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Review Article

A Review on Electric Vehicles: Technical, Environmental, and Economic Perspectives

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ABSTRACT

To pursue a sustainable electric vehicle ecosystem, it is crucial to study operational principles, technical complications, environmental impacts, and economic repercussions individually and collectively. This review article provides an overview of the all-around analysis of the electric vehicle ecosystem with an integrated approach. The review begins with an in-depth introduction and a research methodology exploring various types of electric vehicles, analyzing their applications beyond transportation and their potential for sustainable integration. The technical aspects of electric vehicles are scrutinized, with a logical analysis of batteries, chargers, motors, and other components. The review also explores the novel coordinated vehicle-to-grid concept, offering valuable insights for its practical implementation. The paper discusses electric vehicle's environmental impact with quantitative analysis, which compares the ecological footprint against traditional vehicles, focusing on solar electric vehicles. Economic aspects of electric vehicle adoption are also examined, with a detailed analysis of regional markets, their spending on the electric vehicle ecosystem, and the total cost of ownership for electric vehicles. Finally, the review presents technical challenges related to high upfront costs, zero-emission vehicles, charging infrastructure, infotainment and connected vehicles, and charging technology. This review might be an indispensable tool for researchers and policymakers, offering a nuanced and comprehensive perspective.

KEYWORDS

Electric vehicles, EV Ecosystem, Battery technology, Environmental perspectives, Solar electric vehicle.

INTRODUCTION

The popularity of electric vehicles (EVs) has recently marked a transformative era in the automotive industry, revolutionizing transportation and challenging traditional fuel-powered automobiles. EVs extend their influence far beyond the confines of commercial or personal transportation toward larger sustainability goals. Beyond transportation, EVs serve as reliable ancillary service providers to the grid, enhancing renewable energy integration to smooth grid fluctuations and instability. Vehicle-to-grid (V2G) technology represents an interdependent relationship between EVs and the power grid. This enables a bidirectional energy flow, allowing EVs to charge from the grid and feed excess energy back during low-demand periods [1]. This bidirectional energy exchange optimizes energy usage and contributes to grid stability and resilience [2].

Moreover, all the EV batteries connected to the same grid can serve as a large-capacity decentralized energy storage. EV batteries can store excess energy from the grid, and later, this energy can be utilized to balance power demand and supply fluctuations, contributing to grid resilience and efficiency [3]. EV storage can also be used by offering flexible EV charging schedules. EV owners can charge their vehicles during high renewable energy production periods, aligning consumption with the availability of clean energy, thus reducing reliance on conventional power plants [4]. This charging approach promotes a greener and more sustainable energy mix. Technically, EVs represent innovation in cutting-edge power electronics, battery technologies, electronic chargers, motor drives, regenerative braking systems, and sophisticated energy management [5].

Furthermore, the proliferation of EVs is also linked with environmental, social, and economic aspects [6]. The environmental impact of EVs is evident in their reduced carbon footprint compared to traditional cars. EVs are known to lower emissions and help mitigate the adverse effects of climate change, especially when charged with electricity from renewable sources. Similarly, contributing to better air quality and reduced noise in urban areas, EVs eliminate toxic emissions such as nitrogen oxides and particulate matter, thereby reducing respiratory issues and other health problems [7]. Reducing air and noise pollution provides a healthier and more peaceful living environment. From a social perspective, the adoption of EVs fosters healthier communities and encourages people to embrace eco-friendly practices [8]. The EV industry promotes economic development through research, manufacturing, maintenance support, and supply chain services.

On the other hand, EVs have lower operating expenses than conventional cars due to fewer moving parts, indicating reduced maintenance requirements and lower fuel costs [9]. With straightforward design, EVs often require fewer raw materials and resources for manufacturing, contributing to sustainable manufacturing practices. Moreover, EVs reduce reliance on imported fossil fuels, enhancing energy security and safeguarding economies from global oil market volatility [10]. Governments also incentivize EV adoption through subsidies and tax credits, encouraging innovation and investment to boost economic development [11]. As the adoption of EVs aids in reducing pollution and emissions, economies stand to gain from improved public health and lower costs associated with environmental cleanup.

Although many review articles have examined EVs' technical, environmental, and economic aspects independently, there is a noticeable lack of comprehensive reviews that integrate all these dimensions in the existing literature [7]. This article addresses this research gap by offering a comprehensive technical, environmental, and economic analysis, insights for policymakers and technology regulators, and uncovering fresh academic research avenues. The fusion of technical, environmental, social, and economic insights also guides policymakers, industry stakeholders, and researchers toward a sustainable EV ecosystem.

This review addresses three main topics: (1) Technical Aspects, which focus on EV operation, architecture, and state-of-the-art technologies to improve performance; (2) Environmental Issues, highlighting the role of EV technology in meeting climate change goals and emphasizing the importance of public perception and communication about health benefits to encourage greater adoption; and (3) Economic Viability, discussing the commercial and financial aspects of EVs along with their challenges.

The paper begins with Section I, introducing EVs and establishing the background for the proposed review article. Section II outlines the utilized research methodology. Section III focuses on the operating principles of EVs, encompassing various types, benefits, and prospects. Section IV is dedicated to the technical aspects of EVs, offering insights into the recent research on batteries, chargers, motors, and machines. Section V delves into the extended concept of coordinated V2G technology, acknowledging its pivotal role. Section VI presents a comprehensive review of environmental aspects, including a quantitative comparison with conventional vehicles and an exploration of the advantages of solar EV chargers. Section VII explores economic aspects and the growth of regional EV markets. Finally, section VIII summarizes the technical influences and challenges discussed throughout the paper.

METHODS

The research interest in the EV industry has grown significantly, as seen by the substantial increase in publications, according to Figure 1. The EV and related domain publications have increased by more than 1200% since 2010. This surge in publication activity indicates the EV demands and future trends. For this review, relevant research papers were sourced from the Google Scholar and Science Direct databases. The search protocol employed specific keywords, including 'Electric Vehicles,' 'Energy Storage Systems,' and 'Vehicle to Grid technologies' since 2010. This initial search yielded a substantial selection of 792,000 records, chosen based on keyword relevance, title specificity, and associated thematic content. This initial pool was narrowed down through a secondary selection process to streamline the review process and ensure the selection of the most authoritative and pertinent resources. The selected papers are evaluated based on the journal's impact factor, renowned conferences, and documents with the most citations.

Consequently, this screening process resulted in a more focused selection of 310 papers. Finally, a more rigorous selection process yielded 163 research articles identified as most relevant and influential to this study. More than 70 papers have been published within the last three years. This research offers the latest insights into the ongoing trends and advancements in EV technologies within technical, environmental, social, and economic contexts.

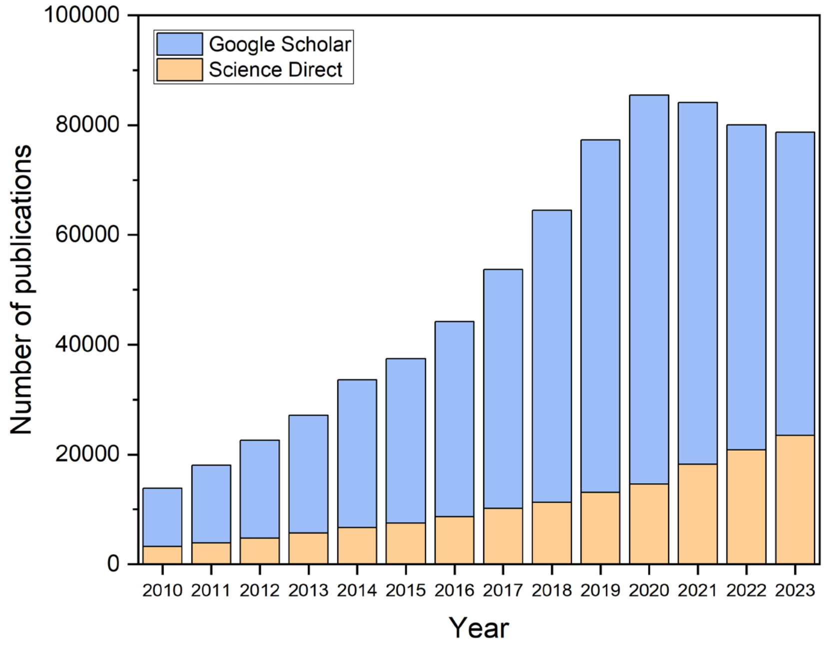


Figure 1. Electric vehicle publications in Science Direct and Google Scholar databases from 2010 to 2023.

OPERATIONAL PRINCIPLE OF ELECTRIC VEHICLES

EVs use lithium-ion battery banks to drive electric motors, enabling rapid acceleration. During EV deceleration or slowing down, the traction motor undergoes generator action, converting kinetic energy back into electricity and feeding it back to the battery for storage and future use; this is called regenerative braking [12]. Power electronics, including inverters and converters, manage the precise flow of electricity between the battery and the motor to optimize performance and efficiency. Recharging the EV involves connecting it to external power sources, such as charging stations or home outlets [13]. Charging EVs also need sophisticated thermal management to regulate the battery's temperature for optimal performance [14]. Additionally, EVs utilize diverse drive modes and controls to customize the user's driving experience and energy consumption. A lithium-ion battery is used in EVs because of its high efficiency and portability [15],[16].

Types of Electric Vehicles

EVs come in various types, each with distinct propulsion technologies. Battery Electric Vehicles (BEVs) operate exclusively on electric power stored in high-capacity batteries [17]. An electric motor converts this stored energy into mechanical power, propelling the vehicle with zero tailpipe emissions. Users recharge BEVs by plugging them into external power sources, like charging stations or home outlets. An intermediate vehicle combining the BEV and internal combustion engine (ICE) technologies is known as a Plug-in Hybrid Electric Vehicle (PHEV) [18]. PHEVs usually run on electric power for shorter trips and utilize the ICE for longer distances to achieve higher efficiencies than ICE. Users can recharge the battery by plugging it into an Alternating Current (AC) outlet or relying on the engine and regenerative braking to maintain the battery charge.

In contrast, Hybrid Electric Vehicles (HEVs) employ an ICE and an electric motor to assist the engine and enhance fuel efficiency, mainly during low-speed driving and idling [10]. However, unlike PHEVs, HEVs cannot be charged externally. Moreover, EVs compete with another green transport option, Fuel Cell Electric Vehicles (FCEVs). FCEVs employ H_2 gas to produce electricity through a fuel cell [19]. This electricity powers an electric motor, propelling the vehicle. FC vehicles emit only water vapor as a byproduct, offering a clean and sustainable alternative. Users refuel FCEVs with compressed hydrogen at dedicated fueling stations. Figure 2 shows the block diagram of four types of EVs.

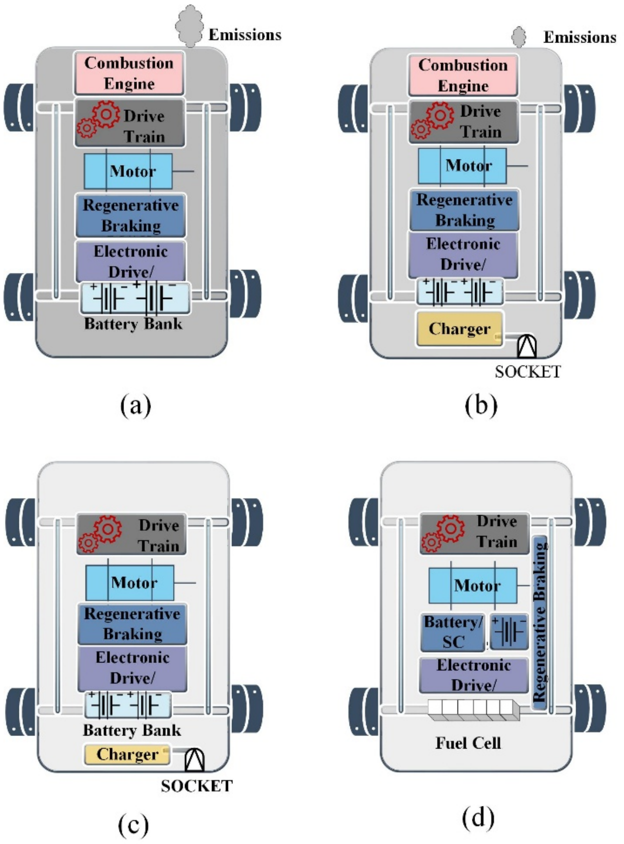


Figure 2. Types of electric vehicles: (a) Hybrid electric vehicle (b) Plugin-in hybrid electric vehicle (c) Battery electric vehicle (d) Fuel cell electric vehicle

Electric Vehicles Beyond Transportation

EVs represent more than personal transportation technology through innovations like V2G technology, enabling bidirectional energy flow between vehicles and the electrical grid [1]. EVs also serve as dynamic energy storage entities, with their batteries acting as decentralized storage units. This optimizes grid performance and contributes to efficient energy distribution [20]. The widespread adoption of EVs supports more renewable energy integration into the overall energy mix, thus reducing reliance on fossil fuels while mitigating climate change [21]. EVs ecosystem creates new jobs and economic growth, ensuring a more sustainable, interconnected, and technologically advanced future [4]. Figure 3 shows a Venn diagram that illustrates the interconnected relationships between EVs' technical, environmental, and economic aspects. Technical aspects include research and development, components like chargers and batteries, and energy management, focusing on the technological advancements necessary for EVs.

On the other hand, the environmental aspects emphasize resource management, environmental protection, and carbon emission control, highlighting the ecological benefits of EV adoption [7]. The economic elements cover business development, cost savings, research and development spending, and production processes, stressing the EV sector's financial and market growth opportunities [22]. The overlaps between these areas indicate their interrelationships below.

- **Technical and Environmental** – Developing infrastructure and integrating renewable energy sources (RES) with EVs enhances both technological and environmental benefits.
- **Technical and Economical** – Economic policies like tax incentives and subsidies that support technological advancements in the EV sector.

- **Environmental and Economical** – Financial benefits from environmentally friendly practices, such as cost savings from reduced emissions and economic incentives for sustainability.

At the center, where all three aspects intersect, are the social benefits, including improved drive quality, job creation, and reduced pollution. This central integration emphasizes the overall positive impact of EV adoption on society, driving increased EV sales, public involvement in sustainable practices, and the importance of transparent reporting and publishing of data and advancements. This comprehensive approach shows the need to study these aspects together, providing a holistic view crucial for effective policy-making and implementation.

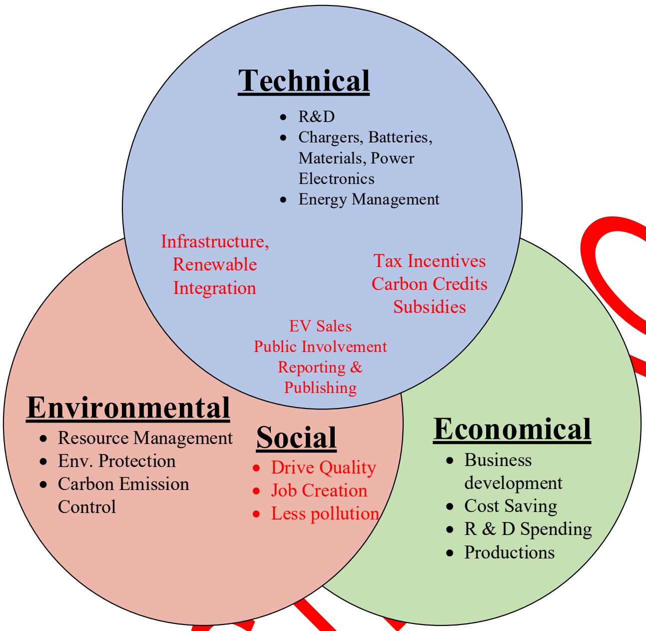


Figure 3. EV relationship between technical, environmental, and economic aspects

Electric Vehicle Technology and Sustainability Integration

The transition to EVs as mainstream transportation requires a robust electrical grid optimized for technical, environmental, and economic efficiency. An integrated approach that considers all three aspects will accelerate EV adoption [23]. The conceptual framework of the EV ecosystem is shown in Figure 4 [24]. The envisioned framework aligns EV technical, environmental, and financial aspects together to pave the way for a complete EV transition. The interdependency among stakeholders, including market players, regulatory bodies, and environmental policies, will be the key to EV adoption and sustainability [25].

It is observed that many EVs are connected to the power grid in clusters and other grid entities like power plants, consumers, and grid operators [26]. The smart grid can be controlled with state-of-the-art communication and artificial technologies [27]. The centralized controller is often used in literature with varying terminologies. Given the grid, which accommodates EV charging infrastructure, renewable energy, conventional power plants, and consumers, the role of the controller is vital and sophisticated; this grid controller is termed a Primary Energy Management System (PEMS) [3], [17], [28]. PEMS operates within a multi-layered power framework, starting at the generation layer, where multiple Generation Companies (GENCOs) produce electricity from diverse sources [29]. The generated power is transmitted and streamlined via the transmission layer [30]. Then, the Transmission System Operator (TSO) oversees the efficient flow of electricity through high-voltage networks, seamlessly transitioning it to the distribution layer [31]. This layer also integrates geographically dispersed renewable power plants, facilitating decentralized electricity generation and distribution to end-users [32].

The distribution system consists of static commercial, industrial, and residential users and an expanding network of EVs. At the core of this detailed system, the PEMS controls a delicate equilibrium between supply and demand, tariffs, policies, and sustainability objectives [33], [34]. PEMS operates as an Artificial Intelligence (AI) powered entity, accessing real-time data from various layers [27], [35]. It executes informed decisions and activations to optimize energy management on macro and micro scales. It directs GENCOs, TSOs, Distribution System Operators (DSOs), and the EV fleet through intelligent algorithms to maximize overall performance [27]. The economic layer facilitates market players' interaction to shape the EV ecosystem through market data collection and forecasting. Forecasting and machine learning algorithms are interdependent with technical operators to optimize demand, supply, and tariffs [36]. The economic layer also provides long-term assessments to formulate viable government/regulator policies to encourage EV acceptance [37]. Going beyond transportation, the pivotal role of EVs emerges in achieving Coordinated Vehicle-to-Grid (CV2G), actively contributing to grid stability, providing reactive power support, and functioning as energy storage units [29].

Figure 4. Integrated ecosystem of electric vehicles with renewable energy sources and grid management

The main functions of every module in the EV ecosystem are briefly defined below:

- **Generation Layer:** The electricity production in the EV ecosystem begins at the generation layer. GENCOs harness diverse energy sources like coal, nuclear, and hydropower to produce electrical power [38]. The generated electricity is then directed towards the transmission layer.
- **Transmission Layer:** The TSO takes charge of this layer, managing the grid network of high-voltage lines, such as 110 kV (HV), 33 kV, and 66 kV. This layer`s function is to efficiently transmit electricity over long distances [4]. Grid stations at various geographical locations are connected through transmission lines. These grid stations are

vital in transforming high voltages into usable lower levels, ensuring a smooth transition to the distribution layer.

- **Distribution Layer:** Grid stations at various geographical locations are connected through transmission lines. These grid stations are vital in transforming high voltages into usable lower levels, ensuring a smooth transition to the distribution layer [39]. The distribution voltages of 13 kV and 11 kV facilitate efficient electricity dispersal to industrial, commercial, and residential consumers, along with the fleet of EVs.
- **PEMS System:** PEMS is at the core of this ecosystem. PEMS collects real-time data from various layers and issues commands to actuators [27], [40]. It directs a delicate balance between supply and demand by considering tariffs, policies, and sustainability objectives. This ensures an optimized utilization of RES, contributing to a resilient power grid.
- **Economic Layer:** Grid stations at various geographical locations are connected through transmission lines. These grid stations are vital in transforming high voltages into usable lower levels, ensuring a smooth transition to the distribution layer [11]. This economic interaction encourages active participation in grid stability, connecting individual interests with broader sustainability goals.
- **V2G Coordination:** The role of EV fleets becomes pivotal in achieving CV2G. Beyond mere transportation, these EVs actively contribute to grid stability and serve as distributed energy resources [1], [3]. EVs provide ancillary services, including reactive power support and enhancing grid resilience. At the same time, EVs can act as energy storage units, offering flexibility in managing fluctuating energy demands.
- **Sustainability Integration:** The coordinated V2G approach achieves robust grid stability and transport sustainability. The layers concept covers generation, transmission, distribution, PEMS, economic interactions, and V2G coordination to implement ecosystem[41], [42]. Integrating technical advancements, environmental considerations, and social policies will lead to complete electric mobility.

EV ecosystem can be thoroughly comprehended by analyzing it through technical precision, economic collaboration, and sustainability integration [43]. With this comprehensive understanding, policymakers can formulate effective strategies to address barriers within the EV industry, ranging from affordability concerns to charging infrastructure limitations [28]. At the same time, integrating RES and EV charging and storage aligns with environmental benefits and stimulates growth within the green technology sector [44]. This harmonious integration extends to social advantages, such as improved air quality, contributing to global health [9]. The collaboration between academia and industry emerges as a driving force behind innovation in the EV industry, ensuring energy efficiency and economic viability. Initiatives like General Motors and LG Chem's joint research on advanced battery technology exemplify this collaborative effort [45]. The convergence of sustainability and technical goals attracts investors and positions EVs to transition with global ICE phase-out deadlines. EVs societal concerns, including safety, are also consistently addressed by organizations like Consumer Reports, highlighting public apprehensions and fostering increased acceptance of EVs [46]. As global electric car sales continue to rise, the substantial reduction in vehicle-related emissions becomes more relevant to environmental sustainability. Studying technical, environmental, and economical aspects aligns with societal objectives and provides the complete roadmap to implementing an EV ecosystem. This comprehensive approach encapsulates the current trajectory of EVs and sets the course for the future global energy landscape.

TECHNICAL ASPECT OF ELECTRIC VEHICLES

EV technology has undergone substantial advancements in the last decade. In the early stages, EVs faced challenges like limited range and extended charging times [43]. However, modern EVs continuously improve these constraints, especially in battery technology, electronic converters, and motors. Research literature extensively addresses challenges such as battery performance, expanding charging infrastructure, and environmental sustainability [41]. Moreover, integrating RES, smart grids, and storage technologies is pivotal for EVs' long-term success and adoption. This section reviews EV's technical aspects, evolution, and future scope.

Electric Vehicle Batteries

Early EVs were equipped with conventional lead-acid batteries. However, modern EVs have transitioned to advanced battery technologies such as lithium-ion, lithium metal hydride, or cutting-edge alternatives like solid-state batteries [47], [48], [49]. EV energy storage needs higher energy density, longer lifespan, and improved performance. Battery technologies have evolved significantly over time. The transition from lead-acid to nickel-based batteries, and finally to lithium-ion and solid-state batteries, represents a major advancement in energy storage efficiency. Recent developments also point towards sodium-ion batteries as a promising low-cost alternative.

Types of electric vehicle batteries. Batteries for EVs are usually bifurcated as primary and secondary batteries. Primary batteries are non-rechargeable and derive energy directly from chemical reactions. These batteries are commonly used in low-drain, disposable applications [47], [50]. The main material of primary batteries is alkaline, zinc-carbon, or lithium and requires slow trickle charging [51]. However, due to their slow-charging nature, primary batteries are utilized in HEVs.

On the other hand, secondary batteries are rapidly rechargeable, making them ideal for repeated use. Lead-acid batteries, the earliest type used in EVs, offered limited energy density, had more weight, and had a low life. The transition to nickel-based batteries, nickel-cadmium (NiCd) and nickel-metal hydride (NiMH) brought improvements in energy density and reduced environmental concerns [52]. However, these batteries still fell short in capacity and had higher self-discharge rates. The EV battery breakthrough came with the widespread adoption of lithium-ion batteries [53]. Unlike primary batteries, secondary batteries can store and release energy through reversible chemical reactions, allowing for multiple charge and discharge cycles. Tesla's success in popularizing EVs is closely tied to its use of high-performance lithium-ion batteries, contributing to the mass adoption of EVs [54]. Figure 5 presents the types of EV batteries.

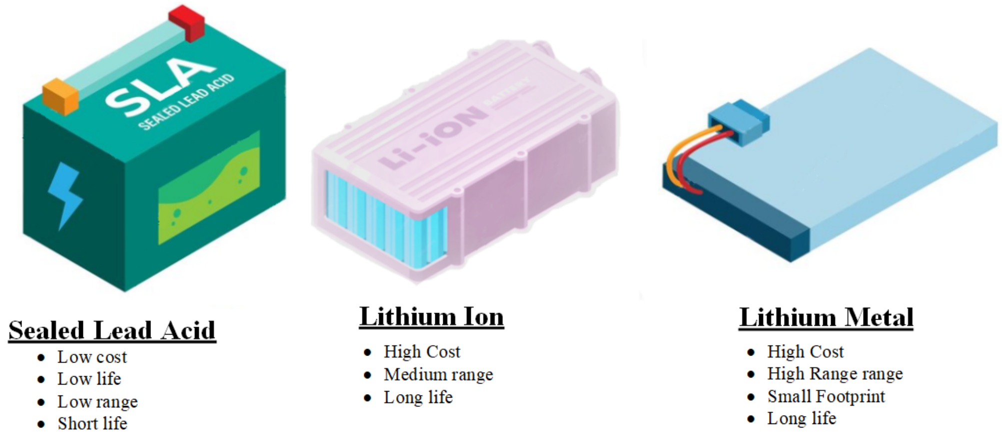


Figure 5. Types of EV batteries

Lithium-ion batteries have high energy density, lighter weight, and longer cycle life. These batteries are well-suited for modern EVs, offering better efficiency and a higher power-to-weight ratio compared to previous technologies [47], [50], [55]. EV performance is directly related to its batteries, making it a crucial component for overall vehicle success and acceptance [56]. The battery's capacity is measured in kilowatt-hours (kWh), which indicates the maximum amount of energy a battery can store. Energy density reflects how much energy a battery can hold relative to its weight, represented in watt-hours per kilogram (Wh/kg). While power density is measured in kilowatts per kilogram (kW/kg), it means the rate at which the battery can deliver energy [49]. The number of cycles denotes the number of charge-discharge cycles a battery can undergo before significant capacity degradation. Charge/discharge cycles are crucial factors influencing the lifespan of EVs. To quantify these attributes, the specific energy E_{spec} and specific power P_{spec} can be calculated using the following equations:

$$E_{spec} = \frac{E_{total}}{m} \tag{1}$$

$$P_{spec} = \frac{P_{total}}{m} \tag{2}$$

Where E_{spec} and P_{spec} are the specific energy and specific power in Wh/kg and kW/kg respectively. E_{total} is the total energy stored in the battery in Wh, P_{total} is total output power in kW, and m is the mass of the battery in kilograms kg. Table 1 provides a comparison among various EV batteries in terms of battery capacity, driving range, charging time and energy efficiency.

Table 1. Comparison of electric vehicle lithium-ion batteries parameters and performance [57]

Vehicle Model	Battery Capacity (kWh)	Range (km)	Charging Time (hrs)	Fast Charging Rate (kW)	Energy Efficiency (kWh/100 km)
Lucid Air Dream, P	120.0	665	9	924	18.05
Lucid Air Grand Touring.	112	665	10	924	16.84

Lotus Eletre	109	495	8	800	22.02
Mercedes EQS SUV 500	108.4	490	11	600	22.08
Mercedes EQS AMG 53 (4MATIC+)	120	540	10	600	22.22
Polestar 3 Long Range Dual motor	107	490	9	600	21.84
Mercedes-Benz EQA	66.5	429	4	100	15.50
Volvo EX90 Twin Motor	107	465	8	800	22.98
Mercedes-Benz EQE	90.56	669	9	800	13.51
Audi Q8 e-tron 55 quattro	106	495	8	800	21.41
Volvo XC40	78	418	4	100	18.66
BMW iX M60	105.2	485	7	150	21.74
Fisker Ocean Ultra	105	525	8	800	20.00
BMW i7 M70 xDrive	101.7	490	8	800	20.76
Volvo EX90 Single Motor	101	460	8	800	21.95
Kia EV9 99.8 kWh RWD	99.8	470	6	150	21.28
Tesla Model S Dual Motor	95	575	7	200	16.52
XPENG G9 RWD Long Range	94	470	5	150	20.00

Lithium nickel manganese cobalt and lithium iron phosphate batteries. Among lithium-ion battery chemistries, LiNMC (Lithium Nickel Manganese Cobalt) has become the dominant battery type in modern EVs, offering a higher energy density and improved driving range compared to Lithium Iron Phosphate (LFP) batteries [58]. However, LFP batteries are favored for affordability, thermal stability, and longer cycle life. Table 2 presents the comparison between the LiNMC and LFP batteries.

Table 2: Comparison of lithium nickel manganese cobalt and lithium iron phosphate batteries [59], [60].

Feature	LiNMC	LFP
Energy Density (Wh/kg)	150-250	90-120
Safety	Moderate (thermal runaway risk)	High (stable chemistry)
Lifespan (cycles)	1000-2000	>2000
Cost	Higher	Lower
Market Adoption	High-performance EVs	Budget and commercial EVs

Future battery technologies. Solid-state batteries replace liquid electrolytes with solid materials, improving energy density, safety, and cycle life [61]. These batteries can significantly enhance EV range and reduce charging time, but their high production cost remains a barrier to widespread commercialization [62]. Solid-state batteries could also move charge around faster, meaning shorter charging times. Moreover, because some solvents in electrolytes can be flammable, solid-state batteries improve safety by cutting fire risk.

Moreover, researchers are exploring new materials and chemical compositions to improve battery performance, reduce costs, and increase safety [63]. In addition to these research areas, many companies are improving the manufacturing process for EV batteries. For example, Schneider Electric offers an end-to-end solution called EcoStruxure for EV battery manufacturing, which aims to improve productivity, efficiency, and sustainability[64]. Similarly, sodium-ion batteries are emerging as a cost-effective alternative to lithium-ion technology. With sodium being more abundant and less expensive than lithium, these batteries could reduce the dependency on rare lithium resources, making EVs more affordable and sustainable. Table 3 presents the comparative performance of lithium-ion, sodium-ion, and solid-state batteries.

Table 3: Comparative performance of lithium-ion, sodium-ion, and solid-state batteries [65], [66], [67].

Feature	Lithium-Ion	Sodium-Ion	Solid-State
Energy Density	High	Moderate	Very High
Cost	Moderate	Low	High
Safety	Moderate	High	Very High
Commercial Availability	Widely Available	Emerging	In Development

On the other hand, lithium Metal Batteries (LMB) are known for their high energy density and negative standard reduction potential. LMBs were developed in the late 20th century, leading to the initial prototype of rechargeable Li/TiS$_2$ batteries [10], [51], [68]. Safety concerns of LMB are mainly related to dendrite formation and thermal runaways, making room for the development of lithium-ion batteries. Moreover, the research in LFP batteries has addressed safety concerns associated with early LMB batteries, making them even more suitable for automotive applications [69]. However, Lithium Sulfur (Li–S) and Lithium Superoxide (Li–O$_2$) batteries have become focal research areas in battery technology. Li–S cells, in particular, are advancing rapidly, with companies like OXIS Energy developing high-performance prototypes [70]. Many researchers are revisiting the LMB technology because it has the potential to surpass current battery capabilities, aiming for 500 Wh/kg. The transition to Generation 4 (all-solid-state with lithium metal) and Generation 5 (Li–S and Li–O2) batteries is anticipated by 2025 [10], [51], [68], [70]. Advances in materials and nanotechnology have brought renewed focus to LMBs. Many R&D programs targeting significant improvements in battery performance, cost, and manufacturing volume are actively pursuing better batteries for EVs. Additionally, efforts to enhance recycling processes for battery components contribute to the sustainability of EV technology. Improving charging infrastructure and reducing charging times are also active research areas needed to make EVs more practical and appealing to consumers.

Market trends and environmental impact. Battery technology is rapidly evolving, with LiNMC maintaining market dominance, LFP expanding in budget-friendly EVs, and solid-state and sodium-ion technologies expected to rise in the next decade. Figure 6 presents the projected market share of battery technologies from 2025 to 2034. It is found that the total market size for 2024 is $121.23 billion in 2024. This market is expected to grow by 111.235% in 2034 to $256.08 billion, expanding at a CAGR of 7.76% [71].

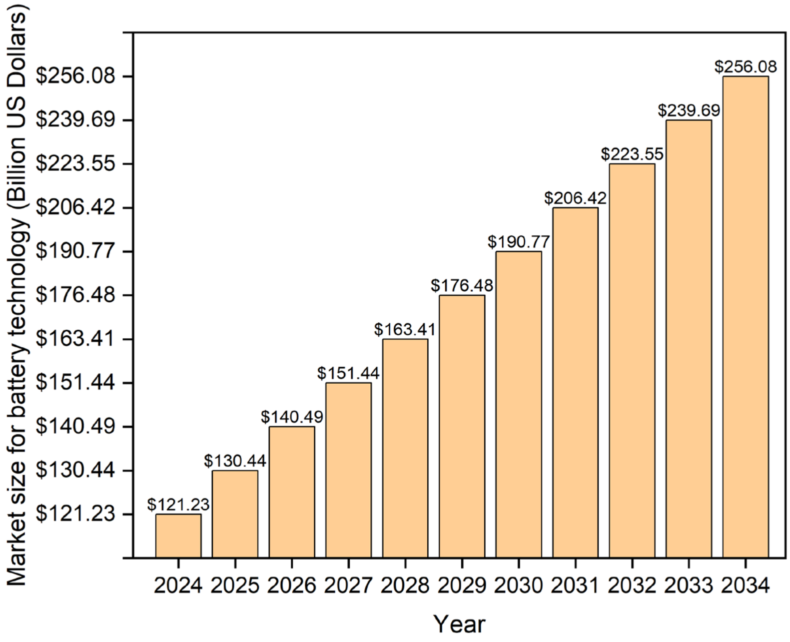


Figure 6. Projected market share of battery technologies from 2025 to 2035.

The primary factors driving this strong growth are the rapidly increasing demand for electronic equipment, the rising adoption of secondary batteries in the aviation and automotive industries, the expanding market for EVs, and the growing application of battery technologies in renewable energy sectors [72]. Additionally, advancements in battery technology continue to enhance performance, efficiency, and safety.

Figure 7 presents the EV battery demand from 2016 to 2023 [73]. The demand for EV batteries exceeded 750 GWh in 2023, representing a 40% increase compared to 2022. However, the annual growth rate slowed slightly compared to 2021-2022. High EV sales drove this growth. The United States and Europe experienced the fastest growth of major EV markets, followed by China. However, the United States remains the smallest market of the three, with approximately 100 GWh of battery demand in 2023, compared to 185 GWh in Europe and 415 GWh in China. In the rest of the world, battery demand grew by more than 70% in 2023 compared to 2022, driven by increasing EV sales.

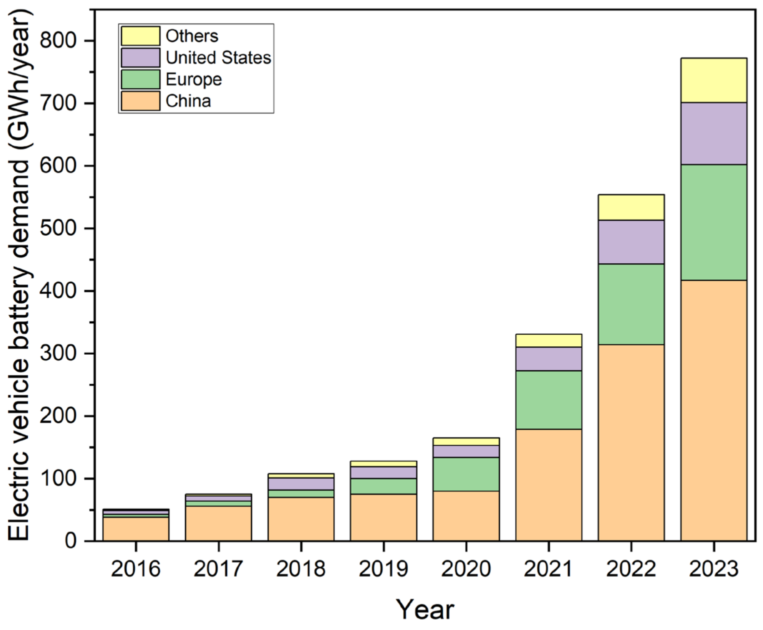


Figure 7. Electric vehicle battery demand by region from 2016 to 2023.

Lithium-ion batteries held the largest market share in 2022, driven by the surge in global demand for EVs. This growing adoption is expected to further accelerate demand in the foreseeable future. However, concerns about lithium-ion batteries, such as their reactivity with water, which can lead to safety hazards and accidents, have raised industry-wide concerns [74]. In response, the industry is actively addressing these challenges, leading to the development of new battery technologies. These safety concerns may also drive increased adoption of alternative battery technologies, including lead-acid, sodium-ion, and solid-state batteries, which are expected to contribute to the evolution and diversification of the battery market.

Electric Vehicle Chargers

The charging process involves transferring electrical energy to the vehicle's battery, enabling it to store power for propulsion. There are various charging methods, such as charging at residential or public places, slow, medium, ultra-fast charging, etc. However, challenges such as grid overload during peak hours and the need for RES to power charging stations remain critical areas of research in EV charging technology [5], [42], [75], [76]. Regulatory bodies like the Electric Power Research Institute (EPRI), the Society of Automotive Engineers (SAE), and the International Electrotechnical Commission (IEC) categorize, manage, and define safety standards across different countries [77], [78]. EV charging has three broad categories: conductive, wireless, and battery swapping, as shown in Figure 8. Conductive chargers use physical conductors to transfer energy to the battery bank, while wireless charging leverages electromagnetic fields to avoid conductors. On the other hand, battery swapping involves interchanging the battery pack and saving time. Moreover, conductive chargers are categorized as onboard and offboard charging [75], [79].

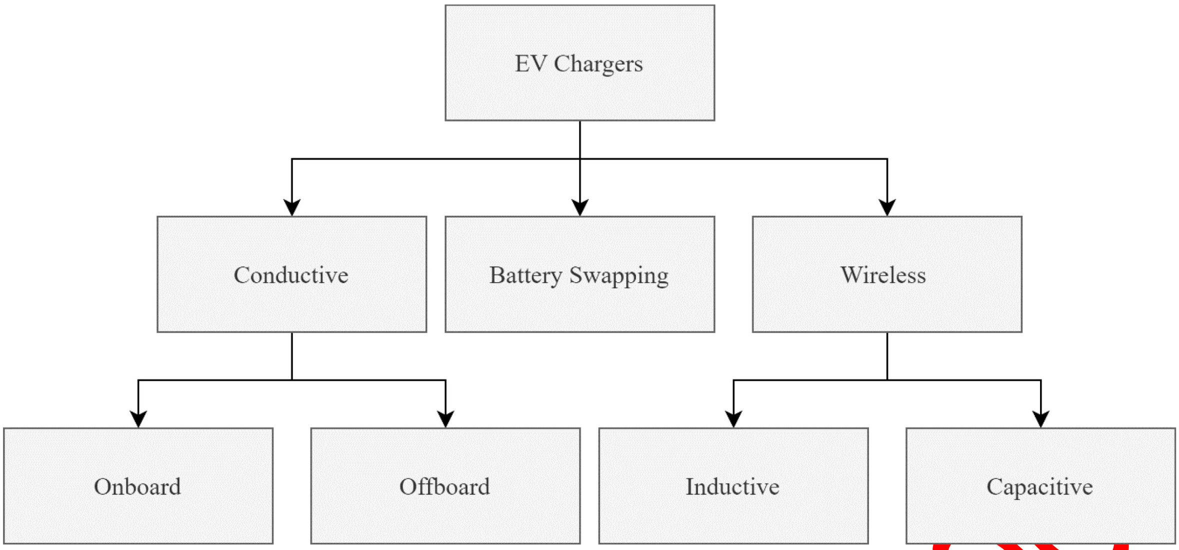


Figure 8. Types of EV battery chargers [42]

The onboard charger, installed in EVs, offers a relatively lower transfer of energy (kW) during the charging process and does not significantly address concerns related to battery heating. Onboard AC to Direct Current (DC) rectification is employed for managing battery management systems (BMS), but it adds size and weight constraints. While providing flexibility to recharge at any location with an electrical outlet, the onboard charger faces challenges with communication protocols and standardized charger operation across all manufacturers. The onboard BMS relies on the charging station to supply voltage, maximum current capacity, and phase configuration [3], [24]. In contrast, the offboard charger allows for higher energy transfer and addresses the battery heating issue. By eliminating added weight on the EV, offboard chargers enable more advanced and efficient BMS systems. However, onboard chargers lack the flexibility to recharge at various locations, and the charging speed is limited by the capability of batteries to accept the charge [2], [76]. Offboard chargers offer fast charging at higher power levels, presenting better contractual opportunities for utility companies and charging station owners but at higher costs and complexity.

Conductive charging. Conductive charging is the most common method that relies on physical connectors to transfer electrical energy from the charging infrastructure to the EV. The process involves a conductive cable with connectors at both ends. One end connects to the charging station, and the other to the EV [80]. During charging, the electrical connection allows the current to flow from the power grid to the vehicle's battery. Conductive charging systems come in various power levels, such as AC Level-1, AC Level-2, and DC Fast Charging (DCFC) [81]. A recent regulatory development introduced Direct Current Charging (DCC) in DC Level-1 and DC Level-2 [82].

- **Level 1 Charging:** Level 1 is the most basic charger for EVs. It utilizes a standard household outlet with 120/240 AC volts. This slow-charging method accomplishes "trickle charging" due to its limited charging speed. Level 1 charging is primarily suited for overnight charging at home, making it convenient for EV owners with plenty of time to charge their vehicles slowly [81]. At the same time, it offers universality and minimal infrastructure requirements. However, its slow charging speed makes it less practical for daily life, especially for those with higher mileage requirements. In the United States, level 1 has standard specifications of 120 V/15A, using 1-phase and ground outlets like National Electrical Manufacturers Association (NEMA) 5-15R. The connection employs a standard connector, J1722, for the AC port of the EV. The estimated installation cost for a level 1 charger ranges from $500 to $900 [82].

- **Level 2 Charging**: Level 2 charging represents a more advanced and faster option. It employs dedicated charging stations with higher voltage, usually three phase 240 volts. These stations require higher capacity electrical installation than standard household outlets. Level 2 charging offers an hourly charging rate of approximately 10-60 miles, depending on the specific charger and vehicle. Level 2 is preferred for its efficient fast-charging capabilities and the convenience of a standardized vehicle-to-charger connection. A technical study suggests an installation cost ranging from $1,000 to $3,000 for level 2 chargers [83], [84]. SAE J1772 features a combo connector with an AC connection on the top side and a 2-pin DC connector on the lower side, offering AC and DC fast-charging [85]. Level 2 charging has become a popular choice for residential and public installations, as it is an excellent tradeoff between charging speed and infrastructure requirements. While it demands dedicated equipment installation, it caters well to daily charging needs and is widely available at public charging stations.
- **DC Fast Charging**: DC fast charging is the most advanced and rapid-charging option for EVs. It utilizes regulated DC and high-powered charging, bypassing the vehicle's onboard charger and delivering DC power directly to the EV's battery [85], [86]. It operates at around 480 V 3-phase circuit input power. Level 3 charging uses the Charge de Move (CHAdeMO) standard, rapidly gaining recognition globally, enabling an 80% charge within 30 minutes at 50 kW [87]. However, its implementation requires external dedicated charging equipment, costing between $30,000 and $160,000, with additional maintenance costs. DC Fast chargers can provide around 60 to 100 miles of range in approximately 20-30 minutes. DCFCs are suitable for long-distance travel and offer quick recharging [86]. However, this technology comes with some challenges, including expensive infrastructure requirements, not all EVs having fast charging ports, and the EV battery degrading due to the high charging power [75]. Despite these challenges, DC fast charging is beginning to appear on highways and major travel routes. Level 1 and 2 chargers are widely utilized in residential, workplace, and public charging stations. Table 4 presents the comparison of EV chargers.

Table 4. Comparison of electric vehicle chargers

Charging Level	**Power Level**	**Typical Charging Time after 100 miles**	**Bidirectional Capability**	**Application**	**Connector Type**
Level 1 **[81]**, **[82]**	1.9 to 3.6 kW	8-20 hours	No	Residential	SAEJ1772 & GB/T 20234
Level 2 [66], **[85]**	7.2 to 22 kW	4-8 hours	No	Residential/Commercial	CHAdeMO & IEC6219-2
DC Fast Charger **[87]**	50-350kW	0.5 -1 hour	Yes	Residential/Commercial/ Cluster	Tesla super charger/CCS Combo1 &2

Conductive charging systems are known for their simplicity and high efficiency. Onboard conductive chargers utilize slow charging techniques, while off-board chargers employ fast charging. Due to infrastructural limitations and a lack of standardized physical connectors, conductive charging still needs improvements. Research is focused on improving charging speeds, connector standardization, and developing low-cost and robust conductive chargers.

Figure 9 shows AC level 1, 2, and DC fast chargers, connector configurations, and common attributes. These systems apply to various existing vehicles, including Nissan Leaf, Chevrolet Volt, Mitsubishi i-MiEV, and Tesla Roadster [57].

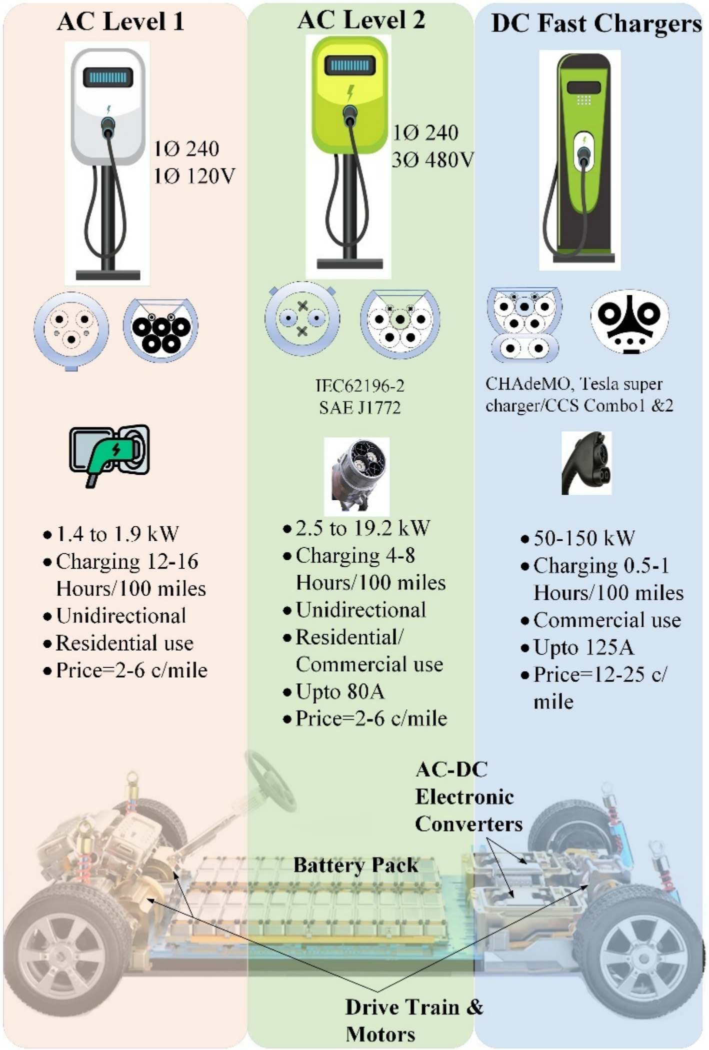
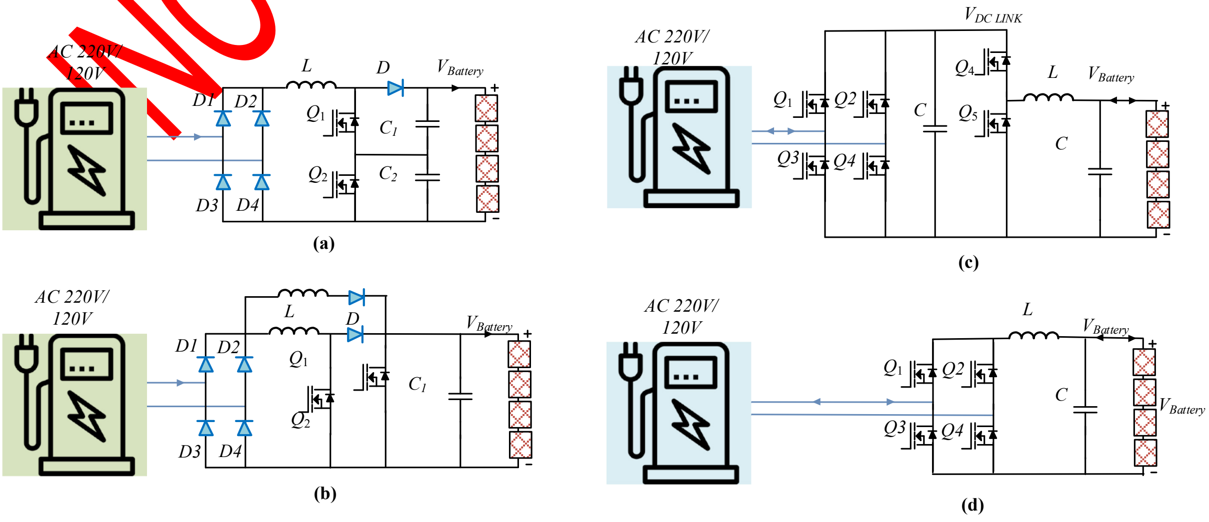


Figure 9. AC Level 1, AC Level 2, and DC fast chargers

Wireless charging. The wireless charging works with two coupled coils. The first coil in the charging station develops an electromagnetic field. The generated electromagnetic field is connected wirelessly to the onboard EV coil, which produces the charging voltage in EVs. Wireless charging can be developed up to power levels 1 and 2. Wireless charging has several benefits, such as enhanced user convenience, electrical safety in diverse weather conditions, increased durability, and eliminating cable costs [80], [84]. Another form of wireless charging is capacitive EV charging, which employs high-frequency electric fields for power transfer. The system comprises two pairs of metal plates forming capacitive couplers. These couplers facilitate the power flow from the source to the EV side. The effectiveness of the coupling capacitances relies on factors such as plate area, plate distance, and dielectric properties between the plates [76]. Capacitive charging addresses EV systems' long-distance and high-power challenges [88]. Capacitive wireless charging extends to the possibility of integrating charging strips on main highways, enabling charging on the go and reducing reliance on fast-charging infrastructure. However, limitations related to size, cost, power density, power loss, lower efficiency, and the complexity of the infrastructure are the primary challenges to its implementation.

Battery swapping. Battery swapping allows EV owners to replace low-charged batteries with fully charged ones. This technique provides several advantages, such as enhanced battery life, time-saving, and cost-effectiveness [79], [89]. China leads the battery swapping method with the highest number of stations. Companies like NIO, a frontrunner in China, introduced the Battery-as-a-Service (BaaS) model, allowing customers to purchase EVs without batteries and opt for a battery-swapping service at designated stations [90]. China's comprehensive infrastructure development includes strategically placed battery-swapping stations along major highways, driven by supportive government policies and financial incentives. Standardization efforts are needed to ensure compatibility across various EV manufacturers. Beyond its role in preventing power grid peak demand, this swift approach results in substantial cost savings. However, battery swapping stations encounter challenges, including high initial investment costs and significant space requirements during construction.

Charging topologies. An ideal battery charger comprises minimum weight and volume, high reliability and efficiency, increased power density, and minimal cost. The choice of charger topology, switching frequency, component, and control algorithm heavily influence the charger performance. Unidirectional EV chargers transfer electric power exclusively from the grid to the EV battery, lacking the ability to feed electricity back to the grid. Unidirectional chargers are usually designed for power levels 1 and 2 [84]. The topologies for these chargers involve a diode bridge, filtering devices, and DC/DC converters [91]. These converters use a single stage to reduce weight, volume, and cost. Some topologies also required high-frequency isolation transformers to achieve specific isolation requirements. Figure 10(a) illustrates an arrangement of a level 1 onboard series resonant full-bridge unidirectional charger [92]. A typical two-stage charger consists of a front-end AC-DC converter and a back-end DC-DC converter, as shown in Figure 10(b) and Figure 10(c) [93]. Two-stage bidirectional topologies can achieve V2G or Power Factor Correction (PFC) functionalities. Modern EV chargers often adopt a buck/boost converter topology to achieve active PFC [94]. Some designs utilize a dedicated diode bridge for rectification, followed by a boost topology, while others, like the bridgeless boost PFC circuit, eliminate the input rectifier bridge to address heat management issues. However, bridgeless topologies often increase Electromagnetic Interference (EMI) and do not pass local/international regulations on EMI. Compliance with standards, such as the US National Electric Code: 690, SAE: J2894, and Institute of Electrical and Electronics Engineers (IEEE): 1000-3-2, is necessary to minimize harmonics and DC injection [95], [96], [97]. Challenges like current ripples during battery charging and the size of inductors are resolved through the interleaving concept, as seen in the topology illustrated in Figure 10(b). Implementing different charging control algorithms involves analog and microcontrollers, integrated circuits, signal processors, and various converters.



(a)

(c)

(b)

(d)

Figure 10. Charging topologies, (a) Two-stage unidirectional multilevel charger (b) Two stage unidirectional interleaving charger (c) Two stage bidirectional charger with DC-link control (d) Single-stage bidirectional bridge charger

Figure 10(c) displays a unidirectional charger with two boost converters operating in parallel but 180 degrees out of phase. This topology reduces the stress on the switches and capacitors, cancels the output ripple, and minimizes the heat at the input bridge rectifier. This topology is suitable until 3.5 kW. For power levels beyond 3.5 kW, the study in [98] presented a bridgeless interleaved configuration. The typical choice for lower power charging (levels 1 and 2) is the multilevel single-phase unidirectional charger, as shown in Figure 10(b). However, at power level 3, multilevel converters are preferred due to their ability to reduce component stress, size, and switching frequency. These topologies are complex to control but offer low-cost filtering [86]. High-power Level 3 charging systems can be efficiently implemented using 3-phase bidirectional multilevel converters, providing high power quality, reduced harmonic distortion, a high-power factor, and regulated DC output voltage. To support EV charging at commercial stations, 3-level bidirectional converter topologies have been discussed extensively in the literature [99].

Charging connectors. EV charging connectors are broadly categorized into AC and DC types. AC connectors are primarily used for standard charging, while DC connectors are used for fast chargers. The connector's pin-out, size, and shape vary based on the EV manufacturer, grid voltage and frequency, and power [2], [100]. Most voltage-controlled devices use a standard AC connector with large pins for voltage sensing and smaller pins for communication. Table 5 summarizes the most common EV charging connectors with their brief description, rating, and special features [2], [93], [100], [101], [102].Table 5. Comparison of electric vehicle charging connectors [2], [93], [100], [101], [102]

Connector Type	**Description**	**Voltage/ Current/ Rating**	**Application**	**Special Features**
AC Connectors	Universal connectors used for standard charging. Voltage-controlled devices typically feature large pins for voltage sensing and smaller pins for communication.	Varies	Standard charging worldwide	Standard configuration varies by region
Connector Type 1	Round configuration with five pins, two AC lines, two control signal lines, and earth pin. Supports single-phase charging with a maximum of 120V or 240V and 80A.	120V or 240V/80A	Single-phase AC charging	Earth pin for protection; Varies by region
Connector Type 2	Enables both AC and DC charging, 3-φ AC input(400V/63A). Single-phase AC input 230V/80A	230V/80A (Single-phase) or 400V/63A (Three-phase)	AC and DC charging; 3-φ AC compatible	Simultaneous AC and DC charging
US Tesla Connector	Tesla propriety charger for United States. Supports single-phase AC and DC input,	17.2 kW/240VAC	AC and DC charging in the United States	Simultaneous AC and DC charging.

DC Connectors	Fast charging connectors designed to replace standard AC charging. Commonly used offboard to avoid interference with power lines, and safety considerations become crucial.	Varies	Fast charging; Replaces level 1 and level 2 chargers	Power outputs from 50 kW to 500 kW; Varies by type
CCS Combos 1 and 2	Propriety charger from CharIN e.V., Simultaneous AC and DC charging.	350 kW	Simultaneous AC and DC charging	Defined by IEC standards; Handles 200V to 1 kV
CHAdeMO	Industry Standard charger. Enables V2X with its version 1.1 protocol.	200 kW to 400 kW	V2X capable; by CHAdeMO Association	Part of IEEE and IEC standards, Enables V2X
Tesla DC Connector	For Tesla's Super Charger. Works with both AC/Dc charging.	120 kW	Simultaneous AC and DC charging;	Supports CHAdeMO stations with an adapter
GB/T China Connector	Follow the standard 20234.3–2015, simultaneous charging of two batteries.	250 A, 750V-1kV	Dual-battery charging: Defined by GB/T	Controller Access Network (CAN) enabled

Electric Vehicle Motors and Machines

Research breakthroughs, market demands, and environmental considerations have shaped the EV motor technology. The key performance factors in EV motor development are higher power density and efficiency, extended range, and improved driving experience. EV motors are developed with rare-earth magnet materials like Neodymium-Iron-Boron (NdFeB) to achieve high efficiency and instant torque at low speeds [103]. Similarly, improved material technology provides high-conductivity materials such as copper and lightweight aluminum alloys in motor windings [104]. These innovations address weight constraints while enhancing motor efficiency.

Two advanced winding strategies used in EVs are hairpin windings and distributed windings, which ensure enhanced thermal performance and high-power density [105]. Moreover, cooling systems have developed considerably. Liquid cooling systems and innovative cooling channels within EV motor structures are now imperative for long-range EVs [106]. These advancements enable sustained high-power operation without overheating. Motor technology also includes integration with EV transmission systems. Direct drive systems and multi-speed transmissions are designed to simplify drivetrains, reduce weight, and enhance efficiency. Studies suggest that direct drive systems eliminate the need for traditional transmissions while providing efficient drivetrain solutions[105].

Benchmark models like the Tesla Model S Plaid and Porsche Taycan epitomize the practical application of advanced EV motor technology. The Tesla Model S Plaid's tri-motor setup redefines high-performance EVs, reflecting market trends and pushing technological boundaries [107]. Similarly, the Porsche Taycan, with its 800V architecture and innovative two-speed transmission, exemplifies the market's demand for sophisticated drivetrain solutions [108]. These benchmark models reflect market trends and underscore the importance of pushing technological boundaries to meet consumer expectations. Enhancements in motor control algorithms and regenerative braking systems facilitate efficient energy recapture during deceleration, aligning with market demands for improved energy efficiency [103]. Therefore, motors supporting regenerative braking systems are essential for advanced EVs. Incorporating regenerative systems contributes to market-driven efficiency goals and aligns with environmental imperatives by minimizing energy waste during driving cycles.

COORDINATED VEHICLE-TO-GRID

EV's growing popularity comes with several challenges for the grid, especially when the EVs are charged during peak hours. The increased electricity demand during peak hours strains the existing infrastructure. Therefore, numerous studies have evaluated the effect of EV charging strategies on the load profile and peak demand of distribution grids.

A study [109] investigates the peak demand resulting from the extensive deployment of EVs. The study revealed that a 100% penetration level of EVs with uncoordinated charging may surpass the available electricity production capacity. The proposed solution suggests that up to 93% of the EV load must be accommodated during off-peak hours; otherwise, additional electricity generation is required for regular operation. A study [110] demonstrated that an uncoordinated charging scenario with a 30% EV penetration level increased the peak demand by up to 53%. According to [34], even a 10% EV penetration level significantly escalated the peak demand due to uncontrolled charging in residential areas. The cumulative peak demand can be evaluated using the following equation.

$$P_{peak,new} = P_{existing} + \sum_{i=1}^{N} P_{EV,i} \tag{3}$$

Where;

$P_{peak,\ new}$ is the total peak electricity demand after the integration of EV charging.
$P_{existing}$ is the existing peak electricity demand without considering EV charging.
$P_{EV,i}$ is an additional peak demand contributed by the charging of the i-th electric vehicle.
N is the total number of electric vehicles contributing to the additional demand.

Research in [111] observed a substantial increase in peak demand even under everyday EV charging scenarios, stressing the necessity for optimal charging management. Current EV infrastructure utilizes low-level management techniques to integrate EVs, GENCOS, DSO, and control through conventional communication networks [87].

A study [96] examined the loading of power conductors during peak EV charging hours, revealing that cables can safely handle penetration levels of 25% for slow charging and 15% for rapid charging conditions, respectively. However, the study concluded that the distribution networks need upgradation to accommodate massive EV integration.

A study [112] assessed transformer ageing based on charging power levels, observing a higher ageing impact for uncoordinated AC power level 2 charging compared to level 1 charging. The evaluation of EV impacts on distribution components highlighted the severe impact of random charging scenarios with level 2 charging conditions and massive penetrations, particularly on power cables and the lifespan of power transformers.

Technical studies [109], [113],[114] explored the impact of EV charging on the distribution network and have revealed that uncontrolled charging scenarios can significantly increase system losses. As demonstrated by [112], a probabilistic approach showed that massive EV integration increases power losses in distribution networks. Despite good performance and utilization from power generation, transmission, and distribution systems, numerous EVs often collectively engage in uncoordinated charging, impacting the overall power quality and reliability, thus making room for clustered V2G research. The mass-scale integration of EVs will introduce an additional load to the distribution network, disrupting the system's load profile.

Additionally, EV owners' charging behavior is unpredictable, making it challenging to manage the grid with techniques. Consequently, widespread EV penetration and diverse charging behavior significantly intensify the peak load on the distribution grid. Therefore, the grid management research is directed towards optimized charging approaches, time-of-use plans, and RES integration as probable solutions for a peak load problem. These solutions can mitigate peak demand and load profile issues in the power network [110]. Optimal grid management shows tremendous potential to solve the EV penetration problem in the distribution network. However, V2G support is beneficial if managed and organized on technical and business fronts. A specialized regulatory agency for EV aggregation becomes essential to scale up EV integration [30], [32]. The aggregator facilitates collaboration between EVs and business entities such as generation, transmission, and distribution companies, strategically grouping EVs based on owner preferences to maximize commercial opportunities [87], [101].

Figure 11 presents the concept of the V2G system, illustrating the bidirectional energy flow between EV clusters, chargers, aggregators, homes, renewable sources, and the grid. During the day, energy flows from the grid to vehicles through the aggregator, primarily utilizing renewable sources. In the evening, vehicles discharge energy back to the grid to support peak demand. At night, energy flows from the grid to vehicles again for charging during off-peak hours. The system highlights the role of EV aggregators in managing energy exchange efficiently, integrating renewable energy, and stabilizing the grid.

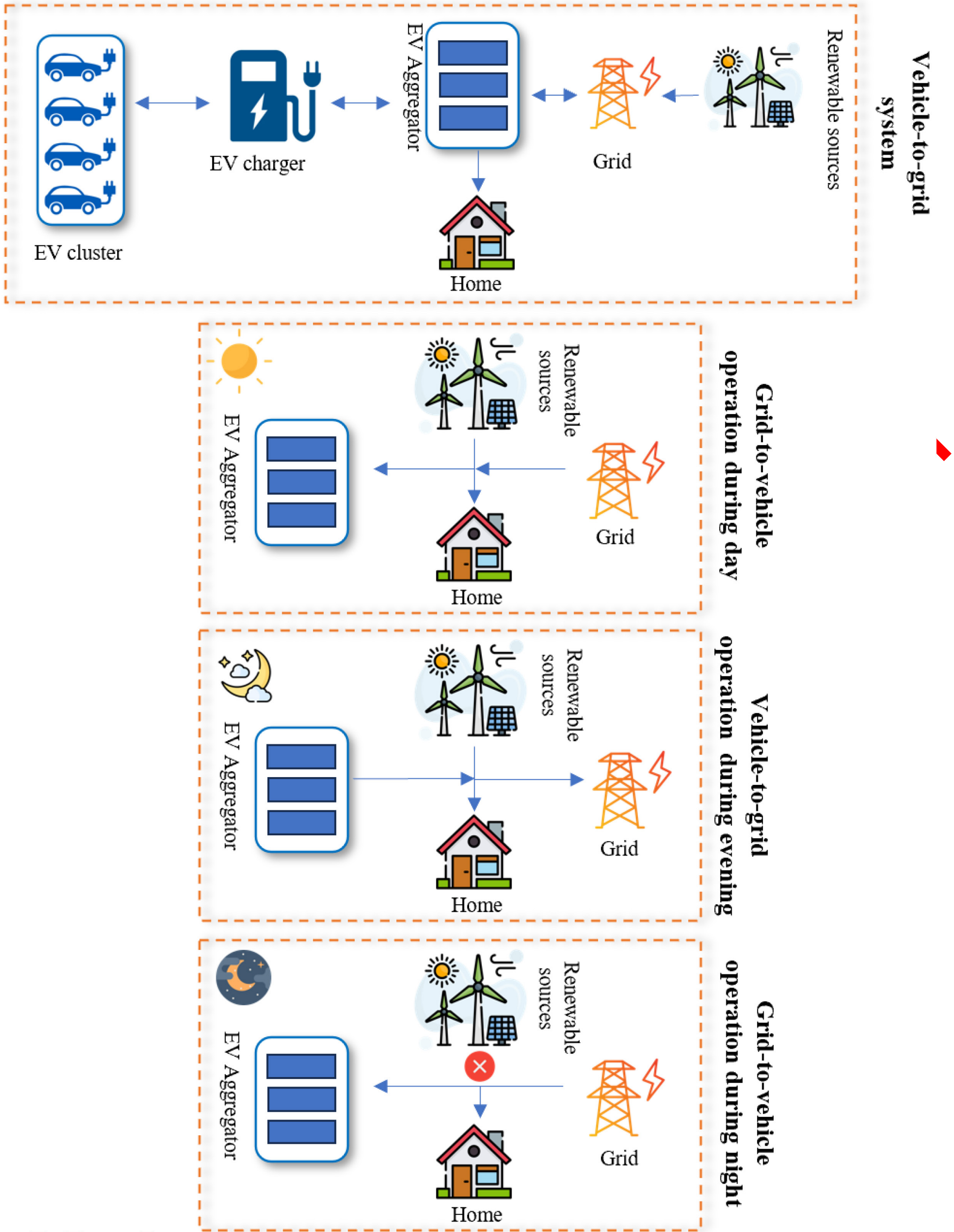


Figure 11. Bidirectional energy flow in a vehicle-to-grid system illustrating day, evening, and night time operations

Individual EV contributions as V2G may be modest, but the collective EV impact on the grid may be significantly enhanced through collaboration with business aggregators [2]. V2G functionality can mitigate conventional grid management issues if organized in an intelligent energy management setup. Through V2G, EVs can discharge stored electrical energy back to the grid, providing support during peak demand periods or acting as a grid resource by enabling bidirectional energy flow between EVs and the electrical grid [113], [115].

Clustered V2G technology aims to exert control over multiple EVs within the existing control structure by acting as a dynamic balancing agent. During shifts in energy demand, aggregated EV batteries exhibit a rapid response, contributing to grid stability by absorbing excess energy during periods of surplus and discharging stored energy during high-demand intervals. Furthermore, the stored power in these aggregated batteries can be strategically dispatched to provide ancillary services. Research findings emphasize that the power stored in EV batteries can be intelligently sent back to the grid, offering ancillary services tailored to the specific needs identified by grid operators [116]. This approach contributes to the reliability of the power supply and underscores the multifunctional and responsive nature of EVs as integral components of a dynamic energy ecosystem.

Coordinated Vehicle-to-Grid Advantages and Future Direction

The main advantages of clustered EVs are active and reactive power support, assistance in power factor regulation, and facilitation of the integration of variable RES. Clustered EVs may provide load balancing through valley fillings and, conversely, peak load shaving [117]. These features are achieved by charging EVs during low-demand periods, such as off-peak hours, and discharging EV batteries during peak hours. This charging and discharging phenomenon is observed in Figure 11, whereby the vehicle is charged during the day and night time and discharged during the evening time. Furthermore, bidirectional CV2G contributes to grid voltage regulation by supplying reactive power. Reactive power injection is suitable during grid voltage swell, sag, or grid faults [114]. Reactive power injection requires appropriately sized capacitors in the DC linkage of the EV chargers with precise switching control. Another premium service offered by bidirectional charging with V2G is PFC, which minimizes power losses in the grid [118], [26]. Clustering or grouping EVs to create a larger virtual energy storage pool offers several advantages, mainly supporting the grid during emergencies [119], [120].

The aggregation of the collective energy storage capacity of multiple EVs enhances the resilience of the electrical grid, providing a more substantial and reliable power source in the event of blackouts or other emergencies. Intelligent algorithms and coordination systems optimize the distribution of energy based on factors such as proximity to critical loads, battery charge levels, and real-time grid conditions, ensuring efficient and effective utilization of available energy resources [121], [122]. Tapping into the energy stored in clustered EVs during peak demand periods or emergencies helps manage peak loads effectively and prevents overloads on the grid infrastructure. Participating in a clustered EV system can incentivize EV owners, encouraging a collaborative approach to grid support. A study [123] modeled clustered EV operation as an optimization problem and successfully demonstrated demand-side management and energy storage features through V2G technology. The research finds that the operating costs of EVs and their chargers could be reduced by 26.5% by adopting this approach [121] [75].

The clustered EV controller can make real-time decisions based on data acquired from smart meters and receive the latest information from the energy market [117]. Thus, clustered V2G technology responds dynamically to fluctuations in energy demand and market conditions to achieve energy efficiency and cost savings. Although considerable research on bidirectional charging with CV2G technology is underway, CV2G's widespread adoption faces significant challenges. One of these challenges is recurrent charging/discharging, which is inherent to bidirectional V2G. Recurrent charging/discharging contributes to battery degradation, posing a barrier to CV2G implementation [124]. The degradation of EV battery based on the number of cycles can be calculated using the following equation:

$$C_{remaining} = C_{initial} \times \left(1 - D \times N_{cycles}\right) \tag{4}$$

Where $C_{remaining}$ is the remaining capacity of the battery after degradation and $C_{initial}$ is the initial capacity of the battery when it is new. D is the degradation rate of the battery per cycle (fraction of capacity lost per charge-discharge cycle) and N_{cycles} is the number of charge-discharge cycles the battery has undergone.

Concerns about EV battery life, increased cost, scarce infrastructure, insignificant social acceptance, and resistance from oil and automotive sectors further complicate the adoption of bidirectional CV2G. However, given the CV2G problems, there are plenty of opportunities in research areas like data security in the EV ecosystem and reliable two-way communication networks between EVs and aggregators [75], [79]. Some considerations on safety measures for CV2G technology include anti-islanding protection, infrastructural challenges, metering problems, and added costs of bidirectional converter [125].

ENVIRONMENTAL ASPECTS OF ELECTRIC VEHICLES

EV integration into transportation brings far-reaching environmental implications. The most evident environmental benefit of EVs is the elimination of tailpipe emissions (carbon monoxide, nitrogen oxides, and particulate matter), which significantly mitigates air pollution and respiratory diseases [126], [127]. Along with the proliferation of EVs, the power grid is increasingly integrating more sustainable energy sources, with technologies significantly contributing to carbon footprint reduction [128]. International Energy Agency and the Union of Concerned Scientists confirm EVs' lower average carbon footprint. Projections indicate a potential reduction in CO_2 emissions by 1% to 6% by 2025 and 3% to 28% by 2030, achievable through integrating EVs into power networks [129], [130]. Governments worldwide are also setting ambitious targets to phase out combustion engine vehicles, making it a crucial component of broader emissions reduction strategies.

Moreover, advancements in battery technology and manufacturing processes are improving the energy efficiency of EV production, further contributing to emission reductions [128]. The integration of EVs and renewable energy into infrastructure has a significantly lower environmental impact than fossil fuel alternatives. Solar panels and wind turbines have a smaller ecological footprint, require fewer resources during production, and generate minimal waste when properly decommissioned, thereby supporting the development of sustainable and circular energy systems [7].

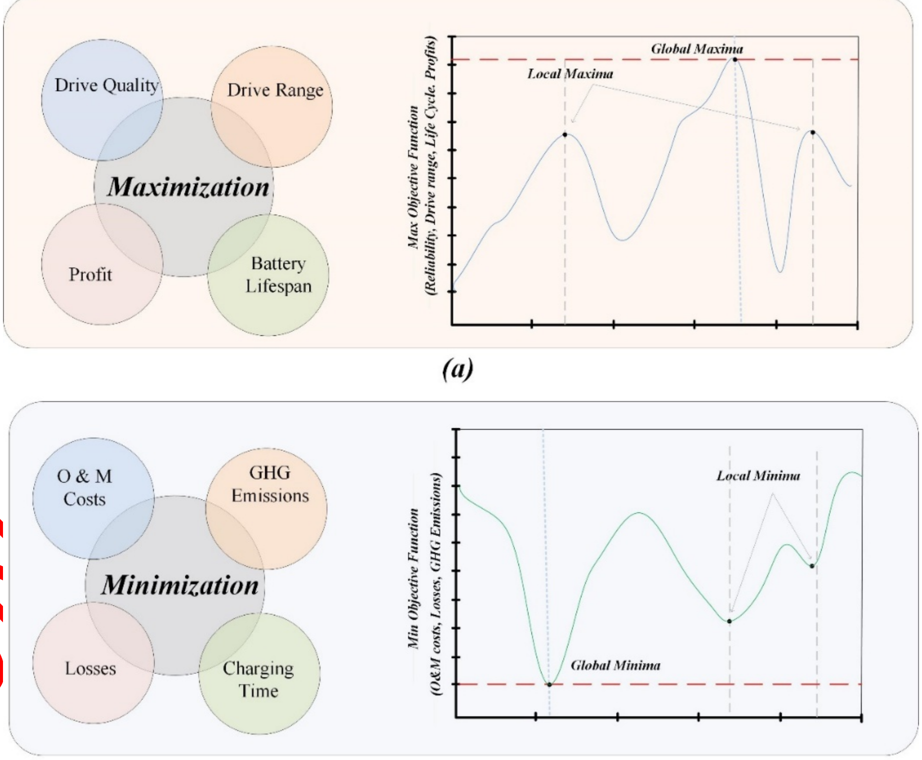
The evaluation of the environmental impact of EVs introduces the concept of 'well-to-wheels,' a comprehensive approach that considers the entire lifecycle of emissions, including exhaust emissions and the energy and materials used to power the vehicle [131], [132]. EVs exhibit the least intensity of carbon gas emissions when assessed through a life cycle evaluation strategy [125]. Moreover, models developed for large-scale deployment of EVs in specific regions demonstrate a positive trend in reducing greenhouse gas emissions over time, attributed to improvements in the electricity production mix [133]. However, challenges arise in the recycling process of lithium-ion batteries, with potential groundwater pollution due to incomplete recycling [15]. Addressing this issue requires government intervention to develop facilities for the efficient and sustainable recycling of these batteries, ensuring a cleaner and safer environment [123]. EV production is becoming more energy-efficient and less carbon-intensive due to improvements in battery and manufacturing techniques. This continuous improvement contributes to further emission reductions as the EV industry evolves.

Environmental Economics

Computable General Equilibrium (CGE) models have been widely used for the environmental assessment of EVs. A comprehensive analysis has evaluated the conditions under which PHEVs can most effectively contribute to reducing greenhouse gas emissions in the USA and Japan [134]. The CGE analysis considered factors such as vehicle cost and climate policy, revealing a crucial relationship between the carbon intensity of electric power generation. This underscores the intricate relationship between the environmental effectiveness of PHEV adoption and the underlying energy generation infrastructure. Similarly, a comprehensive analysis explored the social costs and benefits of EVs in Austria, integrating a CGE assessment with a discrete choice model to estimate overall vehicle demand [135]. A notable aspect of the analysis is incorporating a price index for aggregated vehicle purchases. However, the assessment does not account for the stimulus effects of subsidies on BEV adoption and vehicle manufacturing production.

In the context of German EV adoption, an optimal subsidy model for BEV adoption has been developed using spatial CGE modeling [136]. Rebates and taxes are incorporated into the comprehensive analysis, but the study does not explicitly model the direct effects of subsidies on the vehicle manufacturing sectors. This signifies a gap in understanding the full spectrum of impacts, as subsidies can cascade effects on various EV ecosystem components. An economic assessment of BEV adoption subsidies for the Japanese EV market was conducted in a typical city. Hypothetical simulation scenarios indicated that increased subsidies for BEV-related sectors could stimulate economic growth while reducing greenhouse gas emissions [137]. This positive correlation between economic incentives and environmental benefits suggests that well-designed policies and subsidies can create an advantageous relationship between the growth of the EV industry and environmental sustainability.

The optimization problem for the EV economy involves maximizing drive quality, drive range, life cycle, and profits while minimizing operating and maintenance costs, losses, greenhouse gas emissions, and charging time, as shown in Figure 12. The comprehensive, objective function integrates these diverse goals, accounting for their relative importance through assigned weights. Multi-objective optimization methods, metaheuristic algorithms, machine learning, simulation, and optimal control strategies are employed to find near-optimal solutions. An overall approach ensures that EV technology meets environmental standards, economic viability, and consumer expectations, contributing to a sustainable and efficient future in electric mobility. Advanced technologies and optimization techniques play a crucial role in addressing the intricate balance between EV performance, economic feasibility, and environmental impact, driving the evolution of electric mobility.



(a)

(b)

Figure 12. EV economy optimization

A modern electricity infrastructure is needed to meet the growing charging demand for EVs. The desirable features of the future grid are smart metering and strategic city planning to make cities EV-ready. The feasibility of Photovoltaic (PV)-based charging at workplace parking garages may be explored as an alternative, considering day and night charging scenarios. While night-time charging at home is widely accepted due to unused grid capacity, opportunity charging during the day increases efficiency. However, it also presents challenges, such as potential grid overload and the need for extensive charging infrastructure.

Quantitative Analysis to Compare Electric Vehicle Environmental Aspects

Quantitative analysis (QA) is widely used to understand, measure, and improve the environmental impact of EVs. QA provides evidence-based decision-making, fostering innovation and driving positive change toward a more sustainable future in the transportation sector [138]. The analysis enables a direct and accurate comparison between EVs and traditional combustion vehicles. Metrics such as emissions per mile or well-to-wheel efficiency provide tangible data for evaluating the ecological footprint of different transportation options. The users can set benchmarks for evaluating environmental initiatives through numerical data related to emissions, energy efficiency, and cost-effectiveness [139]. QA empowers consumers and industry stakeholders to make informed decisions. Policymakers also rely on quantitative data to formulate effective environmental policies.

Moreover, it allows tracking progress over time, setting industry standards, and motivating continuous improvement in EV technology and infrastructure. QA enables regulatory bodies and governments to design targeted incentives, regulations, and investments to transition transportation towards EVs. On the social front, the data generated by QA can clearly show reduced emissions, energy efficiency, and cost savings. This data effectively communicates the benefits of sustainable transportation, fostering more significant public support and adoption.

Quantitative analysis of the solar-charged electric vehicle. Integrating solar power with EVs represents a strategic initiative to optimize environmental benefits [140]. This integration eliminates direct emissions and reduces the environmental impact of the entire energy production cycle. One key benefit is its ecological impact, as solar panels harness solar energy to charge EVs. Additionally, solar-charged EVs promote energy self-sufficiency, decreasing reliance on conventional fuels and enhancing eligibility for government incentives related to solar energy adoption [141]. It represents an innovative solution that fosters sustainability while maintaining fiscal prudence, contributing to a cleaner and more sustainable future [142], [143].

To conduct a fundamental quantitative analysis comparing solar-charged EVs with conventional ICE cars, consider a scenario where a gasoline car emits 10,000 pounds of CO_2 equivalent annually. In comparison, a typical EV emits approximately 4,450 pounds of CO_2 equivalent per year, demonstrating a significant reduction in emissions.

Now, consider a homeowner investing $12,000 in a 5-kW solar panel system to power their EV.

Given date:

- Conventional Car Emissions: 10,000 pounds of CO_2 equivalent annually.
- Solar Panel System Cost: $12,000 for a 5kW installation.
- Solar Panel System Generation: 1,500 kWh per kW annually.
- EV Efficiency: 4 miles per kWh.

The total energy generated from the solar system is calculated using the equations below:

$$Total\ Solar\ Generation\ = Capacity\ \times Annual\ Generation \tag{5}$$

$$Total\ Solar\ Generation\ = 5\ \times 1{,}500 =\ 7{,}500kWh \tag{6}$$

The total EV mileage driven by solar energy can be calculated as follows:

$$Total\ EV\ Mileage\ = Total\ Solar\ Generation\ \times EV\ Efficiency \quad (7)$$

$$Total\ EV\ Mileage\ = 75{,}00\ kWh\ \times 4\, miles/kWh = 30{,}000\ miles \quad (8)$$

If conventional car emits 10,000 pounds of emission, then the emissions per mile can be calculated by:

$$Emission\ Reduction\ per\ Mile\ = \frac{Conventional\ Car\ Emissions}{Total\ EV\ Mileage} \quad (9)$$

$$Emission\ Reduction\ per\ Mile\ = \frac{10{,}000\ pounds}{30{,}000\ miles} \quad (10)$$

$$Emission\ Reduction\ per\ Mile\ = 0.333\ pounds/mile \quad (11)$$

The above scenario demonstrates that a 5-kW solar panel system can generate enough clean energy to cover around 30,000 EV miles annually. The emissions reduction achieved by the EV compared to a conventional car is substantial. This calculation reaffirms the environmental benefits of integrating solar power into the EV ecosystem, emphasizing the potential for sustainable transportation solutions [139].

Vehicle-integrated photovoltaics. Recent advances in solar PV technology have significantly reduced the cost of solar roofs for EVs, enabling the development of Solar Electric Vehicles (SEVs) [144], [145]. These solar-enhanced vehicles generate electricity directly from the sun, allowing for improved range, reduced dependency on charging infrastructure, and a lower environmental footprint.

The cost of PV panels has significantly declined due to advances in thin-film solar cells, perovskite-based solar panels, and flexible PV materials. This cost reduction has made integrated solar roofs feasible for EVs [146]. Studies show that integrating PV panels into EVs can increase the driving range by up to 30 km per day under optimal sunlight conditions, reducing reliance on charging stations [147]. Conventional EVs rely solely on grid-based electricity, which may still be partially generated from fossil fuels, while SEVs generate their electricity, further reducing CO_2 emissions.

One of the key challenges in EV adoption is range anxiety, which Vehicle-Integrated Photovoltaic (VIPV) helps mitigate by providing continuous solar charging while driving. The efficiency of modern VIPV systems depends on panel type, geographic location, and solar irradiance levels. Table 6 compares the range, emissions, and energy efficiency of gasoline vehicles, standard EVs, and solar EVs.

Table 6. Comparison of conventional electric vehicles, solar electric vehicles, and gasoline-powered vehicles [148], [149], [150], [151]

Feature	**Gasoline Vehicle**	**Standard EV**	**Solar EV**
Energy Source	Gasoline/Diesel	Grid Electricity	Grid + Solar
Range per Charge/Tank	400-700 km	250-500 km	>700 km
Additional Daily Range	N/A	N/A	+20-30 km (Solar)
CO_2 Emissions (g/mile)	411	200	~0 (if fully solar)
Charging Infrastructure Needed	Yes	Yes	Less frequent

Several manufacturers are developing SEVs to improve range and reduce dependence on the grid. Some notable models include:

- Lightyear 0 – A commercial solar EV capable of gaining 70 km/day from solar charging.
- Aptera SEV – A three-wheeled solar-powered vehicle with a range of up to 1,600 km on a full charge.
- Sono Sion – A compact SEV with integrated solar panels covering the roof, hood, and doors, capable of self-charging 112-245 km per week.

To quantify the additional driving range gained from solar energy, the following equation can be used:

$$R_{solar} = \frac{P_{solar} \times H_{solar} \times \eta_{panel}}{E_{EV}} \tag{12}$$

Where:

R_{solar} = Additional driving range from solar power (km)
P_{solar} = Power output of the vehicle's solar panels (W)
H_{solar} = Average daily sunlight hours (h)
η_{panel} = Efficiency of the solar panels (%)
E_{EV} = Energy consumption of the EV per km (Wh/km)

For instance, a SEV with a 1.5 kW solar panel system, receiving 5 hours of sunlight per day, with an efficiency of 20%, and consuming 150 Wh/km, would gain 10 km per day. This means the vehicle can drive an additional 10 km per day purely from solar energy.

As solar panel efficiencies continue to improve, future SEVs could achieve additional driving range per day, reducing the need for daily charging in sunny regions. Figure 13 illustrates the projected market growth of SEVs from 2025-2035. The market size for SEVs is projected to grow to $1,514.50 million at a CAGR of 12.2% by 2034 [152]. The increasing shift toward RES drives this growth. Furthermore, government initiatives aimed at reducing carbon footprints, coupled with rising investments in research and development of eco-friendly and renewable energy technologies, are accelerating the adoption of SEVs.

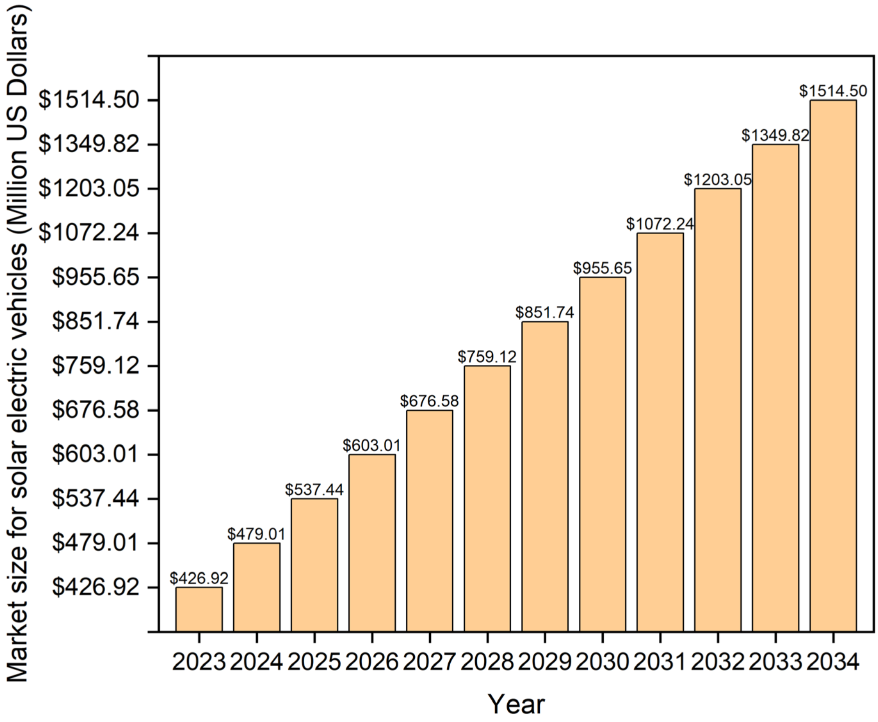


Figure 13. Projected market size for solar electric vehicles from 2025 to 2034

ECONOMICAL ASPECT AND REGIONAL ELECTRIC VEHICLE MARKET

From an economic perspective, the EV market has witnessed remarkable growth recently, surpassing 10 million in sales in 2023, despite challenges like supply chain disruptions, economic uncertainty, and high commodity prices [120]. This milestone signifies a pivotal shift in the automotive industry towards sustainable and environmentally friendly technologies. The expected growth in EV sales is driven by a decline in global ICE vehicle sales, which have fallen by 30% since their peak in 2017 and continue to follow a long-term downward trend [120]. However, the decline in ICE vehicle sales did not hinder the electric car segment [136]. Studying the total cost of ownership (TCO) of an EV is essential to making informed decisions about EV investments. The TCO of an EV includes the purchase, charging, maintenance, taxes and registration, and insurance costs. According to a report by the International Energy Agency (IEA), the TCO of a BEV is estimated to be $0.26/km or $2611/year. This is comparable to a petrol vehicle's TCO, estimated at $0.25/km or $2532/year [120]. However, the TCO of an EV can vary depending on factors such as the type of car, electric rates, and charging habits. Switching from a gas car to an EV could save up to $200/month in fuel alone [137]. Additionally, Consumer Reports estimates that full battery and PHEV owners incur only half a conventional car's repair and maintenance costs. Meanwhile, the operating expenses of pure EVs return 60% savings.

Total Cost of Ownership for Electric Vehicles

TCO is a powerful tool for consumers and businesses contemplating the feasibility of switching to EVs. It allows for a more accurate assessment over the long term of owning an EV.

- **The Initial Purchase Price:** Although the initial cost of an EV may be higher than that of traditional ICE vehicles, the gap is narrowing. For example, if the EV purchase price is $40,000 and government incentives are $7,500, the initial cost is $32,500. This compares to an ICE vehicle with an initial purchase price of $30,000. Government incentives, advancements in battery technology, and increased market competition contribute to making EVs more financially accessible. However, the initial cost is only the starting point in the TCO calculation [153].

- **Operating Costs:** One of the significant advantages of EVs lies in their lower operating costs, fewer moving parts, and no reliance on traditional fuels; EV owners benefit from reduced maintenance and fuel expenses. Charging an EV is often more cost-effective than refuelling a gasoline vehicle, especially with the increasing availability of affordable at-home charging solutions [154].
- **Depreciation and Financing Costs:** Depreciation is a crucial factor in TCO, representing the reduction in the vehicle's value over time. EVs historically faced higher depreciation rates, but as the technology matures, this trend is shifting. Financing costs, including loan interest rates, contribute to the overall expenditure and influence the TCO [154].
- **Government Incentives:** Many governments worldwide offer incentives to promote EV adoption, ranging from tax credits to rebates. These incentives directly impact the TCO, making EVs more financially appealing by accelerating consumer return on investment [153]. Understanding the various cost components and their interactions gives consumers the knowledge to make an informed decision on investing in EVs.

The Compelling Economics and Environmental Advantages

Several factors influence consumer attitudes and drive the widespread adoption of EVs as a practical, environmentally friendly, and economically viable mode of transportation. Technological advancements and government policies have also played a crucial role in encouraging EV adoption [103]. Unlike conventional vehicles, EVs' TCO tends to equalize or even become more favorable over time, primarily due to lower operating and maintenance costs [155]. The inherent efficiency of EVs translates into reduced energy costs per mile, with electricity proving to be a more cost-effective alternative to traditional fuels [154]. Additionally, governmental incentives such as tax credits and rebates prompt consumers toward EV transition. In addition to economic considerations, the environmental impact is a significant driver in the growing acceptance of EVs. When charged using RES, EVs contribute substantially to reducing greenhouse gas emissions throughout their lifecycle compared to ICEVs [141]. Advances in battery technology have supported confidence in the long-term sustainability of EVs by saving degradation and replacement costs.

Furthermore, the resale value of EVs is now influenced by technological advancements and market trends, diminishing apprehensions associated with depreciation [28]. Moreover, the public and private sectors are actively investing in the development of comprehensive charging networks, alleviating concerns about the accessibility of charging stations [93]. As EV technology evolves, incorporating advancements such as improved battery efficiency and energy density, people are becoming more convinced of the viability and sustainability of EVs.

Electric Vehicle Market Management

Market or business management needs a layered architecture to achieve long-term EV sustainability. EV market entities may interact in layers for effective operation and optimal decision-making, as shown in Figure 14. The individual EV owners, electricity consumers, and charging stations reside at the bottom load layer of the EV market architecture. The EV load requirement is reported to the EV Market Aggregator (EMA), while the electricity demand by the consumers is reported to the Load Profiler (LP) [156]. EMO and LP communicate their data to the technical operator (i.e., DSO) and the General Market Operator (GMO). These demand/response aggregators can join TSOs and DSOs to manage variable loads from households, businesses, industries, and EVs [157].

EMAs also facilitate the utilization of market mechanisms for resource acquisition and enhanced grid flexibility by offering flexible demand packages. EMAs can extend their services beyond grid operations by optimizing their energy portfolio for various electricity partners. EMAs play a crucial role in addressing daily technical challenges by acting as a compensatory force for non-flexible loads, effectively balancing them with EV charging loads [158]. The EMA modulates the EV charging curve based on network operating requirements to prevent exceeding the maximum available power for EV charging at any given time [156].

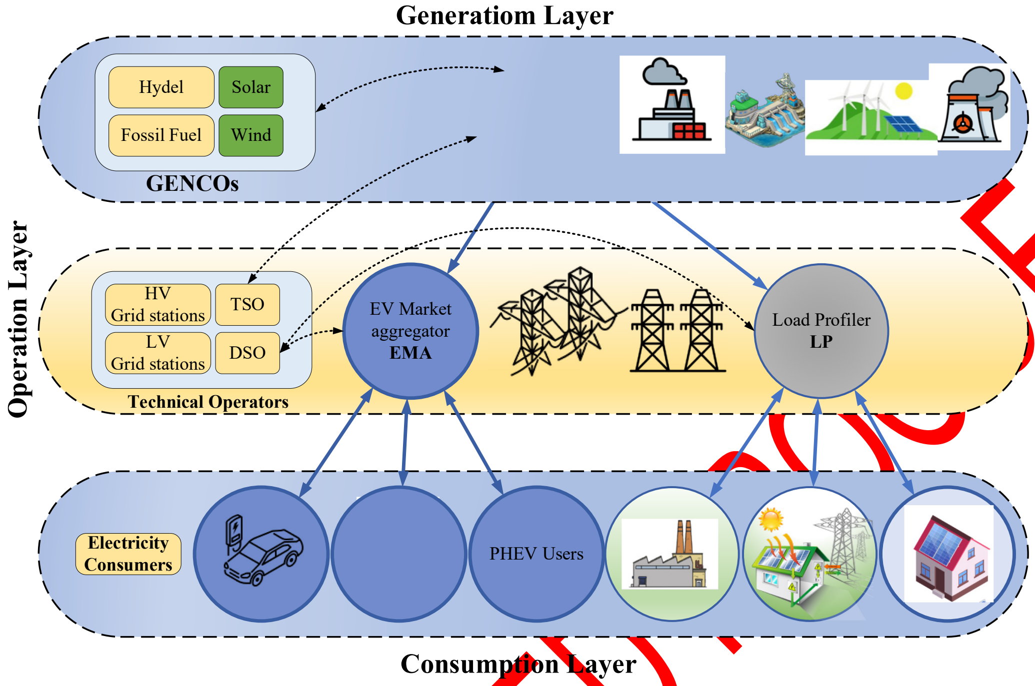


Figure 14. EV market management model

GENCOs are connected to GMOs and exchange generation forecasting data and information on EV storage availability. EMA communicates and assesses the potential of available EVs/Chargers for participating in CV2G. EMA optimizes to maximize profit for EV/charger owners while providing information about the available V2G support. Uncoordinated EV charging poses potential future challenges for system Operators (TSO & DSOs), particularly considering the variability in residential load patterns [159]. EMOs are the essential partners for TSOs and DSOs, offering technical services and acting as intermediaries between operators and consumers. At the same time, entities like TSOs and DSOs fall under the regulated category, operate within natural monopolies, and are regulated by incentive-based approaches [160].

The DSO in an EV-rich microgrid faces multiple challenges, including the ageing of assets, limited energy sources, and high demand due to EV penetration into the network. Nexans Asset Electrical provides a solution to navigate these complexities [161]. By meticulously balancing performance, operational efficiency, and capital expenditures, the solution involves creating digital twins for comprehensive network analysis. It integrates repair, renewal, and inspection strategies into the network plan, allowing for the simulation of various scenarios. A unique asset-aging model calculates the impact on different network components. The outcomes are substantial, with savings exceeding 10% in total expenditures and a noteworthy increase of over 20% in return on assets, as validated by [162]. This solution empowers DSOs to meet operational challenges with increased efficiency and efficacy. In the EV ecosystem, additional agents, including EV owners, Electric Vehicle Suppliers-Aggregators (EVSA), and Charging Point Managers (CPM), may play important roles in fulfilling large-scale EV integration to the grid [157].

Global Spending into Electric Vehicle Ecosystem

In 2023, the global EV market experienced significant growth, with 14 million EVs sold, most concentrated in China, Europe, and the United States. This surge brought the worldwide EV count to 40 million, marking an increase of 3.5 million compared to the previous year, translating to a 35% annual growth rate. Notably, BEVs comprised 70% of the EV fleet, signaling a strong consumer shift toward fully electric models. Regional sales distribution showed China leading with 60% of new EV registrations, followed by Europe at 25% and the United States at 10% [163].

Major economies like the European Union and the United States continue to align legislative efforts with electrification goals, emphasizing the sustained commitment to the EV sector. The EV market's expansion to include two or three-wheelers and commercial vehicles reflects the industry's adaptability. Electric buses and trucks are notably undergoing increased electrification to fulfill global commitments to reduce emissions from public transport [164]. As the industry embraces electrification, the outlook beyond 2024 is optimistic, with projections indicating continued growth and potential sales surpassing earlier estimates based on current government policies and national targets [163]. The global EV stock trend is observed in Figure 15.

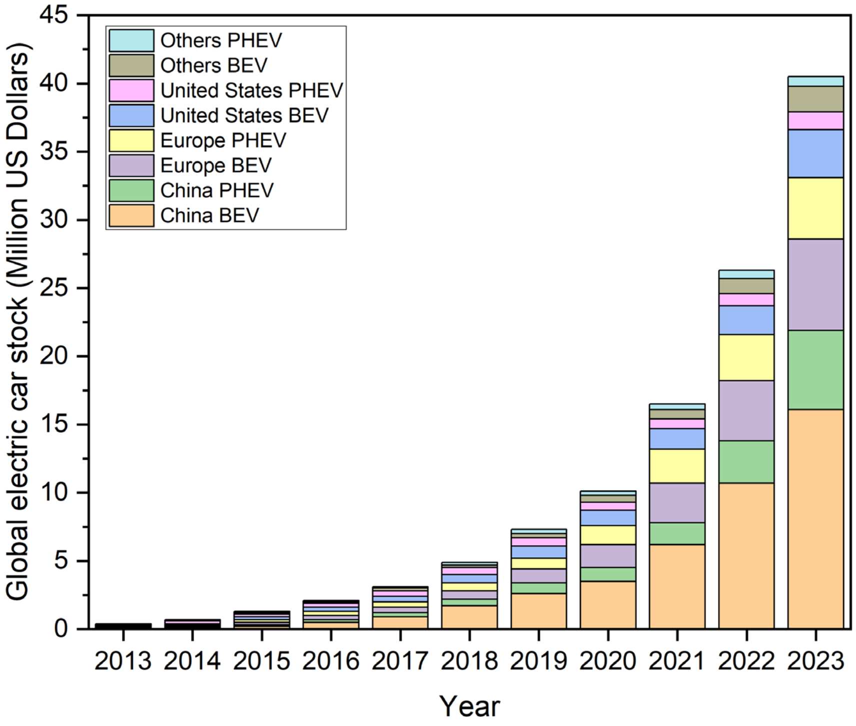


Figure 15. Global EVs stock trend

Emerging markets like Indonesia, India, and Thailand have also contributed to the global surge, reaching 80,000 units in 2022 [129], [165]. These figures are a direct result of government support through financial incentives. The Indian government has issued almost $2 billion to support the EV industry [166]. The sustained growth in these regions is propelled by ongoing government incentives and supportive policies that actively promote EV adoption.

Electric vehicles in China. In 2023, new EV registrations in China reached 8.1 million, reflecting a 35% increase compared to the previous year. This surge in EV sales was a key driver of overall market growth, even as conventional ICE vehicle sales declined by 8%. Despite this contraction, the total automotive market expanded by 5%, underscoring the pivotal role of EV adoption in the sector’s development. Notably, 2023 marked the first year that China's New Energy Vehicle (NEV) industry operated without national purchase subsidies, which had supported market expansion for over a decade. However, tax exemptions and non-monetary incentives remained in place, continuing to facilitate EV adoption. As the industry matures, increased price competition and market consolidation are becoming defining trends.

Additionally, China maintained its position as the world's largest auto exporter, with over 4 million vehicles exported in 2023, of which 1.2 million were electric. This represents a substantial increase from the previous year, with overall car exports rising by nearly 65% and EV exports growing by 80%. The primary destinations for these exports included Europe and Asia-Pacific markets such as Thailand and Australia.

Electric vehicles in Europe. In 2023, Europe received nearly 3.2 million new EV registrations, marking a 20% increase compared to the previous year. Several nations reached important milestones. Germany became the third country in the world to surpass half a million new BEV registrations in a single year. It followed China and the United States in achieving this landmark. BEVs accounted for 18% of total car sales in Germany, while plug-in hybrids contributed 6%.

Despite this progress, the removal of key financial incentives slowed sales momentum. Germany phased out subsidies for plug-in hybrids at the beginning of 2023, leading to a decline in adoption. By December 2023, all government subsidies for EV purchases had been withdrawn, causing the country's EV sales share to drop from 30% in 2022 to 25% in 2023. However, EV adoption continued to grow in other parts of Europe. EVs accounted for approximately 25% of all new car sales in France and the United Kingdom, while the Netherlands saw EV sales reach 30% [167]. Sweden stood out, with 60% of new car sales being electric. Norway remained the clear leader, with nearly 95% of all cars sold being electric, despite a contraction in its overall car market [168].

Electric vehicles in USA. The EV registrations in the United States reached 1.4 million, marking a growth of over 40% compared to the previous year. Although the pace of growth was slower than in the preceding two years, overall demand for EVs remained robust. The expansion was partly driven by adjustments to the Clean Vehicle Tax Credit and reductions in EV prices, making certain models newly eligible for financial incentives. Tesla Model Y sales surged by 50% after qualifying for the full $7,500 tax credit [129], [163].

The Inflation Reduction Act (IRA) significantly bolstered EV sales in 2023, despite initial concerns that more stringent domestic content requirements for vehicle and battery production could create supply chain disruptions. As of 2024, revisions to the tax credit eligibility criteria have reduced the number of qualifying models from approximately 45 to fewer than 30. However, leasing options continue to provide an alternative means of accessing tax incentives, ensuring continued momentum in EV adoption across the country.

Moreover, the growing awareness from corporations and regulatory bodies increases EV awareness. Another factor is the improvements in charging infrastructure and driving range, which have alleviated concerns and increased consumer acceptance. A survey by the American Automobile Association in 2022 revealed that a quarter of Americans anticipate EV as their next car [169]. In 2021, the Bipartisan Infrastructure Law allocated $5 billion for EV charging infrastructure through the National Electric Vehicle Infrastructure (NEVI) formula program and an additional $2.5 billion in competitive grants (Charging and Fueling Infrastructure Discretionary Grant Program) over the 2022-2026 period [170].

From the launch of the Tesla Roadster in 2008, marking the inception of accessible EVs, to the 2023 milestone when the average EV TCO became competitive, significant events shaped the industry as shown in Figure 16 [171], [172]. The Paris Agreement in 2015 and initiatives like the ZEV Alliance underscored global commitment, while France 2019 set a precedent by legislating a ban on traditional vehicles by 2040. By 2020, major companies committed to transitioning fleets to EVs, ushering in a transformative era in the automotive landscape. Notably, EV sales share increased from 8.3% in 2021 to 13% by the end of 2022, and in the same year, EV sales surged by 55%, reaching 11.8% of total vehicle sales in the US.

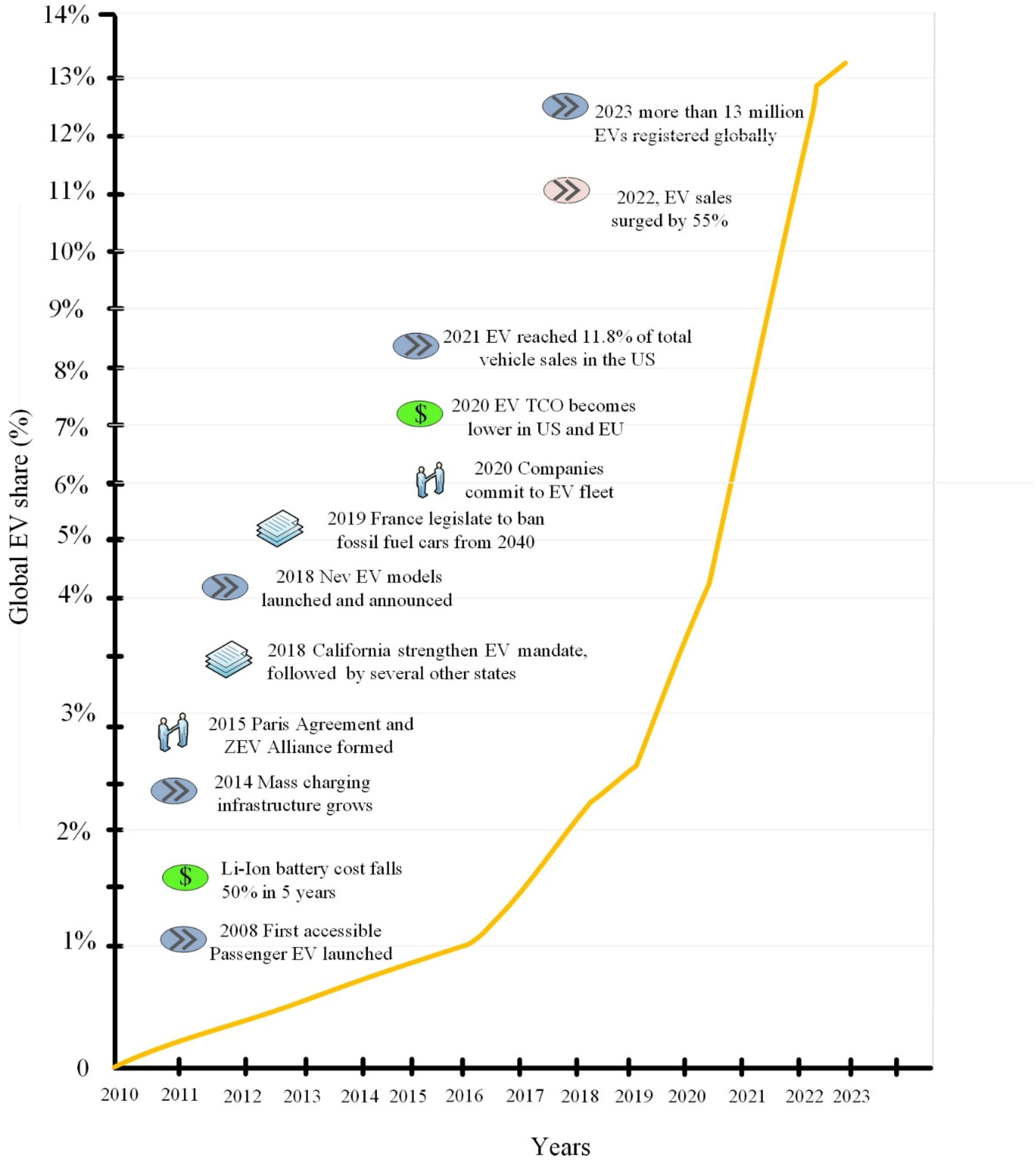


Figure 16. Global electric vehicle sale share

Economic Implications of Battery Degradation

Battery degradation plays a critical role in determining the economic viability of EVs [173]. Since battery costs comprise nearly 50% of an EV's total cost, understanding the economic impact of declining battery health is essential [174]. The State of Health (SOH), which reflects the battery's capacity relative to its original condition, significantly influences the vehicle's range and resale value.

Battery degradation directly reduces an EV's range, affecting consumer confidence and usability. For example, a 10% decline in SOH can reduce range proportionally, critical for long-distance travel. As SOH declines, the second-hand market value of EVs decreases. Buyers often consider SOH a key parameter, with vehicles showing higher SOH values commanding better resale prices.

To evaluate the lifecycle cost implications, the relationship between battery degradation and replacement cost, resale value, and TCO must be analyzed. The following equations can quantify these relationships:

$$C_{replacement} = \frac{C_{battery}}{SOH} \tag{13}$$

Where $C_{replacement}$ is the battery replacement cost and $C_{battery}$ is the original battery cost.

$$V_{resale} = V_{initial} \times SOH \tag{14}$$

Where V_{resale} is the car resale value, and the $V_{initial}$ is the car's initial cost.

The battery degradation rate (BDR) can be calculated by using the equation below:

$$BDR = \frac{\Delta SOH}{t} \tag{15}$$

Where ΔSOH is the change in the SOH and t is the time in years.

Battery degradation can affect consumer adoption rates. Improved BMS and advancements in battery chemistry are promising solutions. Policymakers can incentivize second-life battery applications to offset economic losses and promote sustainability.

FUTURE CHALLENGES

The EV industry has demonstrated remarkable resilience and growth in recent years, outpacing prominent sectors in capital markets such as oil and gas, semiconductors, conventional automotive, and big-tech [106]. This exceptional performance underscores the immense potential of EVs in the contemporary economic landscape. While EVs have existed for over a century, initially serving basic transportation needs, their current prominence in advancing sustainability and actively contributing to the global energy transition sets them apart as a transformative force [103]. Extending beyond conventional transportation requirements, modern EVs are at the forefront of sustainable mobility solutions. Their increasing market share reflects a shift in consumer preferences. It aligns with the global imperative to reduce carbon emissions and combat climate change [7]. This pivotal role positions the EV industry as a key player in shaping the future of transportation and energy. Despite experiencing a peak in electric car sales in 2020, the EV industry is open to challenges that may impede its seamless progress. Manufacturers and consumers alike anticipate and navigate unprecedented obstacles that could impact the trajectory of the EV market [23], [28]. These challenges encompass a spectrum of issues, including but not limited to high upfront costs, infrastructure limitations, battery charging constraints, emission regulations, ancillary support V2G, and market competition.

High Upfront Costs

Most traditional gas-powered vehicles are primarily attributed to their comparatively lower upfront costs. Despite the potential for EVs to yield lower operational costs over time, the formidable initial expenses still need to be reduced. The core of this challenge is the expensive battery technology, a pivotal component in EVs [175]. Advancements in developing efficient, high-capacity batteries and power electronic converters promise to mitigate these upfront costs. However, battery manufacturing utilizes costly minerals and raw materials, contributing to the overall expense [4]. A critical examination of the EV market reveals a limited selection of economically viable models [46]. Compelling research from the U.S. Department of Energy (DOE)'s National Renewable Energy Laboratory (NREL) and the Idaho National Laboratory suggests that EV users can realize substantial savings ranging from $4,500 to $12,000 exclusively on operating costs. The actual savings are contingent upon the driver's geographical location, with regions such as Europe offering the lowest and China presenting the highest potential for cost savings [53].

Nevertheless, the overarching challenge remains a significant hurdle in EV sales and alleviating the concerns regarding initial costs. Therefore, strategic investments in research and development activities and industry collaborative efforts are a way forward. Addressing technological and economic aspects would position EVs as a compelling and economically feasible choice for consumers worldwide.

Charging Time and Charging Infrastructure Challenges

The EV market has recently achieved substantial gains, but public EV charging stations and connected infrastructure development remain in their early stages [79]. Most EV charging occurs at home and workplaces, highlighting the need for robust public charging networks. In 2020, the global count of public chargers reached 1.3 million units, with 30% being DC chargers [86]. The pace of charger installations increased by 45% but at a slower rate than in 2019 due to the impact of the pandemic [81]. Globally, China is leading in infrastructure development, with more than half of the world's public chargers containing both slow and fast charging stations [22]. In Europe, over 250,000 AC charging stations were operational by the end of 2020, with a 30% increase in installations [119]. The Netherlands leads the European charge with over 63,000 AC charging stations, closely followed by Sweden, Finland, and Iceland. The deployment of DC fast charging stations outpaced slow charging stations globally, reaching over 38,000 units with a remarkable 55% increase in 2020 [164].

Despite these strides, European countries face challenges in meeting public charging station targets outlined in the Alternative Fuel Infrastructure Directive [176]. The average ratio of EVs per charger stood at 11 at the close of 2020, just below the recommended 10 EVs per plug. Notable variations exist between countries, with the Netherlands and Italy surpassing the target. In contrast, countries with high EV penetration, such as Norway, Iceland, and Denmark, report lower ratios. In response to these challenges, the European Union's Green Deal aims to install 1 million publicly available chargers by 2025, aligned with 40 million EVs [177]. The Fit 55 Legislative train, currently in place, reflects calls to revise the 1-plug per 10 electric cars ratio, emphasizing citizens' "right to plug" and including provisions for Heavy Duty Vehicles, regardless of location [167]. EU member states are actively implementing the revised (EPBD III) standard, which requires residential and non-residential buildings to install charging points for EVs [178]. Furthermore, the Recovery and Resilience Facility allocates funding for installing EV charging stations, underscoring the commitment to fostering a robust and accessible charging infrastructure across the European Union.

Challenges in Charging Technology

EVs rely on crucial charging technologies, presenting challenges and innovations. Inductive charging uses electromagnetic fields for power transfer; it is robust and safe but becomes less efficient with increased distance [179]. Conductive charging requires a metal-to-metal connection, demanding considerations for safety and circuit interfaces [179], [180]. Moreover, charging infrastructure includes residential, public, and ultra-fast charging stations. Residential stations are handy for nighttime charging at lower energy tariffs.

In contrast, public stations are ultrafast and strategically placed, offering quick charging but at higher costs [4]. Plug-In Electric Vehicle (PEV) charging strains electrical grids, with peak-hour tariffs adding to consumer costs [110]. The growing demand prompts the installation of more charging stations. Therefore, renewable resources like solar and wind energy are utilized [142]. Solar PV charging stations follow PV-grid or PV-standalone approaches and grid-connected wind-powered charging stations with advanced Maximum Power Point Tracking (MPPT) techniques are also under research [140]. Various renewable resources, including concentrated solar power, geothermal, tidal, wave, and hydro, can contribute to PEV charging [30]. Evaluations indicate that wind-powered BEVs have the most negligible environmental impact. Converting all on-road vehicles to wind-powered BEVs in the United States is estimated to reduce CO_2 emissions by 32.5–32.7% and eliminate 15,000 vehicle-related air pollution deaths annually [181]. Addressing challenges in charging technologies and embracing renewables are crucial for the sustainable future of PEVs.

Zero-Emission Vehicle Challenge

Global road transport contributes 13% to worldwide carbon emissions, a critical factor in achieving ambitious climate goals [128]. Recognizing the scale of this challenge is imperative for driving forward technological advancements that can pave the way for a sustainable future [7]. General Motors' recent commitment to exclusively sell zero-emission vehicles by 2035 exemplifies the unstoppable momentum propelling the shift toward cleaner mobility [182]. An instrumental avenue for achieving environmental improvement lies in continuously enhancing energy storage technologies, mainly clustered EV batteries. The significant reduction in the cost of EV batteries (approximately $100 per kilowatt-hour compared to $1,200 in 2010) symbolizes the advancements in storage technologies. Furthermore, the surge in investments in EV-related technologies and equipment, nearly doubling in 2020, underscores the industry's dedication to advancing sustainable mobility [129].

An encouraging trend is the commitment of 18 out of 20 major automakers to switch toward hybrid EVs or transition entirely to EVs [164]. This strategic move is driven by the dual objectives of capturing a larger market share and aligning with increasingly stringent regulatory requirements. While these advancements are significant, the required research and development efforts remain insufficient to meet the 1.5 °C climate targets unless the current trajectory of EV technology transitions toward Zero Emission Vehicles (ZEVs) throughout the entire value chain. Realizing a sustainable and low-carbon future depends on continuously improving individual components and the holistic transformation of the entire automotive ecosystem toward comprehensive zero-emission solutions.

Extended Vehicles to Grid Challenges

As V2G technology progresses, collaborative efforts and technological innovations are pivotal in shaping a more sustainable and efficient energy future. The adoption of V2G is driven by its ability to act as a backup generator in emergencies, benefiting crucial facilities such as shelters, hospitals, and neighborhoods [125]. Moreover, V2G enhances grid reliability, efficiency, and stability by engaging EVs in various grid services, including voltage and frequency control, active power regulation, and renewable power monitoring. V2G optimization schedules activities intelligently during peak times and charges EVs during low-demand periods to optimize power management [123]. Controlled battery chargers strategically shift energy usage, while electric price algorithms minimize charging costs for EV owners. These advancements, including load shifting and coordinated charging, collectively reduce the overall grid impact of EVs.

The proliferation of V2G technology in existing energy infrastructures necessitates a collaborative, interdisciplinary approach. Researchers, policymakers, and industry stakeholders may collaborate to establish an adaptive regulatory framework. These are crucial for ensuring compliance and fostering a unified vision for the evolution of V2G technology [183]. Modern communication, AI, and cyber security can leverage V2G technology. Blockchain technology emerges as an effective solution for mitigating cybersecurity concerns and ensuring the integrity of data exchanges within V2G transactions [101].

Similarly, machine learning algorithms for grid predictions empower intelligent scheduling of V2G activities. This strategic approach optimizes energy usage and minimizes grid impact, particularly during peak demand [110]. Complementing this, exploring decentralized energy management systems introduces an innovative solution where individual EVs contribute autonomously based on real-time local grid conditions, enhancing overall grid stability and resilience.

Despite these strides, challenges persist, encompassing battery degradation, infrastructure adjustments, increased communication demands, distribution network impacts, energy losses, and technical challenges. Coordination between operators and aggregators remains pivotal to mitigating V2G's effect on the distribution network. Addressing these challenges is not merely a requisite; it is the fulcrum for realizing the full potential of V2G in shaping a sustainable and reliable energy future. Overcoming these challenges through strategic initiatives and technological innovations will pave the way for a more resilient and efficient energy landscape.

Cybersecurity and Connected Vehicle Challenges

The electric automotive industry requires innovative connectivity solutions while addressing the growing cybersecurity and data privacy concerns [103]. The increasing sophistication of infotainment systems, which offer many features ranging from navigation and entertainment to real-time vehicle diagnostics, has led to a surge in data collection and transmission [184]. One key challenge is the vulnerability of connected vehicles to cyber threats. Instances of hacking into vehicle systems and potential data breaches have raised serious concerns among consumers and regulatory bodies. Robust cybersecurity measures are essential to safeguard sensitive information and ensure the safety of connected vehicles [103].

Additionally, the industry is struggling to standardize communication protocols for connected vehicles [185]. A universal standard is needed to ensure interoperability among vehicles and systems, hindering seamless communication and integration. Stakeholders in the automotive ecosystem are actively working on establishing common standards to promote compatibility and enhance the overall efficiency of connected vehicle systems. Despite these challenges, the market for connected vehicle technologies continues to grow. The global connected EV market is projected to reach \$561.3 billion, reflecting the increasing consumer demand for innovative features and connectivity [186]. Major automotive manufacturers invest significantly in research and development to address these challenges and stay at the forefront of innovation. Developing comprehensive guidelines and regulations aims to create a secure, standardized environment for connected vehicles.

Limited Drive Range

Another challenge for EVs is their driving range. While the range of EVs has improved over the years, it is still not as good as that of traditional gasoline-powered vehicles or FCEVs [187]. However, research is being done to improve the range of EVs, and new battery technologies are being developed that could significantly increase the range of EVs. Better charging infrastructure can be enhanced to compensate for the driving range issue. Fast-charging technologies are being developed that could substantially reduce the charging time of EVs [86]. Similarly, EV efficiency can be improved by reducing the weight, improving aerodynamics, and using more efficient semiconductors and traction motors.

Advancing Battery Technology Challenges

Developing lightweight, long-lasting, and maintenance-free batteries is a crucial challenge for the future of EVs [124]. While lithium-ion batteries are currently the most common type of battery used in EVs, several new battery technologies are being developed that could significantly improve the performance of EVs. Semiconductor or solid-state batteries are promising technologies that can replace liquid electrolytes with ceramics or other solid materials [188]. This swap unlocks possibilities that pack more energy into a smaller space, improving the range of EVs. Solid-state batteries could also move charge around faster, meaning shorter charging times.

Moreover, because some solvents used in electrolytes can be flammable, advocates of solid-state batteries say these batteries improve safety by reducing fire risk. Another promising technology is the use of carbon fiber and electrolyte matrix. This technology could lead to the development of lightweight " massless " batteries with a high energy density [189].

Challenges in Recycling Electric Vehicle Batteries

Due to their zero tailpipe emissions, EVs are more environmentally friendly than gasoline-powered cars and FCEVs. However, the production of EV batteries is energy-intensive and requires minerals such as lithium, nickel, and cobalt, which are crucial for modern EV batteries [15]. Significant fossil fuel resources are needed for mining and processing these materials, which can result in substantial carbon emissions. Recycling EV batteries is an essential step in reducing the environmental impact of EVs [190]. Rare metals such as lithium, cobalt, and nickel can be recycled [191]. However, the recycling process is still in its early stages, and more research is needed to develop efficient and cost-effective recycling methods.

Vehicle Aerodynamic Challenges

Aerodynamic challenges affect all vehicles, including ICE cars, but are particularly crucial for EVs due to their reliance on battery energy storage and the need to maximize range. Aerodynamics plays a crucial role in improving the range of EVs by reducing the energy required to move the car through the air [192]. At highway speeds, over 50% of energy is spent pushing the air away [193]. Researchers are developing new technologies to optimize airflow around EVs. For example, virtual wind tunnels are being used to analyze the airflow around EVs digitally, which helps to cut expensive wind tunnel time.

Unlike ICE vehicles that can refuel quickly, EVs are particularly affected by aerodynamic drag, as increased resistance leads to greater energy consumption, thereby reducing driving range per charge. To address this, EV manufacturers focus on achieving lower drag coefficients through design optimizations. Additionally, since EVs do not require large front grilles for engine cooling, they can adopt more aerodynamically efficient front-end designs, further minimizing air resistance and enhancing overall energy efficiency.

Additionally, advances in simulation technology will result in better aerodynamic design. Lighter materials can also help to improve the performance of EVs. The Vehicle Technologies Office (VTO) is working to improve the properties of lightweight materials, such as strength, stiffness, and ductility [194]. Carbon fibre and electrolyte matrix technology could lead to the development of lightweight EVs.

CONCLUSION

This review comprehensively analyzed EVs' technical, environmental, and economic aspects, highlighting their transformative potential in modern transportation. The study explored the operational principles, battery technologies, charging infrastructure, and V2G integration, providing insights into the key advancements shaping the EV ecosystem. Technological innovations, such as high-energy-density batteries, fast-charging solutions, and intelligent grid management, are critical for the widespread adoption of EVs. However, battery degradation, charging infrastructure, and grid stability challenges must be addressed through continued research and policy interventions.

From an environmental perspective, EVs significantly reduce greenhouse gas emissions and improve air quality, particularly when charged using RES. Life cycle assessments demonstrate that EVs have a lower carbon footprint than ICE vehicles, reinforcing their role in achieving global climate goals. The study also highlighted the importance of developing sustainable battery recycling processes to minimize environmental impact. Economic analysis indicates that despite the high initial costs, EVs offer long-term financial benefits through lower operating and maintenance expenses. The TCO is becoming more competitive with conventional vehicles as battery costs decline and government incentives promote EV adoption. The expansion of EV markets in regions like China, Europe, and the United States, along with emerging Asian markets, signals a promising trajectory for global EV adoption.

The EV industry must focus on enhancing energy storage solutions, improving charging networks, and integrating smart grid technologies for efficient energy management. Future research may explore solid-state batteries, bidirectional charging systems, and AI-driven energy optimization strategies to further advance EV sustainability. Policymakers can prioritize regulatory frameworks that support renewable energy integration, standardized charging protocols, and incentives for battery recycling. The rapid advancement of EV technology and supportive policies and investments drive the transition toward a more sustainable transportation system. Addressing the technical, environmental, and economic challenges will ensure the long-term success and widespread adoption of EVs globally.

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STATEMENTS & DECLARATION

During the preparation of this work, GPT-4o was utilized to improve content readability. Following its use, the text was reviewed and edited as necessary, ensuring accuracy and integrity.

NOMENCLATURE

Symbols

E_{total}	Total Energy	Wh
E_{spec}	Specific Energy	Wh/kg
M	Mass of Battery	Kg
P_{total}	Specific Energy	kW
P_{spec}	Specific Power	kW/kg
V	Voltage	V
N	Total number of electric vehicles	-
R_{solar}	Additional driving ranges from solar power	km
H_{solar}	Average daily sunlight hours	h

Abbreviations

EV	Electric Vehicle
V2G	Vehicle-to-Grid
CV2G	Coordinated Vehicle-to-Grid
BMS	Battery Management System
BEV	Battery Electric Vehicle
PHEV	Plug-in Hybrid Electric Vehicle
HEV	Hybrid Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
LiNMC	Lithium Nickel Manganese Cobalt
LFP	Lithium Iron Phosphate
LMB	Lithium Metal Battery
Li-S	Lithium-Sulfur
Li-O_2	Lithium-Oxygen
GENCO	Generation Companies
TSO	Transmission System Operator
DSO	Distribution System Operator
PEMS	Primary Energy Management System
AC	Alternating Current
DC	Direct Current
DCFC	Direct Current Fast Charging
DCC	Direct Current Charging
SAE	Society of Automotive Engineers
IEC	International Electrotechnical Commission
EPRI	Electric Power Research Institute
NEMA	National Electrical Manufacturers Association
CCS	Combined Charging System
CHAdeMO	Charge de Move
GB/T	Chinese EV Charging Standard
NdFeB	Neodymium-Iron-Boron (magnet material)
AI	Artificial Intelligence
RES	Renewable Energy Source
CGE	Computable General Equilibrium
ICE	Internal Combustion Engine
TCO	Total Cost of Ownership
EMA	EV Market Aggregator
LP	Load Profiler
GMO	General Market Operator
EVSA	Electric Vehicle Suppliers-Aggregators
CPM	Charging Point Managers
BaaS	Battery-as-a-Service
PV	Photovoltaic
VIPV	Vehicle-Integrated Photovoltaics
SEV	Solar Electric Vehicle
IRA	Inflation Reduction Act
MPPT	Maximum Power Point Tracking
ZEV	Zero-Emission Vehicle
SOH	State of Health
VTO	Vehicle Technologies Office

DOE	Department of Energy
NREL	National Renewable Energy Laboratory
IEEE	Institute of Electrical and Electronics Engineers
NEVI	National Electric Vehicle Infrastructure
Li–O2	Lithium Superoxide
PEV	Plug-In Electric Vehicle
PFC	Power Factor Correction
EMI	Electromagnetic Interference

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