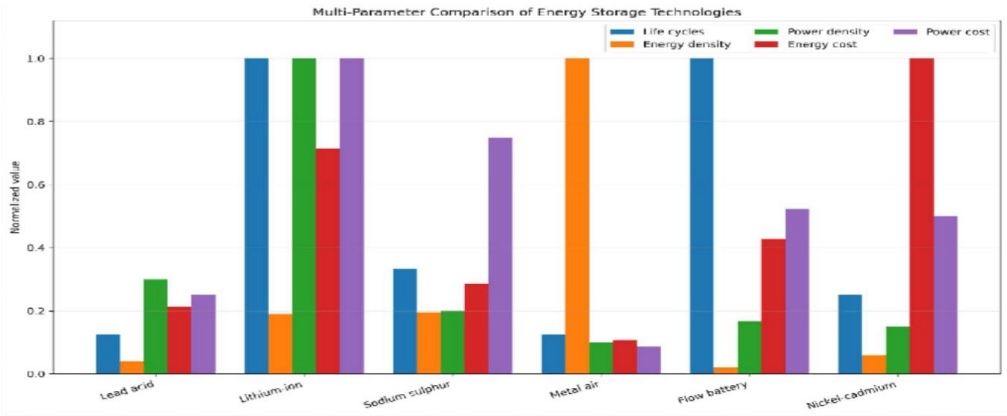


Fig. 13: Multi-parameter comparison of energy storage technologies

The comparison shows that different storage technologies have different strengths. Li-ion has high normalized life cycles, power density, and power-cost performance, while metal-air has very high energy density. This demonstrates that the selection of storage technology depends on the required application and performance parameter.This makes them a promising technology for improving the driving range of electric vehicles. Other battery technologies also have different advantages in terms of cost, charging time, efficiency, safety, and lifespan. However, no single energy storage technology is best in all performance parameters. Each technology has certain limitations along with its advantages. Each technology has certain limitations along with its advantages. Therefore, the selection of a suitable energy storage technology depends on the vehicle's requirements, application, driving range, power demand, cost, and overall performance. Choosing the right storage technology helps improve the efficiency, reliability, and sustainability of electric vehicles.

4.5 Comparison of EV Charging Standards and Power Levels

Table 5: Charging modes, voltage, current and power levels

Charging mode	Max. voltage (V)	Max. current (A)	Max. power (kW)	Max. voltage (norm.)	Max. current (norm.)	Max. power (norm.)
SAE AC Level 1	120	16	1.9	12	6.4	0.76
SAE AC Level 2	240	80	19.2	24	32	7.68
SAE DC Level 1	500	80	40	50	32	16
SAE DC Level 2	500	200	100	50	80	40
IEC-62196 maximum	480	250	120	48	100	48
GB/T DC	1000	250	250	100	100	100

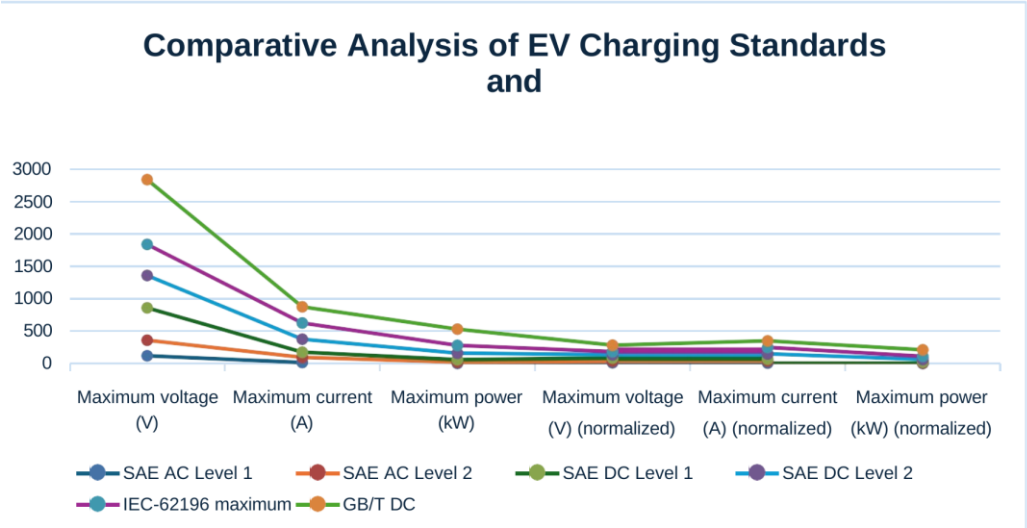


Fig. 14: Comparative analysis of EV charging standards and charging power levels

The graph compares IM, SRM, and BLDC motors. BLDC provides the highest power and high maximum speed, while IM and SRM also offer suitable power and speed characteristics for EV applications. These motors are widely considered for electric vehicle powertrain systems. BLDC motors provide good efficiency and fast response during vehicle operation. IM motors are known for their reliable operation and simple construction. SRM motors offer a robust structure and can operate effectively at high speeds. They also offer fast response, smooth operation, and good speed control during vehicle operation. Induction Motors (IM) are known for their simple construction, reliable operation, low maintenance requirements, and durability. They are widely used in electric vehicles because of their ability to operate under different driving conditions. Switched Reluctance Motors (SRM) have a simple and robust structure, low manufacturing cost, and the ability to operate effectively at high speeds

4.6 Emission Band Comparison

Table 6: Distribution of vehicle types across CO_2-equivalent emission bands (%)

Emission band (kg CO_2-eq/(V·km))	ICEV-D	ICEV-P	HEV-P	PHEV-P	FCEV	BEV
0–0.05	0	0	0	0	0	4
0.05–0.10	0	0	0	18	29	18
0.10–0.15	25	8.3	33	18	57	25
0.15–0.20	12.5	20.8	50	45	0	41
0.20–0.25	0	45.8	17	18	0	11
0.25–0.30	0	12.5	0	0	14	0
0.30–0.35	0	8.3	0	0	0	0
0.35–0.40	0	4.2	0	0	0	0

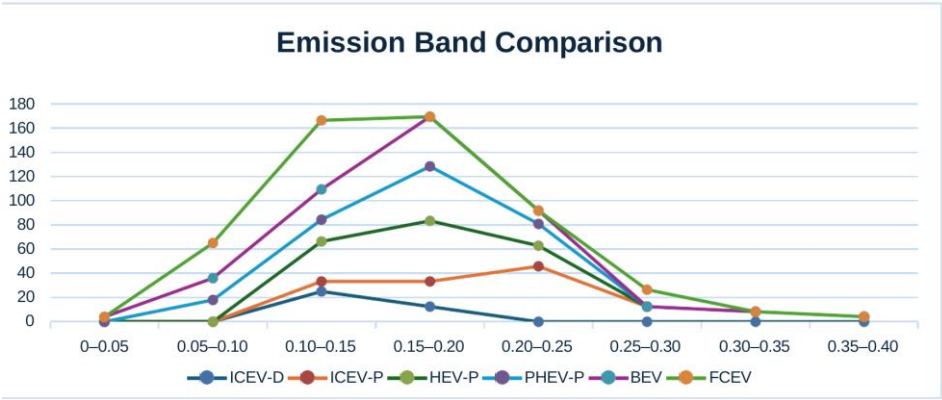


Fig. 15: Emission band comparison

Energy-management systems can significantly improve the performance and efficiency of electric and hybrid vehicles. The findings discussed in the article indicate that these systems can provide several important benefits, including an **18.4% improvement in fuel efficiency** and a **17% reduction in battery degradation**. These improvements help vehicles use energy more effectively and increase the useful life of the battery. In addition, efficient energy management can support better vehicle performance and reduce energy losses during operation.These improvements help vehicles utilize available energy more effectively, reduce unnecessary energy consumption, and increase the useful life of the battery. Furthermore, energy-management systems can control power flow according to driving conditions, vehicle speed, and power requirements. They also help reduce energy losses during acceleration, braking, and other operating conditions. Efficient energy management can improve driving range, reduce operating costs, and provide better vehicle performance. It also contributes to reducing fuel consumption and harmful emissions, making electric and hybrid vehicles more sustainable and environmentally friendly.

4.7 Comparison of Efficiency and Charging Time

Table 7: Efficiency and representative charging time of charging strategies

S. No	Charging strategy	Efficiency (%)	Representative charging time (h)
1.	Level-1	90	10
2.	Level-2	91	4.5
3.	DC fast	87.5	0.67
4.	Smart charging	92	1.5
5.	Vehicle to grid	87.5	1.5

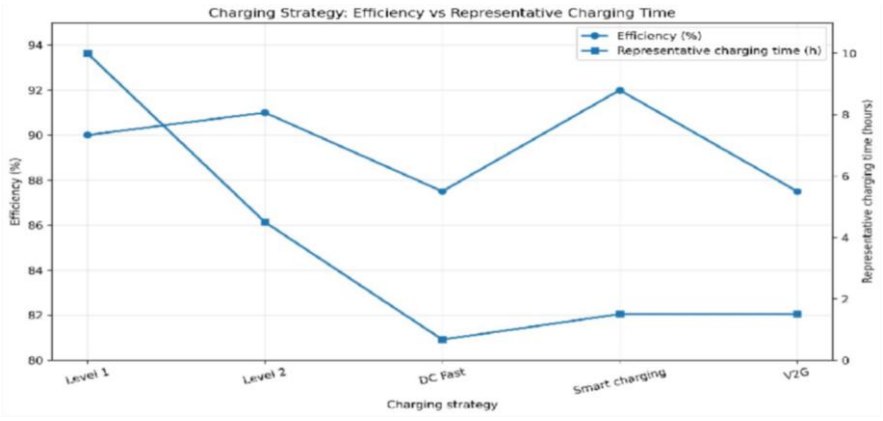


Fig. 16: Charging strategy: efficiency versus representative charging time

The graph shows that charging strategies have different efficiency and charging times. Level 1 and Level 2 have relatively high efficiency but longer charging times, while DC fast charging greatly reduces charging time with some reduction in efficiency.However, it still requires more time than DC fast charging. On the other hand, DC fast charging supplies high power directly to the battery and significantly reduces charging time, making it suitable for long-distance travel and quick charging requirements. However, it may have a slightly lower overall efficiency due to higher energy losses during the charging process. Frequent use of fast charging may also increase battery heating and affect battery life if proper thermal management is not maintained. Therefore, the selection of a suitable charging strategy depends on charging time, efficiency, battery health, cost, and vehicle requirements.

5. CONCLUSIONS

The study of reviewed 30 papers offer evidence regarding the evolution of electric vehicle technology, driven by progress in battery technology,

charging systems, electric motors, energy management, autonomous driving. The integration of renewable energy. They emphasize the importance of energy density, efficiency, cycle life, and battery charging performance, along with the potential of fast and ultra-fast charging, regenerative braking. Advanced energy-management systems to improve the range and convenience of EVs. Moreover, the studies show how important battery recycling and second-life utilization are for minimizing waste and maximizing resources. In general, advances in batteries, charging infrastructure, intelligent control systems, and smart management of energy storage are essential for enhancing the performance and sustainability of electric vehicles.

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