

Electric vehicles: technologies, energy supply systems, battery technologies, charging protocols, applications, advantages, disadvantages, and economic & environmental perspectives

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ABSTRACT

The rapid growth of electric vehicles (EVs) has become one of the most significant technological developments in the transportation sector, driven by increasing concerns regarding greenhouse gas emissions, fossil fuel depletion, and global climate change. Compared with conventional internal combustion engine vehicles, electric vehicles provide higher energy efficiency, lower operating costs, reduced environmental impacts, and improved driving performance. Continuous advances in battery technology, electric propulsion systems, charging infrastructure, and intelligent energy management have significantly accelerated the global adoption of EVs. This paper presents a comprehensive review of electric vehicle technologies, including the classification of EVs, electric propulsion systems, battery technologies, energy supply systems, charging methods and international charging standards, battery management systems, and regenerative braking technologies. Different battery chemistries, including Lithium-Ion, Lithium Iron Phosphate (LFP), Nickel Manganese Cobalt (NMC), Nickel Cobalt Aluminum (NCA), and emerging Solid-State Batteries, are comparatively discussed in terms of energy density, safety, cost, lifespan, and practical applications. Furthermore, the study investigates modern charging infrastructures, including AC and DC charging systems, Combined Charging System (CCS), CHAdeMO, GB/T, North American Charging Standard (NACS), Vehicle-to-Grid (V2G), and Plug-and-Charge technologies. In addition, the economic feasibility of electric vehicles, life-cycle environmental impacts, battery recycling challenges, and future technological trends are critically reviewed. The findings indicate that electric vehicles represent one of the most promising solutions for achieving sustainable transportation. Nevertheless, several challenges—including battery manufacturing costs, charging infrastructure development, critical raw material supply, and end-of-life battery management—must be addressed to enable widespread commercialization.

and long-term sustainability. Continued technological innovation and supportive governmental policies are expected to further accelerate the global transition toward electric mobility.

Keywords: Electric Vehicles (EVs), Battery Electric Vehicle (BEV), Lithium-Ion Battery, Battery Management System (BMS), Charging Infrastructure, CCS, NACS, Vehicle-to-Grid (V2G), Sustainable Transportation, Energy Storage.

1. INTRODUCTION

The transportation sector is one of the largest consumers of fossil fuels and one of the primary contributors to greenhouse gas emissions worldwide. According to the International Energy Agency (IEA), transportation accounts for approximately one-quarter of global carbon dioxide (CO₂) emissions associated with energy consumption, making the decarbonization of this sector an international priority [1]. Growing environmental concerns, increasingly stringent emission regulations, rapid urbanization, and remarkable advances in battery technologies have accelerated the development and commercialization of electric vehicles (EVs). Over the past decade, global EV sales have experienced exponential growth, supported by technological innovations, government incentives, and continuous improvements in charging infrastructure [1]. Unlike conventional internal combustion engine (ICE) vehicles, electric vehicles utilize electric motors powered by rechargeable battery systems or hydrogen fuel cells. This approach significantly improves energy efficiency while reducing local air pollution and greenhouse gas emissions. Modern electric motors typically achieve efficiencies exceeding 90%, whereas conventional gasoline engines generally operate with efficiencies between 25% and 35% [2].

Recent technological advances in lithium-ion batteries, battery thermal management systems, regenerative braking, and intelligent energy management have substantially increased vehicle driving range while reducing operating costs and improving reliability [2,3]. Simultaneously, the expansion of fast-charging infrastructure and the introduction of advanced charging standards such as CCS, GB/T, CHAdeMO, and NACS have enhanced the practicality of electric mobility in both urban and intercity transportation [4–6]. Besides passenger vehicles, electrification has expanded into buses, heavy-duty trucks, motorcycles, industrial machinery, and public transportation systems. Consequently, electric vehicles have become an essential component of sustainable transportation strategies worldwide [8,9].

Despite these advantages, several technical and economic challenges remain. Battery production costs, charging infrastructure deployment, charging duration, battery degradation, critical raw material availability, and battery recycling continue to limit the large-scale adoption of electric vehicles [2,3,8]. Ongoing research focuses on addressing these challenges through innovations such as solid-state batteries, ultra-fast charging technologies, artificial intelligence-based battery management, and vehicle-to-grid (V2G) systems [6,10].

Therefore, this review aims to provide a comprehensive overview of electric vehicle technologies by discussing vehicle classifications, propulsion systems, battery technologies, energy supply systems, charging protocols, international charging standards, practical applications, economic considerations, environmental impacts, and future development trends.

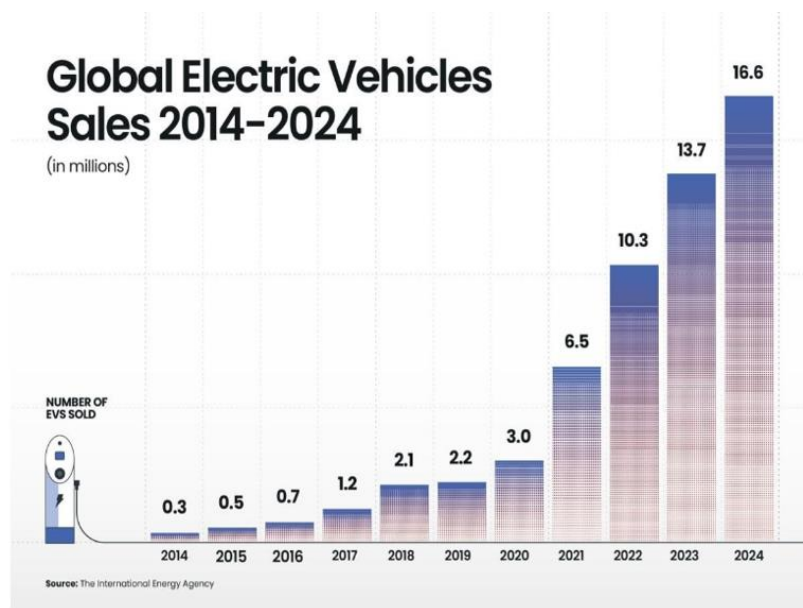


Figure 1. Global electric vehicle sales growth between 2014 and 2024. Adapted from [1]

Table 1. Comparison between conventional internal combustion engine vehicles and battery electric vehicles (Adapted from Madaram et al. [2]).

Parameter	Internal Combustion Engine Vehicle	Battery Electric Vehicle
Energy Source	Gasoline/Diesel	Rechargeable Battery
Energy Conversion Efficiency	25-35%	90-97%
Tailpipe Emissions	High	Zero
Maintenance Cost	High	Low
Noise Level	High	Very Low
Regenerative Braking	No	Yes

2. CLASSIFICATION OF ELECTRIC VEHICLES

Electric vehicles (EVs) can be classified according to their propulsion architecture and energy source. Based on the degree of electrification and the method of energy storage, EVs are generally categorized into four major groups: Battery Electric Vehicles (BEVs), Hybrid Electric Vehicles (HEVs), Plug-in Hybrid Electric Vehicles (PHEVs), and Fuel Cell Electric Vehicles (FCEVs). Each category has distinct technical characteristics, operational advantages, and practical applications [2,9].

2.1 Battery Electric Vehicles (BEVs)

Battery Electric Vehicles (BEVs) are powered exclusively by electric motors using electrical energy stored in rechargeable battery packs. Unlike conventional vehicles, BEVs do not contain an internal combustion engine, fuel tank, or exhaust system. Electricity is supplied from

high-voltage lithium-ion battery packs and converted into mechanical power through an inverter and electric motor [2].

Typical examples include:

Tesla Model 3, Tesla Model Y, Hyundai Ioniq 5, Kia EV6, Nissan Leaf, BMW i4, Mercedes-Benz EQE

- Zero tailpipe emissions
- High energy efficiency
- Low maintenance requirements
- Instant torque and excellent acceleration
- Quiet operation
- Reduced dependence on fossil fuels

Disadvantages

- Higher initial purchase cost
- Charging time is longer than conventional refueling
- Driving range depends on battery capacity
- Battery degradation over time
- Dependence on charging infrastructure

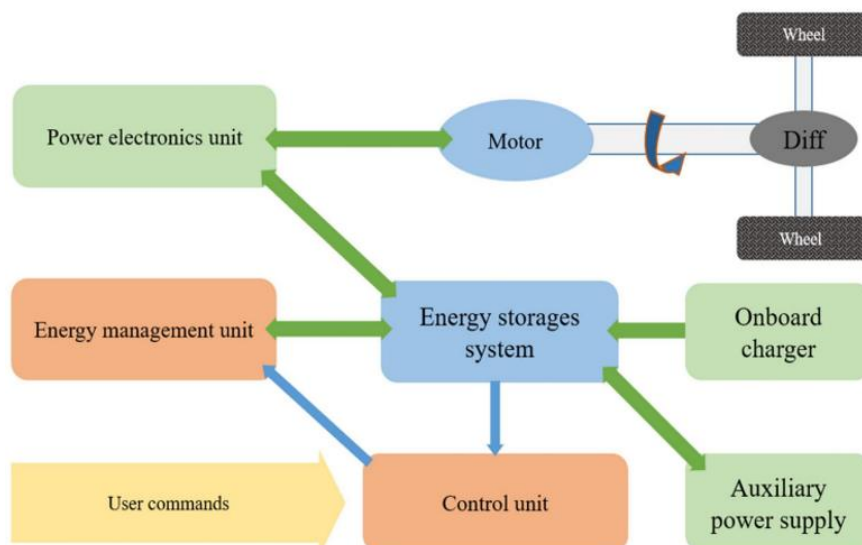


Figure 2. General structure of a Battery Electric Vehicle (BEV). Source: Adapted from Madaram et al. [2]

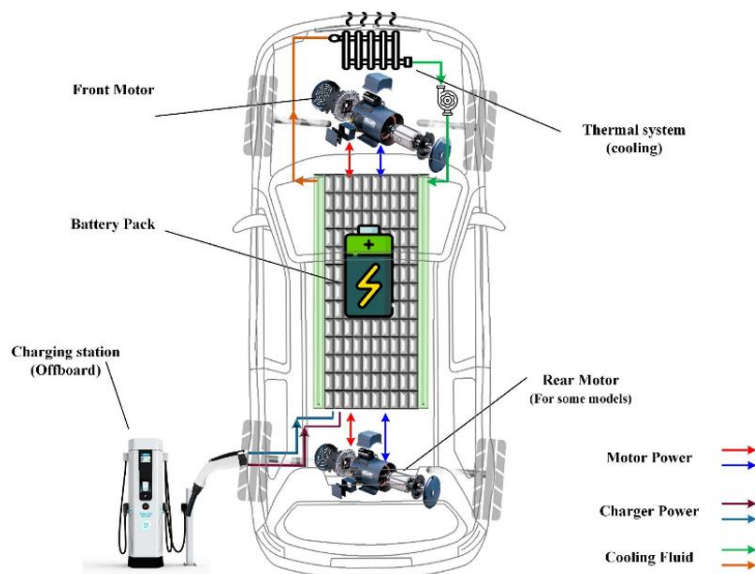


Figure 3. General architecture of a Battery Electric Vehicle (BEV), including the battery pack, inverter, electric motor, transmission, and charging system. Source: Adapted from Madaram et al. [2]

2.2 Hybrid Electric Vehicles (HEVs)

Hybrid Electric Vehicles combine an internal combustion engine with one or more electric motors. The battery is charged through regenerative braking and by the internal combustion engine; therefore, HEVs do not require external charging [9].

Representative models include:

Toyota Prius, Toyota Corolla Hybrid, Honda Accord Hybrid, Hyundai Elantra Hybrid

Advantages

- Lower fuel consumption than conventional vehicles
- No external charging required
- Long driving range
- Mature and reliable technology

Disadvantages

- More complex powertrain
- Higher maintenance cost than BEVs
- Continued dependence on fossil fuels
- Tailpipe emissions remain unavoidable

2.3 Plug-in Hybrid Electric Vehicles (PHEVs)

Plug-in Hybrid Electric Vehicles combine the advantages of BEVs and HEVs. Their batteries can be charged from both external electrical sources and regenerative braking, while the internal combustion engine provides additional driving range when the battery becomes depleted [2].

Typical examples include:

Mitsubishi Outlander PHEV, BMW 330e, Volvo XC60 Recharge, Toyota RAV4 Prime

Most commercially available PHEVs provide an electric-only driving range between 40 and 120 km, depending on battery capacity.

Advantages

- Reduced fuel consumption
- Flexible operation for both short and long-distance travel
- Lower greenhouse gas emissions
- Reduced range anxiety

Disadvantages

- Higher vehicle complexity
- Increased weight
- Higher purchase cost
- Maintenance of both electric and combustion systems

2.4 Fuel Cell Electric Vehicles (FCEVs)

Fuel Cell Electric Vehicles generate electricity onboard through an electrochemical reaction between hydrogen and oxygen inside a proton exchange membrane fuel cell. Unlike battery electric vehicles, hydrogen is stored in high-pressure tanks and converted into electricity during vehicle operation [8].

Representative models include:

Toyota Mirai, Hyundai Nexo, Honda Clarity Fuel Cell

Advantages

- Zero tailpipe emissions (only water vapor)
- Long driving range
- Refueling time comparable to gasoline vehicles
- High energy conversion efficiency

Disadvantages

- High vehicle cost
- Limited hydrogen infrastructure
- Expensive hydrogen production and storage
- Limited commercial availability

Table 2. Comparison of Major Electric Vehicle Types (Adapted from Sriabisha et al. [9])

Vehicle Type	Primary Energy source	External Charging	Tailpipe Emission	Typical Driving Range
BEV	Rechargeable Battery	Yes	Zero	Medium – High
HEV	Gasoline + Battery	NO	Low	High
PHEV	Gasoline + Battery	YES	Very Low	High
FCEV	Hydrogen Fuel Cell	Hydrogen Refueling	Zero	Very High

3. CORE TECHNOLOGIES USED IN ELECTRIC VEHICLES

The remarkable performance of modern electric vehicles is primarily attributed to continuous advancements in electric propulsion technologies. The major components include electric motors, power electronic converters, regenerative braking systems, and battery management systems, all of which contribute significantly to vehicle efficiency, reliability, and driving performance [2,3].

3.1 Electric Motors

The electric motor is the primary propulsion unit in an electric vehicle, converting electrical energy into mechanical energy with very high efficiency. Three motor technologies are widely adopted in modern EVs.

3.1.1 Induction Motor (IM)

The induction motor, originally developed by Nikola Tesla, has been widely used in electric vehicles due to its robustness and relatively simple construction.

Advantages

- High reliability
- Low manufacturing cost
- No permanent magnets required
- Excellent thermal durability

Disadvantages

- Lower efficiency than PMSM
- Larger size and higher weight
- Slightly lower torque density

Applications include several Tesla vehicle models.

3.1.2 Permanent Magnet Synchronous Motor (PMSM)

PMSMs are currently the most widely used electric motors in passenger electric vehicles because of their excellent efficiency and power density [2].

Advantages

- Efficiency up to approximately 97%
- High torque density
- Compact dimensions
- Smooth and quiet operation

Disadvantages

- Higher manufacturing cost
- Dependence on rare-earth permanent magnets
- Supply-chain concerns for critical materials

Common applications include vehicles manufactured by BMW, BYD, Hyundai, Mercedes-Benz, and Volkswagen.

3.1.3 Switched Reluctance Motor (SRM)

Switched Reluctance Motors have attracted increasing research interest because they eliminate the need for permanent magnets.

Advantages

- Simple construction
- Low production cost
- High temperature tolerance
- High mechanical robustness

Disadvantages

- Higher vibration
- Increased acoustic noise
- More sophisticated control algorithms required

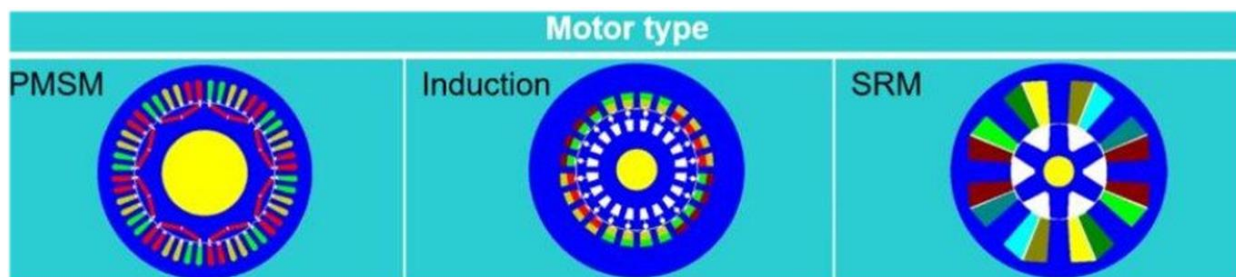


Figure 4. Comparison of the structures of Induction Motors, Permanent Magnet Synchronous Motors, and Switched Reluctance Motors. Source: Adapted from Madaram et al. [2]

Table 3. Comparison of Electric Motors Used in Electric Vehicles (Adapted from Sujitha and Krithiga [7])

Characteristic	IM	PMSM	SRM
Efficiency	High	Very High	High
Manufacturing Cost	Medium	High	Low
Torque Density	High	Very High	Medium
Permanent Magnets	No	Yes	No
Thermal Performance	Excellent	Good	Excellent
Typical Applications	Tesla	BMW, Hyundai, BYD	Research & Emerging EVs

3.2 Power Electronics and Inverter

Electric vehicle batteries supply direct current (DC), whereas most traction motors operate using three-phase alternating current (AC). Therefore, an inverter is required to convert DC into AC while simultaneously controlling motor speed, torque, and efficiency [2].

Modern electric vehicles increasingly employ Silicon Carbide (SiC) power semiconductor devices due to several advantages:

- Reduced switching losses
- Higher conversion efficiency
- Higher switching frequency
- Smaller cooling systems
- Reduced inverter size and weight
- Improved overall vehicle efficiency

3.3 Regenerative Braking System

One of the most significant technological advantages of electric vehicles is regenerative braking. During deceleration, the electric motor operates as a generator, converting kinetic energy into electrical energy and storing it back in the battery [3].

Benefits include:

- Increased driving range
- Reduced energy consumption
- Lower brake pad wear
- Improved overall system efficiency

Studies indicate that regenerative braking can recover approximately 10–30% of the energy consumed during urban driving conditions [2,3].

3.4 Battery Management System (BMS)

The Battery Management System (BMS) is one of the most critical components of an electric vehicle. It continuously monitors battery operating conditions to maximize safety, performance, and service life [3].

Its principal functions include:

- Cell voltage monitoring
- Current measurement
- Temperature monitoring
- State of Charge (SOC) estimation
- State of Health (SOH) estimation
- Cell balancing
- Overcharge and over-discharge protection
- Fault diagnosis and safety management

An advanced BMS significantly enhances battery lifespan, improves vehicle safety, and optimizes energy utilization.

Section Summary

Electric vehicle classification demonstrates that different propulsion architectures are designed to satisfy diverse transportation requirements. Meanwhile, continuous improvements in electric motors, power electronics, regenerative braking systems, and battery management technologies have substantially increased the efficiency, reliability, and commercial viability of modern electric vehicles. These technological developments form the foundation for further

advancements in battery technologies and energy storage systems, which are discussed in the following section.

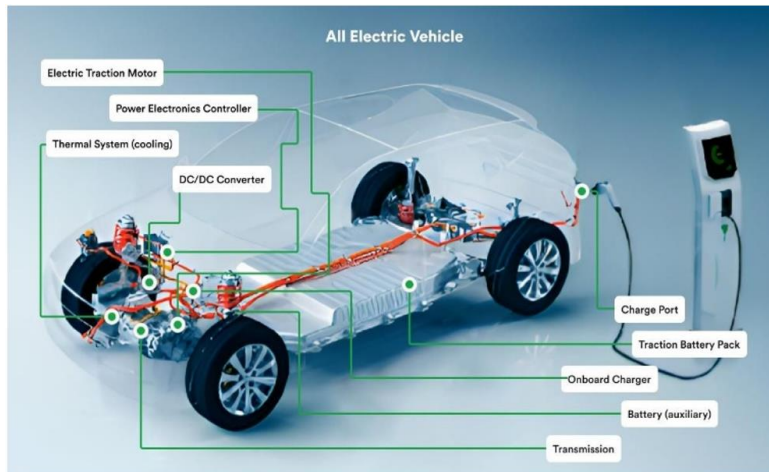


Figure 5. Main components of electric vehicle powertrains. Source: Adapted from Madaram et al. [2]

4. ENERGY SUPPLY SYSTEMS AND BATTERY TECHNOLOGIES FOR ELECTRIC VEHICLES

The energy storage system is considered the core component of every electric vehicle, directly influencing driving range, vehicle performance, charging speed, safety, lifespan, and overall operating cost. In recent years, continuous advancements in electrochemical energy storage technologies have significantly improved the commercial viability of electric vehicles. Currently, Lithium-ion batteries dominate the global EV market, while technologies such as solid-state batteries, supercapacitors, and hydrogen fuel cells are being actively developed for future applications [2,3].

4.1 Lithium-Ion Batteries

Lithium-ion (Li-ion) batteries are the most widely adopted energy storage technology in modern electric vehicles because of their high energy density, long cycle life, relatively low self-discharge rate, and excellent charging efficiency [2,3].

Typical characteristics include:

- ✓ Energy density: 150–300 Wh/kg
- ✓ Round-trip efficiency: >90%
- ✓ Nominal cell voltage: 3.6–3.7 V
- ✓ Cycle life: 1,000–3,000 charging cycles

Advantages and Disadvantages

- High energy density
- Lightweight construction
- Fast charging capability
- High efficiency
- Low self-discharge rate
- High manufacturing cost

- Capacity degradation over time
- Thermal sensitivity
- Requirement for an advanced Battery Management System (BMS)
- Excellent compatibility with regenerative braking systems

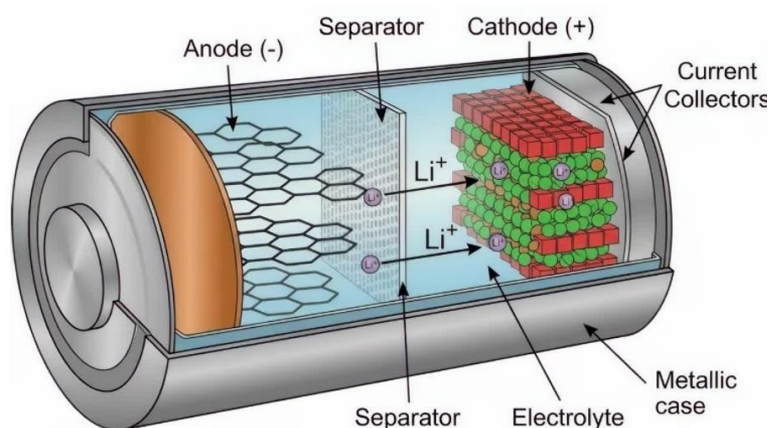


Figure 6. Basic structure of a Lithium-ion battery cell, including the anode, cathode, separator, and electrolyte. Source: Adapted from Koech et al. [3].



Figure 7. The internal structure of a lithium-ion battery cell. Source: Adapted from Koech et al. [3].

4.2 Lithium Iron Phosphate (LFP) Batteries

Lithium Iron Phosphate (LFP) batteries have become increasingly popular due to their superior thermal stability, safety, and long service life. Manufacturers such as BYD and Tesla have adopted LFP batteries in several commercial EV models [3].

Advantages

- Excellent thermal stability

- High safety
- Long cycle life (often exceeding 4,000 cycles)
- Lower manufacturing cost

Disadvantages

- Lower energy density
- Heavier battery packs
- Shorter driving range compared with NMC batteries
- Good environmental performance

4.3 Nickel Manganese Cobalt (NMC) Batteries

Nickel Manganese Cobalt (NMC) batteries are among the most commonly used battery chemistries in European, Japanese, and Korean electric vehicles due to their balanced performance characteristics [3].

Advantages

- High energy density
- High specific power
- Lightweight design
- Long driving range
- Excellent charging performance

Disadvantages

- Higher production cost
- Dependence on cobalt
- Greater thermal management requirements

4.4 Nickel Cobalt Aluminum (NCA) Batteries

Nickel Cobalt Aluminum (NCA) batteries are widely recognized for their very high energy density and have been extensively utilized in several Tesla vehicle platforms [2].

Advantages

- Very high energy density
- Lightweight construction
- Excellent power output
- Long driving range

Disadvantages

- Higher manufacturing cost
- Increased thermal sensitivity
- More demanding battery cooling systems

4.5 Solid-State Batteries

Solid-state batteries represent one of the most promising next-generation battery technologies. Unlike conventional lithium-ion batteries, they utilize solid electrolytes instead of liquid electrolytes, significantly improving both safety and energy density [3].

Advantages

- Improved safety
- Higher energy density
- Faster charging capability
- Longer lifespan
- Reduced fire risk
- **Disadvantages**
- High production cost
- Manufacturing complexity
- Limited large-scale commercialization

Several major automotive manufacturers are investing heavily in the commercialization of solid-state battery technology for future electric vehicles.

Table 4. Comparison of Major EV Battery Technologies (Adapted from Koech et al. [3])

Battery Type	Energy Density	Cycle Life	Safety	Relative Cost
LFP	Medium	Very High	Excellent	Low
NMC	High	High	Good	High
NCA	Very High	High	Moderate	High
Solid-State	Very High	Very High	Excellent	Very High

4.6 Supercapacitors

Supercapacitors are energy storage devices capable of storing and delivering electrical energy within a very short period. Although their energy density is significantly lower than that of batteries, they provide exceptionally high power density and rapid charge-discharge capability [2].

Typical applications include:

- ✓ Regenerative braking systems
- ✓ Vehicle acceleration assistance
- ✓ Peak power support
- ✓ Battery load reduction
- ✓ Extending battery lifespan

4.7 Hydrogen Fuel Cell Systems

Fuel Cell Electric Vehicles (FCEVs) generate electrical energy through an electrochemical reaction between hydrogen and oxygen. Unlike battery electric vehicles, electricity is produced onboard during vehicle operation rather than stored entirely in batteries [8].

Advantages

- Long driving range
- Rapid refueling
- Zero tailpipe emissions
- High energy conversion efficiency

Disadvantages

- High infrastructure cost
- Limited hydrogen refueling stations
- Expensive hydrogen production

Storage and transportation challenge

4.8 Battery Thermal Management System (BTMS)

Battery performance is highly dependent on operating temperature. Excessive temperatures accelerate battery degradation, while low temperatures significantly reduce charging efficiency and available capacity [3].

Modern electric vehicles employ Battery Thermal Management Systems (BTMS) to maintain battery temperature within an optimal operating range.

Common cooling techniques include:

- Air cooling
- Liquid cooling
- Cooling plates
- Phase Change Materials (PCM)
- Refrigerant-based cooling

For most lithium-ion batteries, the optimal operating temperature is approximately 20–40°C.

4.9 Future Trends in Battery Technology

Continuous research is focused on improving battery performance through several technological innovations:

- ❖ Development of solid-state batteries
- ❖ Cobalt-free battery chemistries
- ❖ Silicon-based anodes
- ❖ Lithium-sulfur batteries
- ❖ Lithium-metal batteries
- ❖ Artificial intelligence-based battery management
- ❖ Advanced battery recycling technologies
- ❖ Second-life applications for retired EV batteries

These innovations are expected to reduce battery costs while simultaneously increasing driving range, safety, and charging speed over the coming decade [2,6].

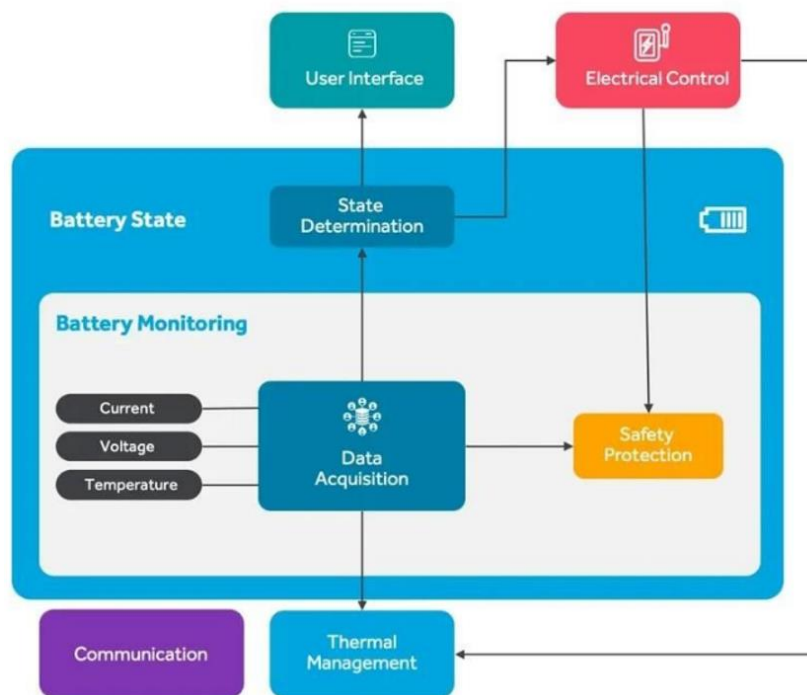


Figure 8. Typical Battery Thermal Management System (BTMS) used in modern electric vehicles. [11]

Section Summary

Battery technology remains the most influential factor affecting the performance, safety, cost, and commercial success of electric vehicles. Although lithium-ion batteries currently dominate the market, continuous improvements in battery chemistry, thermal management, charging strategies, and recycling technologies are expected to further accelerate the transition toward sustainable electric transportation. Emerging technologies such as solid-state batteries and advanced Battery Thermal Management Systems will likely play a central role in the next generation of electric vehicles.

5. ELECTRIC VEHICLE CHARGING TECHNOLOGIES AND CHARGING PROTOCOLS

The rapid expansion of electric vehicles (EVs) has significantly increased the demand for efficient, reliable, and standardized charging infrastructures. Charging technologies directly influence user convenience, driving range, battery lifespan, and the overall acceptance of electric mobility. Consequently, numerous international standards and communication protocols have been developed to ensure compatibility, safety, and high-performance charging across different vehicle manufacturers and charging networks [2,4–6].

5.1 Electric Vehicle Charging Methods

5.1.1 AC Charging

Alternating Current (AC) charging is the most common charging method used in residential buildings, workplaces, and public parking facilities. In AC charging systems, the onboard charger (OBC) installed inside the vehicle converts alternating current supplied by the electrical grid into direct current (DC) required for battery charging [4].

Typical characteristics include:

- Charging power: 3.7–22 kW
- Charging duration: 4–12 hours
- Suitable for overnight charging
- Low installation cost
- High charging efficiency

Advantages

- Affordable charging equipment
- Longer battery life due to moderate charging rates

Disadvantages

- Relatively slow charging speed
- Limited suitability for long-distance travel
- Widely available infrastructure
- Convenient for daily use

5.1.2 DC Fast Charging

Direct Current (DC) fast charging bypasses the vehicle's onboard charger by converting AC to DC inside the charging station. The DC electricity is delivered directly to the battery, allowing significantly shorter charging times [4,5].

Typical characteristics include:

- Charging power: 50–350 kW
- Charging time (20–80% SoC): 15–40 minutes
- Suitable for highways and commercial charging stations

Advantages

- Extremely fast charging
- Ideal for long-distance travel
- Increased vehicle availability

Disadvantages

- Higher installation cost
- Greater electrical infrastructure requirements
- Increased thermal stress on battery cells during frequent use

Table 5. Comparison of AC and DC Charging Systems (Adapted from Brenna et al. [4])

Parameter	AC Charging	DC Fast Charging
Current Type	Alternating Current	Direct Current
Power Conversion	Inside the vehicle	Inside the charging station
Typical Power	3.7-22 kW	50-350 kW
Charging Time	4-12 h	15-40 min
Installation Cost	Low	High
Typical Application	Home & workplace	Public fast-charging stations

5.2 International Charging Standards

To ensure interoperability among electric vehicles and charging infrastructures, several international charging connector standards have been developed.

5.2.1 Combined Charging System (CCS)

The Combined Charging System (CCS) is currently one of the most widely adopted charging standards in Europe and North America. CCS supports both AC and DC charging through a single connector, making it highly flexible and practical [4].

Advantages:

- ✓ Supports both AC and DC charging
- ✓ High charging power
- ✓ Broad manufacturer support
- ✓ Continuous technological development

5.2.2 CHAdeMO

CHAdeMO was the first commercially successful DC fast-charging standard, originally developed in Japan.

Typical characteristics include:

- ✓ Charging power: 50–150 kW
- ✓ Excellent operational reliability
- ✓ Native support for bidirectional charging (V2G)

It has been widely adopted by early Nissan and Mitsubishi electric vehicles [5].

5.2.3 GB/T Standard

GB/T is the national charging standard developed in China and is extensively used by Chinese electric vehicle manufacturers.

Its major advantages include:

- ✓ Low implementation cost

- ✓ Excellent compatibility within the Chinese market
- ✓ Continuous technological improvements
- ✓ High-power charging capability in newer versions

5.2.4 North American Charging Standard (NACS)

Originally developed by Tesla, the North American Charging Standard (NACS) has recently gained widespread industry acceptance throughout North America.

- ✓ Key features include:
- ✓ Compact connector design
- ✓ High reliability
- ✓ AC and DC charging compatibility
- ✓ High charging power capability

Several major automotive manufacturers have announced future compatibility with NACS charging infrastructure [5].



Figure 9. Comparison of Standard Charging Connectors for Electric Vehicles. Adapted from Brenna et al. [4].

5.2.5 Megawatt Charging System (MCS)

The Megawatt Charging System (MCS) has been specifically designed for heavy-duty electric vehicles, including trucks, buses, and industrial transportation systems.

Typical characteristics include:

- ✓ Charging power exceeding 1 MW
- ✓ Ultra-fast charging capability
- Support for commercial transportation electrification

Table 6. Comparison of Major EV Charging Standards (Adapted from Brenna et al. [4])

Charging Standard	Main Region	Charging Type	Maximum Charging Power
CCS	Europe, North America	AC & DC	Up to 350 kW
CHAdeMO	Japan	DC	Up to 150 kW
GB/T	China	AC & DC	Up to 250 kW
NACS	North America	AC & DC	Up to 500 kW*
MCS	Heavy-duty Vehicles	DC	>1 MW

*Depending on charger generation and implementation.

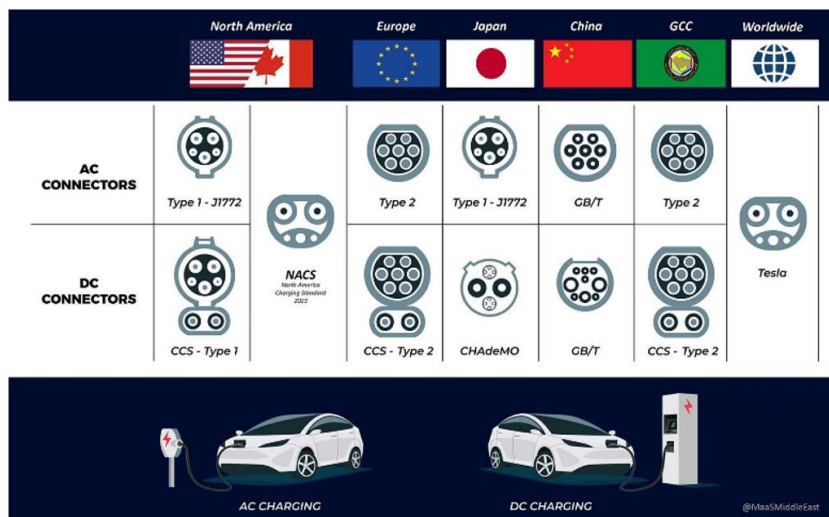


Figure 10. Comparison between AC charging and DC fast charging systems for electric vehicles. Source: Adapted from Brenna et al. [4].

5.3 International Charging Standards and Communication Protocols

Several international standards regulate the safety, interoperability, and communication between electric vehicles and charging stations.

The most important standards include:

- IEC 61851 – Conductive charging systems
- IEC 62196 – Charging connectors and plugs
- ISO 15118 – Vehicle-to-charger communication
- SAE J1772 – AC charging interface
- IEC 60364 – Electrical installation safety

These standards ensure charging safety, communication reliability, and interoperability among different manufacturers [4].

5.4 Vehicle-to-Grid (V2G) Technology

Vehicle-to-Grid (V2G) technology enables bidirectional power flow between electric vehicles and the electrical grid. Instead of functioning solely as electricity consumers, electric vehicles can temporarily return stored energy to the grid during peak demand periods [5,10].

Advantages

- Grid stabilization
- Peak load reduction
- Improved renewable energy integration
- Additional revenue opportunities for EV owners
- Enhanced energy management

Challenges

- Battery degradation
- Infrastructure investment
- Regulatory considerations
- Cybersecurity requirements

5.5 Plug-and-Charge Technology

Plug-and-Charge is an intelligent charging technology based on ISO 15118, enabling automatic authentication and billing immediately after connecting the charging cable.

Unlike conventional charging methods, users do not require RFID cards or mobile applications.

Advantages:

- ✓ Improved user convenience
- ✓ Secure communication
- ✓ Faster charging initiation
- ✓ Fully automated authentication

5.6 Challenges in Charging Infrastructure Development

Despite significant technological progress, several barriers continue to limit the widespread deployment of charging infrastructure.

Major challenges include:

- High installation costs for fast-charging stations
- Electrical grid capacity limitations
- Uneven geographical distribution
- Long charging times compared with gasoline refueling
- Lack of complete global standardization
- Demand for renewable electricity integration

5.7 Future Developments in EV Charging

Future charging technologies are expected to focus on:

- Ultra-fast charging (>500 kW)
- Megawatt Charging Systems (MCS)
- Wireless charging

- Dynamic charging while driving
- AI-based charging optimization
- Smart grid integration
- Renewable energy-powered charging stations
- Bidirectional charging expansion
- Battery swapping technologies

These innovations are expected to significantly reduce charging time while improving charging efficiency and grid stability [5,10].



Figure 11. Typical high-power DC fast-charging station equipped with a CCS connector.
Source: Adapted from Energy Reports [5].

Section Summary

Charging technologies represent one of the most critical enabling factors for the widespread adoption of electric vehicles. Continuous improvements in fast-charging systems, communication protocols, and international charging standards have significantly enhanced charging performance and interoperability. Emerging technologies such as Vehicle-to-Grid (V2G), Plug-and-Charge, Megawatt Charging Systems (MCS), and wireless charging are expected to transform future charging infrastructures and facilitate the global transition toward sustainable electric transportation.

6. Applications, Advantages, Disadvantages, Economic Analysis, and Environmental Perspectives of Electric Vehicles

Electric vehicles (EVs) have become an essential component of modern transportation systems due to their high energy efficiency, low operating costs, and environmental benefits. Their applications have expanded rapidly from passenger cars to public transportation, logistics, industrial equipment, marine transportation, and aviation. At the same time, EVs have introduced new economic opportunities and environmental challenges that require comprehensive evaluation throughout their entire life cycle [2,8,9].

6.1 Applications of Electric Vehicles

6.1.1 Passenger Transportation

Passenger cars represent the largest segment of the electric vehicle market. Continuous improvements in battery technology and charging infrastructure have significantly increased the popularity of Battery Electric Vehicles (BEVs) and Plug-in Hybrid Electric Vehicles (PHEVs) among private consumers.

Major manufacturers include:

Tesla, BYD, Hyundai, BMW, Mercedes-Benz, Volkswagen, Kia

The primary benefits include:

Reduced fuel expenses, Lower maintenance costs, Quiet operation, High driving comfort, Zero local emissions

6.1.2 Public Transportation

Electric buses have become increasingly common in metropolitan areas worldwide because they reduce urban air pollution and noise while lowering operating expenses.

Typical advantages include:

- ✓ High passenger capacity
- ✓ Reduced greenhouse gas emissions
- ✓ Lower operating costs
- ✓ Improved urban air quality
- ✓ Quiet operation

China currently operates the world's largest fleet of electric buses [8].

6.1.3 Commercial Transportation

Electric delivery vans and commercial vehicles are increasingly utilized in urban logistics.

Typical applications include:

- ✓ Parcel delivery
- ✓ Postal services
- ✓ Food distribution
- ✓ E-commerce logistics
- ✓ Last-mile delivery

The relatively predictable daily driving distances make electric commercial vehicles economically attractive.

6.1.4 Heavy-Duty Transportation

Heavy-duty electric trucks are emerging as an important solution for reducing emissions in freight transportation.

Current applications include:

- Long-haul trucking
- Construction equipment
- Mining operations
- Port logistics
- Industrial transportation

The development of Megawatt Charging Systems (MCS) is expected to accelerate heavy-duty vehicle electrification [10].

6.1.5 Two-Wheelers and Micro-Mobility

Electric motorcycles, scooters, and bicycles have experienced rapid market growth due to their affordability and convenience.

Applications include:

- Urban commuting
- Campus transportation
- Tourism
- Shared mobility services

6.1.6 Marine and Aviation Applications

Although still in early stages of commercialization, electric propulsion technologies are increasingly being investigated for:

- Ferries
- Small passenger vessels
- Recreational boats
- Short-range aircraft
- Urban air mobility systems

6.2 Advantages of Electric Vehicles

Electric vehicles provide numerous technical, economic, and environmental advantages compared with conventional internal combustion engine vehicles.

Technical Advantages:

- ✓ High drivetrain efficiency (typically above 90%)
- ✓ Instant torque delivery
- ✓ Smooth acceleration
- ✓ Quiet operation
- ✓ Reduced mechanical complexity
- ✓ Regenerative braking capability

Economic Advantages:

- ✓ Lower operating costs

- ✓ Lower maintenance requirements
- ✓ Reduced fuel expenditures
- ✓ Higher energy efficiency
- ✓ Lower lifetime ownership cost in many applications

Environmental Advantages:

- ✓ Zero tailpipe emissions
- ✓ Reduced greenhouse gas emissions
- ✓ Improved urban air quality
- ✓ Reduced noise pollution
- ✓ Greater compatibility with renewable energy systems

Table 7. Major Advantages and Disadvantages of Electric Vehicles (Adapted from Sriabisha et al. [9])

Advantages	Disadvantages
High energy efficiency	Higher purchase price
Low operating cost	Limited charging infrastructure
Zero local emissions	Longer charging time
Quiet operation	Battery degradation
Reduced maintenance	High battery replacement cost
Renewable energy compatibility	Dependence on critical raw materials

6.3 Disadvantages and Technical Challenges

Despite significant technological progress, electric vehicles still face several important limitations.

➤ **Battery Cost**

Battery packs remain the most expensive component of an electric vehicle, accounting for a substantial portion of the total manufacturing cost [3].

➤ **Charging Infrastructure**

Although charging networks continue to expand globally, infrastructure availability remains insufficient in many developing regions [10].

➤ **Charging Time**

Even modern DC fast chargers generally require 15–40 minutes to recharge a battery from approximately 20% to 80%, whereas conventional fuel refueling typically requires less than five minutes [4].

➤ **Battery Aging**

Repeated charging cycles gradually reduce battery capacity and driving range. Battery degradation is influenced by:

- High charging rates
- High operating temperatures
- Deep discharge cycles
- Battery chemistry

6.4 Economic Perspectives

The economics of electric vehicles should be evaluated using the Total Cost of Ownership (TCO) rather than the initial purchase price alone.

The TCO includes:

- Vehicle purchase price
- Fuel or electricity costs
- Maintenance expenses
- Insurance
- Battery replacement
- Residual value

Although EVs generally have higher upfront costs, reduced energy consumption and lower maintenance expenses often compensate over the vehicle's operational lifetime [8].

Government incentives also contribute significantly to EV adoption.

Common incentive policies include:

- Purchase subsidies
- Tax exemptions
- Reduced registration fees
- Free parking
- Toll exemptions
- Investment in charging infrastructure

6.5 Environmental Perspectives

Electric vehicles play a critical role in achieving global climate objectives. However, their environmental impacts should be assessed throughout the complete vehicle life cycle.

The Life Cycle Assessment (LCA) generally includes:

- Raw material extraction
- Battery manufacturing
- Vehicle production
- Vehicle operation
- End-of-life recycling

Studies indicate that electric vehicles generally produce lower lifetime greenhouse gas emissions than conventional vehicles, particularly when electricity is generated from renewable energy sources [8].

6.5.1 Battery Recycling

Battery recycling has become one of the most important research areas in sustainable electric transportation. The primary recoverable materials include: Lithium, Nickel, Cobalt, Copper, Aluminum, Graphite, Advanced recycling technologies can significantly reduce dependence on newly mined critical materials while minimizing environmental impacts [3].

6.5.2 Second-Life Applications

After their automotive service life, EV batteries often retain approximately 70–80% of their original capacity, making them suitable for second-life applications.

Examples include:

- Residential energy storage
- Solar energy storage systems
- Grid stabilization
- Backup power systems
- Industrial energy storage

Second-life utilization extends battery service life and improves overall sustainability.

6.6 Future Outlook

The future development of electric vehicles is expected to be driven by several technological innovations:

- Solid-state batteries
- Artificial intelligence-based battery management
- Autonomous electric vehicles
- Wireless charging
- Vehicle-to-Grid (V2G)
- Smart charging systems
- Renewable energy integration
- Ultra-fast charging
- Battery swapping technologies
- Circular battery economy

These developments are expected to improve vehicle performance while reducing manufacturing costs and environmental impacts [6,10].

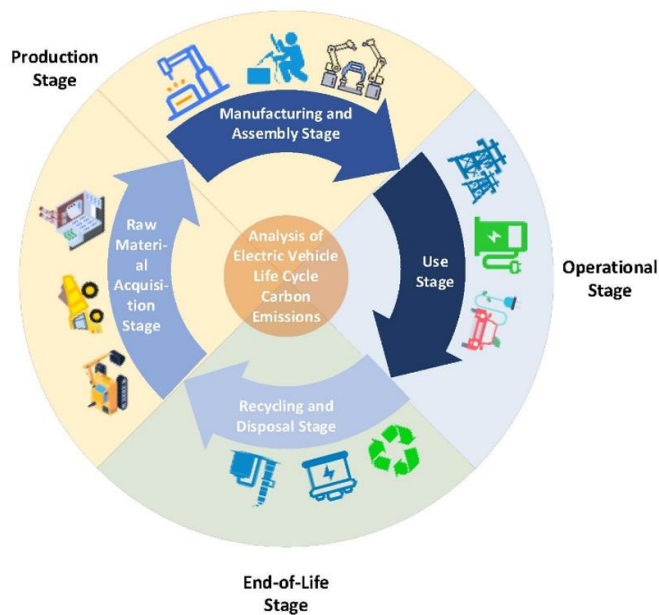


Figure 12. Life Cycle Assessment (LCA) framework for electric vehicles, illustrating the major stages from raw material extraction to end-of-life recycling. Source: Adapted from Leijon [6].

Section Summary

Electric vehicles are rapidly transforming global transportation systems by providing cleaner, more efficient, and economically attractive mobility solutions. Despite existing challenges—including battery costs, charging infrastructure, and critical material supply—the continuous advancement of battery technologies, charging systems, and energy management solutions is expected to accelerate worldwide EV adoption. Moreover, life-cycle analysis demonstrates that electric vehicles can substantially reduce greenhouse gas emissions and contribute to achieving long-term sustainability goals when integrated with renewable energy resources [6,8,10].

7. CONCLUSION

Electric vehicles (EVs) have emerged as one of the most transformative technologies in the modern transportation sector, offering a sustainable alternative to conventional internal combustion engine vehicles. Continuous advancements in battery technologies, electric propulsion systems, charging infrastructure, and intelligent energy management have significantly accelerated the global transition toward electrified transportation. Today, EVs are no longer considered an emerging technology but have become a strategic solution for reducing greenhouse gas emissions, improving energy efficiency, and enhancing energy security [1,2].

This review comprehensively discussed the classification of electric vehicles, including Battery Electric Vehicles (BEVs), Hybrid Electric Vehicles (HEVs), Plug-in Hybrid Electric Vehicles (PHEVs), and Fuel Cell Electric Vehicles (FCEVs). Their operating principles, advantages, limitations, and practical applications were systematically compared. Furthermore, the study examined the core technologies employed in modern EVs, including electric motors, power electronic converters, regenerative braking systems, Battery Management Systems (BMS), and battery thermal management systems. A detailed review of current battery

technologies demonstrated that lithium-ion batteries remain the dominant energy storage solution for electric vehicles due to their high energy density, efficiency, and commercial maturity. Among lithium-ion chemistries, LFP, NMC, and NCA batteries each present distinct advantages and limitations depending on specific application requirements. Meanwhile, solid-state batteries have been identified as one of the most promising future technologies because of their superior safety, higher energy density, and longer operational life [2,3]. The review also highlighted the importance of modern charging technologies and international charging standards. AC charging, DC fast charging, CCS, CHAdeMO, GB/T, NACS, Vehicle-to-Grid (V2G), Plug-and-Charge, and Megawatt Charging Systems (MCS) collectively represent the technological foundation of future charging infrastructures. Continued expansion of charging networks and improved interoperability among international standards are expected to accelerate EV adoption worldwide [4,5,10]. From an economic perspective, although electric vehicles generally require higher initial investments, lower operating costs, reduced maintenance expenses, and improved energy efficiency frequently result in competitive or even lower Total Cost of Ownership (TCO) throughout the vehicle lifetime. Government incentives, technological innovation, and economies of scale are expected to further reduce battery costs and increase market competitiveness [8]. Environmental analysis indicates that electric vehicles substantially reduce greenhouse gas emissions, urban air pollution, and dependence on fossil fuels, particularly when electricity is generated from renewable energy sources. Nevertheless, challenges associated with battery manufacturing, critical raw material extraction, recycling, and end-of-life battery management remain important research priorities. Life Cycle Assessment (LCA) confirms that sustainable battery production, efficient recycling technologies, and second-life battery applications will be essential for maximizing the environmental benefits of electric mobility [3,6,8]. Despite remarkable technological progress, several challenges continue to limit widespread EV deployment. These include limited charging infrastructure in some regions, charging duration, battery degradation, raw material availability, and high battery manufacturing costs. However, ongoing research in artificial intelligence-based battery management, wireless charging, ultra-fast charging, solid-state batteries, and smart grid integration is expected to address many of these challenges in the near future [6,10]. Overall, electric vehicles represent one of the most effective technological pathways toward sustainable transportation. Continued collaboration among governments, academic researchers, automobile manufacturers, and energy providers will play a crucial role in accelerating the transition toward cleaner, safer, and more efficient transportation systems. Future developments in battery technology, charging infrastructure, renewable energy integration, and intelligent energy management are expected to make electric vehicles the dominant transportation technology over the coming decades.

Overall Summary

Electric vehicles are revolutionizing the transportation industry by combining high energy efficiency, reduced environmental impacts, and advanced intelligent technologies. This review has presented a comprehensive overview of EV classifications, battery technologies, charging systems, charging protocols, applications, economic considerations, and environmental impacts. The analysis demonstrates that battery technology remains the key factor influencing

vehicle performance, cost, driving range, and market acceptance. Simultaneously, the expansion of charging infrastructure and the adoption of standardized charging protocols will be critical for supporting large-scale EV deployment. Although several technical and economic challenges remain unresolved, continuous innovation in battery chemistry, renewable energy integration, artificial intelligence, and smart charging technologies is expected to overcome these limitations. Consequently, electric vehicles will continue to play a central role in achieving global sustainability objectives, reducing carbon emissions, and transforming future transportation systems.



Figure 13. An electric vehicle charges in Monrovia, California [12]



Figure 14. A Tesla charges in the rain at an electric vehicle charging station in Portland, Oregon [12]



Figure 15. Chinese-made vehicles including BYD cars (L) wait to be transhipped for export at a port in Suzhou, in China's eastern Jiangsu province on April 27, 2026 [12]

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