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Research Article

Electric Vehicles in China, Europe, and the United States: Current Trend and Market Comparison

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Abstract: The fast-growing light-duty plug-in electric vehicle market in China, Europe, and the United States are a multifaceted phenomenon with far-reaching implications. It not only reshapes the automotive industry but also plays a pivotal role in advancing sustainable energy practices on a global scale. The trends and policies emerging from China are closely monitored by international stakeholders as they navigate the evolving landscape of electric vehicles (EVs). This article presents a comparative analysis of EVs in China, Europe, and the United States, offering valuable insights into the evolving landscape of sustainable transportation. Through an exploration of unique technological approaches and market dynamics in these key regions, the study provides a snapshot of the current state and future potential of EVs. The derived insights contribute significantly to the broader discourse on the global transition towards cleaner and more efficient transportation solutions, underscoring the importance of cross-border collaboration and innovation. As researchers collectively strive for a greener future, this examination serves as a concise yet impactful contribution to the ongoing dialogue surrounding electric vehicles, illuminating their pivotal role in reshaping the automotive industry. To conclude, the growth of the EV market in China not only impacts local manufacturers but has global ramifications. It has catalyzed investments in research and development, production capacity, and charging infrastructure, making China a focal point for international automakers keen on tapping into the burgeoning electric vehicle market.

Keywords: Electric Vehicles; China, Europe; the United States, Market.

1. Introduction

Electric vehicles (EV's) are the key technology to decarbonize road transport, a sector that accounts for around one-sixth of global emissions. Ambitious policies continue to be critical to growth in electric vehicle markets worldwide [1]. If the EV sales growth experienced in recent years is sustained, CO2 emissions from cars can be put on a path in line with the Net Zero Emissions by 2050 Scenario [2,3]. However, despite huge growth in China, some European countries, and some U.S. states, electric vehicles are not yet a global phenomenon. Sales in developing and emerging countries have been slow due to higher purchase costs and a lack of charging infrastructure. The global EV fleet consumed about 110 TWh of electricity in 2022, which accounts for less than 0.5% of the current total final electricity consumption worldwide. The use of EVs displaced around 0.7 Mb/d (1.3 EJ) of oil in 2022. EVs would need to displace around 8 Mb/d (17 EJ) of oil in 2030 to be in step with the Net Zero Scenario [4].

Despite facing challenges such as disruptions in the supply chain, macroeconomic and geopolitical uncertainties, and elevated commodity and energy prices, electric car sales achieved yet another record-breaking year in 2022. This growth unfolded within the backdrop of a contraction in global car markets, with total car sales experiencing a 3% decline compared to 2021. The aggregate sales of EV, encompassing both battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs), surpassed 10 million units last year, reflecting a substantial 55% increase from the preceding year [4].

This noteworthy figure of 10 million EV sales worldwide not only surpasses the total number of cars sold across the entire European Union (approximately 9.5 million vehicles) but also constitutes nearly half of the total number of cars sold in China in 2022. The progression of EV sales is particularly remarkable as, within a span of just five years, from 2017 to 2022, sales escalated from around 1 million to over 10 million. In contrast, it took five years, from 2012 to 2017, for EV sales to transition from 100,000 to 1 million units, underscoring the exponential nature of the growth in EV sales. The proportion of EV in the overall car sales market surged from 9% in 2021 to 14% in 2022, reflecting a more than tenfold increase in their market share since 2017.The surge in sales propelled the global count of EV on roadways to 26 million, indicating a substantial 60% increase compared to 2021. Battery electric vehicles (BEVs) constituted over 70% of the overall annual growth, consistent with trends observed in preceding years. Consequently, BEVs comprised approximately 70% of the total global inventory of EV in 2022. While the absolute increase in sales from 2021 to 2022 mirrored the elevation witnessed from 2020 to 2021, registering a notable uptick of 3.5 million units, the relative growth rate was comparatively lower. This is noteworthy considering that sales had doubled from 2020 to 2021. Table 1 demonstrates the global stock of EV from 2018 to 2022.

Table 1. The global stock of EV from 2018 to 2022, in Million.

	2018	2019	2020	2021	2022
United States (BEV)	0.6	0.9	1.1	1.5	2.1
United States (PHEV)	0.5	0.6	0.6	0.7	0.9
Europe (BEV)	0.6	1.0	1.8	3.0	4.4
Europe (PHEV)	0.6	0.8	1.4	2.5	3.4
China (BEV)	1.8	2.6	3.5	6.2	10.7
China (PHEV)	0.5	0.8	1.0	1.6	3.1

The exceptional upswing in 2021 can be attributed to the recovery of EV markets following the disruptions caused by the coronavirus (Covid-19) pandemic [5,6]. In comparison to recent years, the annual growth rate for electric car sales in 2022 demonstrated a similarity to the average rate observed during the period spanning 2015 to 2018. Likewise, the annual growth rate for the global inventory of EV in 2022 aligned closely with that of 2021 and the period between 2015 and 2018, indicative of a resilient rebound in the expansion of the EV market to pre-pandemic levels.

According to [7], the report explores vehicle manufacturing and battery production, considering supply chains from battery cells to assembly. Over 2.1 million PEVs have been sold in the United States through December 2021, with 1.3 million of these all fully-electric battery electric vehicles (BEV), and 800,000 plug-in hybrid electric vehicles (PHEV) which have the capability of using gasoline. The sales-weighted average range for BEVs reached 290 miles in 2021 and 28 miles for PHEVs. We estimate that electric vehicles have driven 68 billion miles on electricity since 2010, thereby reducing national gasoline consumption by 0.54% in 2021 and 2.5 billion gallons cumulatively through 2021. In 2021, PEVs used 6.1 terawatt-hours of electricity to drive 19.1 billion miles, offsetting 700 million gallons of gasoline. We find that this fuel switching reduced consumer fuel costs by $1.3 billion in 2021. Since 2010, 65% of PEVs sold in the United States have been assembled domestically, and over 110 gigawatt-hours of lithium-ion batteries have been installed in vehicles to date.

In [8], this paper considers these geographic differences to produce a historical assessment of the fuel-cycle carbon emissions of plug-in electric vehicles (PEVs) in the United States from 2011 to 2021. The paper finds that PEVs in the United States decreased in electricity-derived carbon intensity, from 187 grams per mile to 110 grams per mile from 2011 to 2021 due to improvements in the electric grid and vehicle efficiency. Through 2021, PEVs emitted a total of 13.6 million metric tons of greenhouse gas (GHG) emissions in the United States, including both emissions from electricity and gasoline, while driving a total of 100 billion miles. Of this total, 8.39 million metric tons was due to electricity consumption. Over the same distance, comparable gasoline vehicles would have emitted between 29 and 41 million metric tons of GHG, leading to a reduction of 15 to 27 million metric tons. Relative to national-level assessments that do not factor in this regional difference, these electric vehicles resulted in 13% greater reductions in GHG emissions than previously calculated. In the future, announced goals to further decarbonize the electricity sector will continue to reduce the emissions of PEVs, including reducing emissions rates for vehicles already on the road, further improving the benefits relative to the unchanging emissions of contemporaneous gasoline vehicles.

Ambrose et al., [9] focused on examining life cycle greenhouse gas (LCGHG) emissions of battery electric vehicles (BEVs) that have addressed on efficiency-oriented vehicle designs with limited battery capacities. However, two dominant trends in the US BEV market make these studies increasingly obsolete: sales show significant increases in battery capacity and attendant range and are increasingly dominated by large luxury or high-performance vehicles. In addition, an era of new use and ownership models may mean significant changes to vehicle utilization, and the carbon intensity of electricity is expected to decrease. Thus, the question is whether these trends significantly alter our expectations of future BEV LCGHG emissions. In this direction, LCGHG emissions for current market BEVs were found to range from 136 gCO2e/mile for an efficiency-oriented compact BEV in California up to 324 gCO2e/mile for the larger PSUV in the US average scenario. LCGHG emissions for 2025 BEVs decrease to 105 gCO2e/mile for an efficiency-oriented compact BEV in California, while potentially increasing to 374 gCO2e/mile for the larger PSUV in the US average scenario. This compares to conventional ICEV life cycle emissions of 460–504 gCO2e/mile and to HEV

This is still an area of active research [10] that evaluated global scenarios of EV deployment and their impacts on total global CO2 emissions. For this assessment, we enhance the MIT Economic Projection and Policy Analysis (EPPA) model to represent the fleet dynamics of light-duty vehicles (LDV), including internal combustion engine (ICE) vehicles and EVs. For EV fleet, both plug-in hybrid vehicles (PHEV) and battery electric vehicles (BEV) are considered. We consider several illustrative scenarios and find that global LDV stock is projected to grow from 1.1 billion vehicles in 2015 to 1.65–1.75 billion in 2050, while global EV stock is growing from about a million in 2015 to about 585–825 million in 2050. At this level of market penetration, EVs would constitute one-third to one-half of the overall LDV fleet by 2050 in different scenarios, with the stricter carbon constraints implied in the Paris to 2 °C scenario leading to the largest EV share. The modeling suggests that EV uptake will vary across regions. China, the U.S., and Europe remain the largest markets in our study timeframe, but the EV presence is projected to grow in all regions. While the global LDV fleet grows by about 50% by 2050, the corresponding CO2 emissions from LDV are reduced by about 50% in 2050 relative to 2015. Global carbon intensity of LDVs reduced by about 70% from 2015 to 2050. Moreover, this report [11] examined the sales of plug-in electric vehicles (PEVs) in the United States from 2010 to 2017, exploring vehicle sales, electricity consumption, petroleum reduction, and battery production, among other factors. Over 750,000 PEVs have been sold, driving nearly 16 billion miles on electricity, thereby reducing gasoline consumption by 0.1% in 2016 and 600 million gallons cumulatively through 2017, while using over 5 terawatt-hours of electricity. Over 23 gigawatt-hours of battery capacity has been placed in vehicles, and 98% of this is still on the road, assuming typical scrappage rates.

In this direction, the article [12] discusses the electric drive technology trends for passenger electric and hybrid EVs with commercially available solutions in terms of materials, electric machine and inverter designs, maximum speed, component cooling, power density, and performance. The emerging materials and technologies for power electronics and electric motors are presented, identifying the challenges and opportunities for even more aggressive designs to meet the need for next-generation EVs. Some innovative drive and motor designs with the potential to meet the DOE 2025 targets are also discussed. The report [13] analysis demonstrated that BEV300s currently provide GHG benefits in nearly every state, with the median state's BEV300 emission rate being between 50% to 60% lower than their gasoline ICEV passenger car, passenger truck, and light commercial truck counterparts.

The comparative analysis of electric vehicles in China, Europe, and the United States offers a valuable contribution to the understanding of the evolving landscape in sustainable transportation. By examining the unique technological approaches and market dynamics in these major regions, this exploration provides a snapshot of the current state and future potential of EVs. The insights garnered from this comparison contribute to the broader discourse on the global transition to cleaner and more efficient transportation solutions, emphasizing the significance of collaboration and innovation across borders. As researchers collectively strive for a greener future, this examination serves as a concise yet impactful contribution to the ongoing dialogue surrounding electric vehicles and their role in reshaping the automotive industry. The arrangement of this article is as follows: Section 2 concentrates on the electric vehicle's initiative, which encompasses China, Europe, and the United States. Section 3 provides an in-depth discussion of the energy consumption. Section 4 presents a consideration of the implementation of EV technology. Section 5 addresses the investment of EV. Section 6 serves to provide a summary of the key aspects discussed in the article.

2. Electric Vehicles Initiative

The Electric Vehicles Initiative (EVI) was established in 2010 as a multi-governmental policy forum operating under the auspices of the Clean Energy Ministerial (CEM). Its primary objective is to expedite the global adoption of Electric Vehicles (EVs) by comprehensively addressing the associated policy challenges. The EVI is committed to enhancing the understanding of policy impediments related to electric mobility, facilitating governmental responses to these challenges, and serving as a knowledge-sharing platform for policymakers [14,15]. Furthermore, the EVI plays a pivotal role in fostering collaborative initiatives between government policymakers and various stakeholders. These initiatives cover crucial aspects of the transition to electric mobility, including but not limited to charging infrastructure, grid integration, and the EV battery supply chain. In this context, in 2022, the EVI introduced the Zero Emission Government Fleet Declaration, representing a robust commitment among participating governments to transition to 100% zero-emission vehicles in public procurement, thereby advancing the broader goals of sustainable transportation [16]. Throughout the period spanning 2022-23, governmental participation in the EVs initiative has been notable, involving countries such as Canada, Chile, China, Finland, France, Germany, India, Japan, the Netherlands, New Zealand, Norway, Poland, Portugal, Sweden, the United Kingdom, and the United States.

A. China

In recent decades, with the rapid development of industrialization and urbanization, China's demand for automobiles has maintained a momentum of rapid growth. Statistics from the China Association of Automobile Manufacturers (CAAM) show that the number of automobiles per 1,000 people has increased from 24 in 2005 to 193 in 2020 [17]. While improving people's living standards, it has also brought about increasingly serious energy consumption and environmental pollution problems. The China Oil Distribution Industry Development Report (2020–2021) statistics show that China's crude oil consumption exceeded 649.65 million tons, and its dependence on foreign oil exceeded 70% in 2020. At the same time, statistics from the National Energy Administration of China show that China's total CO_2 emissions in 2020 reached 10 billion tons, accounting for about 30% of global CO_2 emissions [18-20]. Due to the advantage of EVs that can reduce exhaust emissions and improve energy efficiency, vigorously developing EV industry can not only alleviate energy and environmental pressures, but also accelerate the transformation and upgrading of the automotive industry, fostering new economic growth points and new international competitive advantages.

The fast-growing light-duty plug-in electric vehicle (PEV) market in China has important implications for both the global vehicle market and energy policies. From the perspective of demand pull-supply push, this study examines China's PEV market by reviewing sales, product performance, and government policies from the last decade; and by comparing it with the market in the United States.

Moreover, the upswing in electric car sales exhibited regional and powertrain-specific variations, with the preeminent contributor being China [21-25]. Thus, in 2022, Battery Electric Vehicle (BEV) sales in China recorded a 60% increase relative to 2021, reaching 4.4 million units, while Plug-in Hybrid Electric Vehicle (PHEV) sales nearly tripled, totaling 1.5 million units. The accelerated growth in PHEV sales in comparison to BEVs warrants meticulous examination in the forthcoming years, considering that PHEV sales, though experiencing substantial growth, remain comparatively lower overall [26,27]. It is conceivable that PHEV sales are presently catching up to the post-Covid-19 surge, especially given that BEV sales in China tripled from 2020 to 2021 following moderate growth during the 2018-2020 period. The noteworthy aspect is that electric car sales increased despite a 3% contraction in total car sales in 2022 compared to 2021. Table 2 illustrates Monthly new electric car registrations in China, 2022.

Table 2. Monthly new EV registrations in China, 2022, in Thousand.

	Jan.	Feb.	Mar.	App.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
BEV	287	216	368	210	298	439	368	413	474	408	455	471
PHEV	88	75	88	70	101	118	134	140	161	169	173	200

In this context, China's dominance in the global landscape of new electric car registrations was significant, accounting for nearly 60% of the total. Additionally, for the first time in 2022, China represented over 50% of the global electric car fleet, amounting to a total of 13.8 million vehicles. This robust growth is a consequence of more than a decade of unwavering policy support for early adopters in China. Such support includes the extension of purchase incentives initially slated for phase-out in 2020, and prolonged until the end of 2022 due to the impact of Covid-19. Figure 1 displays the market shares of the top 10 electric vehicle manufacturers during the first half of 2023.

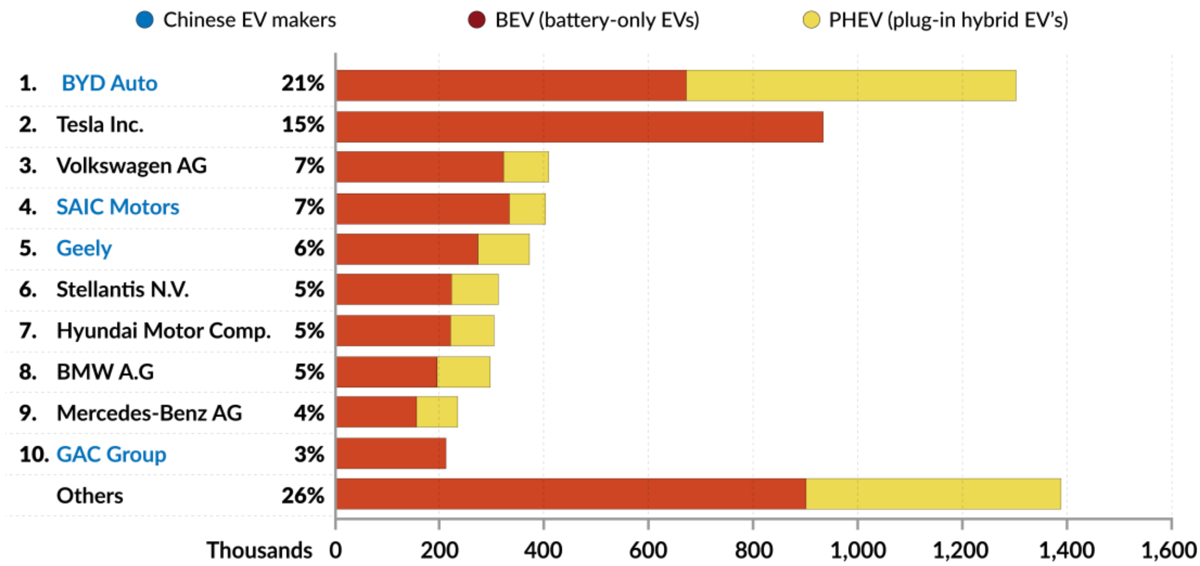

Figure 1. Market shares of top 10 EV makers, first half of 2023.

It is important to conclude that regional support within China has played a pivotal role in propelling some of the world's largest EV manufacturers. For instance, BYD, headquartered in Shenzhen, has been a major supplier of electric buses and taxis in the city, contributing to Shenzhen's ambitious goal of achieving a 60% NEV sales share by 2025. Similarly, Guangzhou, with a target of 50% NEV sales share by 2025, has facilitated the growth of Xpeng Motors, positioning it as one of the leading electric vehicle companies on a national scale.

In 2022, the proportion of EV in the total sales of domestic automobiles in China reached 29%, a marked increase from 16% in 2021 and less than 6% from 2018 to 2020. Consequently, China has surpassed its 2025 national target of achieving a 20% sales share for new energy vehicles (NEVs) well ahead of schedule. Indications strongly suggest continued growth; although the national NEV sales target is yet to be revised by China's Ministry of Industry and Information Technology (MIIT), the governing body overseeing the automotive industry, the commitment to enhanced electrification of road transport is reaffirmed in various strategic documents. China aims to attain a 50% sales share in designated "key air pollution control regions" by 2030 and 40% nationwide by 2030, aligning with the national action plan for carbon peaking. Table 3 displays the most recent studies on EVs conducted in China.

Table 3. The most recent studies on EVs conducted in China.

Ref.	Year	Publisher	Summarized
[28]	2023	ScienceDirect	▪ The results of the study demonstrate that the GRA-DWT-BiLSTM model achieves an average Mean Absolute Percentage Error (MAPE) of 9.884. Additionally, the 31 samples exhibit strong applicability in the context of EV sales forecasting. ▪ By 2027, China's EV sales are expected to experience a higher growth rate in the demand-side scenario compared to the supply-side scenario. ▪ In an optimal situation, China's EV adoption rate is projected to be 27.31%, 42.40%, and 52.97% by the years 2025, 2030, and 2035 respectively. The forecast outcomes serve as a foundation for formulating successive supply-demand side policies in China's EV industry.
[29]	2023	Springer	▪ The current research utilizes data from January 2020 to August 2022, encompassing 212 prefecture-level cities, to investigate the association between income groups and their responsiveness to variations in oil and electricity prices. ▪ The findings indicate that distinct income groups exhibit varying degrees of sensitivity to these price disparities. ▪ Fluctuations in gasoline prices and charging costs are expected to have a substantial impact on the sales of electric vehicles in cities with low and middle-income populations, while the sales of electric vehicles in areas with high-income populations would remain unaffected.
[30]	2023	ScienceDirect	▪ The article determines an alternative strategy that involves implementing varying license plate fees based on vehicle types in Shanghai, which is the largest regional market for electric vehicles in China. ▪ Analysis of monthly vehicle registration data from Shanghai reveals that a 1,000 yuan ($150) increase in the price difference between internal combustion engine vehicles (ICEVs) and EVs will result in a significant 56%–65% surge in EV sales. ▪ Researchers also analyze the disparity in license plate pricing in relation to the purchase subsidy policy.
[31]	2023	ScienceDirect	▪ China is continually efforts to enhance the production, market dominance, sales, and adoption of NEVs as a means to replace traditional fuel-powered vehicles in the transportation sector, with the aim of achieving their carbon reduction goal by 2060. ▪ This investigation utilized the Simapro life cycle assessment program and Eco-invent database to determine the market share, carbon footprint, and life cycle analysis of gasoline vehicles, NEVs, and batteries.

			▪ The analysis spanned a period of five years in the past and projected 25 years into the future, with a specific emphasis on sustainable development. ▪ Global data reveals that China possessed a total of 293.98 million automobiles, representing the biggest market share worldwide at 45.22%.
[32]	2023	ScienceDirect	▪ Research indicates that the majority of NEVs and HEVs exhibit a reduction in emissions when compared to ICEVs. ▪ In 2020, the vehicles' emission reduction rate ranges from 6.56% to 44.4%. By 2025, this rate is expected to be between 13.97% and 53.39%, and by 2030, it is projected to be between 19.65% and 57.49%.

B. Europe

The European Union (EU) is undertaking measures to progressively diminish its dependence on fossil fuels, aiming to decarbonize both the energy and automotive sectors comprehensively. The overarching objective is to achieve carbon neutrality by 2050. This ambitious initiative reflects the EU's commitment to mitigating the environmental impact and transitioning towards more sustainable and eco-friendly practices in line with global climate goals [33]. In Europe, EV sales witnessed a more moderate increase of over 15% in 2022 compared to 2021, reaching a total of 2.7 million units. This growth rate was notably lower than the rapid expansion observed in previous years, with annual growth exceeding 65% in 2021 and averaging 40% over the period from 2017 to 2019. Specifically, in 2022, Battery Electric Vehicle (BEV) sales experienced a 30% rise compared to 2021, while Plug-in Hybrid Electric Vehicle (PHEV) sales slightly decreased by around 3%. Europe contributed to 10% of the global growth in new EV sales. Despite the deceleration in growth in 2022, EV sales in Europe continued to rise amidst an overall contraction in the traditional car market, which experienced a 3% dip in total EV sales in 2022 compared to the previous year. Notably, in the first two months of 2023, battery EV sales surged by over 30% year-on-year, outpacing the overall car sales growth of just over 10% year-on-year [34].

The slowdown observed in Europe relative to previous years can be attributed, in part, to the extraordinary growth in EV sales during 2020 and 2021 in the European Union. During this period, manufacturers swiftly adjusted their corporate strategies to align with the CO2 emission standards enacted in 2019. These standards, covering the 2020-2024 period, exerted a considerable influence, with EU-wide emission targets slated to become more stringent only from 2025 and 2030 onward. In 2022, elevated energy prices had a nuanced impact on the competitive landscape between Electric Vehicles (EVs) and Internal Combustion Engine (ICE) cars. While gasoline and diesel prices for ICE cars surged, residential electricity tariffs, pertinent to EV charging, also experienced increases in some instances. The escalation in electricity and gas prices resulted in higher manufacturing costs for both ICE and EVs. Some carmakers expressed concerns that these high energy prices might curtail future investments in new battery manufacturing capacity. Despite these challenges, Europe retained its status as the world's second-largest market for EV in 2022, trailing only behind China. Europe accounted for 25% of all EV sales and held 30% of the global EV stock. The sales share of EVs in Europe rose to 21%, a notable increase from 18% in 2021, 10% in 2020, and less than 3% prior to 2019. Several European countries continued to lead in the sales share of EVs, with Norway at 88%, Sweden at 54%, the Netherlands at 35%, Germany at 31%, the United Kingdom at 23%, and France at 21% in 2022. In terms of volume, Germany emerged as the largest market in Europe with sales of 830,000 units in 2022, followed by the United Kingdom with 370,000 and France with 330,000. Spain also recorded sales exceeding 80,000 units [4].

The share of EVs in total car sales in Germany increased tenfold since before the Covid-19 pandemic, attributed in part to post-pandemic support measures, such as purchase incentives through the Umweltbonus. A surge in sales in 2022 was observed in anticipation of subsidies potentially being further reduced from 2023 onwards. However, in Italy, EV sales decreased from 140,000 in 2021 to 115,000 in 2022, and similar decreases or stagnation were noted in Austria, Denmark, and Finland. As of the latest assessment, encompassing the European Economic Area, Europe has secured the second position globally, boasting a Battery Electric Vehicle (BEV) share of 10% and a Plug-in Hybrid Electric Vehicle (PHEV) share of 9%. The impetus for this notable market presence can be traced back to the European CO2 standards for new cars, which mandated an average target of 95 grams per kilometer (g/km) for the period 2020/21 [35].

In response to these CO2 standards, manufacturers intensified their efforts to introduce a considerable number of electric vehicles (EVs) into the market, particularly in 2020, when the EV market share almost quadrupled within a single year. However, following the successful compliance of vehicle manufacturers with the 2020/21 CO2 targets without incurring penalties, their enthusiasm for EV sales appears to have somewhat diminished. The subsequent regulatory target for 2025 is perceived as relatively lenient, lacking the strength to significantly impact manufacturers' portfolio strategies. Table 4 presents an update of the most important recent research carried out in Europe on EVs. Compounded by the reduction of tax incentives for EVs in certain European countries and persistent supply shortages leading to prolonged waiting lists for EVs, the market appears to be experiencing a state of stagnation, with a zero-growth rate observed thus far in 2022. These factors collectively contribute to the current dynamics and challenges within the European electric vehicle market.

Table 4. An update of the most important recent research carried out in Europe on EVs.

Ref.	Year	Publisher	Objective
[36]	2024	ScienceDirect	▪ The main purpose of this study is to develop an understanding of the country's charging infrastructure on the likelihood of individuals selecting BEVs and PHEVs and the historical data regarding the network of charging stations in the UK was acquired from the European Alternative Fuels Observatory.
[37]	2023	MDPI	▪ The primary objective of the study was to assess the influence of fiscal incentives on the proportion of electric passenger cars in overall sales across 31 European nations over the years 2021 and 2022. ▪ The research methods encompassed an evaluation of the proactive fiscal incentives and the inherent financial advantages of owning electric vehicles compared to petrol-powered vehicles. ▪ This involved determining the relationship between these factors and the overall reduction in emissions, and additionally performing regression analysis to determine the influence of these variables, along with indicators of national affluence and the urbanization distribution of the population, on the proportion of electric vehicles in total sales.
[38]	2023	ScienceDirect	▪ The current research investigation attempts to evaluate the impact of national-level policy intervention in the European Union on the transition to EVs, which presents a substantial potential to address this issue. ▪ This study utilizes the ELECTRE (ELimination Et Choix Traduisant la REalité - ELimination and Choice Expressing the REality) TRI-nC technique to categorize 27 EU Member States (MSs) depending on their governance in promoting EV technology.
[39]	2017	ScienceDirect	▪ The investigation contributes to the discourse surrounding policy interventions aimed at promoting the adoption of advanced vehicle technology.

			▪ An elaborate system dynamics-based market agent model is utilized to analyze powertrain technology transitions in the European Union until 2050, with a specific focus on passenger automobiles. ▪ This study primarily examines the impact of subsidies on infrastructure deployment and vehicle acquisition, specifically in relation to the EU fleet pollution requirements.
[40]	2019	ScienceDirect	▪ This article addresses econometric studies that investigate the magnitude of the impact of purchase incentives. It specifically focuses on analyzing data on sales of PEVs in 32 European nations between 2010 and 2017, with a particular emphasis on the influence of financial incentives.
[41]	2018	ScienceDirect	▪ The researcher developed a dataset encompassing 10 widely-used BEVs in 28 European nations during a span of 3 years, from 2012 to 2014. ▪ The BEVs are categorized into many segments, ranging from compact automobiles to high-performance sports cars.

To sum up, the advantages of EVs include a decrease in reliance on imported fossil fuels and an enhancement in air quality. These benefits have been particularly evident during the COVID pandemic, resulting in increased enthusiasm and acceptance of EVs. More importantly, EVs in Europe experienced a lesser impact from the COVID crisis compared to traditional car sales. This was mostly due to the implementation of purchasing incentives and legislative measures that resulted in an increase in the availability of EV models. Additionally, the decrease in global battery costs also contributed to this resilience. Moreover, With the objective of mitigating carbon dioxide emissions and decreasing air pollution, the European political agenda has prioritized sustainable mobility. To accomplish this objective, ecological transformation is necessary, which involves the integration of low-emission vehicles, such as electric battery-powered cars, into the European automobile industry.

C. United States

Electric vehicle (EV) sales in the United States experienced a significant 55% growth in 2022 compared to 2021, primarily driven by battery electric vehicles (BEVs). The sales of Battery Electric Vehicles (BEVs) had a significant surge of 70%, reaching an impressive total of approximately 800,000 units. This development trend marks the second consecutive year of robust expansion following a temporary decline in sales during the 2019-2020 period. The sales of PHEVs experienced a growth, although a modest one of only 15% [42,43]. Besides, the surge in EV purchases in the United States was notably significant, given that overall automobile sales experienced an 8% decline in 2022 compared to 2021, which was a far steeper decrease than the worldwide average of -3%. Table 5 displays the monthly number of newly registered electric vehicles (EVs) in the United States for the year 2022.

Table 5. Monthly new EV registrations in United States, 2022.

	Jan.	Feb.	Mar.	App.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
BEV (K)	36.4	47.4	75.2	25.2	60	70.6	64.7	66.6	76.3	75.5	71.3	98.4
PHEV (K)	11.8	12.9	17.7	15.4	15.8	17	14	14	13.5	16.3	19.9	21.1

In all, the United States contributed to 10% of the worldwide increase in sales. The global EV inventory has surged to 3 million units, representing a 40% increase compared to the previous year and constituting 10% of the whole global vehicle stock. The proportion of electric vehicles in overall car sales rose to almost 8%, a significant increase from slightly above 5% in 2021 and roughly 2% during the period from 2018 to 2020.

Several factors are contributing to the growth of sales in the United States. The closure of the supply gap was facilitated by the availability of a larger selection of models, in addition to those provided by Tesla, the longstanding frontrunner. Since Tesla and General Motors have already hit their subsidy limit under US assistance in past years, the availability of new models from other firms allows more buyers to take advantage of purchasing incentives, which can reach up to USD 7,500. Subsequently, the American Automobile Association reports that in 2022, 25% of Americans anticipate purchasing an electric vehicle as their next car, indicating a growing awareness and preference for electrification among both government and companies [44]. Despite advancements in charging infrastructure and driving range, US drivers still consider them significant issues due to the normally extensive travel distances and the limited popularity and availability of other transportation options like rail. Nevertheless, the Bipartisan Infrastructure Law of 2021 enhanced assistance for EV charging by allocating a total of USD 5 billion in funding from 2022 to 2026 through the National Electric Vehicle Infrastructure Formula Program. Additionally, USD 2.5 billion in competitive grants will be provided over the same period through the Charging and Fueling Infrastructure Discretionary Grant Program.

The implementation of the Inflation Reduction Act (IRA) has prompted a surge of global electromobility corporations to increase their manufacturing operations in the United States. From August 2022 to March 2023, prominent EV and battery manufacturers disclosed a total of USD 52 billion in investments in North American EV supply chains after the implementation of the expenditure Tax Credit (IRA). Approximately 50% of this expenditure is allocated to battery manufacturing, while over 20% is dedicated to battery components and EV manufacturing respectively. In total, the company's announcements, which include provisional commitments for future battery and electric vehicle production in the United States, amount to around USD 75-108 billion [45,46].

It can be seen that, Tesla intends to transfer its lithium-ion battery gigafactory, now located in Berlin, to Texas. In Texas, Tesla will collaborate with China's CATL to produce advanced EVs. Additionally, Tesla hopes to establish manufacturing operations for next-generation EVs in Mexico. Ford has also disclosed a partnership with CATL to establish a battery facility in Michigan. Moreover, Ford intends to augment its production of electric vehicles by a factor of six by the conclusion of 2023 compared to 2022, reaching a capacity of 600,000 vehicles annually. This expansion is projected to further escalate to 2 million vehicles by 2026. BMW aims to enhance electric vehicle production at its South Carolina facility in the wake of the IRA. To elaborate, Volkswagen has selected Canada as the location for its inaugural battery production outside of Europe. This facility is scheduled to commence operations in 2027. Additionally, the company is allocating a substantial investment of USD 2 billion towards its plant in South Carolina. Although these expenditures are anticipated to result in significant growth in the future, their full influence may only be realized starting from 2024 when the factories become operational [47].

Currently, the IRA has limited the criteria for qualifying for purchase incentives. To qualify for a subsidy, automobiles must be manufactured in North America. Nevertheless, electric vehicle sales have continued to be robust since August 2022, and the initial months of 2023 have followed suit: During the initial quarter of 2023, there was a notable 60% surge in EV sales compared to the same time in 2022. This growth could be attributed to the elimination of subsidy caps for manufacturers in January 2023, allowing market leaders' models to now receive purchase incentives. Over time, the range of models that qualify for subsidies is anticipated to increase. Table 6 presents a comprehensive overview of the latest research undertaken in the United States on electric vehicles (EVs).

Table 6. An overview of the latest research undertaken in the United States on EVs.

Ref.	Year	Publisher	Summarized
[48]	2023	ScienceDirect	▪ As per a market research report, the aggregate value of the global battery market in 2014 amounted to 62 billion US dollars. Predominantly employed in Electric-Drive Vehicles (EDVs), encompassing Battery Electric Vehicles (BEVs), Hybrid Electric Vehicles (HEVs), and Plug-in Hybrid Electric Vehicles (PHEVs),

			the commonly utilized battery types include Lead-Acid, Nickel Metal Hydride, and Lithium-ion batteries.
[49]	2022	MDPI	▪ This study proposes enhancements to the end-of-life management of lithium-ion batteries in the United States, taking into account prevailing and emerging recycling technologies, existing collection and transportation infrastructure, current reuse applications, and an assessment of the extant regulatory policies. ▪ The research consolidates and furnishes a set of actionable recommendations for End-of-Life (EOL) management in the United States, encompassing policy, infrastructure, and technology. ▪ In August 2021, President Biden of the United States established a goal for half of all new vehicle sales by 2030 to consist of zero-emission vehicles, predominantly EVs and trucks. This anticipated surge in electric vehicle adoption raises crucial inquiries regarding the accessibility and sustainability of the raw materials utilized in the lithium-ion batteries that will propel them.
[50]	2020	ScienceDirect	▪ Attaining viable recycled content standards for electric vehicles (EVs) in the United States involves targeting percentages between 11 and 12% for Cobalt (Co), 7–8% for Lithium (Li), and 10–12% for Nickel (Ni) by the year 2030. ▪ The profitability threshold for hydro and direct recycling of EV batteries in the US is approximately 7–8,000 metric tons per year. ▪ While recycling retired EVs domestically in the US proves to be a more expensive endeavor compared to recycling in China, it is considered environmentally preferable.
[51]	2017	ACS Publication	▪ The expense associated with electric vehicle (EV) batteries in the United States witnessed a significant reduction, plummeting from over USD 1000 to 268 per kilowatt-hour (kWh) between 2008 and 2015. Anticipated further declines are expected to bring this cost down to USD 125/kWh or less by 2022, thereby establishing plug-in hybrid EVs as cost-competitive alternatives to internal combustion engine (ICE) vehicles. ▪ Despite the global electric vehicle stock being approximately 1 million in 2015, the market share of these vehicles experienced rapid growth, escalating from 0.1% in 2011 to 0.9% in 2015.
[52]	2015	ScienceDirect	▪ Researchers delve into these inquiries through an investigation focused on subsidizing EVs in the United States. Recognizing the pivotal role of lithium battery costs in determining the overall EV price, researchers compile historical data to construct an experience curve, depicting the reduction in costs for lithium-ion vehicle batteries as a function of cumulative production. ▪ For a learning rate of 9.5%, semi-annual, annual, and biannual tapering incurs total costs of 24, 27, and 34 billion USD, respectively. Conversely, under a 22% learning rate, semi-annual, annual, and biannual tapering costs a total of 2.1, 2.3, and 2.6 billion USD, respectively.

According to [53], the paper scrutinized the interplay among social, economic, geographic, and policy variables to unravel the intricacies of plug-in electric vehicle (PEV) adoption across different U.S. states. The primary objectives include deciphering which factors exhibit noteworthy correlations with variations in market shares of Battery Electric Vehicles (BEVs) and Plug-in Hybrid Electric Vehicles (PHEVs). Additionally, the study aims to discern how these factors diverge between BEV and PHEV markets, and how they compare with the determinants recognized for shaping the early hybrid vehicle (HEV) markets.

Transportation constitutes 28% of total energy consumption and contributes to 26% of carbon emissions in the United States. Battery electric and plug-in hybrid electric vehicles stand out as promising solutions to decarbonize the transportation sector. To expedite the adoption of electric vehicles, various entities, including federal and state governments, electric utility operators, and others, have extended support through both financial and non-financial incentives. In the pages that follow, it will be argued that [54] the impact of these incentives on electric vehicle adoption. The findings reveal that for every $1000 offered as a rebate or tax credit, there is a discernible increase of 2.6% in the average sales of electric vehicles. Furthermore, access to High Occupancy Vehicle (HOV) lanes emerges as a significant driver of adoption, with a notable 4.7% increase linked to the density of HOV lanes (per 100 vehicles per hour).

3. Energy Consumption of EV

An important economic consequence of adopting electric vehicles is being freed from reliance on fossil fuels, resulting in significant advantages for countries that heavily import crude oil. In India, if 30% of EV sales are achieved by 2030, it is projected that the country will save around $14.1 billion USD by not having to import crude oil (petrol/diesel) for internal combustion engine (ICE) vehicles [55-57]. This savings will be due to the elimination of import fees for crude oil, which will be offset by the import prices of cells/battery packs for EVs. The widespread adoption of EVs will result in the emergence of new industrial sectors, specifically in the areas of plastic and composite manufacturing, lithium cell production, electric motor and power electronics manufacturing, as well as recycling and resource recovery [58-59]. In this context, in 2022, the collective EV fleet globally demonstrated an electricity consumption of approximately 110 TWh, constituting a fraction of less than 0.5% relative to the extant total global final electricity consumption. Concurrently, the deployment of EVs resulted in the displacement of approximately 0.7 million barrels per day (Mb/d), equivalent to 1.3 EJ of oil consumption in the same year. To align with the Net Zero Scenario by 2030, it is imperative that EVs attain a heightened capacity to displace an estimated 8 Mb/d (17 EJ) of oil. Table 7 indicates electricity demand and oil displacement resulting from the use of EVs, 2022.

Table 7. Electricity demand and oil displacement resulting from the use of electric vehicles, 2022.

	Electricity demand	**Oil displacement**
Two/three-wheelers	14.0TWh	- 0.1 Mbbl/d
Light-duty vehicles	70.0TWh	- 0.5 Mbbl/d
Buses	23.0 TWh	- 0.1 Mbbl/d
Trucks	4.0 TWh	-

In this context, BEVs' electric consumption can frequently be calculated through measurements of the battery's current and voltage, typically stated in Wh/km. The calculation of the electrical energy consumed by BEVs during a trip, which can be measured in Wh, can be examined using in-vehicle sensor data pertaining to battery information, as expressed by the following equation (1) [60]:

$$E_{trip} = \frac{1}{3600}\sum_{i=1}^{n} V_i * I_i \qquad i = 1,2,3,\dots,n \tag{1}$$

Where V_i and I_i represent the voltage and current of the battery measured at the second i, while n represents the final second of the trip. Following that, the energy consumption of BEVs can be calculated in the unit of Wh/km employing the following formula (2):

$$EC = \frac{E_{trip}}{d_{trip}} \tag{2}$$

Where, the variable "d_{trip}" denotes the total distance of the entirety of the trip, measured in kilometers. It is also feasible to determine the total carbon emissions using a carbon lifecycle analysis in order to evaluate the environmental impact of BEVs. For BEVs, the carbon route mainly refers to the stages of generating, refining, and delivering electric energy sources. The carbon emissions of BEVs can be determined by applying a conversion factor that takes into account their energy usage. As per the guidelines from the Thailand Greenhouse Gas Management Organization [62], the energy consumption of a BEV in terms of kilowatt-hours per kilometer (kWh/km) can be converted into the amount of carbon emissions in grams of carbon dioxide equivalent per kilometer (gCO2eq/km) using a conversion factor of 598.6 gCO2eq/kWh.

Kavianipour et al. [63] pointed out that the annual reduction in CO2 emissions resulting from the electrification of intercity travel is within the range of 0.34 to 1.45 million tons. The investment in network electrification is justified by the cost savings to society. It is important to understand that the DC fast charger network suggested by the charging infrastructure planning framework only needs to meet 3.8%–8.8% of the total energy consumption for EVs. The EV market share for Michigan in 2030 necessitates an annual energy consumption ranging from 22.45 to 51.60 BWh. In addition, Min et al. [64] proposed a technique for optimizing the trajectory of an electric vehicle (EV) in order to minimize energy usage. The vehicle inverse dynamics model is initially constructed by employing a semi-recursive approach to represent the dynamics of many bodies in motion. The dynamic qualities of the suspension, steering, and braking system are taken into account and simulated. Furthermore, the servo constraints are defined based on the specific vehicle states and kinematic constraints in order to solve the inverse dynamics problem of an EV. In addition, a method has been devised to enhance trajectories by employing an inverse dynamics model, servo restrictions, and the Ritz method.

Desreveaux et al., [65] emphasized that in the estimation of energy consumption for electric vehicles, constant consumption variables are frequently included for the sake of modeling simplicity. For a Volkswagen e-golf in Europe, the energy consumption is 12.7 kilowatt-hours per 100 kilometers, while for a Nissan Leaf in Europe, it is 20.6 kilowatt-hours per 100 kilometers. Ghorbani et al. [60] investigated the correlation between energy use and the energy needed in the transportation industry. In 2021, the United States documented that 28% of its energy usage was allocated to the transportation of persons and products. Petroleum derivatives, alternative fuels, methane, and electrical power are the primary categories of energy utilized for transportation. Specifically, petroleum accounted for over 90% of the whole energy consumption in 2021. In this regard, Xie et al., [67] illistrated the single driving cycle, the relative error of battery power and current is below 5%, and the absolute error of battery voltage is below 2.5 V. For the whole driving range, the absolute error of driving range is only about 5.75 km. The main factors influencing energy consumption and driving range are average vehicle speed, running time and the frequency distribution of braking process, besides, the energy consumption of congested traffic with/without regenerative brake control system are 46.07 kWh/100 km and 47.19 kWh/100 km, respectively, meanwhile, vehicle with regenerative braking saves 2.43% energy under congested traffic.

4. Technology Deployment of EV

In 2022, EV sales reached a new record, accounting for 14% of total sales. This accomplishment is particularly impressive considering the challenges posed by supply chain interruptions, macro-economic and geopolitical uncertainties, as well as high commodity and energy prices. Together with, the increase in electric vehicle sales occurred amidst a worldwide decline in automotive markets, with overall car sales in 2022 decreasing by 3% compared to 2021. The sales of EV, which include both battery electric vehicles BEVs and PHEVs, surpassed 10 million units in the previous year, marking a 55% increase compared to 2021. Between 2017 and 2022, the sales of EVs increased significantly, rising from approximately 1 million to over 10 million [68,69]. Table 8 displays the sales figures and market share of EV in the Net Zero Scenario from 2017 to 2022.

Table 8. EV sales and sales share in the Net Zero Scenario, 2017-2022, in Millions.

	2017	2018	2019	2020	2021	2022

China	0.58	1.08	1.06	1.14	3.28	5.96
Europe	0.30	0.39	0.57	1.38	2.30	2.67
United States	0.20	0.36	0.33	0.30	0.36	0.99

Consequently, the growth of EV sales from about 100,000 to 1 million between 2012 and 2017 highlights the exponential pattern of EV sales growth, which occurred over a span of 5 years. By 2030, EV sales in the Net Zero Scenario account for around 65% of all car sales. In order to align with this scenario, there has to be a consistent annual growth rate of approximately 25% in EV sales from 2023 to 2030. In 2022, EV sales experienced a 55% growth compared to the previous year, 2021. While electrification is progressing in other vehicle sectors, the proportion of electric sales for buses and trucks was at approximately 4% and 1% in 2022, respectively.

5. Investment of EV

The global expenditure on EV had a 50% increase in 2022 compared to 2021, reaching approximately USD 425 billion. The majority of this expenditure was made by consumers during car purchases, whereas governments allocated approximately USD 40 billion through direct purchase incentives. The rise in worldwide expenditure on electric vehicles indicates that auto manufacturers, particularly established ones, are earning more earnings from the sale of EVs. Consequently, they are gradually decreasing their dependence on the sales of internal combustion engine (ICE) vehicles to fund the manufacturing, research and development, and creation of new models for EVs. Although there is still considerable progress to be made, this is a significant milestone in the expansion of electric vehicles and the shift towards complete electrification of road transportation. Between 2017 and 2022, the proportion of government spending in overall spending declined from more than 20% to slightly below 10%. Starting from 2023, governments in prominent EV markets are progressively eliminating subsidies for EVs, indicating a reduction in government expenditure within those markets. Table 9 provides a comprehensive summary of the recent studies on the investment of EVs.

Table 9. An overview of the latest research on investment of EVs.

Ref.	Year	Contribution
[70]	2023	▪ This article provides an analytical investigation into the most advantageous investment choices for charging infrastructure in parking lots, considering both state-owned enterprises and private firms. ▪ The objective is to reduce range anxiety and promote the widespread adoption of EVs. Investment decisions are determined by rational short-term choices and are supposed to be unchanging. ▪ The allocation of resources towards the development of charging infrastructure is a strategic plan with a focus on the future, and the choices made may undergo modifications as circumstances change.
[71]	2023	▪ The report provides an assessment of production capacities and the corresponding investment requirements. When we compare the projected production of 5.1 million EVs to the objective of achieving 66% EV sales in the US by 2030.
[72]	2023	▪ In situations where both the United States and Europe aim for increased targets in EV sales, the collective deficit in yearly EV manufacturing capacity might exceed 6 million EVs, in contrast to the required 20 million by 2030. ▪ A funding injection of approximately $42 billion in both regions might effectively mitigate this risk. Nevertheless, there is a pressing time constraint to construct and activate new facilities.

[73]	2023	▪ The article provides an agent-based model (ABM) to replicate the actions of EV expansion and investment in charging infrastructure, while evaluating their influence on the whole system.
[74]	2023	▪ The development of lightweight, flame-retardant, and cost-competitive composite materials represents a prospective avenue for replacing incumbent materials in EVs, thereby mitigating overall vehicle costs. ▪ The global market for EV battery housing witnessed a valuation of $0.87 billion in 2020, with a projected escalation to $4.47 billion by 2025. Anticipated demands for battery housing materials indicate an expected increase to 1167.3 thousand tonnes by 2025. ▪ The reported life cycle cost of EVs ranges from $0.49 to $0.52 per kilometer; however, alternate reports suggest a lower figure of $0.25 per kilometer. ▪ Despite substantial investments in EV technologies, prudent utilization of existing automotive industrial infrastructure and investments is advisable to facilitate a seamless transition to emerging EV industries, without jeopardizing existing commitments in the automotive sector.
[75]	2023	▪ The empirical data employed in the model are derived from pertinent studies and policies concerning Electric Vehicle Charging Infrastructure (EVCI) in China, thereby ensuring the contemporaneous applicability of the model. ▪ Concerning the costs associated with infrastructure construction, as per information sourced from the China EVCI Promotion Alliance, the financial outlay for the construction of charging stations' charging equipment is estimated to be approximately $250,000.

As elucidated by Shang et al. [76], our empirical findings indicate that a 1% augmentation in purchase subsidies corresponds to a 1.36% increase in EV sales and a 2.31% expansion in the EV market share. Furthermore, our analysis identifies non-financial policies, specifically those associated with parking privileges, limitations on the end-number of vehicles, and promotional targets, as particularly efficacious in enhancing both the sales volume and market share of EVs. In order to evaluate the potential enhancements in cost-effectiveness, a vehicle choice model-based counterfactual simulation is constructed, employing an extensive and nationally representative sample of new car buyers in the United States. The findings indicate that prevailing federal incentives prove to be financially demanding, amounting to $36,000 per additional Plug-in Electric Vehicle (PEV) as the subsidy is universally applied to every purchaser. A twofold improvement in cost-effectiveness is attainable by strategically directing incentives based on criteria such as income, vehicle disposal practices, geographic location, and/or the extent of vehicle miles traveled [77].

It is worthy to mention that, the analysis systematically monitors investment plans declared by Original Equipment Manufacturers (OEMs) and suppliers during a pivotal three-year period marked by significant policy interventions and a rapidly expanding EV market share in the United States. From 2020 to 2022, a cumulative sum of approximately $108 billion has been publicly disclosed for prospective EV and associated battery production endeavors in the U.S. through the year 2030. The announced investments for forthcoming EV production exhibited a tenfold surge in 2021, culminating at approximately $15 billion in 2022. Similarly, investments earmarked for future EV battery production experienced a remarkable upswing, notably doubling to nearly $48 billion in the singular year of 2022. Given the policy landscape, such as the Inflation Reduction Act and the US National Blueprint for Transportation Decarbonization, it is anticipated that investments will persist and escalate swiftly in the forthcoming years.

6. Conclusion

In conclusion, the comparative analysis of electric vehicles in China, Europe, and the United States provides valuable insights into the diverse technological landscapes and market dynamics shaping the global electric mobility sector. This exploration highlights the unique strategies, challenges, and advancements adopted by each region, emphasizing the shared commitment towards sustainable transportation solutions. As the world moves towards a greener future, understanding the distinct trajectories of these major players becomes crucial for stakeholders and policymakers alike. This brief examination underscores the transformative potential of electric vehicles and sets the stage for continued collaboration and innovation in the pursuit of a more sustainable and eco-friendly automotive landscape. In this context, the global spending on EVs was up 50% in 2022 relative to 2021, reaching around USD 425 billion. Most of this was directly spent by consumers when buying a vehicle, while governments spent around USD 40 billion through direct purchase incentives. The increase in global spending on EVs means that carmakers – including incumbents – are generating more revenues from EV sales, thereby progressively reducing reliance on sales of internal combustion engine (ICE) vehicles to finance EV manufacturing, R&D and new model development. Another essential point that there is still a long way to go, this is an important step for EV growth and the transition to fully electrified road transport. Over the 2017-2022 period, the share of government spending in total spending decreased from over 20% to just under 10%. In 2023 and beyond, governments in major EV markets are continuing to phase out subsidies for EVs, suggesting government spending will decrease in those markets.

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