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Review

Navigating the Shift: Advancing Light-Duty Electric Vehicles in Sustainable Transportation

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Abstract: With their benefits of reduced exhaust emissions and noise pollution, the growing number of electric vehicles (EVs) for personal transportation in metropolitan areas is progressively changing our culture and surroundings. The carbon footprint of the United States is a complicated issue influenced by different economic sectors. Addressing this issue requires a coordinated effort from multiple stakeholders. A comprehensive study has been conducted on the growing electric vehicle market, specifically light-duty electric vehicles (EVs). This study comprises five chapters comprehensively analyzing the industry, technological advancements, economic considerations, life cycle assessments, and policy landscapes, all supported by extensive research. The study highlights the critical role of light-duty EVs in promoting sustainable mobility and provides valuable insights that can help policymakers, automakers, and energy companies. These insights can drive significant progress in their respective industries and pave the way for an eco-friendly automotive paradigm that caters specifically to light-duty applications. The study's results highlight how different stakeholders must work together to develop policies and infrastructure that encourage the use of light-duty EVs. The electric car plays an important role in the power sector, particularly in the implementation of smart grids and acting as a smart vehicle via grid connectivity. This article elaborates on the issues posed by electric vehicles, as well as their effects on the energy sector.

Keywords: Light-Duty EVs; Sustainable Mobility; Technological Advancements; Carbon Footprint

1. Introduction

The carbon footprint of the United States is an intricate composition formed by the emissions of several economic sectors, each exerting a crucial influence on the nation's environmental condition. Greenhouse gas emissions come from different sources in the United States [1]. These sectors include transportation, accounting for 28% of emissions from cars, trucks, buses, trains, and airplanes; electricity production, constituting 25% of emissions from power plants fueled by coal, oil, natural gas, and other sources; industry, with a 23% share covering emissions from manufacturing, construction, and mining processes; commercial and residential activities contributing 13%, which include emissions from buildings and facilities used for business and residential purposes; agriculture, comprising 10% of emissions from livestock, fertilizers, and other agricultural practices; land use, encompassing emissions from deforestation, forest fires, and other land-use changes; and forestry, contributing 12% and including emissions from forest management practices and timber harvesting (**Figure 1**) [2].

Every sector significantly influences the country's total greenhouse gas emissions, requiring coordinated actions to reduce their environmental impact. Multiple endeavors are underway to reduce emissions in various sectors, mitigate the devastating effects of climate change, and promote a sustainable future. This study examines the growing electric vehicle (EV) market, mainly focusing on light-duty electric cars. This paper seeks to thoroughly examine the current state and future potential of light-duty electric vehicles (EVs) over five distinct chapters.

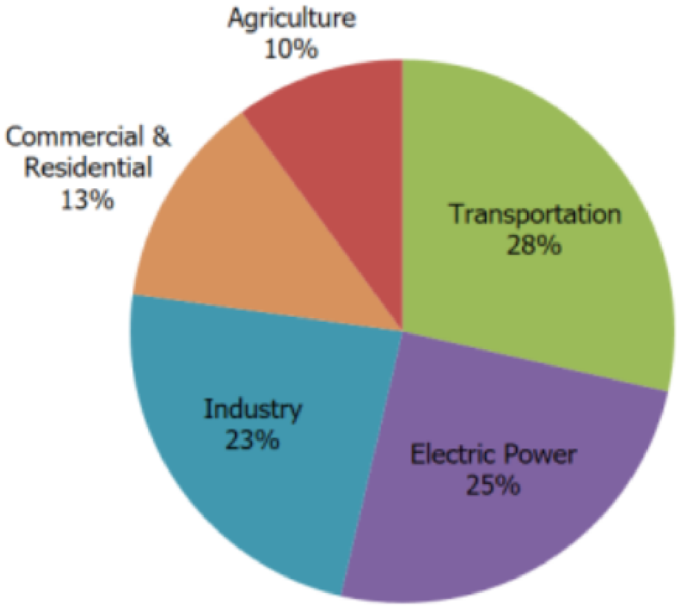

Figure 1. A pie chart that presents a detailed breakdown of greenhouse gas emissions in the United States, categorized by economic sector [2].

The initial chapter is a fundamental cornerstone, thoroughly analyzing the light-duty electric vehicle (EV) industry. This analysis explores insightful data and clarifies the elements fueling the growing consumer demand for electric vehicles (EVs), providing a foundation for a more profound comprehension of this revolutionary industry. Chapter 2 explores the technological improvements and limitations currently affecting and will continue to shape the future of light-duty electric vehicles (EVs). It specifically highlights the critical developments that are influencing the automotive industry. Chapter 3 focuses on the economic aspects of light-duty electric vehicles (EVs), examining the costs of investment and operation, consumer opinions, dependability, and market trends to get insight into the changing market environment. Chapter 4 provides a comprehensive examination of the life cycle of light-duty electric vehicles (EVs), including an analysis of the cost dynamics throughout their lifetime, patterns of energy use, and concerns for managing them at the end of their life. Chapter 5 examines the policy environment related to light-duty electric vehicles (EVs), analyzing the influence of government incentives and regulatory frameworks on market dynamics and industry expansion.

This study delves into the intricacies of the light-duty electric vehicle (EV) industry, underscoring the pivotal role these vehicles will play in promoting sustainable mobility. The findings of this research are significant to policymakers, automakers, and energy companies, as they provide detailed research and innovative insights into the changing landscape of electric mobility. This study aims to guide the way toward a more environmentally friendly automotive paradigm specifically designed for light-duty applications.

2. Need for Electric Vehicles (EV)

The transportation sector's significant energy consumption, accounting for 27% in the United States alone, underscores the urgent need for sustainable alternatives. Electric vehicles (EVs) are not just a part of the solution; they are pivotal in reducing carbon emissions and transitioning towards cleaner energy sources. The concept of a "milestone" signifies a crucial juncture where EV adoption reaches a critical mass, leading to a tangible decrease in fossil fuel consumption and an upsurge in renewable energy generation. This milestone necessitates informed decisions from policymakers, automakers, and energy companies, shaping future investments and policies [3, 4].

It is paramount to understand the trajectory of EV adoption, its impact on energy consumption, and advancements in battery technology and infrastructure development. This essay focuses on the light-duty vehicle sector, offering insights into future trends and strategic actions necessary for a sustainable energy landscape. The global impact of EVs must be balanced, and policymakers and energy companies must recognize their role in this transition [5]. The International Energy Agency (IEA 2020) has determined that the present average carbon intensity of worldwide energy is 518 gCO_2 kWh^{-1}, a level at which typical electric vehicles (EVs) are more environmentally friendly than many conventional vehicles [6]. In 2020, carbon emissions in China rose by 1.7%, far lower than the 3.3% average of previous decades, totaling about one billion metric tons, reflecting China's substantial reliance on fossil fuels [7]. Unlike China, the second-largest CO_2 emitter, the USA experienced an 11% reduction in emissions in 2019, reaching the lowest level since 1983, attributed to Covid-19 lockdowns and limitations [8]. Countries within the EU, including Germany, France, and Norway, have experienced a gradual decline in recent years, particularly in Norway, where the renewable energy mix is crucial. According to the European Environment Agency, CO_2 emissions in the European Union in 2020 were 31% lower than 1990 levels, surpassing the EU's climate objective by 11%, resulting in a total reduction of 124.9 million tons of CO_2 equivalents, as illustrated in **Figure 2**. By 2050, it is anticipated that the production of 20 million EVs, PHEVs, or FCVs might result in a 30% reduction in CO_2 emissions [9].

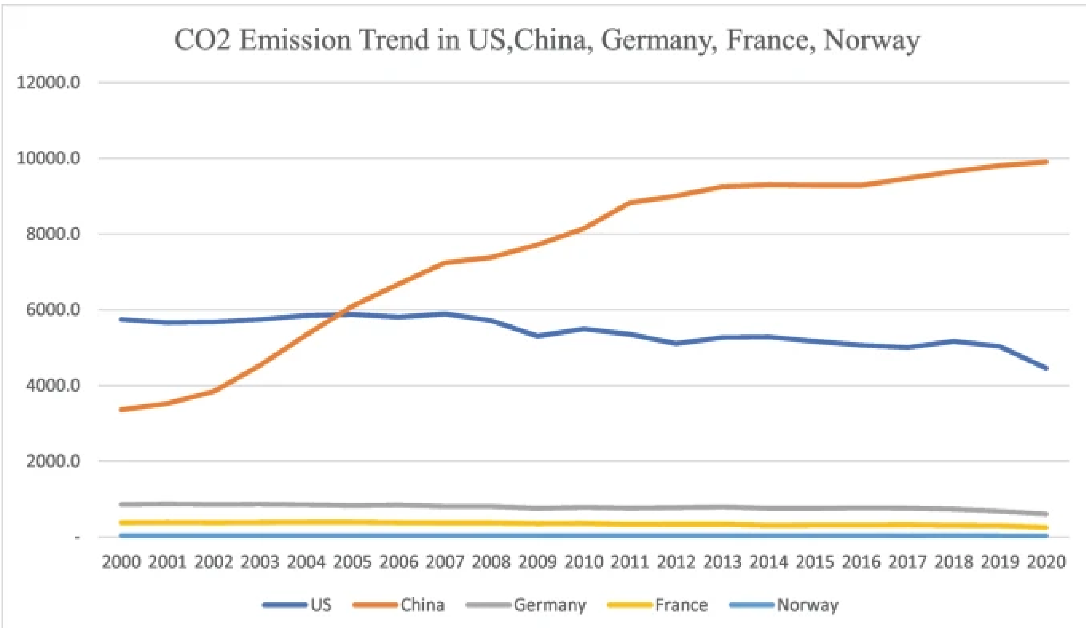

Figure 2. Greenhouse gas emissions in the USA, China, Germany, France, and Norway between 2000 and 2020 [10].

There are other personal benefits related to the adoption of EVs. Firstly, electric vehicles (EVs) are more economical to operate than traditional automobiles [11, 12]. Electricity and oil prices fluctuate worldwide; however, traveling in an electric vehicle is typically more economical than in a petroleum-powered vehicle. In the United States, a 200-mile journey will incur a cost of $7.42 for the electric car traveler, based on average electricity rates and typical EV efficiency. The expense for utilizing a conventional automobile will amount to $22.60, based on normal fuel prices and fuel efficiency. Furthermore, consumers may rely on power pricing exhibiting greater stability over time, in contrast to the erratic oil market. Also, the maintenance expenses and inconveniences related to servicing a conventional car are significantly reduced with an electric vehicle (EV) [12–14]. Conventional vehicles consist of numerous moving components, each with limited operational lifespans and requiring synchronization for maximum functionality. Electric vehicles, by comparison, possess a limited number of moving components, approximately two dozen, resulting in a reduced likelihood of mechanical failure [15]. Electric vehicles, for instance, lack lubricating oils, filters, clutches, spark plugs, pistons, timing belts, fan belts, water hoses, radiators, and catalytic converters. **Table 1** summarizes an article published by Inside EVs that itemized the maintenance cost savings of owning and operating an EV.

Table 1. Maintenance costs over the first 100,000 miles.

Service/Maintenance	Traditional Vehicle	Electric Vehicle
Tires	$700	$700
Oil change (every 5,000 miles)	$600	0
Automatic transmission fluid	$60	0
Spark plugs and wires	$200	0
Mufflers	$180	0
Brakes	$400	$200
Total	$2,140	$900

Based on **Table 1**, maintenance savings for an EV in the first 100,000 miles would be $1,240 [15].

2.1. Types of Electric Vehicles

Electric vehicles (EVs) have significantly changed the automotive industry by providing a cleaner and more sustainable solution to traditional gasoline-powered vehicles. Various types of electric cars are available [16]. Each design is designed to cater to different consumer needs and preferences. The three primary types (**Figure 3**) of electric vehicles are battery Electric Vehicles (BEVs), Plug-in Hybrid Electric Vehicles (PHEVs), and Hybrid Electric Vehicles (HEVs) [7].

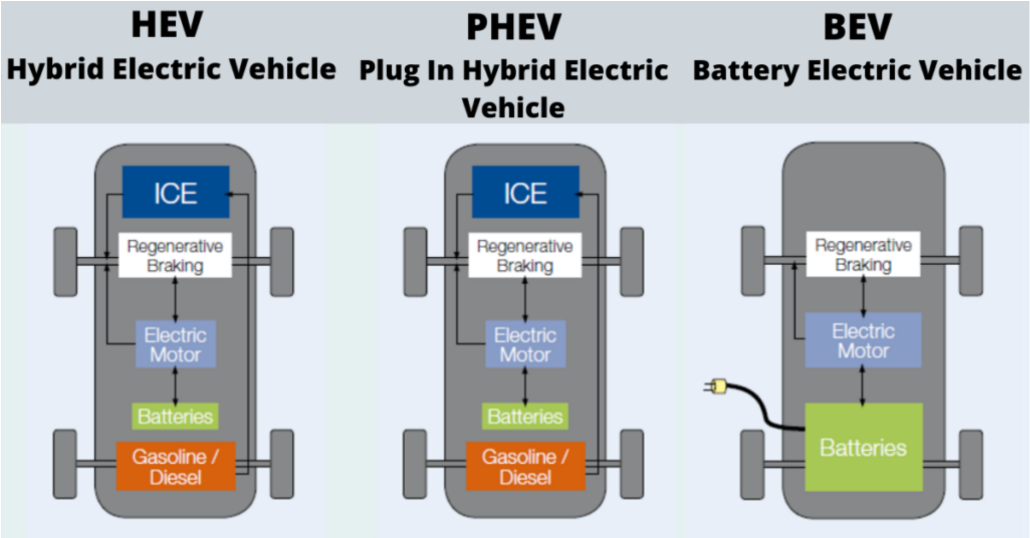

Figure 3. Demonstrates the three types of electric vehicle categorized by the amount or degree of electricity used as a power source [17].

BEVs are the ultimate electric vehicles that rely solely on an electric battery without the need for any gas engine components. These vehicles are designed to run exclusively on electricity, producing zero tailpipe emissions and contributing to a cleaner environment. BEVs generally have fast charging capabilities and support Level 2 (L2) charging, which makes them an efficient and convenient option for recharging. With a growing network of charging stations, BEV owners can charge their vehicles at home, work, or public charging stations, making them a practical and eco-friendly choice for those who care about the environment [18].

PHEVs are a hybrid solution between traditional gasoline-powered vehicles and fully electric BEVs. These vehicles feature a larger battery, electric motor, and a gasoline engine, enabling drivers to switch between electric and gas power modes. PHEVs are equipped with a gas tank and a charging port, offering multiple fuel options that cater to different driving needs and preferences. While PHEVs can charge using Level 2 (L2) chargers, they can also refuel at gas stations, making them a versatile option for those seeking a balance between electric and gasoline-powered driving [19].

HEVs are a step towards electric mobility, incorporating an electric motor to assist traditional gas-powered engines in propelling the vehicle. Unlike BEVs and PHEVs, HEVs rely solely on gasoline as their energy source, with the electric motor as a supplementary power source to enhance fuel efficiency and reduce emissions. While HEVs offer improved fuel efficiency compared to conventional gasoline vehicles, they cannot charge using EV charging infrastructure, limiting their electric-only driving capabilities. Despite these limitations, HEVs remain popular among consumers looking for an eco-friendlier alternative to traditional gas vehicles without the range anxiety associated with fully electric vehicles.

The variety of electric vehicles in the market reflects the evolving landscape of sustainable transportation. From the zero-emission purity of BEVs to the hybridized flexibility of PHEVs and the efficiency gains of HEVs, electric vehicles offer a range of options to meet consumers' diverse needs and preferences. It is paramount to understand the trajectory of EV adoption, its impact on energy consumption, and advancements in battery technology and infrastructure development. This essay focuses on the light-duty vehicle sector, offering insights into future trends and strategic actions necessary for a sustainable energy landscape. The global impact of EVs must be balanced, and policymakers and energy companies must recognize their role in this transition [20].

2.2. Evolution of Electric Vehicles: From Vision to Reality

The journey towards electric mobility traces back to the emergence of hybrid vehicles, bridging conventional internal combustion engines with sustainable transportation aspirations. Notable figures like Ferdinand Porsche and Ferdinand Verbiest laid the groundwork, leading to significant milestones such as the Benz Patent-Motorwagen in 1886, considered the world's first automobile. The inaugural electric vehicle, a tricycle, was constructed in 1881 by Gustave Trouvé. It was driven by a 0.1 HP DC motor powered by lead-acid batteries, with a gross vehicle weight of 160 kg. In 1883, two British professors constructed a comparable electric vehicle that achieved a maximum velocity of 15 km h^{-1} and a range of 15 km [21]. In 1889, William Morris introduced the first electric taxi in the US, with a maximum speed of 32 km h^{-1} and a range of 40 km. In 1900, of the 4,200 automobiles sold in the United States, 38% were electric vehicles (EVs) and 22% were internal combustion engine vehicles (ICEVs). These electric vehicles diminished in significance due to Henry Ford's mass production plan for the Model T, which was offered at one-third the cost of internal combustion engine vehicles. Additionally, due to the nascent battery technology characterized by sluggish speeds and limited range, there was a total fall in electric vehicles in the 1930s. Electric vehicles had a resurgence following the oil crisis of the late 1970s. The 1973 Arab oil crisis stimulated the exploration of alternate energy sources, fostering a resurgence of interest in electric vehicles [22]. The significant advancement in the 1980s and 1990s was the creation of high-power and high-frequency semiconductor switches and microprocessors, which enhanced the efficiency of electromagnetic systems through optimized power conversion designs. In 1990, the California Air Resources Board ruled that 2% of vehicles must be zero-emission vehicles (ZEVs) for every 35,000 vehicles by 1998, then increasing the requirement to 10% by 2003. Nonetheless, because of practical constraints, it was limited to 4% by 2003. The development of more powerful and durable motors, DC to AC inverters, and efficient battery management systems significantly contributed to the comeback of electric vehicles. Following 2015, the Paris Agreement has facilitated the decrease of greenhouse gas emissions, hence enhancing interest in electric vehicles. Despite the dominance of internal combustion engine vehicles throughout the early 20th century, concerns over pollution, oil dependency, and climate change spurred the exploration of alternative propulsion systems [23]. The introduction of hybrid cars, exemplified by the Toyota Prius in 1997, marked a turning point, setting the stage for further electrification advancements [24].

In the 21st century, they witnessed a surge in electric propulsion, catalyzed by breakthroughs in battery technology, government incentives, and heightened environmental consciousness. Companies like Tesla revolutionized the automotive landscape, showcasing the superiority and desirability of electric cars through groundbreaking models like Roadster and Model S. As governments worldwide tightened emission regulations, automakers pivoted towards electric vehicle development, with industry giants like Volkswagen, General Motors, and Ford committing to electrify their fleets. Today, electric vehicles stand poised to transform transportation, offering a cleaner alternative, extended driving ranges, faster charging times, and affordability while addressing sustainability concerns. The role of automakers in this evolution is crucial, and their efforts are acknowledged and appreciated [25].

2.3. Current State of Light-Duty Electric Vehicles

The recent surge in electric vehicle sales underscores the global momentum towards electrification. IEA states that by December 2021, over 2.1 million plug-in electric vehicles were sold in the US, with battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) experiencing significant growth [26]. BEV sales surged by 55% in 2022, marking a second consecutive year of robust expansion, while PHEV sales grew by 15%. Despite an 8% decline in overall US automobile sales in 2022, the EV sector's resilience is evident, with the US contributing significantly to the global increase in EV sales. Focusing on the US, **Figure 4** demonstrates the monthly new electric car registrations in the United States, 2020–2023 [26]. Despite economic challenges, the United States is experiencing a monthly surge in registered electric vehicles (EVs). This indicates the rising popularity and practicality of EVs in the country. The EV market is growing, potentially due to increased government support and incentives for electric mobility. These shifts in the American automotive industry reveal a greater focus on environmentally friendly and sustainable modes of transportation. Globally, electric car inventory reached 3 million units, constituting 10% of the automobile market, with electric car sales rising to about 8% of overall car sales, signaling a promising and irreversible shift towards electrification.

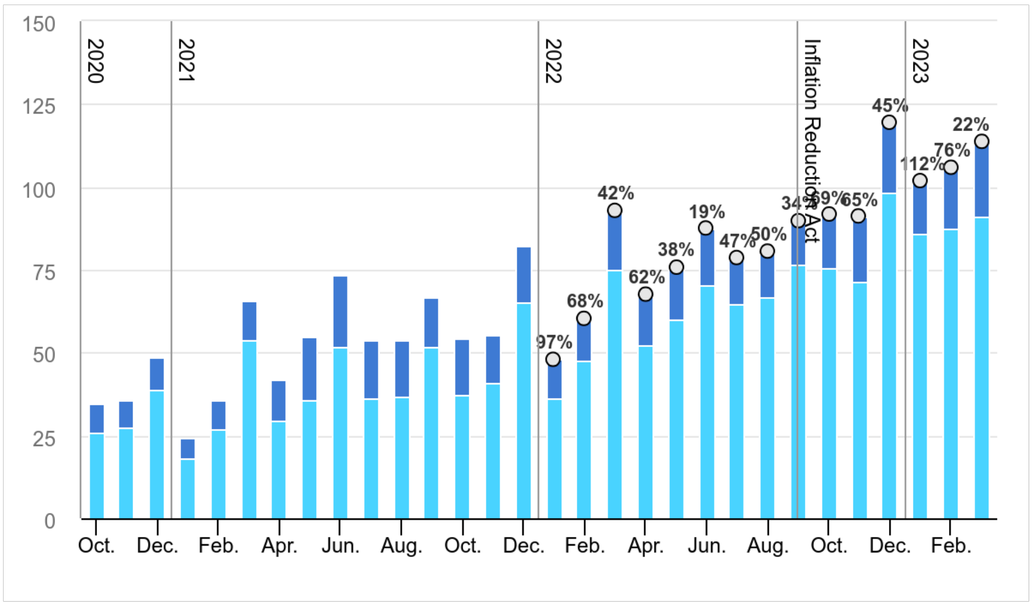

Figure 4. Electric car registrations in the United States every month from 2020 to 2023 [26].

In the United States, more than 320 000 electric cars were sold in the first quarter of 2023, 60% more than over the same period in 2022.

In 2020, there were 3 million new EV registrations. Europe recorded 1.4 million registrations, followed by China with 1.2 million and the United States with 0.3 million. As a result, worldwide electric vehicle stocks reached a record high of 10 million, reflecting a 43% rise since 2019, with China accounting for the largest share at 4.5 million. China has also been the preeminent global producer of lithium-ion (Li-ion) power batteries [27]. Due to advanced vehicle-level integration and control technology, the development of charging, swapping, and other infrastructures, along with the backing of an increasingly robust safety monitoring and assurance system, battery electric vehicles (BEVs) have emerged as the predominant model of new energy vehicles in China, comprising 6.4 million of the total 7.84 million vehicles (approximately 81.63%). The United States ranks seventh globally in electric vehicles, trailing behind China, which holds the top position. In 2021, the global electric vehicle (EV) market, as illustrated in **Figure 5**, recorded sales exceeding 3.2 million EVs in China, accounting for half of all electric cars sold globally, representing an increase of 2 million compared to 2020. The statistic for China surpasses that of any other country globally.

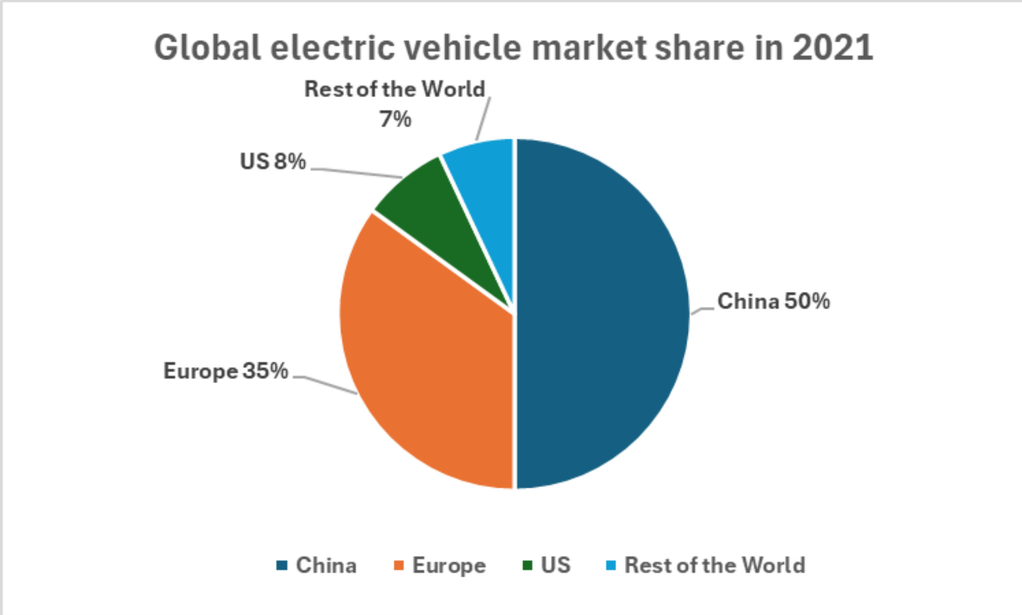

Figure 5. Global electric vehicle market share in 2021 [27].

The paradigm shift towards electric mobility represents a pivotal moment in transportation history, offering a pathway to a sustainable and environmentally friendly future. By understanding the intricacies of light-duty electric vehicles and addressing challenges such as range anxiety, charging infrastructure limitations, and upfront costs, stakeholders can accelerate the adoption of EVs and propel the world toward a new era of sustainable mobility. As we navigate this transition, collaboration between policymakers, industry leaders, and consumers will be crucial in shaping a future where electric vehicles are central to reducing carbon emissions and creating a cleaner, greener world for future generations. Everyone's contribution, no matter how small, is significant in this collaborative effort [28].

2.4. Technology

Electrification is a fundamental component of contemporary existence, with electric motors and machines ubiquitous in manufacturing, consumer electronics, robotics, and electric vehicles. The relentless pursuit of research and development has given birth to next-generation Li-ion chemistries like lithium iron phosphate (LiFePO4), lithium nickel manganese cobalt oxide (NMC), and lithium nickel cobalt aluminum oxide (NCA). These new chemistries offer higher energy densities and enhanced performance characteristics, marking a significant leap forward in battery technology [29]. In the US market, lithium-ion batteries have been widely adopted due to developments in their capacities (**Figure 6**). By 2030, it is anticipated that 64% of all light-vehicle sales will comprise LIB-based EVs, which will account for 24% of all light cars owned. In China, which accounts for over 50% of the present electric vehicle market, it is anticipated that approximately 37% of the vehicle market will comprise lithium-ion battery-based electric vehicles [30].

The recent success and increased adoption of electric vehicles can be attributed to the utilization of better lithium-ion batteries that offer enhanced performance, longevity, and reduced costs (**Figures 7** and **8**). Enhanced energy and power efficiency, extended cycle and calendar longevity, and reduced expenses are resulting in electric vehicles with greater range and superior acceleration at diminished cost premiums, thereby appealing to consumers [31, 32].

One of the most significant advantages of Li-ion batteries for light-duty EVs is their high energy density. This feature allows for the creation of compact and lightweight battery packs that can store large amounts of energy. The result is EVs that can achieve longer driving ranges on a single charge, effectively addressing the consumer concern known as "range anxiety". The advancements in battery chemistry, electrode materials, and cell design have not only improved energy density but also contributed to more excellent driving range and overall efficiency of electric vehicles, reassuring consumers about the future of EVs.

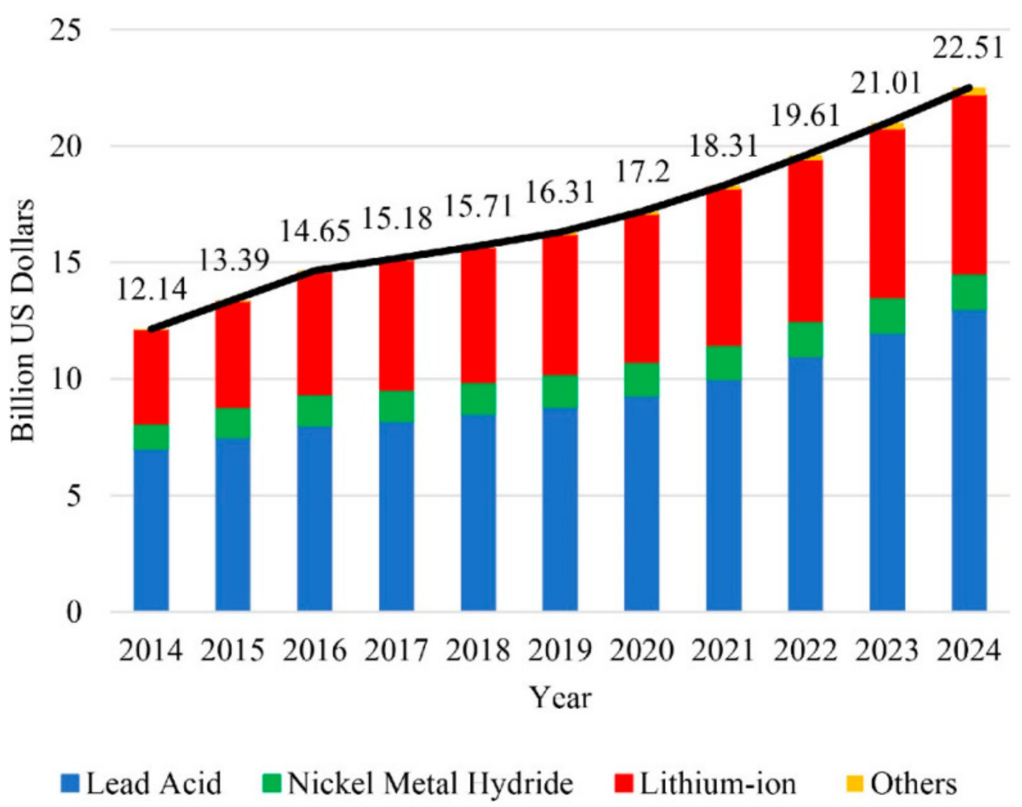

Figure 6. The market share of various EV-based batteries in the United States [30].

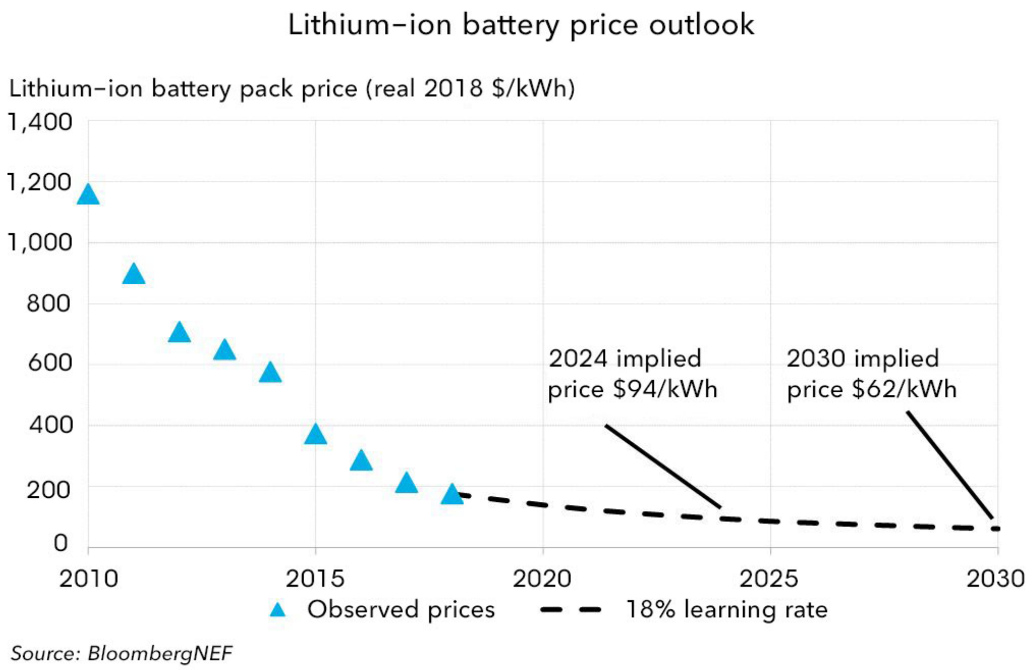

Figure 7. Lithium-ion battery price outlook [31].

For every doubling of cumulative volume, an 18% reduction in price was observed.

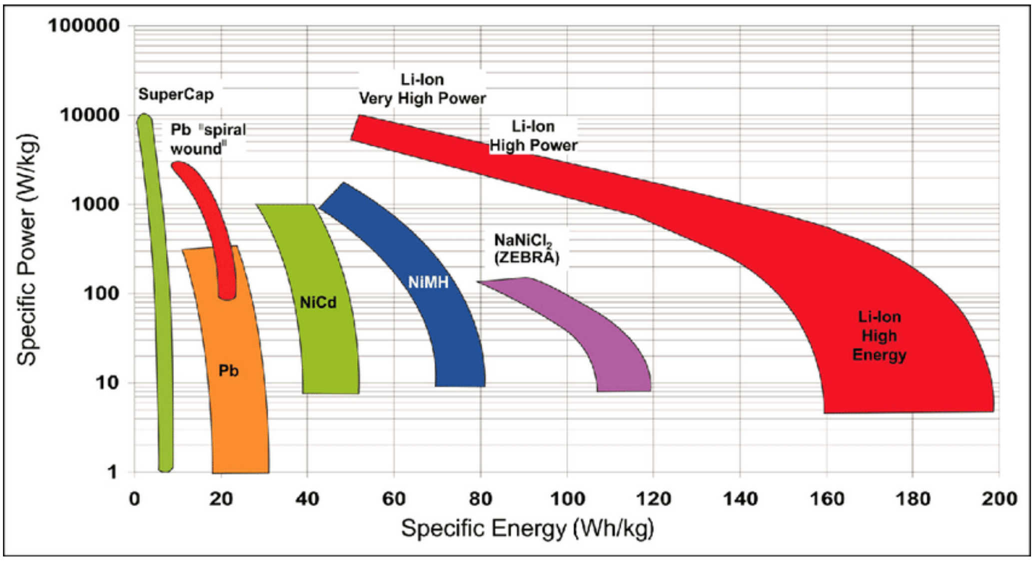

Figure 8. Ragone Chart of different technology [32].

Note: SuperCap: supercapacitor; Pb: lead; Li-ion: lithium-ion; NiCd: nickel–cadmium; NiMH: nickel–metal hydride; NaNiCl2: sodium–nickel chloride; ZEBRA: Zero Emission Battery Research Activities.

Li-ion batteries support fast charging capabilities, enabling rapid energy replenishment and reducing charging times for EVs. With the proliferation of fast-charging infrastructure, drivers can conveniently recharge their vehicles in minutes, making electric mobility more practical and convenient for everyday use. Additionally, advancements in battery management systems and charging protocols have optimized charging efficiency, prolonging battery lifespan and minimizing degradation over time [33].

The safety and durability of Li-ion batteries are of utmost importance when it comes to light-duty EVs. While it's true that if not properly managed, Li-ion batteries can be prone to runaway thermal events, leading to overheating, fire, and explosion risks, manufacturers have taken significant steps to mitigate these risks. Safety features such as thermal management systems, cell-level monitoring, and protective enclosures are incorporated into EV battery packs. Furthermore, ongoing research is dedicated to enhancing battery durability, minimizing degradation, and extending the lifespan of Li-ion batteries using innovative materials and engineering techniques, ensuring the continued safety and reliability of these batteries in light-duty EVs [34].

3. Impact on the Energy Landscape

The rapid growth of electric vehicle charging will significantly influence the power industry regarding total energy use, demand patterns, and interactions with electricity supply. A study demonstrates that in a high-electrification scenario, transportation might increase from the current 0.2% to 23% of total U.S. power demand by 2050, potentially affecting system peak load and associated capacity costs if not adequately managed. Extensive car electrification will affect the power system comprehensively, encompassing generation, transmission, and distribution [35]. Nonetheless, anticipated alterations in U.S. power consumption due to vehicle electrification do not exceed historical increases in load and peak demand. This conclusion indicates that bulk-generation capacity is anticipated to be sufficient to accommodate an expanding EV fleet as it develops over time, despite significant increases in the EV market. Numerous studies have demonstrated that "smart charging" and vehicle-to-grid (V2G) services present prospects to lower system costs and enhance the integration of variable renewable energy (VRE). The essential components for effectively integrating electric vehicles with bulk power systems include charging infrastructure that facilitates smart charging and synchronization with variable renewable energy generation, along with business models and programs that compensate electric vehicle owners for charging flexibility [36]. At the local level, electric vehicle charging may substantially alter electrical loads, thereby affecting distribution networks as well as power quality and dependability. **Figure 9** displays some of the negative effects EVs have on the electric power grid.

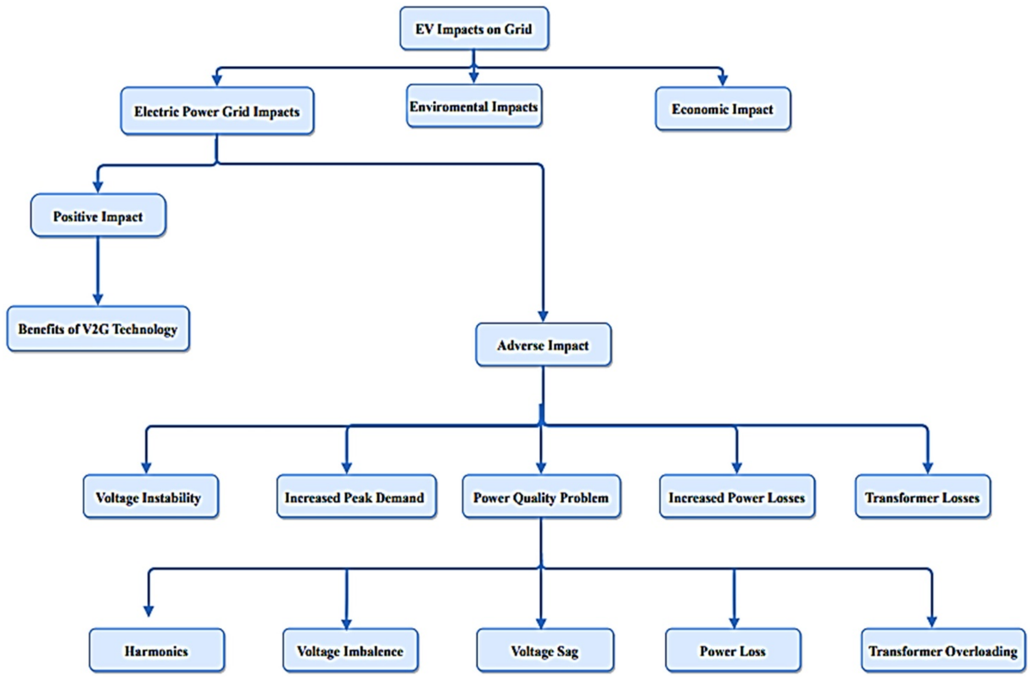

Figure 9. EV impact on the electric power grid [37].

Industry analysts project that the global count of light-duty electric vehicles and their charging outlets would exceed 300 million and 175 million, respectively, by 2035, representing a significant rise compared to 2021. The short travel range of current electric vehicles in India necessitates the establishment of charging infrastructure in major towns and along national roads. The Central Electricity Authority (CEA) and the Ministry of Power (MoP) in India have implemented essential measures for the establishment of grid-integrated charging stations. The CEA reports that 1,742 charging stations have been established nationwide. To enhance rural electric vehicle adoption in India, the state government should grant additional cash for electric vehicle charging stations [38]. Expanding the network of EV charging stations will mitigate range anxiety for EV consumers in remote regions. Augmenting federal investment in charging infrastructure is a strategy to enhance the availability of charging stations in remote regions. An alternative is to enhance the operational efficiency of electrical cooperatives.

Comprehensive nationwide distribution of recharge stations is essential to facilitate long-distance travel for motorists. Estonia was the inaugural nation to achieve comprehensive coverage of fast charging stations, with a recharge station situated around every 50 km along all principal routes and in municipalities with populations above 5,000 [39]. California exemplifies effective interoperability practices; via Executive Orders, it promotes the adoption of zero-emission vehicles, including access to recharging facilities and enacted the Interoperability Electric Vehicle Charging Stations Open Access Act (California Senate, 2013), thereby facilitating a more efficient deployment of EV charging stations and improving user accessibility. Electric vehicles can be recharged at any publicly accessible charging station using a credit card for payment, eliminating the need for network membership. Subsequent legislation (California Assembly, 2014) permits 40% of Californians residing in multi-unit housing complexes, along with commercial tenants, to construct a recharging station within their premises [40].

The shift to sustainable electric mobility in Africa encounters numerous problems, including infrastructural deficiencies and economic obstacles, despite the region's considerable growth potential in this sector. The development of electric vehicle charging infrastructure in Nigeria is still developing, offering both problems and potential for advancement. Despite the country's advancements in fostering electric mobility via governmental incentives and pilot initiatives, the insufficient charging infrastructure continues to pose a substantial obstacle to the extensive adoption of electric vehicles. As of 2022, just a few public charging stations exist in large cities such as Lagos and Abuja, with sparse availability in rural regions. The restricted availability of infrastructure presents difficulties for electric vehicle drivers, especially with range anxiety and accessibility. The primary obstacle to electric vehicle adoption in West and East Africa is the insufficient charging infrastructure [41].

Aside from these downsides, the advantages of electric light-duty vehicles (LDVs) in the energy landscape are diverse and impactful. Electric LDVs produce zero tailpipe emissions significantly by reducing greenhouse gas emissions compared to internal combustion engine vehicles. Reducing emissions helps mitigate climate change and improve air quality, especially in urban areas where transportation substantially contributes to pollution. Also, electric LDVs can be charged using various energy sources, including renewable energy like solar and wind power. By leveraging clean energy sources for vehicle charging, electric LDVs contribute to the diversification of the energy mix, reducing our reliance on fossil fuels and enhancing energy security. Electric LDVs are inherently more energy-efficient than internal combustion engines. Electric motors have higher efficiency rates and waste less energy than heat during operation. As a result, electric LDVs require less energy to travel the same distance, leading to immediate energy savings and reduced fuel costs for consumers [42].

Additionally, electric LDVs offer demand-side management and load-balancing opportunities in the electricity grid. Through intelligent charging technologies and vehicle-to-grid (V2G) capabilities, electric vehicles can help manage peak electricity demand by charging during off-peak hours and potentially supplying electricity back to the grid during times of high demand, thereby enhancing grid stability and reliability [43, 44]. Lastly, the widespread adoption of electric LDVs can incentivize the deployment of renewable energy infrastructure, such as solar-powered charging stations. Integrating renewable energy sources with electric vehicle charging infrastructure further accelerates the transition to a cleaner and more sustainable energy system.

Overall, the immediate benefits of electric LDVs in the energy landscape include reductions in emissions, energy efficiency improvements, and diversification of energy sources, grid flexibility, and promotion of renewable energy integration. These benefits contribute to environmental sustainability, enhance energy security, and promote economic growth in the renewable energy sector [45, 46].

3.1. Life Cycle of Electric Light-Duty

The lifetime of electric light-duty vehicles (LDVs) is a testament to their reliability. Factors such as battery degradation, maintenance, and technological advancements influence this lifespan. Typically, electric cars are designed to outlast traditional internal combustion engines due to their simpler drivetrains and fewer moving parts. However, it's important to note that specific data on the exact lifetime of electric LDVs may vary and is influenced by individual vehicle usage patterns and battery management practices. Comprehensive lifecycle assessments (LCAs) leave no stone unturned in determining the long-term impact of electric LDVs on our energy landscape. These assessments meticulously consider the environmental effects of every stage of a vehicle's life, including raw material extraction, manufacturing, operation, and end-of-life disposal or recycling [29, 47, 48].

LCAs are not just a tool but a key to unlocking the potential benefits of electric LDVs. They provide us with a comprehensive understanding of how these vehicles, over their entire lifecycle, contribute to reductions in energy consumption, greenhouse gas emissions, and other environmental pollutants. This data enlightens us about the significant reductions in greenhouse gas emissions and air pollutants that electric vehicles can bring.

While there is a growing body of research and data on the lifecycle impacts of electric LDVs, ongoing studies, and technological advancements continue to play a crucial role in refining our understanding of their long-term effects on the energy landscape. For instance, recent studies have shown that the environmental impact of electric vehicles can be further reduced with the use of renewable energy sources for charging. As electric vehicle adoption increases and technology evolves, further research and data collection will contribute to a more comprehensive understanding of their lifecycle impacts and overall sustainability [49].

Argonne National Laboratory's Research & Development Greenhouse gases, Regulated Emissions, and Energy use in Technologies (R&D GREET®) model analyzes the life cycle impacts of vehicle, fuel, chemical, and material technologies. R&D GREET facilitates the comparison and analysis of the total greenhouse gas (GHG) emission effects throughout all phases of a vehicle's life cycle. Researchers can evaluate the greenhouse gas emission effects of gasoline and electric vehicles (EVs), encompassing emissions from car manufacturing, disposal, fuel production and consumption, and facility building [50].

Figure 10 illustrates this contrast by quantifying the life cycle greenhouse gas emissions of two representative light-duty sports utility vehicles: one powered by a gasoline internal combustion engine (ICE) and the other an electric vehicle (EV). This analysis examines the emissions generated per mile (g CO_2e mile−1). Each car utilizes a typical fuel: E10 gasoline for the internal combustion engine and the U.S. average electricity grid generating mix for the electric vehicle. For ICE, fuel use (i.e., gasoline combustion in vehicles during use) is the greatest contributor to GHG emissions, while fuel production (i.e., generating electricity) is the largest contributor to electric vehicles. Overall, R&D GREET indicates that the 2025 electric car generates 46% fewer greenhouse gas emissions than a comparable internal combustion engine vehicle. In 2035, R&D GREET forecasts that electric vehicles will generate 76% fewer greenhouse gas emissions compared to internal combustion engines in 2025 [50].

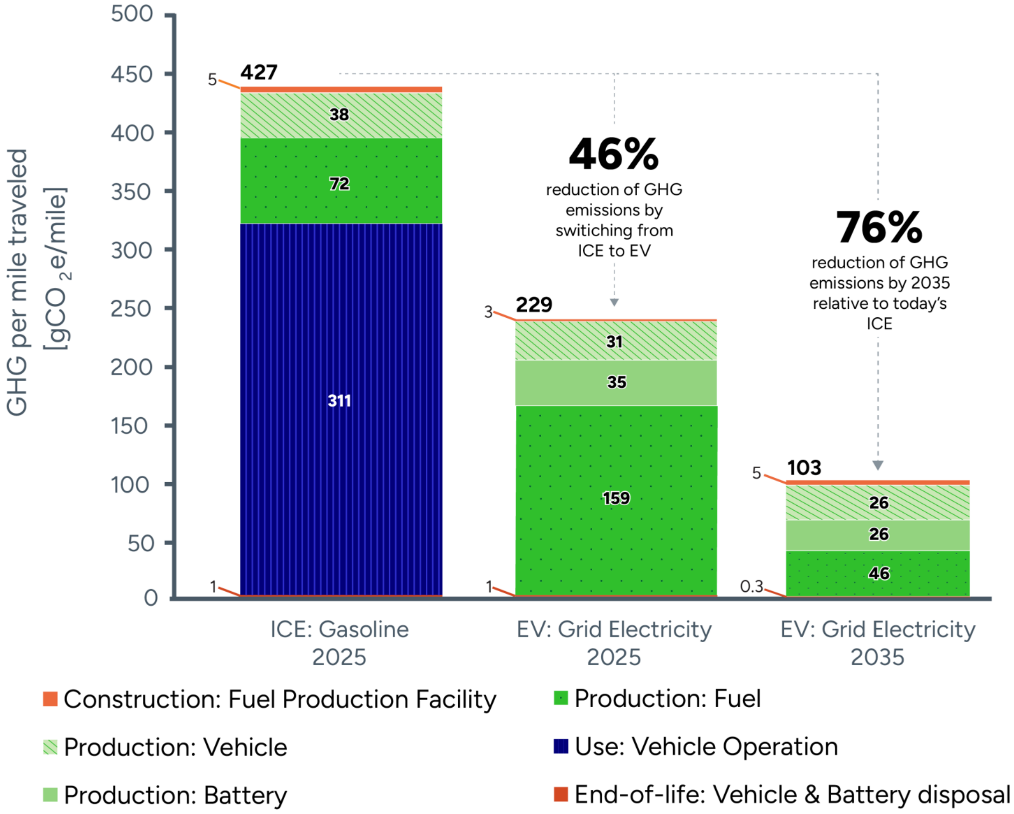

Figure 10. GHGs produced by Electric vehicles in comparison to gasoline vehicles on a life cycle basis. Life cycle GHG emissions include those from construction of the fuel production facility [50].

3.2. CAPEX Cost

The cost of buying electric light-duty vehicles (LDVs) in the USA, also known as capital expenditure (CAPEX), can vary depending on factors like the vehicle model, battery capacity, features, and available incentives or subsidies. As of my latest update in January 2022, the CAPEX for electric LDVs in the USA usually ranges from $30,000 to $50,000 or even more before incentives. It is important to note that the cost of electric LDVs has decreased over time due to advancements in battery technology, economies of scale, and automakers' introduction of more affordable models. Additionally, federal, state, and local incentives and rebates are often available to help reduce the upfront cost of electric vehicles, making them more affordable for consumers. Electric LDVs are attractive due to their lower operational costs. The primary operational expense for these vehicles is electricity, which is cheaper than fuel for traditional cars. This translates to long-term savings for owners [28, 51].

Furthermore, electric LDVs require less maintenance because they have fewer moving parts and no need for oil changes, which reduces maintenance costs over their lifetime. Battery degradation is a concern, but advancements in battery technology have led to longer-lasting batteries with lower replacement needs. However, there are challenges to the widespread adoption of electric LDVs, especially in materials and manufacturing.

4. Challenges and Obstacles for Light-Duty Electric Vehicles

As the world pivots towards embracing electric mobility, the journey is challenging. Within light-duty electric vehicles (LDEVs), navigating challenges from materials and manufacturing to charging infrastructure presents a complex landscape of obstacles. To achieve this goal, it is crucial to comprehend the cost breakdown of electric vehicle supply equipment (EVSE), which includes application, power level charge, hardware, installation, operations, and total cost measures, as seen in **Figure 11.** Cost Breakdown of Light Duty Vehicles [52]. By understanding these cost categories, we can incentivize technology to improve and lessen the cost of LDEVs, ultimately making them more economical and attainable for consumers.

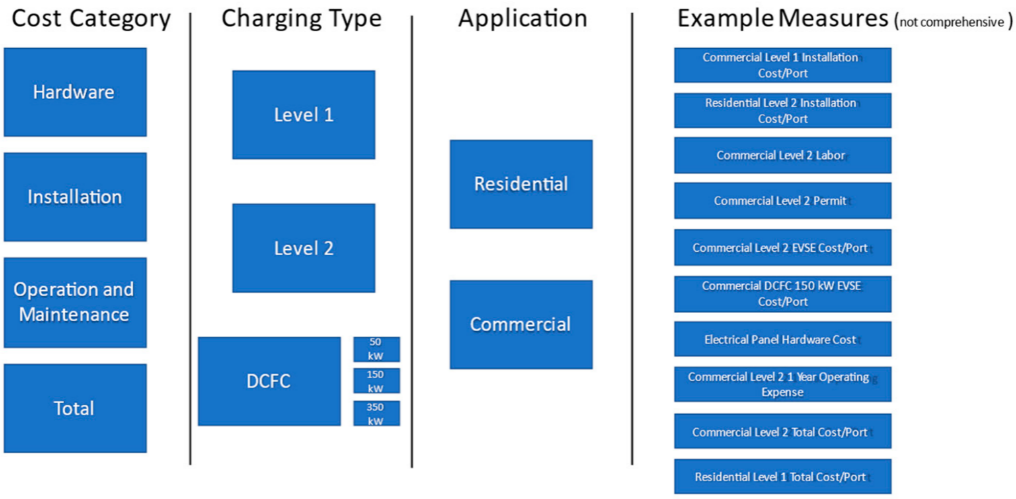

Figure 11. Cost breakdown of light duty vehicles [52].

4.1. Batteries and EV Design

The production of high-performance lithium-ion batteries, a cornerstone of electric vehicles, relies heavily on rare earth elements and minerals such as lithium, cobalt, and nickel. The quest to secure a stable supply chain for these materials while addressing associated constraints remains a formidable challenge. Furthermore, pursuing lightweight electric vehicle design, achieved through materials like aluminum and composite plastics, introduces manufacturing complexities stemming from energy-intensive processes and cost considerations. The imperative to strike a delicate balance between lightweight, environmental concerns, and cost-effectiveness looms large on the horizon for manufacturers [46, 53].

Pros:

1. High Energy Density:
   • Lithium-ion batteries offer high energy density, providing more storage capacity per unit weight or volume.
   • Contributes to longer driving ranges for electric vehicles.
2. Long Cycle Life:
   • Longer cycle life compared to other battery technologies.
   • Withstands many charge and discharge cycles.
3. Fast Charging Capability:
   • Supports fast charging, enabling quicker replenishment of the battery's energy.
   • Reduces charging times and improves EV convenience.
4. Lightweight:
   • Relatively lightweight, enhancing overall energy efficiency.
   • Minimizes the impact on vehicle weight.
5. Low Self-Discharge Rate:
   • Lower self-discharge rate compared to some other battery types.
   • Retains charge for an extended period when not in use.

6. Versatility:
   • Comes in various forms, adaptable to different sizes and shapes.
   • Fits diverse designs of electric vehicles.
7. Established Technology:
   • Mature and well-established technology.
   • Extensive research and development, widely available for mass production.

Cons:

1. Limited Energy Density Improvement:
   • Further improvements in energy density may be challenging.
2. High Cost:
   • Expensive manufacturing contributes significantly to overall EV cost.
   • Ongoing research aims to reduce production costs.
3. Resource Dependency:
   • Production relies on rare earth materials like lithium and cobalt.
   • Environmental and ethical concerns related to mining practices.
4. Safety Concerns:
   • Advancements made, but risk of thermal runaway and overheating remains.
   • Safety concerns, especially in cases of damage or manufacturing defects.
5. Limited Lifespan:
   • Despite long cycle life, gradual degradation over time may necessitate replacement.
   • Decrease in overall capacity during the vehicle's lifespan.
6. Environmental Impact:
   • Extraction, processing, and recycling contribute to environmental challenges.
   • Sustainable practices and recycling efforts are being developed.
7. Charging Infrastructure Challenges:
   • While supporting fast charging, universal optimization for EV charging infrastructure may be lacking.
   • Potential inconsistencies in charging times depending on location and infrastructure development.

4.2. Charging Infrastructure

Developing a robust charging infrastructure network is another critical frontier in the electric mobility revolution. The deployment and accessibility of charging stations emerge as linchpins in fostering the widespread adoption of electric LDVs.

This chapter delves into the potential of light-duty EV integration on power grid systems, analyzing potential issues and solutions to ensure the smooth operation of the grid while promoting the adoption of electric mobility. By understanding the challenges and devising effective strategies, we can confidently navigate the path to a more sustainable future.

1. Grid System Challenges: The unplanned introduction and abrupt adoption of EV charging stations can strain power grid systems, leading to technical challenges such as power quality degradation, voltage fluctuations, harmonic injection, battery degradation, and grid instability. For instance, power quality degradation can result in voltage sags and swells, affecting the performance of other connected devices. To address these issues, solutions such as advanced grid management systems, smart charging algorithms, and grid-scale energy storage can be implemented. Light-duty EVs represent a substantial and dynamic load within the grid, requiring careful consideration of their impact on grid operations and reliability. As such, understanding the interaction between EV charging patterns and grid dynamics is essential for effective grid management and planning [54].

2. Power System Planning: The integration of light-duty EVs into the power grid necessitates comprehensive power system planning. This plan is crucial to accommodate the increased demand for electricity and ensure grid stability (**Figure 12**). By assessing grid access capabilities, upgrading infrastructure, and optimizing distribution networks, you can support EV charging requirements and anticipate future demand, thereby minimizing potential disruptions to the grid [54].

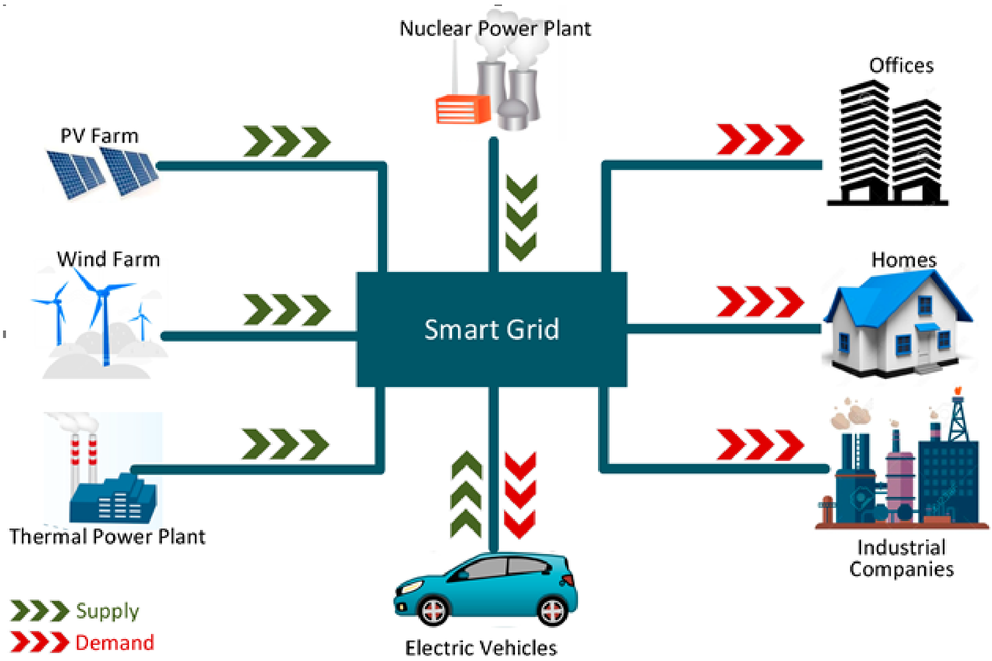

Figure 12. Smart grid distribution for EVs [54].

3. Grid Economy and Environment: The integration of light-duty EVs not only presents economic opportunities but also offers significant environmental benefits. By leveraging EV charging infrastructure as flexible grid assets, utilities can optimize grid operations, reduce peak demand, and lower electricity costs. Furthermore, promoting the use of renewable energy sources for EV charging enhances environmental sustainability and reduces greenhouse gas emissions associated with transportation. This balanced approach ensures a brighter, more sustainable future.

4. Charging Schemes and Infrastructure Configurations: Various charging schemes and infrastructure configurations for EV charging are evaluated based on coordination and speed. Intelligent charging approaches, such as demand response programs (which adjust the charging rate of EVs based on the grid's capacity) and smart charging algorithms (which optimize the charging schedule of EVs to avoid peak demand periods), enable grid operators to manage EV charging patterns dynamically and alleviate stress on the grid during peak demand periods (**Figure 13**). Optimal location selection for charging stations, informed by factors such as proximity to distribution infrastructure and charging demand, enhances charging accessibility and grid efficiency [55].

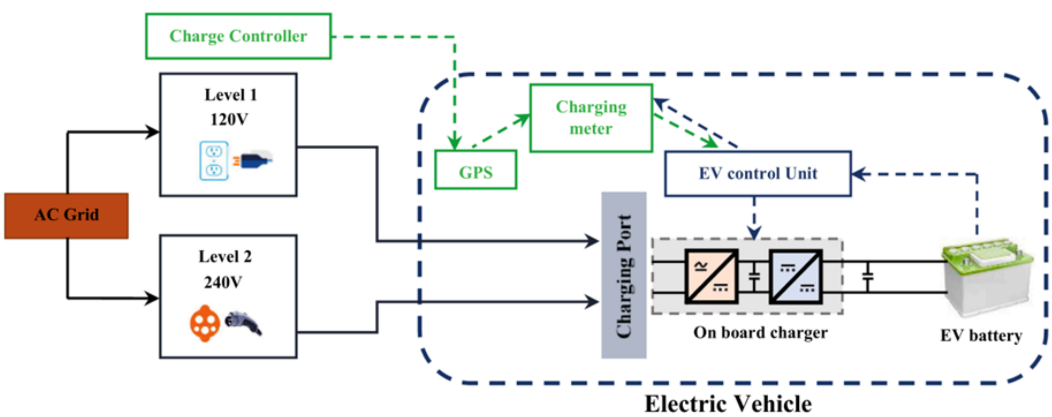

Figure 13. AC on-board charger configuration [44, 55].

5. Implementation Strategies and Concepts: Implementing effective strategies and concepts is crucial for maximizing the benefits of light-duty EV integration while minimizing its impact on the power grid. Intelligent charging approaches, optimal location selection, and infrastructure upgrades are essential components of a comprehensive EV integration strategy. Additionally, public-private partnerships, such as collaborations between utilities and EV manufacturers, can accelerate the deployment of charging infrastructure. Regulatory incentives, such as tax credits for EV purchases or installation of charging stations, can stimulate consumer demand. Stakeholder collaboration, involving utilities, policymakers, and consumer advocacy groups, can ensure that the needs and concerns of all parties are addressed. These factors play a vital role in accelerating EV adoption and supporting sustainable transportation initiatives [43, 48, 55].

Yet, the path to ubiquitous charging accessibility is fraught with challenges. The need for comprehensive deployment across diverse landscapes, spanning urban hubs to rural expanses, underscores the paramount importance of accessibility for all users. Moreover, ensuring seamless interoperability among various charging standards and connectors is indispensable for a frictionless charging experience. Scaling up charging infrastructure necessitates meticulous grid integration and capacity planning, with strained local electricity grids looming large in densely populated areas.

4.3. Out-of-Pocket Cost

In tandem with infrastructure challenges, the economic landscape presents formidable barriers to electric vehicle adoption. High upfront costs deter many prospective buyers despite the long-term savings potential offered by reduced fuel and maintenance expenses. Understanding the cost breakdown of electric vehicle supply equipment (EVSE) illuminates avenues for incentivizing technological advancements to drive down costs and make LDEVs more economically viable.

Technological innovations in battery technology, vehicle design, and charging infrastructure promise to accelerate the electrification of LDVs and amplify their impact on the energy landscape. Breakthroughs in battery energy density, charging speed, and cost-effectiveness signal a future where electric mobility becomes increasingly mainstream [56].

4.3.1. Upfront Costs

The initial purchase price of a light-duty EV is often higher than that of a comparable gasoline-powered vehicle due to the cost of battery technology and electric drivetrain components. However, federal and state incentives, such as tax credits and rebates, can help offset this upfront cost for consumers. Additionally, financing options and lease programs may be available to make EV ownership more affordable, spreading out the cost over time.

4.3.2. Operational Expenses

While the upfront cost of purchasing an EV may be higher, the operational expenses tend to be lower compared to gasoline-powered vehicles. Electric vehicles have fewer moving parts and require less maintenance, resulting in lower maintenance costs over the vehicle's lifetime. Furthermore, the cost of electricity for charging an EV is typically lower than the cost of gasoline, providing additional savings for EV owners. Charging at home using a residential electricity rate is often the most cost-effective option, but public charging stations may incur additional fees depending on the charging provider.

4.3.3. Additional Costs and Considerations

In addition to the upfront and operational expenses, there may be additional costs and considerations associated with owning a light-duty EV. These may include:

- Installation of a home charging station, if not already present, which may require upfront costs for equipment and installation.
- Insurance premiums for electric vehicles may vary depending on factors such as the make and model of the vehicle, driving history, and location.

Registration and licensing fees may also differ for EVs compared to gasoline-powered vehicles, depending on state regulations and policies.

Battery degradation over time may result in reduced driving range and performance, potentially requiring battery replacement or refurbishment in the future, which could incur additional costs.

4.3.4. Potential Savings and Cost Comparison

Despite the initial investment and potential additional costs, owning a light-duty EV can result in long-term savings compared to gasoline-powered vehicles. Factors such as lower fuel and maintenance costs, reduced emissions, and potential incentives and rebates can contribute to overall cost savings for EV owners over the vehicle's lifetime. Consumers can use online calculators and tools to estimate the total cost of ownership for both EVs and gasoline-powered vehicles, considering factors such as fuel prices, maintenance expenses, and incentives.

5. Solutions and Potential for Light-Duty Electric Vehicles

In light-duty electric vehicles (EVs), a spectrum of solutions and opportunities stands ready to surmount the challenges hindering widespread adoption. Among these, a pivotal strategy involves addressing infrastructure hurdles head-on through strategic investments and standardization efforts. This necessitates a collaborative approach among governments, industry stakeholders, and utilities to expedite the proliferation of charging networks. By focusing on underserved regions and advocating for common charging standards, interoperability can be enhanced, significantly improving the user experience. For instance, successfully implementing the "EV Everywhere" initiative in the United States has dramatically increased charging stations, making EV adoption more feasible for consumers [52].

5.1. Technology

Prospects and Challenges: While Li-ion batteries have propelled the widespread adoption of light-duty EVs, ongoing research and development efforts aim to further enhance their performance, affordability, and sustainability. Key areas of focus include increasing energy density, reducing production costs, improving charging infrastructure, and addressing environmental concerns associated with battery manufacturing and disposal. Additionally, the emergence of solid-state batteries, advanced lithium-sulfur chemistries, and other next-generation battery technologies hold promises for further revolutionizing the electric vehicle industry and overcoming existing limitations of Li-ion batteries [44].

5.2. Government Incentives

Governments are at the forefront of the transition towards clean energy alternatives, playing a pivotal role in spearheading this change. Through a comprehensive approach that includes tax credits, rebates, and grants, they incentivize consumers and automakers to embrace electric mobility. Additionally, regulations mandating emissions reductions and fuel efficiency standards have compelled automakers to invest in electric vehicle technology and innovation. Measures like Zero Emission Vehicle (ZEV) mandates require manufacturers to produce a certain percentage of electric or low-emission vehicles, driving the proliferation of EV options in the market. Also namely Advanced Clean Cars I and II, and their subsequent amendments, on the light-duty EV sector. Advanced Clean Cars I (2012) the adoption of Advanced Clean Cars I in 2012 marked a significant milestone in California's efforts to combat air pollution and reduce greenhouse gas emissions from the transportation sector. These regulations aimed to rapidly scale down emissions of light-duty passenger cars, pickup trucks, and SUVs, setting ambitious targets to improve air quality and address climate change concerns. One of the key provisions of Advanced Clean Cars I was the requirement for an increased number of zero-emission vehicles (ZEVs) to be sold by automakers to meet air quality and emissions goals, thereby incentivizing the development and deployment of electric vehicle technologies [57].

Advanced Clean Cars II (2022): Building upon the success of its predecessor, Advanced Clean Cars II, adopted in 2022, reinforced California's commitment to reducing emissions and accelerating the transition to cleaner transportation alternatives. These regulations introduced more stringent tailpipe greenhouse gas emission standards for light-duty vehicles, further incentivizing automakers to invest in low-emission and zero-emission vehicle technologies. Additionally, Advanced Clean Cars II maintained and expanded the ZEV requirements, ensuring continued progress towards achieving air quality and climate change objectives.

Amendments to Advanced Clean Cars II (October 2023): In October 2023, amendments to the Advanced Clean Cars II regulations were introduced, further refining and strengthening California's emissions standards and ZEV requirements. These amendments included limited revisions to the Low-Emission Vehicle (LEV) and ZEV regulations, reaffirming the state's commitment to promoting cleaner transportation solutions. Notably, the tailpipe greenhouse gas emission standard was reinforced, signaling a continued emphasis on reducing vehicle emissions to mitigate the impacts of climate change [58].

The regulatory policies outlined above have had a profound impact on the light-duty EV sector, driving innovation, investment, and market growth. By setting stringent emissions standards and ZEV requirements, Advanced Clean Cars I and II incentivized automakers to prioritize the development and production of electric vehicles. As a result, the EV market has experienced exponential growth, with an expanding array of electric vehicle models and increasing adoption rates among consumers. Furthermore, the amendments to Advanced Clean Cars II in 2023 provided additional clarity and direction for automakers, reinforcing the importance of reducing greenhouse gas emissions and accelerating the transition to zero-emission transportation. These regulatory measures have not only stimulated demand for electric vehicles but also spurred investments in charging infrastructure, research, and development, driving technological advancements and cost reductions in EV manufacturing [56, 58].

By mandating a shift towards electric vehicle production and facilitating the installation of charging infrastructure, governments act as solid catalysts for change. Several jurisdictions, notably in California, have taken bold steps, announcing plans to phase out internal combustion engine vehicles within the next few decades, with a predominant focus on electric light-duty vehicles, providing reassurance about the direction of the transition.

Moreover, financial barriers can be dismantled through targeted incentives, subsidies, and financing mechanisms tailored to bolster EV adoption. Governments can leverage tax incentives and grants to make electric vehicles economically enticing for consumers, while financial institutions can offer favorable loan terms and lease options. Simultaneously, automakers can innovate pricing strategies to make EVs more accessible, democratizing electric mobility. The economic benefits of widespread EV adoption are significant, with studies showing that a transition to electric mobility could lead to a 10% increase in GDP and the creation of 2 million new jobs in the automotive sector alone [51, 58].

In 2017, China initiated its New Electric Vehicle (NEV) regulatory program, primarily modeled after California's credit-based Zero Emission Vehicle (ZEV) program. The objective is for electric vehicles to comprise 12 percent of total vehicle sales in 2020, increasing to 14 percent in 2021. Projecting towards 2025, the objective is 25 percent of all transactions [59]. It is essential to note that these objectives are articulated in volumes, yet the system operates on earned credit. China is fervent about electric vehicles for various reasons, including the prospect of effectively competing with global companies. Additionally, akin to California, a notable consumer-oriented incentive framework enhances the regulatory NEV. Europe has adopted a distinct strategy for promoting electric vehicle growth compared to the United States and China. Europe's strategy remains credit-based; however, instead of establishing numerical targets for electric vehicle numbers, the European Union has implemented numerical CO_2 emission requirements, anticipating that compliance with these criteria can solely be achieved through increased electric vehicle market penetration. The European Union standard for passenger vehicles is a maximum of 95 g CO_2 km^{-1}, to be attained by 2021 [60].

The credit-based method is based on the stipulation that each automaker must achieve a fleet average of 95 g. Excess emissions from certain conventional vehicles can be mitigated by the "supercredits" that manufacturers can acquire through the sale of electric vehicles. The failure of certain automakers to achieve emissions targets can be offset by purchasing credits from those who have exceeded expectations. Emission rules are poised to tighten, with the 2025 target established at 80 g km^{-1} [60].

5.3. Policies on Gas Vehicles

In contrast to policies promoting electric vehicles, traditional gas vehicles have been subject to regulations to reduce their environmental impact and carbon emissions. Emission standards, fuel economy regulations, and taxes on fossil fuels are among the measures implemented to incentivize the adoption of cleaner technologies and discourage reliance on gasoline-powered vehicles. However, the transition from gas vehicles faces challenges, including entrenched interests in the fossil fuel industry, infrastructure limitations, and consumer preferences. While policies targeting gas vehicles have made incremental progress in curbing emissions, the urgency of addressing climate change necessitates more ambitious and comprehensive strategies to accelerate the transition to electric mobility [36, 42].

Looking beyond the challenges of infrastructure and economics, it is crucial to envision the future landscape of light-duty electric vehicles and energy consumption. The path towards electrified mobility gains momentum with ongoing advancements in battery technology and renewable energy integration. Innovative business models, such as vehicle-to-grid (V2G) technologies and shared mobility services, present exciting avenues to optimize EV usage and enhance their value proposition. The convergence of public-private collaboration and relentless research and development endeavors will be instrumental in unlocking the full potential of light-duty electric vehicles, inspiring us about the future of electric mobility and a sustainable energy future [55, 56].

6. Scope and Limitations

When examining the role of electric vehicles in the light-duty sector, various obstacles could impede their efficiency and adoption. The COVID-19 pandemic has emerged as a powerful force that has dramatically impacted the worldwide supply chain and substantially reduced the automobile industry. The pandemic has caused significant disruption in the manufacturing and distribution networks, which may impede the seamless transition to electric mobility.

Moreover, the potential for geopolitical conflicts presents a substantial hazard to the accessibility of the essential raw materials needed for manufacturing electric vehicles. The dependable provision of these vital resources may only be improved if there is an escalation in conflicts or geopolitical uncertainties, which could impede the advancement of sustainable transportation alternatives. Economic downturns, such as recessions, substantially impact the adoption rate of electric cars. During times of financial constraint, consumer spending often declines, reducing demand for electric vehicles and impeding the growth of this growing industry. Concurrently, the government's funding for incentivizing the adoption of electric cars and enhancing infrastructure could fall, intensifying the challenges faced by market participants.

The forthcoming 2024 presidential election could bring about substantial changes to the electric vehicle sector through the implementation of fresh laws and regulations. The result of this political position can either promote or impede the development and growth of electric mobility, underscoring the significance of remaining alert and adaptable in negotiating the regulatory environment. To effectively navigate these intricate limitations, it is imperative to cultivate a thorough comprehension of the electric vehicle industry's dynamic nature. To effectively deal with the impact of external variables, it is crucial to implement a comprehensive and proactive approach that acknowledges the interplay of economic, geopolitical, and regulatory forces forming electricity. By implementing a holistic strategy, stakeholders may effectively navigate the volatile terrain and strategize for a viable and enduring future in the automotive sector.

7. Conclusions

The most significant threat to the planet's ecosystem and biodiversity in the decades to come will be global climate disruption caused by human-generated greenhouse gases. Although electric vehicles (EVs) produce zero exhaust emissions, EV technologies alone are not intrinsically "clean" or comprehensive solutions for mitigating transportation pollution. The environmental advantages of electric vehicle usage are directly linked to the purity of the electricity grid from which they draw power. Although electric vehicles present significant decarbonization potential as the grid mix improves, their benefits do not guarantee a comprehensive solution to alleviate other environmental issues, such as heightened respiratory consequences. The journey towards widespread adoption of light-duty electric vehicles represents a pivotal moment in transportation history, with profound implications for the energy landscape. By addressing infrastructure, economics, and technology challenges and exploring opportunities for innovation and collaboration, stakeholders can accelerate the transition towards a more electrified and sustainable mobility future. As electric vehicles continue to gain momentum, policymakers, industry stakeholders, and consumers must work together to overcome barriers, seize opportunities, and pave the way for a cleaner, greener transportation ecosystem powered by light-duty electric vehicles.

Future study must concentrate on a comprehensive examination of electric vehicle lifecycle impacts, especially through state-level or local evaluations, considering anticipated transitions to cleaner energy and the ramifications of various battery technologies. Creating a thorough and flexible database for light-duty cars that encompasses all essential environmental indicators is vital. In-depth examination of regional disparities in electric vehicle charging practices, particularly regarding rapid charging alternatives and their ecological consequences, is necessary.

Author Contributions

Conceptualization, S.V. and J.P.; methodology, S.V. and J.P.; software, S.V. and A.S.; validation, S.V., J.P. and A.S.; formal analysis, S.V. and J.P.; investigation, S.V. and F.A.; resources, S.V. and J.P.; data curation, S.V. and J.P.; writing—original draft preparation, S.V.; writing—review and editing, A.S. and F.A.; visualization, A.S. and F.A.; supervision, J.P. and A.S.; Project administration, J.P. and A.S. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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