

# Advancements in Electric Vehicle Technologies: A Review of Powertrain Architectures and Battery Innovations

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**Abstract**—The main goal of this paper is to review the advancements in electric vehicle technologies for powertrain and battery innovations. The rapid evolution of electric vehicles (EVs) is driven by advancements in powertrain architecture and battery technologies, enabling improved efficiency, performance, and sustainability. This review explores recent innovations in EV powertrains, including permanent magnet synchronous motors (PMSMs), induction motors, and emerging switched reluctance motors (SRMs), along with advancements in motor control strategies and power electronics. Advanced control techniques like field-oriented control (FOC) and predictive control must be explained in detail for PMSM-based electric vehicle systems. FOC is a popular vector control method that converts the torque and flux components of the stator current into a rotating reference frame to decouple them. However, a more contemporary method called model predictive control (MPC) forecasts future system states using a dynamic model to optimize motor control operations. Additionally, battery technology developments, such as high-energy-density lithium-ion batteries, solid-state batteries, and next-generation fast-charging solutions, are analyzed in terms of energy storage capacity, charging speed, thermal management, and lifecycle improvements. The need for innovation is still shaped by practical obstacles in addition to technical developments in electric vehicle (EV) powertrains. Manufacturers are compelled to investigate alternative chemistries or optimize energy usage through more effective motor control and thermal management, for example, because lithium-ion batteries' reliance on rare and geopolitically sensitive materials like cobalt raises concerns about sustainability and the supply chain. The integration of powertrain and battery innovations with intelligent energy management systems and vehicle-to-grid (V2G) technology is also discussed, highlighting their impact on EV range, reliability, and grid sustainability. This review provides a comprehensive understanding of the current technological landscape and future directions in EV development, addressing key challenges such as material limitations, charging infrastructure, and cost-effectiveness.

**Keywords**—Electric Vehicles; Technologies; Powertrain; Battery; Innovations

## I. INTRODUCTION

The transition from conventional internal combustion engine (ICE) vehicles to electric vehicles (EVs) marks a significant shift in the automotive industry, driven by the need for sustainable and energy-efficient transportation. With increasing concerns over climate change, air pollution, and the depletion of fossil fuel resources, EVs have emerged as a

viable alternative, offering reduced carbon emissions, improved energy efficiency, and lower operating costs. Governments worldwide are implementing stringent emission regulations and providing incentives to accelerate EV adoption, further stimulating research and development in this field. The environmental and geopolitical effects of procuring materials essential to motors and batteries provide a major obstacle for the electric vehicle (EV) sector. High-performance batteries and permanent magnet motors require materials like lithium, cobalt, and rare-earth elements, but their extraction frequently raises serious ethical and environmental issues. For instance, most of the lithium comes from areas such as South America's Lithium Triangle, where water-intensive extraction techniques endanger nearby water supplies. In a similar vein, human rights abuses such as child labor and unfavorable working conditions have been brought to light by cobalt mining, which primarily occurs in the Democratic Republic of Congo.

At the core of EV performance are two critical components: the powertrain and the battery system. The powertrain, which includes the electric motor, power electronics, and transmission system, determines the vehicle's efficiency, acceleration, and overall driving experience. Recent advancements in motor technology, such as permanent magnet synchronous motors (PMSMs), switched reluctance motors (SRMs), and advanced control strategies, have enhanced power density, reliability, and operational efficiency [1]. Moreover, developments in wide bandgap semiconductor materials, such as silicon carbide (SiC) and gallium nitride (GaN), are revolutionizing power electronics, enabling faster switching speeds, reduced losses, and improved thermal performance [2]. The adoption of EVs is greatly influenced by battery technology, which affects cost, charging time, and range. The market is now dominated by lithium-ion (Li-ion) batteries because of their enhanced safety features, long cycle life, and high energy density.

However, challenges such as limited raw material availability, thermal management, and degradation over time remain key concerns [3]. Emerging technologies, including solid-state batteries, lithium-sulfur batteries, and high-capacity anodes, are being explored to overcome these limitations and extend the capabilities of EVs. Additionally, innovations in fast-charging infrastructure, battery management systems (BMS), and vehicle-to-grid (V2G) integration are reshaping the future of electric mobility [4].

This review provides a comprehensive analysis of advancements in EV powertrain and battery technologies, highlighting their impact on vehicle efficiency, performance, and sustainability. The study examines recent trends, key challenges, and future research directions, offering insights into the evolving landscape of electric transportation.

## II. ELECTRIC VEHICLE TECHNOLOGY

Electric vehicle (EV) technologies encompass a broad range of advancements in powertrains, batteries, charging systems, and energy management. These innovations have driven the rapid adoption of EVs by improving efficiency, range, and sustainability [5]. A typical electric vehicle (EV) is a type of vehicle that uses one or more electric motors for propulsion, powered by electricity stored in batteries. Unlike traditional internal combustion engines (ICE) vehicles, EVs have no gasoline or diesel engines, making them more environmentally friendly by producing zero tailpipe emissions. Fig. 1 shows the Block diagram of a typical electric vehicle.

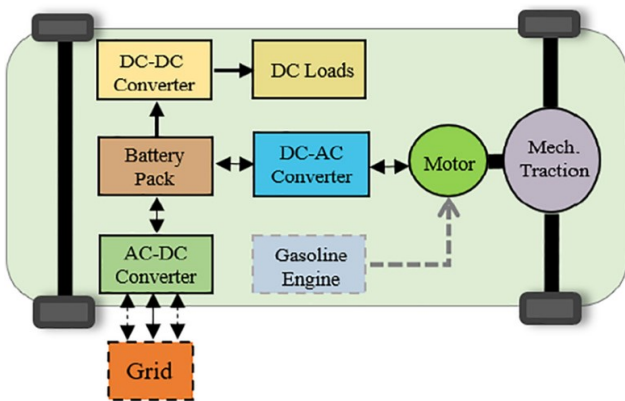


Fig. 1. Block diagram of a typical electric vehicle [6]

### A. Electric Powertrain Systems

EV powertrains differ significantly from conventional internal combustion engine (ICE) systems. Key elements include:

- **Electric Motors:** Permanent Magnet Synchronous Motors (PMSMs), Induction Motors (IMs), and Switched Reluctance Motors (SRMs) are commonly used. PMSMs offer high efficiency and power density, while IMs provide robustness and lower costs. Looking forward, several emerging areas promise to significantly impact the EV landscape. AI-based battery management systems (BMS), for example, will leverage machine learning and predictive algorithms to optimize battery life, charging cycles, and energy efficiency in real time. These AI-driven systems will enhance the safety and performance of EVs, while also helping to mitigate some of the challenges associated with battery degradation and thermal stress. Wireless charging technology is another exciting frontier, offering the potential to eliminate the need for physical connectors and enable seamless charging experiences for users. As wireless charging systems improve, they could reduce infrastructure complexity, improve charging convenience, and even provide opportunities for dynamic charging on the go.

- **Power Electronics:** Devices such as inverters, converters, and motor controllers regulate power flow. Wide bandgap semiconductors like silicon carbide (SiC) and gallium nitride (GaN) enhance efficiency and reduce power losses [7].
- **Transmission Systems:** Unlike ICE vehicles, EVs often use single-speed transmissions due to the wide torque range of electric motors.

### B. Battery Technologies

Batteries are the heart of EVs, determining range, performance, and longevity. Key advancements include:

- **Lithium-Ion Batteries (Li-ion):** The most widely used due to their high energy density, efficiency, and cycle life [8].
- **Solid-State Batteries:** Offering higher energy density, improved safety, and faster charging compared to Li-ion batteries.
- **Alternative Chemistries:** Lithium-sulfur, sodium-ion, and hydrogen fuel cells are emerging technologies aimed at improving cost-effectiveness and sustainability [9].
- **Battery Management Systems (BMS):** Crucial for monitoring temperature, voltage, and state-of-charge to ensure safe and efficient battery operation.

### C. Charging and Energy Management

Charging infrastructure and energy management play a vital role in EV adoption:

- **Fast Charging (DCFC):** Reduces charging time significantly, with technologies like ultra-fast chargers (up to 350 kW) and wireless charging gaining traction.
- **Vehicle-to-Grid (V2G) Technology:** Enables EVs to interact with the power grid, supporting energy storage and grid stabilization.
- **Regenerative Braking:** Captures and reuses braking energy, improving overall efficiency.

### D. Smart and Connected EV Technologies

Autonomous driving and AI integration: EVs are increasingly incorporating AI-driven autonomous systems for enhanced safety and efficiency.

- **Internet of Things (IoT) Connectivity:** Enables real-time monitoring, predictive maintenance, and remote diagnostics [10].
- **Lightweight Materials and Aerodynamics:** Advances in composite materials and aerodynamics contribute to energy savings and extended range.

Electric vehicle technologies are evolving rapidly, addressing challenges such as battery limitations, charging infrastructure, and cost. Continued research in powertrain efficiency, battery innovations, and smart energy management will further accelerate the transition to a sustainable transportation future [11].

## III. EVOLUTION OF ELECTRIC VEHICLE POWERTRAIN TECHNOLOGIES

Electric vehicle (EV) powertrains and internal combustion engine (ICE) vehicles differ significantly in efficiency, performance, maintenance, and environmental impact. EVs use electric motors powered by batteries, offering high energy efficiency of around 85–90% compared to the 25–30% efficiency of ICE vehicles, which lose much of their energy as heat. EVs provide instant torque for rapid

acceleration and utilize regenerative braking to recover energy, whereas ICE vehicles rely on multi-gear transmissions and gradual torque buildup [12]. Maintenance is lower for EVs since they have fewer moving parts, eliminating the need for oil changes and reducing overall wear and tear. While ICE vehicles still dominate in range and refueling speed, EVs are catching up with advancements in battery technology and charging infrastructure [13]. Although the construction of batteries has a significant carbon footprint, EVs have zero tailpipe emissions and can be integrated with renewable energy sources. In contrast, the combustion of fuel in ICE vehicles results in a large contribution to greenhouse gas emissions. EVs are more expensive initially, but they are becoming more and more competitive due to their lower operating costs and government subsidies. As battery technology advances and charging networks expand, EVs are poised to replace ICE vehicles as the primary mode of transportation in the future. The modeling of electric vehicles has been shown in Fig. 2.

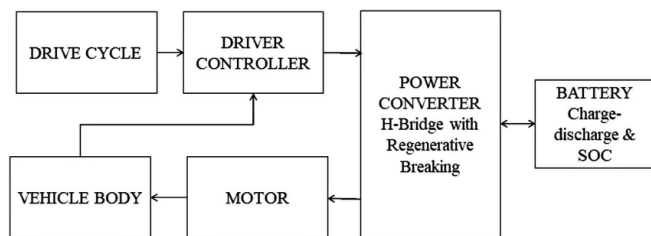


Fig. 2. Block diagram of electric vehicle modelling [14]

Electric vehicle (EV) powertrains can be classified into three main types: Battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), and fuel cell electric vehicles (FCEVs). BEVs are fully electric vehicles powered solely by batteries, using electric motors for propulsion. They require charging from an external power source and produce zero tailpipe emissions. Examples include the Tesla Model 3 and Nissan Leaf. PHEVs, on the other hand, combine an internal combustion engine (ICE) with an electric motor and a rechargeable battery [15]. They have a longer range since they can run on electricity for short distances then switch to petrol when the battery runs low. The Mitsubishi Outlander PHEV and Toyota Prius Prime are two examples. Finally, the electric motor in FCEVs is powered by electricity produced by hydrogen fuel cells. Although they require infrastructure for hydrogen refueling, they have large driving ranges and quick refueling periods. The Hyundai Nexa and Toyota Mirai are two examples. While BEVs provide zero-emission transportation with high efficiency, they face limitations in range and charging time [16]. PHEVs offer a balance between electric efficiency and ICE reliability, but they still rely on fossil fuels. FCEVs, with their fast refueling and long-range capabilities, are promising but currently face challenges related to hydrogen production and distribution.

Recent advancements in electric vehicle (EV) powertrain architecture are significantly enhancing performance, efficiency, and user experience. One notable development is the integration of Silicon Carbide (SiC) and Gallium Nitride (GaN) semiconductors, which improve energy conversion efficiency and thermal management in EV systems. These materials enable faster switching speeds and higher voltage

tolerance, contributing to reduced energy losses and extended vehicle range [17].

Another significant innovation is the adoption of solid-state batteries, which utilize solid electrolytes to offer higher energy density and enhanced safety compared to traditional liquid electrolytes. This technology allows for longer driving ranges and faster charging times, addressing key consumer concerns about EV usability. Companies like Toyota and startups such as Quantum cape are actively investing in the development of solid-state batteries, aiming for commercialization in the coming years [18].

The implementation of dual-motor and tri-motor configurations is also transforming EV performance. These setups provide dynamic torque distribution to individual wheels, enhancing traction, stability, and acceleration. Multi-motor designs enable features like all-wheel drive and improved handling, making EVs more versatile across various driving conditions. Notable examples include the Tesla Model S Plaid and the Rivian R1T, which leverage multi-motor architectures for superior performance [19].

Advancements in lightweight materials and design techniques are further optimizing EV efficiency. Utilizing materials such as carbon fiber-reinforced plastics and aluminum reduces vehicle weight without compromising safety or structural integrity. Additionally, manufacturing methods like 3D printing allow for complex, lightweight structures that enhance aerodynamics and energy efficiency. These innovations contribute to improved range and performance by minimizing energy consumption associated with vehicle weight.

Lastly, the development of wireless power transfer (WPT) technology is paving the way for more convenient charging solutions. WPT enables vehicles to charge without physical connections, potentially allowing for dynamic charging while driving on equipped roadways. This technology could eliminate charging downtime and alleviate range anxiety, further promoting the adoption of EVs.

These advancements collectively represent a transformative period in EV powertrain development, addressing key challenges related to efficiency, performance, and user convenience, and steering the automotive industry toward a more sustainable and electrified future [20].

#### IV. ELECTRIC MOTORS FOR EV POWERTRAINS

Electric vehicles (EVs) use various types of electric motors, primarily categorized into DC and AC motors. While brushed DC motors were used in early EVs, modern vehicles favor brushless DC (BLDC) motors due to their higher efficiency and lower maintenance. Among AC motors, induction motors (IM) operate without permanent magnets and are known for their durability and high efficiency, as seen in some Tesla models. Permanent magnet synchronous motors (PMSM) are widely used due to their superior efficiency and torque density, though they rely on rare earth materials [21], power output, and production cost.

Although SRMs often have higher noise and torque ripple, switched reluctance motors (SRM) and synchronous reluctance motors (SynRM) are new alternatives that do away with rare earth reliance and offer cost and sustainability advantages. The decision depends on the vehicle's design priorities, including range, cost, and performance, as each

motor type has trade-offs. Electric vehicles (EVs) utilize various types of electric motors, each with distinct advantages in efficiency, cost, and performance. Historically, brushed DC motors were used due to their simple design and easy control, but they have largely been replaced by brushless DC (BLDC) motors, which offer greater efficiency, longer lifespan, and lower maintenance. Most modern EVs rely on AC motors, with the two dominant types being induction motors (IM) and permanent magnet synchronous motors (PMSM) [22]. Induction motors, famously used in early Tesla vehicles, operate without permanent magnets, using electromagnetic induction to generate motion, making them durable and cost-effective but slightly less efficient than PMSMs. In contrast, PMSMs use powerful permanent magnets, typically made of rare-earth materials, to achieve high efficiency, superior torque density, and excellent performance, making them the preferred choice in most modern EVs, including Tesla Model 3, Nissan Leaf, and BMW i3.

#### A. Permanent Magnet Synchronous Motors (PMSMs)

Permanent Magnet Synchronous Motors (PMSMs) are widely used in modern electric vehicles due to their high efficiency, compact design, and superior torque density. Their efficiency advantage comes from the use of permanent magnets, which eliminate rotor losses, allowing PMSMs to achieve efficiencies above 95% in optimal operating conditions. For optimizing EV performance and range, they are therefore perfect. A significant disadvantage of PMSMs, however, is their reliance on rare-earth elements, such as terbium (Tb), dysprosium (Dy), and neodymium (Nd), which are employed in permanent magnets to improve temperature stability and magnetic strength. These materials are expensive and scarce worldwide, which has raised questions about supply chain security, price volatility, and sustainability [23]. To address these challenges, researchers and manufacturers are developing alternative motor technologies such as rare-earth-free switched reluctance motors (SRMs), hybrid synchronous reluctance motors (SynRMs), and ferrite-based PMSMs. Additionally, efforts are underway to optimize magnet compositions by reducing the reliance on heavy rare-earth elements while maintaining performance. Despite these challenges, PMSMs remain the dominant choice in EVs due to their unmatched efficiency, power density, and suitability for high-performance applications.

#### B. Induction Motors (IMs)

Induction Motors (IMs) are known for their robustness and cost-effectiveness, making them a strong choice for electric vehicles, especially for early Tesla models. Their rugged construction allows them to withstand harsh operating conditions, including high temperatures and mechanical stress, with minimal wear and tear. Unlike permanent magnet synchronous motors (PMSMs), IMs do not rely on rare-earth materials, reducing supply chain concerns and making them more affordable to manufacture [24].

However, while IMs are cost-effective in terms of material sourcing and durability, they tend to have lower efficiency compared to PMSMs, especially under partial load conditions, due to rotor losses caused by induced currents. This results in slightly higher energy consumption, which can

impact EV range. Despite this, their simple design, reliability, and lower dependence on expensive materials make them a practical choice for cost-sensitive EV applications, heavy-duty electric trucks, and industrial use.

#### C. Switched Reluctance Motors (SRMs)

Switched reluctance motors (SRMs) offer several key benefits, making them an attractive alternative for electric vehicle applications. One of their biggest advantages is the absence of rare-earth materials, as they rely purely on reluctant torque, eliminating the need for expensive permanent magnets [25]. This makes them cost-effective and more sustainable. SRMs are also highly robust and durable, thanks to their simple mechanical structure, which consists of a rugged rotor without winding or magnets. This design enhances their ability to operate in harsh environments and makes them highly reliable. Additionally, SRMs provide high-speed capability and excellent thermal management, as most of the heat is generated in the stator, which is easier to cool than the rotor.

Recycling vital materials like lithium, cobalt, and nickel is essential to reducing the supply chain and environmental issues related to electric vehicle (EV) batteries and motors, in addition to using alternative materials and battery management techniques. Hydrometallurgical and pyrometallurgical procedures are the two main methods utilised to recycle these materials; each has unique environmental effects and efficiency levels.

Despite these advantages, SRMs face significant control challenges, which have limited their widespread adoption in EVs. One major issue is the torque ripple, caused by the discrete nature of reluctance torque generation, leading to vibrations and acoustic noise. This can negatively impact vehicle comfort and drivability. Another challenge is complex motor control, as SRMs require precise, high-speed switching of the stator windings to ensure smooth operation. Unlike permanent magnet synchronous motors (PMSMs) or induction motors (IMs), which have well-established control techniques, SRMs demand advanced algorithms and sophisticated electronics to achieve high efficiency and performance. Additionally, high-frequency electromagnetic noise due to rapid switching can introduce further challenges in system integration.

### V. MOTOR EFFICIENCY IMPROVEMENTS AND FUTURE TRENDS

Electric vehicles (EVs) rely on power electronics to efficiently manage energy flow between the battery and the electric motor. Three critical components inverters, converters, and motor controllers play key roles in this process, as shown in Fig. 3.

Most modern EVs use AC motors (such as induction motors and permanent magnet synchronous motors), while the battery provides DC power. The inverter is responsible for converting DC from the battery into AC with precise frequency and voltage control. This allows the motor to operate at different speeds and torques depending on driving conditions. Additionally, inverters enable regenerative braking, converting kinetic energy back into electrical energy to recharge the battery, improving efficiency.

EVs utilize different DC-DC converters to manage voltage levels for various subsystems. The DC-DC converter

steps down high-voltage battery power (e.g., 400 V–800 V) to 12 V or 48 V for auxiliary systems such as lights, infotainment, and power steering. Boost converters: In some designs, a DC-DC boost converter is used to step up voltage before the inverter, optimizing motor performance and efficiency [26].

The motor controller serves as the "brain" of the EV's drivetrain, governing the operation of the electric motor. It takes inputs from the accelerator pedal, sensors, and vehicle control unit (VCU) to regulate speed, torque, and efficiency. In systems using switched reluctance motors (SRMs) or permanent magnet synchronous motors (PMSMs), motor controllers also manage pulse-width modulation (PWM) and advanced switching techniques to minimize losses and ensure smooth operation [27].

Together, inverters, converters, and motor controllers ensure optimal power conversion, voltage regulation, and motor efficiency. Their seamless integration determines the performance, range, and reliability of an EV, making power electronics a critical aspect of electric vehicle design.

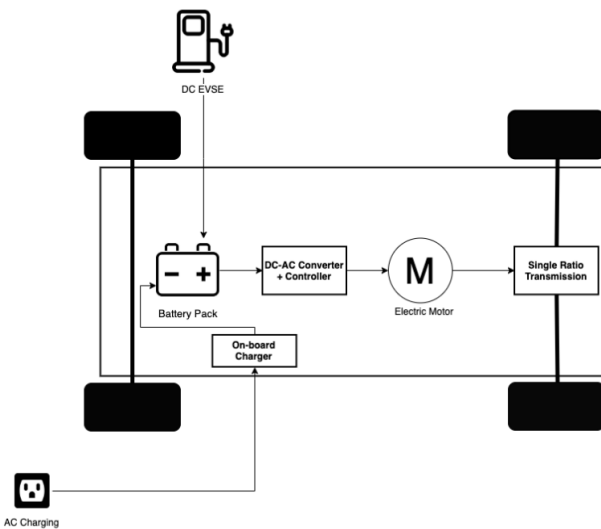


Fig. 3. EV powertrain components

## VI. BATTERY TECHNOLOGIES FOR ELECTRIC VEHICLES

Batteries are the heart of electric vehicles (EVs), determining their range, performance, and cost-effectiveness. Key battery requirements include high energy density, long lifespan, and cost efficiency, each of which influences EV adoption and usability. Energy density defines how much energy a battery can store per unit of weight (Wh/kg) or volume (Wh/L). A higher energy density enables longer driving range without increasing battery size or weight.

Lithium-ion (Li-ion) batteries dominate due to their high energy density (~150–300 Wh/kg) and efficiency. Solid-state batteries and lithium-sulfur batteries promise even higher energy densities, potentially exceeding 400 Wh/kg, enabling lighter and longer-range EVs. EV batteries must take thousands of charge cycles to ensure long-term reliability. Modern Li-ion batteries typically last 1,000–3,000 cycles, translating to 8–15 years of EV operation. High temperatures, deep discharge cycles, and fast charging can accelerate degradation. Advanced battery management systems (BMS) help mitigate this by optimizing charging and temperature

control. Battery cost is a major factor affecting EV affordability, with prices measured in \$/kWh. Li-ion battery prices have dropped from >\$1,000/kWh (2010) to ~\$100/kWh (2023), making EVs more competitive with internal combustion vehicles.

Cost reductions are slowing due to supply chain constraints and the high price of critical materials like lithium, cobalt, and nickel. Alternatives: Research is ongoing into LFP (lithium iron phosphate) and sodium-ion batteries, which offer lower costs and better availability at the expense of slightly lower energy density. An ideal EV battery must balance high energy density for range, long lifespan for durability, and low cost for affordability. Advances in battery chemistry and manufacturing are crucial to improving EV adoption, with ongoing innovations targeting higher energy storage, longer life, and reduced reliance on expensive materials.

Lithium-ion batteries dominate the EV industry due to their high energy density, efficiency, and reliability. Ranges from 150–300 Wh/kg, enabling longer EV range without excessive weight. Li-ion batteries have a high charge/discharge efficiency (~90–95%), reducing energy losses and improving EV performance. With 1,000–3,000 charge cycles, they can last 8–15 years, depending on usage and management. Advances in fast-charging technology allow Li-ion batteries to recharge up to 80% in 15–30 minutes, improving convenience. Effectively captures energy during braking, enhancing vehicle efficiency. Despite their advantages, Li-ion batteries face significant challenges that impact EV adoption. Although prices have fallen (from ~\$1,000/kWh in 2010 to ~\$100/kWh in 2023), material costs for lithium, cobalt, and nickel remain volatile, affecting affordability. Performance declines due to cycle aging, heat exposure, high charge/discharge rates, reducing efficiency and driving range over years of use [28]. Overcharging, short circuits, or external damage can cause overheating and fire risks. Advanced battery management systems (BMS) are essential for safety. The reliance on lithium, cobalt, and nickel raises concerns about supply chain bottlenecks, environmental impact, and geopolitical risks. Widespread fast-charging networks are still developing, with charging time and availability being key challenges for mass adoption.

To overcome these limitations, researchers are exploring solid-state batteries, lithium-iron-phosphate (LFP) batteries, and sodium-ion alternatives for improved safety, cost-effectiveness, and sustainability. While Li-ion batteries remain the dominant EV power source, innovation is essential to enhance their efficiency, longevity, and affordability.

## VII. BATTERY MANAGEMENT SYSTEMS (BMS) AND THERMAL MANAGEMENT

The battery management system (BMS) plays a crucial role in monitoring and controlling the performance of an electric vehicle's (EV) battery, ensuring its safety, efficiency, and longevity. It continuously tracks key parameters such as state of charge (SoC), state of health (SoH), and individual voltage, current, and temperature levels across the battery cells. By preventing issues like overcharging, over-discharging, and short circuits, the BMS ensures the battery operates safely and efficiently. One of its most important

functions is thermal management, which involves maintaining optimal battery temperature to prevent overheating that could lead to degradation, capacity loss, or safety hazards. The BMS works with cooling and heating systems to regulate temperature, often using liquid or air-cooling techniques. Additionally, the BMS optimizes battery performance by balancing cell charges, improving fast-charging capabilities, and enhancing energy efficiency [29]. As the "brain" of the battery system, the BMS also communicates with the vehicle control unit for real-time diagnostics, fault detection, and predictive maintenance, ensuring the overall health and longevity of the battery.

Passive and active thermal management strategies are used to regulate the temperature of electric vehicle (EV) batteries, ensuring optimal performance, safety, and longevity. Passive thermal management relies on natural methods, such as heat sinks, thermal insulation, and airflow, to dissipate heat without using external energy sources. This approach is cost-effective and simple, but it is limited in controlling temperature under high-power conditions or rapid charging, as it depends on ambient conditions and the design of the system. On the other hand, active thermal management involves the use of external cooling or heating systems, such as liquid cooling, fan-based air cooling, or heat pumps, which actively control battery temperature by circulating a cooling fluid or air around the battery pack. Active systems can maintain a consistent temperature range, even during high-stress conditions, ensuring better efficiency and performance. While active systems are more complex and costly, they provide superior control, especially in high-performance or long-range EVs. The choice between passive and active thermal management depends on the vehicle's design requirements, cost considerations, and performance goals.

### VIII. CHARGING INFRASTRUCTURE AND ENERGY MANAGEMENT

Charging technologies play a crucial role in the adoption and convenience of electric vehicles (EVs), with AC charging, DC fast charging, and wireless charging being the main methods. AC charging is the most common and affordable option, typically used for home charging, where alternating current (AC) from the grid is converted to direct current (DC) by the vehicle's onboard charger. While it is slower, taking anywhere from 4 to 12 hours to fully charge, it is suitable for overnight or workplace charging. On the other hand, DC fast charging delivers direct current (DC) directly to the battery, by passing the vehicle's onboard charger, enabling much faster charging speeds. It can charge an EV up to 80% in as little as 20-30 minutes, making it ideal for long-distance travel and public charging stations. Commonly found in public spaces, DC fast chargers use standards like CHAdeMO and CCS [30]. Finally, wireless charging, also known as inductive charging, provides a more practical, cordless choice by transferring energy from a charging station to the car via electromagnetic fields. Even while wireless charging is currently slower than other ways, it offers more convenience, particularly in public or at home, where the car only needs to park over a charging pad. These charging techniques will continue to improve the entire EV experience as technology develops. Integrating renewable energy into electric vehicle (EV) charging infrastructure is a

critical step toward creating a sustainable and eco-friendly transportation system. By using energy sources like solar, wind, and hydropower, EV charging can be powered by clean, renewable energy, significantly reducing the carbon footprint of electric vehicles. Solar-powered charging stations, for example, can harness energy from the sun during the day to charge EVs, and excess energy can be stored in batteries for use at night or during cloudy periods. In regions with high wind or hydro potential, wind turbines and hydropower can also be used to supply power for charging stations. This integration not only helps reduce reliance on fossil fuels but also aligns EV charging with broader sustainability goals, contributing to the overall decarbonization of the energy and transportation sectors. Additionally, combining renewable energy with smart grid technology and energy storage systems can further optimize energy distribution, ensuring consistent and efficient power supply, even when renewable energy generation fluctuates. In the long term, renewable energy integration offers a pathway to a net-zero carbon future for both EVs and the energy grid, supporting the global transition to sustainable mobility.

### IX. FUTURE TRENDS AND CHALLENGES IN EV POWERTRAIN AND BATTERY TECHNOLOGIES

The adoption of lightweight materials and improved aerodynamics is crucial for enhancing the efficiency and range of electric vehicles (EVs). Using materials like carbon fiber, aluminum, and advanced composites helps reduce the overall weight of the vehicle, which in turn improves energy efficiency and extends battery life.

Recycling vital materials like lithium, cobalt, and nickel is essential to reducing the supply chain and environmental issues related to electric vehicle (EV) batteries and motors, in addition to using alternative materials and battery management techniques. Hydrometallurgical and pyrometallurgical procedures are the two main methods utilized to recycle these materials; each has unique environmental effects and efficiency levels. Additionally, optimizing the aerodynamic design reduces drag, contributing to better fuel economy and faster speeds, especially at highway speeds. AI and IoT are transforming EV energy management by providing real-time monitoring and control of battery usage, charging cycles, and overall vehicle performance. These technologies enable predictive analytics that forecast energy needs and optimize charging schedules, leading to more efficient use of power and longer battery life. Another key area is the recycling and second-life applications for EV batteries, where batteries that have reached the end of their useful life in vehicles can be repurposed for energy storage systems or recycled to recover valuable materials like lithium and cobalt, reducing environmental impact. However, policy and regulatory challenges remain a barrier to widespread EV adoption, as governments face challenges in creating consistent incentives, charging infrastructure, and regulatory frameworks that support the transition to electric mobility. Issues such as standardization of charging protocols, battery recycling regulations, and incentives for consumers and manufacturers require careful planning to ensure sustainable growth in the EV sector.

## X. CONCLUSION

Key advancements in powertrain and battery technologies are shaping the future of electric vehicles (EVs). In powertrains, the development of more efficient motors, including permanent magnet synchronous motors (PMSMs) and induction motors (IMs), has led to improvements in energy conversion and driving performance. Innovations in inverters and motor controllers are enabling more precise control, enhancing both efficiency and vehicle dynamics. In battery technologies, the focus has been on improving energy density, charging speed, and battery lifespan. Lithium-ion batteries have dominated the market, but solid-state batteries and lithium-sulfur batteries are emerging as potential alternatives offering higher energy densities and enhanced safety. Additionally, fast charging and thermal management systems have significantly improved the convenience and longevity of EVs. Looking ahead, future research directions will likely focus on next-generation battery chemistries, such as solid-state and sodium-ion, as well as improvements in battery recycling and second-life applications. In the powertrain sector, advancements in AI-driven energy management and autonomous vehicle integration are expected to further optimize performance. Industry perspectives indicate a growing emphasis on sustainability and cost reduction, aiming to make EVs more affordable and widely accessible, while tackling challenges related to charging infrastructure, raw material sourcing, and battery disposal. The combination of innovation in both battery and powertrain technologies, along with supportive regulatory frameworks, will be crucial in accelerating the global shift toward electric mobility.

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