MSc (CE) Program
Renewable Energy Systems

Analysis and Evaluation of Environmental, Energetic and Economic Performance of Electric Vehicles in China

A Master's Thesis submitted for the degree of
“Master of Science (Continuing Education)”

supervised by
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Vienna, 20.08.2025

Affidavit

I, **TIANYI YAO, MSC**, hereby declare

1. that I am the sole author of the present Master's Thesis, "ANALYSIS AND EVALUATION OF ENVIRONMENTAL, ENERGETIC AND ECONOMIC PERFORMANCE OF ELECTRIC VEHICLES IN CHINA", 89 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
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Table of content

Abstract

This thesis evaluates the environmental, energy, and economic performance of electric vehicles in China using Life Cycle Assessment and the GREET model. It compares gasoline, hybrid, plug-in hybrid, and battery electric vehicles across production, use, and disposal phases. Results show that electric vehicles can significantly reduce life cycle carbon emissions and energy use, especially with cleaner electricity. The findings highlight the importance of improving the power mix and supporting EV adoption to achieve sustainable transportation.

1. Introduction

Energy is an indispensable pillar for human survival and the economic and social activities that support human development. The environment is the foundation upon which humans depend for survival and is the basic prerequisite for the development of human civilization. The use of traditional fossil fuels in automobiles has long been recognized as the primary cause of energy shortages and environmental destruction. Therefore, under the dual pressures of energy and environment and within the context of sustainable development, alternative fuels for automobiles have garnered significant attention. They not only supplement the use of traditional energy sources and alleviate the imminent energy crisis but also address severe environmental pollution, reducing environmental pressure. Thus, research into alternative fuels for automobiles holds vast potential.

Electric vehicles (EVs), with their environmental friendliness, are gradually becoming an important technology to address climate change. Electric vehicles are expected to reduce reliance on fossil fuels, thereby lowering greenhouse gas emissions, enhancing energy efficiency, and supporting the broader application of renewable energy.

In recent years, although the vigorous development of China's automobile industry has brought considerable economic benefits, the oil consumption of the automobile industry accounts for almost half of the total oil consumption, and the air pollution and energy problems caused by automobile emissions have become increasingly prominent [1]. In the context of "dual carbon", various industries actively support the "green and sustainable development" strategy, and in the automotive industry, new energy vehicles will be an important part of the orderly construction of China's energy system. China's new energy vehicle technology development is in full swing, but at the same time, due to the early development of traditional fuel vehicles, the competitiveness of new energy vehicles in the market is insufficient, consumers' recognition of new energy vehicles is low, and there is less research on the environment, economy, and energy aspects of new energy vehicles [2].

Since the early 21st century, the global electric vehicle market has experienced explosive growth. According to reports from the International Energy Agency (IEA), global electric vehicle sales increased from tens of thousands in 2010 to over 10 million in 2020. This growth has been primarily driven by government policy support and increasing market demand. In Europe, China, and the United States, governments have vigorously promoted the development of electric vehicles by offering purchase subsidies, tax incentives, and building charging infrastructure [3] .

Electric vehicles have played a significant role in reducing urban air pollution and lowering greenhouse gas emissions. Due to their zero-emission characteristics during use, they are considered effective tools for improving urban air quality. Additionally, the widespread adoption of electric vehicles has stimulated the development of related industries, including battery manufacturing, electric vehicle assembly, and charging infrastructure construction, all of which have had profound impacts on the economy and society.

Government policies and international agreements have been crucial in promoting the development of electric vehicle technology and market acceptance. For example, emission reduction targets and environmental regulations implemented by various governments have directly influenced the strategic adjustments of the automotive industry, prompting automakers to increase their research and production of electric vehicles. Tax incentives and subsidy policies for EV purchasers and investments in charging infrastructure are also key factors for EV development.

According to the International Energy Agency (IEA) [4], China's carbon dioxide emissions in 2020 were 9.894 billion tons, accounting for about 30.9% of global carbon dioxide emissions, of which the road transportation industry and its related oil industry and power industry are important sources of carbon emissions. In response to global warming, the Chinese government has pledged to peak carbon emissions by 2030 and achieve carbon neutrality by 2060. In October 2021, China's State Council issued the Notice on Printing and Distributing the Action Plan for Carbon Peaking Before 2030, which clarified that by 2030, the proportion of new energy and clean energy powered transportation vehicles should reach about 40%. In 2021, China's domestic sales of new energy vehicles reached 2.989 million units, a year-on-year increase of 169.1%.

The rapid development of the electric vehicle industry has also had far-reaching impacts on the global economic structure. On one hand, the promotion of electric vehicles has reduced dependence on oil, affecting the demand and supply patterns of the global energy market [5]. On the other hand, the emerging electric vehicle and component manufacturing industries have brought new growth points to the economy and created numerous job opportunities.

In recent years, China has carried out a lot of research and analysis on the economic, energy and environmental impact of electric vehicles [6]: for example, although new energy vehicles can be clean, low-carbon and pollution-free during driving, what is the environmental impact of new energy vehicles from the perspective of the whole life cycle? Is it more environmentally friendly and low-carbon than traditional combustion vehicles? This requires a comprehensive and systematic analysis of the production, manufacturing, driving, scrapping and disposal of new energy vehicles from the perspective of the whole life cycle, and scientifically and reasonably measuring the environmental impact, so as to provide reference and support for the green and low-carbon development of China's new energy vehicle industry. This dissertation will further examine the economic, energy, and environmental impacts of electric vehicles on the basis of existing research.

This paper assesses the economic, energy, and environmental benefits brought by electric vehicles in China. Using LCA and GREET models, the study analyzes the various stages of electric vehicle production and manufacturing, assembly and distribution, use and maintenance, and end-of-life treatment. The focus is on assessing and comparing the life cycle energy consumption, carbon emissions and pollutant emissions of gasoline internal combustion engine vehicles (GICEVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs) and pure electric vehicles (BEVs).

The content of this work is structured as follows: In the Introduction chapter, the global significance of energy and environmental issues is highlighted, emphasizing how traditional fossil fuel vehicles contribute to energy shortages and environmental degradation. This chapter sets the stage by explaining why electric vehicles (EVs) have become a critical technology in addressing these challenges. In the chapter 2, a comprehensive overview of the evolution of electric vehicles is provided, with a particular focus on their development in China. This chapter explores the historical context, industry policies, and infrastructure that have shaped the growth of the EV industry in China, while also discussing global trends in EV adoption and how they relate to China’s specific circumstances. In the chapter 4, the Life Cycle Assessment (LCA) method and the GREET model are used to evaluate the full life cycle of EVs—from production and usage to disposal—detailing the framework, data sources, and analytical processes used in the study. In the chapter 5, the study's findings are presented, focusing on several key areas, including life cycle carbon emissions for different types of vehicles, carbon emissions comparisons under various power structures, life cycle energy consumption analysis, pollutant emissions evaluation, and environmental impact assessment. Additionally, this chapter offers a life cycle cost analysis of electric vehicles, comparing them with traditional internal combustion engine vehicles (ICEVs) and hybrid electric vehicles (HEVs). The main findings of the study are summarized in the chapter 6 to emphasize the economic, energetic, and environmental benefits of electric vehicles in China.

2. Background

Since 2016, major automobile manufacturing and sales countries worldwide have successively proposed ambitious EV development targets. However, the emission reduction effectiveness and potential of EVs remain subjects of considerable debate, particularly in countries like China, which heavily relies on coal-fired power generation. While EVs do not produce carbon emissions during their operational phase, the fuel they consume generates carbon emissions during extraction, processing, storage, and transportation (i.e., the upstream stages of the fuel cycle). Additionally, the manufacturing of key components (batteries, motors, controllers, etc.) involves relatively high carbon emissions.

In recent years, to stimulate the demand for new energy vehicles, both central and local governments have introduced policies such as purchase subsidies and exemptions from purchase taxes since 2009. This move marked a significant step in promoting the strategic transition from traditional vehicles to new energy vehicles. Electric vehicles, as a type of new energy vehicle, have long been widely recognized. Currently, hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and battery electric vehicles (BEVs) are the main directions of EV development in China. From a full life cycle perspective, whether EVs still hold these advantages and the extent of their environmental benefits in terms of energy saving and emission reduction require further study.

2.1 Development of Electric Vehicles in china

With technological advances and policy support, the electric vehicle industry is rapidly expanding globally, especially in China, where the development of electric vehicles has important economic, social and environmental implications.

2.1.1 The Development of the EV Industry

Chinese government has implemented a series of measures to address the oil crisis, global climate warming, and improve urban air quality, including tightening new vehicle emission standards, improving fuel quality, strengthening the management of vehicles in use and phasing out old vehicles, and implementing traffic restrictions and purchase limitations. Technologically, there are two main directions: one focuses on energy-saving and emission-reducing technologies for traditional internal combustion engine (ICE) vehicles, including turbocharging and downsizing, hybridization, stratified charge combustion, and vehicle lightweighting. The other direction emphasizes alternative energy technologies, particularly non-fossil fuels like electricity and hydrogen. Among these various technological pathways, electric vehicles (EVs) have attracted global attention, including from the Chinese government, because they reduce dependency on oil and significantly cut greenhouse gas and air pollutant emissions during their operational phase.

As electrified components replace those in ICE vehicles, traditional ICE vehicles are gradually transitioning through hybrid vehicles to become either BEVs or FCVs. The maturity of different power technologies (both technically and in terms of cost coordination) varies significantly. Generally, the less reliant a technology is on ICE components, the lower its maturity. Therefore, selecting an appropriate pathway is crucial for the future automotive development strategy of the nation.

International electrification strategies provide valuable insights for China. Developed countries, leveraging their technological, economic, and societal advantages, have identified their own development pathways. Hybrid electric vehicles serve as transitional technology from ICE vehicles to electric vehicles. In 1997, Toyota introduced the world's first mass-produced hybrid model, the Prius, which initiated a new wave of electrification. The United States is not only the largest market for hybrid vehicles but also a leading nation in the global development of electric vehicles.

According to TrendForce, in 2023, a total of 13.03 million new energy vehicles in the world were sold, a year-on-year increase of 29.8%, a significant decrease from 54.2% in 2022, of which 9.11 million pure electric vehicles (BEVs), a year-on-year increase of 24%; Plug-in hybrid electric vehicles (PHEVs) were 3.91 million units, up 45% year-over-year. Compared to the sales volume in 2014, this is an increase of almost 20 times [7].

China has effectively leveraged its institutional advantages in the process of vehicle electrification. In 2009, the Chinese government released the "Automobile Industry Revitalization Plan," followed by the "Ten Cities, Thousand Vehicles" project initiated by multiple ministries, promoting HEVs, PHEVs, and BEVs in 25 demonstration cities. This marked the policy genesis of China's vehicle electrification. In 2009, the government established a differentiated subsidy policy based on vehicle type and electric power ratio, offering up to 60,000 RMB for an electric car and

500,000 RMB for an electric bus, narrowing the cost gap between electric vehicles and traditional ICE vehicles. Additionally, economic stimulus policies extended to upstream R&D and charging infrastructure construction for electric vehicles, gradually forming a comprehensive support structure for key industry segments.

2.1.2 The Development of EV in China

In recent years, the sales of new energy vehicles in China have increased steadily. Sales in 2021 reached 3.521 million units, a year-on-year increase of 157.6%, and in 2022, sales reached 6.887 million units, a year-on-year increase of 95.6%. The number of motor vehicles in the country has reached 435 million, including 336 million automobiles, and the number of motor vehicle drivers has reached 523 million, of which 486 million are automobile drivers [8].

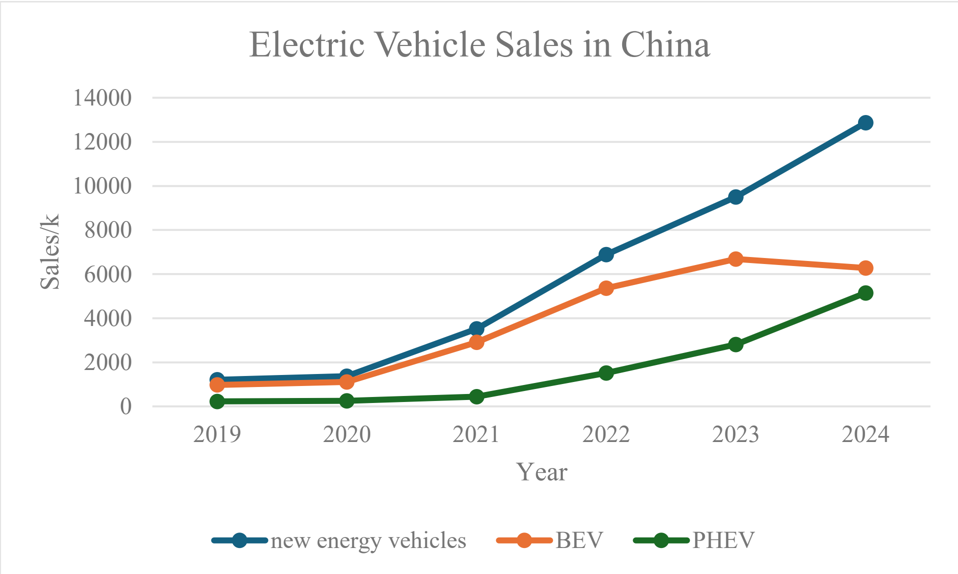

Fig.1 Eletric Vehicle Sales in China[1]

According to the Fig.1, electric vehicle (EV) sales in China have shown a significant upward trend from 2015 to 2023. In 2015, sales stood at 331,000 units, marking the early stage of the new energy vehicle market. By 2016, sales had risen to 507,000 units, driven by government subsidies. This growth continued in 2017 with sales reaching 779,000 units. In 2018, EV sales exceeded the one-million mark at 1.256 million units, indicating increasing market acceptance. Although sales slightly dipped to 1.206 million units in 2019, they rebounded in 2020 to 1.367 million units,

[1] Data Source: National Bureau of Statics(https://data.stats.gov.cn), China Association of Automobile Manufacturers(http://www.caam.org.cn/),Zhiyan Consulting(https://www.chyxx.com/)

demonstrating industry resilience despite the global pandemic. In 2021, sales surged to 2.989 million units, a 169% year-on-year increase. The momentum continued in 2022, with sales nearly doubling to 6.887 million units, highlighting EVs' growing dominance. For 2023, sales are forecasted to exceed 9 million units, reflecting strong governmental support and consumer preference for cleaner vehicles. Overall, the steady rise in EV market share underscores China's commitment to carbon neutrality and its robust infrastructure development.

Among the top eight automakers in the 2022 sales ranking, the sales of all automakers are growing, and there are 6 automakers with a growth rate of more than 100%. Among them, Geely Automobile rose the most, from 80694 to 304911, an increase of 277.9%; BYD Auto won the 2022 sales championship with 1 799947 units, a year-on-year increase of 208.2%, and its market share reached 31.7%; Car companies such as GAC Aion and Chery Automobile have also seen significant growth, and China's new energy vehicle companies are developing better and better in the field of new energy vehicles through technology research and development [9]. Among the 31 provinces and cities, Guangdong Province will have the highest number of insured vehicles in 2022, as high as 756,900 vehicles, accounting for 14.46% of the national market share. followed by Zhejiang and Jiangsu, with 619,600 and 479,700 new energy passenger vehicles respectively, and Shandong, Shanghai and Henan all exceeded 300,000. The insured volume of new energy passenger vehicles in Sichuan Province is 235,100 units, and the insured volume of new energy passenger vehicles in ten provinces and cities such as Anhui, Guangxi and Hebei is between 10~200,000 units; In the remaining provinces, the number of new energy passenger vehicles insured is less than 100,000 [10].

In 2009, the "Automobile Industry Adjustment and Revitalization Plan" proposed: to open a national conservation and new energy vehicle demonstration project, by the central financial allocation of funds to support, to determine the pilot enterprises in the service area to purchase clean energy vehicles to subsidize, thus opening the curtain of China's clean energy vehicle subsidy era [11]. At the same time, the "10 cities and 1,000 vehicles" project, the full name is "10 cities and 1,000 energy-saving and new energy vehicles demonstration and application project", through the provision of national financial subsidies, the plan will take about three years, the annual development of nearly 10 large and medium-sized cities, to each large and medium-sized city in the country to introduce nearly 1,000 clean energy vehicles and pilot demonstration work, basically covering these large and medium-sized cities in the field of public transport, taxi, official business, municipal, postal and other services [12].

2.2 Industry Policies and Infrastructure Construction in China

Since 2013, China has launched a new round of demonstration and promotion projects for new energy vehicles, extending through 2020. This initiative places greater emphasis on the rationality of industry policies and the development of charging infrastructure in tandem with the growth of electric vehicles. In 2015, a series of important policies were released in quick succession. Among these, the State Council's "Made in China 2025" included energy-saving and new energy vehicles as one of the nine strategic emerging industries. Based on this, the Ministry of Industry and Information Technology set a global sales target of 3 million electric vehicles by 2025, marking the first time post-2020 production and sales targets were planned.

The Ministry of Science and Technology's "12th Five-Year Plan for Electric Vehicle Technology Development," released in 2012, explicitly proposed the construction of 400,000 charging piles and 2,000 charging and swapping stations. Together with the industry plan released in 2012, these three national-level plans formed a comprehensive system of short- and medium-term goals covering infrastructure, vehicle production, and export.

The subsidy policy for electric vehicles applicable from 2016 to 2020 was more aligned with industry development realities, lowering the threshold for electric vehicle entry, differentiating subsidy levels based on driving range and fuel consumption, and implementing a more stringent phase-out mechanism. The scope of pilot programs was gradually expanded nationwide. Consequently, the evaluation of electric vehicles' energy-saving and emission-reduction effects has shifted from a broad approach to a more precise management process that aligns with objective realities.

At present, China's latest support policies for electric vehicles include the following aspects:

1. Purchase tax relief: New energy vehicles with a purchase date between January 1, 2024 and December 31, 2025 are exempt from vehicle purchase tax, of which the tax exemption for each new energy passenger vehicle does not exceed 30,000 yuan; The vehicle purchase tax will be halved for new energy vehicles purchased between

January 1, 2026 and December 31, 2027, of which the tax reduction for each new energy passenger vehicle shall not exceed 15,000 yuan and the policy will be extended until the end of 2027.

2. Charging infrastructure construction: The Chinese government has issued the Guiding Opinions on Further Building a High-Quality Charging Infrastructure System, aiming to basically build a high-quality charging infrastructure system with extensive coverage, moderate scale, reasonable structure and perfect functions by 2030.

3. New Energy Vehicles in the Countryside and Rural Revitalization: China's National Development and Reform Commission and the National Energy Administration have formulated the Implementation Opinions on Accelerating the Construction of Charging Infrastructure to Better Support the Revitalization of New Energy Vehicles in the Countryside and Rural Revitalization, so as to moderately advance the construction of charging infrastructure, support the purchase and use of new energy vehicles in rural areas, and strengthen the service management of new energy vehicles in rural areas.

4. Automobile consumption promotion activities: According to the "2023 Consumption Promotion Year" activity arrangement, the Ministry of Commerce will organize and carry out automobile consumption promotion activities, among which, the launching ceremony of the "Thousands of Counties and Towns" new energy vehicle consumption season will be organized in the near future, and guide all localities to carry out various forms of new energy vehicle consumption promotion activities such as new energy vehicle "caravans" into rural areas in more than 1,000 counties (districts) and more than 10,000 towns (townships) across the country.

In 2024, China will set an annual subsidy limit of 2 million units for the first time. In addition, China has also extended the purchase tax exemption policy for new energy vehicles from the original date of the end of 2023 to the end of 2027. These policies significantly promote the development of the new energy vehicle industry and expanding consumption.

Encouraged by a series of subsidy policies by the Chinese government, the new energy vehicle industry has continued to develop and achieve continuous progress in new energy vehicle technology. Under the regulation of the market and the government, the scale of China's new energy vehicle industry has gradually expanded, the industrial structure has been gradually optimized, and the market scale and industrial competitiveness of independent brands have been continuously improved, achieving a global leading position. However, China has a vast territory, large differences in local resources, different energy advantages, and different manufacturing capacities, and the analysis of the whole life cycle of electric vehicles needs to be analyzed and studied. In addition, with the development of emerging technologies such as the Internet of Vehicles and autonomous driving, and the continuous breakthrough of the core three-electric technology, new energy vehicles, as the key technical direction of China's key development in the future, should form a more forward-looking strategic layout for industrial integration and development, and the related economic, energy and environmental benefit assessment of electric vehicles also need to be further developed and improved, so as to provide support for the life cycle environmental management of new energy vehicles and the green and low-carbon development of related industries.

3. Current Research Status

This chapter discusses energy and environmental impact studies for the life cycle of electric vehicles, from global trends to specific practices in China. It covers the development of the electric vehicle industry, life cycle assessment methods, and how these technologies can help alleviate the energy crisis and reduce environmental pollution. The discussions highlighted the importance of green technologies in driving sustainable mobility solutions and explored potential directions for future development of electric vehicle technology.

3.1 Electric vehicle Life cycle Energy and Environment research

This section provides a thorough investigation into the energy consumption and environmental impacts associated with electric vehicles (EVs) throughout their entire life cycle. The subsequent sub-chapters will explore various aspects of this research, starting with a focus on studies conducted in China, followed by an assessment of the life cycle energy consumption and emissions of motor vehicles, and concluding with an overview of the current state of electric vehicle life cycle assessment research.

3.1.1 Research on Energy and Environmental of EV in China

The global automotive industry is accelerating the transformation and development to electrification, the development route of new energy vehicle technology is becoming more and more mature, and the resource depletion and environmental impact problems caused by the rapid development of the new energy vehicle industry have gradually attracted attention. These industries play an important role in reducing carbon emissions and it is of great significance to construct an EV environmental benefit and cost evaluation system for the green and sustainable development of EVs.

In the study of the climate and health impacts and social costs of replacing fuel vehicles with electric vehicles, Hu Yuhan et al. [13] directly estimated the marginal changes in the environmental-health-economic costs brought about by replacing a gasoline vehicle with a pure electric vehicle (referred to as "bicycle substitution") and the corresponding social net benefits. In the most conservative case, due to the impact of technological progress and changes in economies of scale, the manufacturing cost gap between the two vehicles is narrowing year by year, and the net social benefit of the whole life cycle of bicycle substitution will increase from −9855 yuan/year to −2797 yuan/year in 2020, and achieve positive social net benefits (about 2041 yuan/year) in 2025 [13].

Many scholars have also focused on the carbon emissions of the whole life cycle of new energy vehicles. Regarding the life cycle assessment of BEVs, Qiao et al [14]. compared the life cycle carbon emissions of BEV and ICEV manufacturing processes in China from three aspects: different components, materials and energy consumption, and the life cycle carbon emissions of BEV production (in terms of CO2-eq) were 15.0~15.2 t, which was 50% higher than that of ICEV. Wu et al. [15] found that the optimization of the power structure and the expansion of cogeneration can reduce the life-cycle carbon emissions of BEVs by 13.4% compared with ICEVs in 2020. Based on the real data, different scholars compared and evaluated lithium iron phosphate batteries, lithium manganese oxide batteries and ternary lithium batteries [16]. Regarding the carbon emissions of FCV life cycle assessment, different scholars have made quantitative evaluations under the key factors such as different hydrogen energy pathways, changes in vehicle heat load, carbon fiber manufacturing of hydrogen storage tanks, fuel cell decline, future vehicle sales and fuel cell power density [17]. Regarding the life cycle assessment of hybrid electrical vehicles (HEVs), Yang et al. [18]found that the life cycle carbon emissions of plug-in hybrid electric vehicles (HEVs) were lower than those of ICEVs, but the PM2.5 and SO2 emissions were higher than those of ICEVs.

Under the new development technology and future trend of China's electric vehicles, the domestic energy revolution, intelligent revolution and Internet revolution in 2022 will inject strong momentum into the innovation and development of automotive technology, cultivate and promote the rapid iterative development of automotive technology. The technical parameters of automobiles are constantly improving, and how to accurately calculate the economic, energy and environmental benefits of energy-saving and new energy vehicles under technological progress is an urgent need faced by China's automotive industry [19].

3.1.2 Life Cycle Energy Consumption and Emission Assessment of Motor Vehicles

The following sections provide an overview of the key components in vehicle life-cycle assessment: the Fuel life-cycle, which examines the energy and emissions from fuel production to usage; the Material life-cycle, focusing on the environmental impacts of vehicle material production and recycling; and the Integrated Vehicle life-cycle, which combines these aspects to assess the overall environmental footprint of vehicles throughout their lifetime.

（1）Fuel life-cycle

The application of life-cycle assessment (LCA) to motor vehicles emerged almost simultaneously with the introduction of the LCA concept. Early motor vehicle life-cycle assessments primarily focused on vehicle fuel, known as the "fuel cycle" or Well-to-Wheels (WTW) analysis. Following the oil crisis, scholars worldwide sought alternative fuels to gasoline and diesel, leading to the development of various fuel types. The energy efficiency comparisons among these petroleum-based, coal-based, and natural gas fuels cannot be simply based on the running stage (Tank-to-Wheels, TTW) fuel calorific value and combustion efficiency. Instead, attention must also be given to the upstream fuel production stage (Well-to-Tank, WTT), prompting scholars in the automotive field to turn to fuel cycle analysis. In the early 1990s, American scholar Delucchi completed WTW emission studies involving almost all fuels (including electricity) and gradually expanded to the field of automotive materials, beginning to consider the situations in other countries. This thinking profoundly influenced the later development of the GREET model by Argonne National Laboratory (ANL). The basic elements of the fuel cycle method are: 1) Studying multiple fuel pathways and the energy coupling relationships within them. 2) Evaluation indicators including energy consumption, greenhouse gas emissions, and pollutant emissions. 3) Clearly defined vehicle technology types with corresponding energy consumption rates and pollutant emission factors. The development of fuel cycle models has focused on optimizing these elements.

Currently, both domestic and international WTW evaluations have achieved simulations of multiple fuel pathways. Evaluation indicators have expanded from primary energy consumption and greenhouse gas emissions to include various conventional pollutants. Large automotive companies and governments use WTW results to strategize technological pathways. The basic conclusion is that while Battery Electric Vehicles (BEVs) can significantly reduce the demand for petroleum resources, their greenhouse gas and pollutant emissions are closely related to the upstream power structure. Plug-in Hybrid Electric Vehicles (PHEVs) produce different results depending on the proportion of pure electric coverage. Similarly, heavy vehicles (such as buses) should show comparable results. Early LCA studies on the electrification of buses were relatively few, with more research focused on diesel and fuel cell buses. Although buses have a low stock, their high energy consumption intensity and long operational mileage make the energy-saving and emission reduction potential of electric buses a growing topic of interest among scholars.

（2）Material life-cycle

The expansion of automotive LCA from the fuel cycle to the material cycle represents a deeper understanding of life-cycle issues. The process of evaluating the material life-cycle of automobiles is complex, involving numerous influencing parameters. ISO 14040 describes the framework for material cycle analysis, where the core parameter list includes upstream production paths for materials, vehicle composition profiles, and the manufacturing paths for automobiles and their components. Production or manufacturing paths encompass not only the material (blank) processing and shaping stages but also the energy consumption of each process. The process energy consumption is further calculated through the fuel cycle, accounting for the WTT (Well-to-Tank) stage's upstream energy production and emissions. The basic unit of the material cycle model is the unit process, which takes in energy and raw materials for the process, and outputs finished products and environmental waste. These processes are integrated through material flows, collecting overall energy and environmental inventories to form a material path. Materials are further integrated into components, vehicles, and the entire material cycle using composition profiles and the principle of mass conservation. The results of material cycle evaluations are significantly influenced by the design of research boundaries and the industrial production levels presented by the researchers. Therefore, dynamically updating databases is crucial for accurate material cycle analysis.

Research on the material life-cycle of power batteries focuses on three main issues: the comparison between different batteries, the battery manufacturing process, and regenerative manufacturing. These hot topics highlight the significant impact of research boundary selection on material life-cycle results. Energy consumption and emission comparisons between batteries show notable differences at both the unit battery and battery system levels. According to the ANL laboratory's battery energy consumption review, the average CO2 emission intensity for lithium-ion batteries, nickel-metal hydride batteries, and lead-acid batteries is 12.4, 13.6, and 3.2 kg/kg, respectively. Majeau-Bettez confirmed that various high-energy-density lithium-ion batteries can achieve energy consumption reductions at the vehicle level compared to nickel-metal hydride batteries, thereby gaining advantages in environmental assessment indicators.

The material life-cycle of batteries is mainly divided into two parts: upstream material manufacturing and battery manufacturing. Upstream material manufacturing is related to the battery composition profile and shows little variation for the same type of battery. However, the battery manufacturing part shows significant differences. For instance, in different studies, battery manufacturing can account for 25% to 65% of the fossil energy consumption in the battery material life-cycle. The discrepancies in battery manufacturing primarily stem from the debate over energy consumption allocation methods: "bottom-up" versus "top-down." The "bottom-up" approach, which considers only battery assembly, typically shows lower energy consumption intensity. In contrast, the "top-down" approach, which includes as many auxiliary processes as possible, shows higher energy consumption intensity. In reality, energy consumption does not disappear or increase due to different classification methods; it is the statistical boundaries that vary, introducing subjectivity into the material life-cycle analysis results.

The application of the material life-cycle model should not only achieve localized parameter settings but also localize the foundational database. Parameter localization is relatively common; whether for light vehicles or heavy vehicles, setting basic parameters for local vehicles and the energy and transportation characteristics of the study area allows for the direct output of evaluation result matrices and the assessment of parameter impacts. If the foundational database of the model is local, the results are more convincing. Merely modifying parameters without using a database that reflects local industrial characteristics is not sufficiently objective. For instance, in the energy consumption inventory for aluminum manufacturing, electricity accounts for over 50% in China, while natural gas accounts for nearly 70% in the United States. Previous WTW studies have shown that even if process energy intensity is the same, China's energy structure, with its high coal power ratio, significantly increases energy consumption and emissions. Therefore, material life-cycle studies without localization of upstream material databases will cause system bias.

The focus of localizing the automotive material life-cycle database is to establish a connection between the upstream material database and vehicles. China has already entered the practical application stage of material cycle analysis, completing numerous life-cycle assessments for automotive materials such as steel, aluminum, copper, and plastics. The output of these material data inventories is often raw parts such as profiles and ingots, which cannot be directly used for the automotive material life-cycle. Component manufacturing is the key link between upstream materials and vehicles. Past research has often focused on whole vehicle manufacturing while neglecting component manufacturing. Statistics from the "China Automotive Industry Yearbook" show that in 2013, the total energy consumption of component manufacturing enterprises in China exceeded that of whole vehicle enterprises, which cannot be ignored. Additionally, component manufacturing is more decentralized, with significant differences in the types and intensities of energy used for material processing, making it a challenging aspect of optimizing the material life-cycle model.

The scientific selection of automotive power systems is a crucial step in the development of the material cycle from the material to the entire vehicle level. In the current stage of material cycle analysis, both domestically and internationally, the selection of power systems often references technical parameters of a few mass-produced models or averages results after surveying similar models. These selections are often isolated. For example, designing a BEV with a smaller battery capacity but assuming no battery replacement throughout its lifespan is unrealistic given the current cycle life of batteries. Alternatively, using heavier battery modules to meet single-trip range requirements without assessing whether the increased weight meets the acceleration and top speed requirements is also problematic. If these evaluations are ultimately applied to decision-making, they could lead to contradictory results, indicating a lack of rigor. Therefore, regardless of whether it is for light vehicles or heavy vehicles, utilizing automotive dynamic equations and the power characteristics of motors and batteries can aid in the scientific selection and validation of automotive components, ensuring that the selected components meet the performance requirements of the vehicle, including acceleration, top speed, and range.

（3）"Vehicle Materials - Vehicle Fuels - Vehicle Operation" life-cycle

Integrating the material life-cycle with the fuel life-cycle forms the core of vehicle life-cycle assessment (LCA). Numerous life-cycle studies, both domestically and internationally, have shown that the fuel life-cycle predominantly influences the life-cycle results of light vehicles. This stage's energy consumption and CO2 emissions contribution rates typically exceed 70%, and for Internal Combustion Engine Vehicles (ICEVs), it can be as high as 85%. Even for Battery Electric Vehicles (BEVs), while the material life-cycle impact increases due to the battery, the Well-to-Wheels (WTW) results are still more efficient. The WTW stage can contribute over 70% of the total fossil energy consumption and CO2 emissions. However, these studies also indicate that the increased impact of the material life-cycle, particularly the battery, weakens the overall energy-saving and emission-reducing benefits of electric vehicles (EVs) during their life-cycle. In specific scenarios, EVs might even lose their energy-saving and emission-reducing advantages over ICEVs.

More importantly, mainstream life-cycle analyses often assume long vehicle driving distances and sufficiently long battery lifespans, which are strong parameter assumptions. Considering the fact that power batteries are high-energy-consuming components of EVs, these vehicles need to achieve cumulative energy and emission advantages progressively over increased total driving distances. This highlights that evaluating the life-cycle energy-saving and emission-reducing potential of EVs is a more objective process than merely considering the WTW fuel cycle. Such evaluation must include the transportation, energy, and technological characteristics of the regions where EVs are promoted.

3.1.3 Current Status of Electric Vehicle Life Cycle Assessment Research

In 1991, Mark A. Delucchi [22] conducted a "Cradle-to-Grave" life-cycle assessment of automobiles in the United States. The study indicated that when the fuel for automobiles is derived from coal, their greenhouse gas emissions increase. Conversely, if the electricity for battery electric vehicles comes from clean energy sources such as nuclear and solar power, the greenhouse gas emissions would be significantly reduced.

In 1994, Russell S. Cohn [23] used the life-cycle assessment method to study the environmental impact of electric vehicles in the United States. The study showed that compared to traditional gasoline vehicles, electric vehicles have the lowest emissions of CO, NO_x, and CO_2.

In 1995, Edgar Furuholt [24] used the life-cycle assessment method to evaluate the environmental impact of traditional gasoline, diesel, and gasoline containing methyl tert-butyl ether (MTBE) in Norway. He compared the potential impacts of the three types of gasoline. The study results indicated that diesel has a smaller environmental impact than gasoline, while gasoline containing MTBE has a greater environmental impact than traditional gasoline. This is primarily because the production of MTBE has significant environmental impacts. The largest emissions of NO_x and SO_2 occur during the raw material and fuel transportation stages.

In 1996，Elin Eriksson [25] studied the energy consumption and gas emissions of the life-cycle stages of Sweden's road transport sector. This included fuel production during the fuel stage, energy consumption during the driving stage, and the vehicle production, maintenance, and disposal stages. The study revealed that the environmental impact of road transportation mainly comes from the vehicle production, maintenance, and disposal stages.

In 1996, Volkswagen AG conducted a comprehensive life-cycle assessment of its Golf model [26] , including both the fuel cycle and the vehicle cycle. The fuel cycle begins with raw material extraction and ends with waste oil treatment, while the vehicle cycle spans from material production to the disposal stage, including shredding. This study provided a foundational inventory for subsequent automotive life-cycle assessments by scholars. Since then, Volkswagen AG has performed life-cycle assessments and produced reports for each new vehicle model it releases.

In 2000, the Massachusetts Institute of Technology (MIT) [27] conducted a comprehensive life-cycle assessment of five vehicle technology routes and three fuel routes. The evaluation scope included both the fuel cycle and the vehicle cycle. The fuel cycle covered the raw material stage and the vehicle driving stage, while the vehicle cycle spanned from raw material extraction to disposal and recycling. The study found that the hybrid electric vehicle (HEV) equipped with an internal combustion engine had the best overall life-cycle environmental benefits. It outperformed the HEV with a fuel cell in terms of greenhouse gas emissions and energy savings.

In 2001, General Motors (GM) [28] conducted a comprehensive "Well-to-Wheel" analysis of the environmental impacts of 15 vehicle technology routes and 13 fuel routes in the United States during their fuel cycles. The study revealed that the HEV had the lowest fuel cycle energy consumption when using crude oil and natural gas as fuel routes. The HEV using the hydrogen fuel route had the lowest greenhouse gas emissions, while the HEV using diesel-based fuel technology had the highest greenhouse gas emissions.

In 2007, Sanden B A [29] studied hydrogen-powered electric vehicles, introducing the concepts of the "rebound effect" and the "learning curve" to evaluate the environmental impact and cost of traditional gasoline vehicles versus hydrogen-powered electric vehicles. The study indicated that as electric vehicle technology improves and investment in technological research increases, the cost of electric vehicles will decrease, ultimately achieving energy-saving and emission-reducing goals.

In 2011, Kate S. [30] conducted a study using life-cycle assessment to analyze decision-making by automotive companies and governments. The research indicated that corporate and governmental decisions have an indirect impact on automotive energy consumption and gas emissions. Therefore, when evaluating the life-cycle of automobiles, it is necessary to consider the influence of activities by these entities.

In recent years, more scholars conduct comparative analyses of the energy consumption and environmental effects of traditional internal combustion engine vehicles (ICEVs) and new energy vehicles (NEVs) throughout the entire life-cycle. Early studies on vehicle life-cycle assessment primarily focused on the fuel cycle, known as the "Well-to-Wheels" (WTW) analysis [31]. In these studies, most scholars concluded that electric vehicles (EVs) emit less carbon dioxide (CO_2) than ICEVs. Some research pointed out that in China, battery electric vehicles (BEVs) can reduce CO_2 emissions by 15% to 32% compared to gasoline internal combustion engine vehicles (GICEVs) [32].

Gerfried Jungmeier in his work [33] identified and described key issues in applying the LCA methodology to electric vehicles (EVs) and hybrid electric vehicles (HEVs), including battery production and lifespan, energy consumption during vehicle operation, electricity production and sources, and vehicle and battery disposal. Adriana Tintelecan in [34] highlighted the crucial role of electric vehicle technology in sustainable transportation. The work categorized EVs into subsystems and, for the first time, analyzed permanent magnets in electric motors. Additionally, Adriana Tintelecan in [35] reviewed articles on life-cycle impact assessment methods for EVs or their components (batteries, electric motors, etc.). The research indicated that the type of energy consumption in EVs is the most significant environmental impact factor. While components such as batteries, motors, and electronic devices also affect the environment, their impact is considerably less than that of the energy consumption type. Nickel-metal hydride (NiMH) batteries were found to be more polluting than lithium batteries, suggesting that future research should focus on lithium batteries. Finally, the study concluded that transitioning from ICEVs to electric or hybrid vehicles is particularly beneficial for addressing global warming and fossil fuel consumption issues.

The extension of automotive life-cycle assessment from the fuel cycle to the full life-cycle, including the material cycle, represents a further deepening of understanding in life-cycle evaluation. The Well-to-Wheels (WTW) method underestimates the full life-cycle emissions of vehicles and the differences in material cycle emissions between various types of vehicles. The full life-cycle assessment method effectively addresses these issues. From a global perspective, research results vary across different countries. Hawkins et al. [40] suggested that if the life-cycle driving distance is 150,000 km, the Global Warming Potential (GWP) of electric vehicles using European electricity is 10% to 24% lower than that of gasoline vehicles. Another study from Europe reached a similar conclusion: within a 200,000 km driving distance, the GWP of electric vehicles is significantly lower than that of internal combustion engine vehicles (ICEVs) [41] . Additionally, with wind power, the CO_2 emissions of BEVs and PHEVs are 42 g/km and 33 g/km, respectively, while similarly equipped gasoline sport utility vehicles (SUVs) emit 225 g/km. Souza et al. [42] found that in Brazil, the CO_2 emissions of BEVs and GICEVs are 151 g/km and 291 g/km, respectively. Karaaslan et al. [43] reported that in the United States, over a 200,000 km driving distance, the GHG emissions of GICEVs and BEVs are 118 t CO_2e and 77 t CO_2e, respectively. Some scholars believe that in Italy, Poland, and the Czech Republic, electric vehicles emit less CO_2 than GICEVs [44] . However, a study focusing on Lithuania reached the opposite conclusion: with the 2015 electricity mix, BEVs produced 26% more greenhouse gases than GICEVs[45].

With the rapid development of electric vehicles, research on carbon emissions from electric vehicles in China has reached unprecedented levels of interest. Wu et al.

[46] compared the emission levels of GICEVs and BEVs from a full life-cycle perspective and found that in 2014, the life-cycle greenhouse gas emissions of GICEVs and BEVs were 35 t CO2e and 31 t CO2e, respectively, with 62% to 70% of the emissions coming from the vehicle operation stage. Qiao et al. [47] pointed out that the life-cycle greenhouse gas emissions of BEVs in 2015 were about 41 t CO2e, which is 18% lower than that of GICEVs. Zhou et al. [48] used the Tsinghua-LCAM model to evaluate the greenhouse gas emissions of BEVs, PHEVs, and ICEVs, and found that under the average power structure in China, the emission intensities of the three types of passenger cars were 206 g CO2e/km, 227 g CO2e/km, and 249 g CO2e/km, respectively. Similar to Zhou's research, Wu et al. [50] chose Chinese class A passenger cars as the research object, and the results were very close. Ou et al. [51] believed that compared to GICEVs, the life-cycle greenhouse gas emissions of coal-powered electric vehicles could be reduced by 3% to 36%. Shi et al.[52] compared the CO2 emissions of BEVs and GICEVs in Beijing and found that BEVs reduced CO2 emissions by 50% compared to GICEVs. Yang et al.[53] rgued that both BEVs and PHEVs reduce CO2 emissions compared to GICEVs, mainly due to the high efficiency of electric vehicles and the high fuel consumption of internal combustion engine vehicles. Wu et al.[54] suggested that in coal-dominated regions such as the Beijing-Tianjin-Hebei area, reducing carbon emissions is more challenging than reducing fossil energy use or oil consumption. He further noted that in regions with a high proportion of coal power, HEVs are more beneficial for reducing CO2 emissions during the operation phase compared to PHEVs and BEVs. Conversely, in regions with a high proportion of clean electricity, promoting electric vehicles can significantly reduce CO2 emissions. Wang et al. [55] believed that in terms of greenhouse gas emissions, the 2017 FCVs based on renewable energy electrolysis for hydrogen production performed the best, with emissions of 31 g CO2e/km, while FCVs based on grid electricity electrolysis performed the worst, with emissions of 431 g CO2e/km. Zhou et al.[48] compared the greenhouse gas emissions differences between electric vehicles (PHEVs and BEVs) and GICEVs in 2009, concluding that, at the national average level, BEVs and PHEVs can reduce emissions by 17% and 9%, respectively.

The evaluation of the life-cycle carbon emissions of electric vehicles can provide some references for the formulation and implementation of the automotive industry's "carbon neutrality" goals. However, there are still areas for improvement. Firstly, most existing studies focus on the national level, and the results are not sufficiently instructive for regions with distinct characteristics. There is a need for more in-depth and detailed studies at the provincial level. Secondly, there is no definitive conclusion on the current and future emission reduction potential of electric vehicles. The main reason is that different studies use different vehicle models, most of which are not very representative. It is necessary to adjust some parameters according to China's actual conditions. Lastly, the power structures used in existing studies are relatively uniform. It is necessary to set multiple scenarios for research to propose targeted policy recommendations. Furthermore, current research pays relatively little attention to fuel cell vehicles, which may be related to the development stage of fuel cell technology. However, as a technology with significant future potential, it is necessary to include it in the research framework.

3.2 Research Significance

This section explores how the growing energy demands of the automotive sector and the environmental pressures caused by traditional vehicles underscore the need for alternative solutions, such as electric vehicles (EVs). The following sub-chapters will delve into the specific issues of the energy crisis and environmental degradation, examining how these factors drive the necessity for innovation in the automotive industry.

3.2.1 Energy Crisis Leading to Automotive Energy Shortages

The rapid development of China’s automobile industry has created a significant demand for energy, highlighting the country’s dependency on oil as a primary fuel source. This increasing demand has intensified concerns about energy security and the sustainability of oil supply, particularly in the face of global uncertainties and market fluctuations. Addressing this dependency and enhancing energy diversification have become critical strategies for ensuring the long-term stability of China’s transportation sector. As the country moves towards a more automotive-driven society, the need to reduce reliance on traditional fossil fuels and seek alternative energy solutions is more pressing than ever.

3.2.2 Environmental Pressure Caused by Automobiles

Automobiles are a major contributor to environmental degradation, which extends beyond emissions, encompassing the entire life-cycle of vehicle production, operation, and disposal. As the global automotive industry transitions towards cleaner technologies, such as electric vehicles, efforts to mitigate the environmental footprint of vehicles are gaining momentum. The adoption of more sustainable vehicle technologies will be essential in addressing the environmental challenges posed by traditional automotive systems.

4. Research Methods

Life cycle assessment (LCA) and GREET models are adopted to assess the environmental footprint and energy use of electric vehicles throughout their life cycle from raw material extraction to end-of-life treatment in the first two sections. The third part describes the objectives, scope and key evaluation indicators of EV life cycle assessment, and defines the precise boundary conditions. The fourth section provides a solid basis for ensuring the accuracy and reliability of our assessment results by presenting the specific data for EV life-cycle stage.

4.1 Life Cycle Assessment Method (LCA Model)

The following sub-chapters will discuss the analytical framework of Life Cycle Assessment (LCA), introduce the comprehensive life cycle model specifically for electric vehicles, and explore the life cycle cost analysis of EVs. These components together provide a robust approach to understanding the full range of impacts associated with EVs from production through disposal.

4.1.1 Analytical Framework of LCA

1. Goal and Scope Definition

Defining the goal and scope is the beginning and a crucial step in LCA. The "goal" involves clearly specifying the questions that the Life Cycle Assessment aims to answer. The "scope" describes the functional unit of the product, the system boundaries, and the assumptions made. Additionally, the breadth and depth of the study must be sufficient to meet the goal's requirements.

(1) Functional Unit

A system can have multiple functions simultaneously. In the study, functions are selected by defining the purpose and scope of the LCA. The functional unit quantifies the chosen product function. The primary purpose of the functional unit is to provide a standardized measure for related inputs and outputs. When performing LCAs on different systems, the functional unit establishes a common basis, ensuring comparability of the LCA results across different systems.

(2) System Boundaries

LCA involves simulating the product system by creating a model that includes significant factors of the physical system. The purpose of defining system boundaries is to determine the unit processes included within the product system. While theoretically, all inputs and outputs at the boundary should be considered as basic flows, in practice, inputs and outputs that have a negligible impact on the overall study results can be omitted. In theory, the following stages and unit processes should be considered when setting system boundaries: Raw material acquisition, Inputs and outputs of major manufacturing processes, Transportation and distribution, Fuel production and use, Product use and maintenance, Waste disposal, Product end-of-life and recycling, Production of auxiliary substances, Production, maintenance, and disposal of used equipment.

2. Inventory Analysis

Inventory analysis is the expression of basic data in LCA and serves as the foundation for life cycle impact assessment. The process of building an inventory involves establishing the system inputs and outputs corresponding to the functional unit for each unit process within the defined product system. Inventory analysis quantitatively analyzes the resources and energy consumption, as well as the environmental emissions, associated with a product, process, or activity throughout its entire life cycle. It begins with raw material extraction, and till the final consumption and disposal of the product. The system is delineated by its boundaries, separating it from the surrounding systems. All areas outside these boundaries are referred to as the system environment, which act as the inputs to the system and the sink for all outputs from the system.

The steps of inventory analysis is a continuous and iterative process, involving reviewing and collecting data, linking the data to the unit processes, and associating the data with the reference flows of the functional units. Finally, the inventory results for each unit process and functional unit within the product system are obtained. When calculating energy flows, it is important to consider different fuels or power sources, energy conversion, transmission efficiency, and the inputs and outputs associated with the generation and use of these energy flows.

3. Impact Assessment

Impact assessment is sometimes also referred to as result interpretation. List analysis inventories the material, energy, and environmental exchanges (all inputs and outputs) throughout the entire life-cycle of a product, of which the results are then applied to various decision-making processes through life-cycle assessment. Impact assessment involves interpreting the potential impacts of these material and energy exchanges, analyzing each life-cycle stage of the production or service system to identify sensitivity factors, recording their impact indicators, and explaining the relative importance of various exchanges as well as the contribution of each production stage.

4. Improvement Analysis

The purpose of improvement analysis is to analyze the results, draw conclusions, interpret limitations, provide recommendations, and report the results of life-cycle interpretation in a transparent manner, based on the studies from the previous LCA stages and the results of the inventory analysis. It aims to provide a clear, comprehensive, and consistent explanation of the LCA study results. This involves a systematic procedure of identifying, determining, examining, evaluating, and drawing conclusions based on the findings of the LCA study to meet the application requirements specified in the study's purpose and scope. The entire interpretation phase needs to be continuously repeated.

4.1.2 Full Life Cycle Model of Electric Vehicles

The LCA of electric vehicles can be divided into four main parts: vehicle production and distribution, electricity and gasoline production and distribution, energy conversion and vehicle maintenance during the usage phase, and the end-of-life (EOL) phase.

For different types of EV technologies, the vehicle components also differ. The battery of a BEV is equivalent to the fuel tank of a GICEV, the wiring is equivalent to the fuel lines of a GICEV, and the traction motor is equivalent to the internal combustion engine (ICE) of a GICEV. In some cases, EV may require battery replacements. The stages of raw material extraction, processing, and manufacturing apply to all automotive components.

When evaluating the usage phase of a vehicle, it is necessary to consider driving patterns to determine electricity and fuel consumption, for example, the frequency and depth of battery cycles are important factors in determining battery life and efficiency. Additionally, the energy consumption requirements of a vehicle largely depend on the load, such as passengers or cargo. Vehicle maintenance must also be included in the usage phase. The supply during the usage phase includes electricity and gasoline, and the LCI should encompass material extraction, processing, transportation, and distribution related to these energy sources.

The end-of-life phase plays a crucial role in the LCA results of EV. Previous studies have typically evaluated the reduction in environmental impact during the material production phase by using recycled materials. However, understanding the feasibility of material recycling and the degradation properties of materials is also important. Given current material prices, not all battery materials can be reused in batteries. In most cases, materials are downgraded to other applications where the environmental impact of material production is much lower than that of the corresponding EV components.

The fuel chain of the full life-cycle of an electric vehicle includes the following processes and stages: acquisition and processing of raw materials such as crude oil and coal, storage and transportation, gasoline refining and electricity production, transportation and distribution, and consumption during the vehicle operation phase. The full life-cycle fuel chain of an electric vehicle includes the following processes and stages: raw material acquisition and refining, material processing and manufacturing, production of automotive components, vehicle assembly, maintenance during the usage phase, and vehicle disposal and recycling. All the formulas used in this work are derived from the research presented in[57].

(1) Fuel Chain

The fuel chain for transportation fuels covers the following processes: primary energy/raw material production, transportation and storage, fuel/energy production, transportation, storage, and distribution, as well as fuel combustion and conversion during the vehicle operation phase. The processes before the vehicle operation phase are typically defined as upstream activities, while the vehicle operation phase is defined as downstream activities. The fuel chain, as one of the important components of the full life-cycle of an automobile, serves as the foundation for vehicle chain research. This work first analyzes the algorithm of the fuel chain for electric vehicles.

To analyze the algorithm of the fuel chain, the vehicle operation phase, also known as the Well-to-Pump (WTP) phase, is usually referred to as the downstream phase. All stages before the vehicle operation phase (raw material production and transportation, and product fuel production and distribution) are collectively referred to as the upstream phase.

1. Upstream Phase (WTT) Algorithm Analysis

(1) Calculation of Direct Energy Consumption for Any Unit Process in the Upstream Phase

To analyze the algorithm for the upstream phase of the fuel chain, this work introduces the term "Unit Process," which is defined as the smallest unit for data collection during life-cycle inventory analysis [57].

$$\eta^a = E_{out}/E_{in} \tag{1}$$

$$E_{in}^a = 1/\eta^a \tag{2}$$

$$E_{in}^a = E_{feed}^a + E_{process}^a \tag{3}$$

Among them:

a : Any unit process in the upstream phase of the fuel chain(dimensionless);

E_{out}: Energy of the product output from any unit process a in the upstream phase (g/MJ);

E_{in}: Total energy input required to produce the output energy E_{out} for any unit process a in the upstream phase (g/MJ);

E_{in}^a Total energy input required per unit of energy product output for any unit process a in the upstream phase, i.e., total energy consumption (MJ/MJ);

η^a : Energy efficiency of any unit process a in the upstream phase(dimensionless);

E_{feed}^a: Energy of the feed stock required for any unit process a in the upstream phase (g/MJ);

$E_{process}^a$: Energy required for the process fuel in any unit process a in the upstream phase (g/MJ).

From Equation (10), the total energy input for the process can be calculated. The total energy input consists of two parts: feed stock energy and process fuel. In most cases, feed stock energy can serve both as the primary material for fuel production and as the process fuel used during production. To calculate emissions, especially conventional emissions, it is necessary to distinguish between feed stock/primary material and process fuel within the total feed stock energy input. The conversion of feed stock/primary material to fuel products is often a chemical process that may or may not produce emissions, while the combustion of process fuel inevitably produces emissions which is estimated based on the quantity of process fuel burned and the corresponding combustion emission factors of the equipment used.

The quantity of process fuel can be calculated using the following formula [57]:

$$E_{process}^{a} = 1/\eta^{a} - 1 \tag{4}$$

Among them:

$E_{process}^{a}$ refers to the energy of the process fuel required to produce a unit energy product in any unit process *a* (MJ/MJ);

η refers to the energy efficiency of unit process *a*(dimensionless).

The total consumption of process fuels calculated for a certain stage needs to be allocated among the various types of process fuels consumed at that stage. The process fuels considered in this study include coal, crude oil, natural gas, residual oil, diesel, gasoline, and electricity. When calculating emissions for a certain stage, it is necessary to allocate the total amount of process fuel consumed at that stage to the different types of process fuels consumed. The combustion emissions largely depend on the type of process fuel burned. In this study, the shares of various process fuels are primarily based on statistical data on the types of process fuels used in the fuel production process, as reported by the National Bureau of Statistics [49].

The energy consumption of any unit process in the upstream phase is calculated according to Equations (1) and (4). The relationships between unit processes are established based on the conservation of carbon atom mass, as shown in Equation (5) [57]:

$$MC_{out}^{a} = MC_{in}^{a} = MC_{out}^{a-1} \tag{5}$$

Among them:

MC_{out}^{a}: Carbon content in the output energy product of unit process *a*(g/MJ);

MC_{in}^{a}: Carbon content in the input feed stock energy of unit process *a*(g/MJ);

MC_{out}^{a-1}: Carbon content in the output energy product of the previous unit process *a*-1(g/MJ).

(2) Calculation of Direct Emissions for Any Unit Process in the Upstream Phase

In this study, the emissions of gases such as VOC、CO、NO、SO_2、PM10、CH、N_2O、CO_2 during the upstream phase of the fuel chain, originating from the combustion of process fuels and non-combustion processes such as chemical reactions, fuel leaks, and evaporation, are calculated in units of g/MJ of fuel output. Non-combustion emissions resulting from chemical reactions, fuel leaks, and evaporation are related to the type of fuel and the stage of the process.

For any unit process a, the emissions from the combustion of process fuels depend on the type of process fuel, the amount consumed, and the equipment used. The emissions of substance i from the combustion of process fuels can be calculated using the following formula [57]:

$$EM_{c,i}^{a} = \sum_{j}\sum_{k} EF_{i,j,k} * E_{process,j,k}^{a} \tag{6}$$

$$E_{process,j,k}^{a} = E_{in}^{a} * \alpha_j * \beta_{k,j} \tag{7}$$

Among them:

$EM_{c,i}^{a}$: Emissions of combustion pollutant i from any unit process a(g/MJ);

$EF_{i,j,k}$: Emission factor of pollutant i for process fuel j used in energy device k (g/MJ);

$E_{process,j,k}^{a}$: Consumption of process fuel j in energy device k for any unit process a (g/MJ);

E_{in}^{a}: Total energy consumption for unit process a (MJ/MJ);

α_j : Proportion of total process fuel consumption that is process fuel j(dimensionless);

$\beta_{k,j}$: Proportion of energy device k among all devices consuming process fuel j(dimensionless).

In this study, the emission factors of SO_2 and CO from process fuel combustion in different energy devices are calculated based on the mass conservation laws of sulfur (S) and carbon (C) elements. It is assumed that all sulfur in the process fuel is converted into SO_2, as shown in Equation (8). The specific calculation formula for the emission factor of SO_2 from process fuel combustion is as follows [57]:

$$S + O_2 \rightarrow SO_2 \tag{8}$$

$$EF_{SO_2,j} = D_j * LHV_j * r_{s,j} * 64 \div 32 \tag{9}$$

Among them:

$EF_{SO_2,j}$: Emission factor of SO_2 for the combustion of process fuel j (g/MJ);

D_j: Density of process fuel j (g/Lfor liquid fuels, g/m³ for gaseous fuels);

LHV_j: Lower heating value of process fuel j (MJ/L for liquid fuels, MJ/m³ for gaseous fuels, MJ/ton for solid fuels);

$r_{s,j}$: Sulfur mass ratio in process fuel j;

64: Molar mass of SO_2;

32: Molar mass of sulfur.

In this study, the emission factor of CO_2 from the combustion of process fuels is calculated using the mass conservation method for carbon elements. Since VOC, CO, and CH_4 emissions produced during the combustion of process fuels contain carbon atoms, it is necessary to subtract the carbon atoms in these emissions when calculating the CO_2 emission factor. The calculation formula is as follows [57]:

$$C + O_2 \rightarrow CO_2 \tag{10}$$

$$EF_{CO_2,j,k} = [D_j * LHV_j * r_{c,j} - (E_{voc,j,k} * 0.85 + EF_{CO,j,k} * 0.43 + EF_{CH_4,j,k} * 0.75)] * 44 \div 12 \tag{11}$$

Among them:

$EF_{CO_2,j,k}$: Emission factor of CO_2 for the combustion of process fuel j in combustion device k (g/MJ);

D_j: Density of process fuel j (g/L for liquid fuels, g/m³ for gaseous fuels, MJ/ton for solid fuels);

LHV_j: Lower heating value of process fuel j (MJ/L for liquid fuels, g/m³ for gaseous fuels, MJ/ton for solid fuels);

$r_{c,j}$:Carbon mass ratio in process fuel j(dimensionless);

$E_{voc,j,k}$: Emission factor of VOC for the combustion of process fuel j in combustion device k (g/MJ);

0.85: Average carbon mass ratio in VOC emissions(dimensionless);

$EF_{CO,j,k}$: Emission factor of CO for the combustion of process fuel j in combustion device k (g/MJ);

0.43: Carbon mass ratio in CO emissions(dimensionless);

$EF_{CH_4,j,k}$: Emission factor of CH_4 for the combustion of process fuel j in combustion device k (g/MJ);

0.75: Carbon mass ratio in CH_4 emissions(dimensionless);

44: Molar mass of CO_2 (g/mol);

12: Molar mass of carbon (g/mol).

The GHG emission factors are expressed in CO_2-equivalent (CO_2-eq) based on the 100-year Global Warming Potentials (GWPs) for CO_2, CH_4, and N_2O published by the Intergovernmental Panel on Climate Change (IPCC). The calculation formula is as follows [57]:

$$EF_{GHG} = EF_{CO_2} * 1 + EF_{CH_4} * 25 + EF_{N_2O} * 298 \quad (12)$$

Among them:

EF_{GHG}: GHG emission factor, (g/MJ);

EF_{CO_2}: CO_2 emission factor, (g/MJ);

EF_{CH_4}: CH_4 emission factor, (g/MJ);

EF_{N_2O}: N_2O emission factor, (g/MJ);

1: Global Warming Potential (GWP) of CO_2;

25: GWP of CH_4 relative to CO_2;

298: GWP of N_2O relative to CO_2.

From Equations (9) and (11), it can be seen that calculating the emission factor requires knowing the specifications of the corresponding fuel, such as its lower heating value, fuel density, carbon mass ratio, and sulfur mass ratio.

Therefore, the direct emissions of any upstream unit process *a* are [57]:

$$EM_i^a = EM_{c,i}^a + EM_{nc,i}^a \quad (13)$$

Among them:

EM_i^a: Emissions of pollutant *i* from unit process *a* (g/MJ);

$EM_{c,i}^a$: Combustion emissions of pollutant *i* from unit process *a* (g/MJ);

$EM_{nc,i}^a$: Non-combustion emissions of pollutant *i* from unit process *a* (g/MJ).

(3) life-cycle Energy Consumption and Emissions of Any Process in the Upstream Phase

As analyzed above, the life-cycle energy consumption and emissions of any process in the upstream phase come not only from the consumption of process fuels within that process but also from the upstream life-cycle stages of those process fuels (such as production and distribution to the consumption site). Therefore, the life-cycle energy consumption and emissions of any process *a* in the upstream phase can be calculated using the following formula [57]:

$$EU_i^a = E_{in}^a + \sum_j (E_{up,in,j} * E_{process,j}^a) \quad (14)$$

$$EMU_i^a = EM_i^a + \sum_j (EF_{up,in,j} * E_{process,j}^a) \tag{15}$$

Among them:

EU_i^a: life-cycle energy consumption of process *a* for energy type *i* (MJ/MJ);

E_{in}^a: Direct energy consumption of process *a* for energy type *i* (MJ/MJ);

$E_{up,in,j}$: Upstream energy consumption of process fuel *j* (MJ/MJ);

$E_{process,j}^a$: Consumption of process fuel *j* in process *a* (MJ/MJ);

EMU_i^a: life-cycle emissions of pollutant *i* from process *a* (g/MJ);

EM_i^a: Direct emissions of pollutant *i* from process *a* (g/MJ);

$EF_{up,in,j}$: Upstream emissions of pollutant *i* from the production and distribution of process fuel *j* (g/MJ).

From Equations (14) and (15), it can be seen that when calculating the energy consumption and emissions in the upstream phase of the product fuel, the energy consumption and emissions of the process fuel's own upstream phase also need to be calculated. This constitutes a recursive iterative process.

(4) life-cycle Energy Consumption and Emissions in the Upstream Phase

Based on the above analysis, the life-cycle energy consumption and emissions of each process in the upstream phase can be summed to obtain the total energy consumption and emissions for the upstream phase of the fuel cycle, as shown in the following formula [57]:

$$E_{up} = \sum_a EU_i^a = \sum_a [E_{in}^a + \sum_j (E_{up,in,j} * E_{process,j}^a)] \tag{16}$$

$$EM_{up,i} = \sum_a EMU_i^a = \sum_a [EM_i^a + \sum_j (EF_{up,i,j} * E_{process,j}^a)] \tag{17}$$

Among them:

E_{up}: life-cycle energy consumption in the upstream phase of the fuel cycle (MJ/MJ);

$EM_{up,i}$: Mass of the i-th type of emissions in the life-cycle of the upstream phase of the fuel cycle (g/MJ);

The rest of the variables are the same as previously defined.

2. Algorithm Analysis for the Vehicle Operation Phase (PTW)

In this study, the energy consumption and emissions during the vehicle operation phase are calculated based on the vehicle traveling 1 km. The energy consumption at this stage is determined by the vehicle's fuel economy and the fuel's heating value [57]:

$$E_{op} = B * LHV * LS \tag{18}$$

Among them:

E_{op}: Energy consumption during the vehicle operation phase (MJ/km);

B: Vehicle fuel economy (L/100 km or kW/100 km);

LHV: Lower heating value of the fuel (MJ/L);

LS: Fuel loss rate during the vehicle operation phase(%).

The emissions of VOC, CO, NO_x, PM10, and PM2.5 at this stage are calculated based on the corresponding data for gasoline GICEVs from GREET1.2012, which is derived from the MOBILE6.2 data of the U.S. Environmental Protection Agency (EPA). The CO_2 and SO_2 emissions for various vehicle technologies are calculated based on the mass conservation of carbon (C) and sulfur (S) elements, respectively.

3. Vehicle Chain

The vehicle life-cycle includes the following processes: raw material acquisition, material processing and manufacturing, vehicle component production, vehicle assembly, maintenance, and vehicle disposal and recycling.

For ease of calculation, this study divides the impact sources of the entire vehicle production process into four parts: battery, vehicle body (Glider, which includes all other components), fluids, and vehicle assembly.

The energy consumption and emissions of the vehicle chain come from the following seven groups: battery, car body (Glider, other parts except batteries), fluids, vehicle assembly, distribution and distribution, vehicle maintenance and scrap recycling. For each material, calculate its energy consumption (MJ/kg product) and emissions (g/kg) in the order of: raw material acquisition and processing - material processing and manufacturing - final product delivery, that is, embedded energy (Embodied energy) and embedded emissions (Embodied emissions). Embedded energy means the total energy consumption in the product production chain (from raw material acquisition, processing, transportation, etc.). Embedded emissions refer to the total emission value of a product’s production chain. Embedded energy and embodied emissions serve as input data for these seven groups.

The battery pack includes material production and processing of starting batteries and power batteries. The fluid group includes the production and processing of coolant, engine oil, wiper fluid, steering fluid, brake fluid and transmission fluid. The vehicle assembly group includes vehicle assembly, painting and other processes. The maintenance phase during the vehicle life cycle only considers the environmental impact caused by the replacement of parts and fluids during the vehicle life cycle, which includes two parts: one is caused by the production of these replaced parts, and the other is caused by the replacement process; and the latter is very is small and is ignored in this article. The end-of-life end-of-life group includes end-of-life processing and recycling. Energy consumption and emissions for various activities within these seven groups (including fuel combustion and specific processes) need to be calculated.

This article assumes that the final step in the production process of various materials is the processing and shaping of automotive parts. According to the energy consumption factor and emission factor of the material production process (i.e., embedded environmental impact factor), the corresponding environmental impact of the automobile parts production process can be calculated. From this, the calculation formula for the vehicle cycle environmental impact can be derived as follows:

(1) Main automobile production

This article puts other automotive parts except batteries and fluids into the same group, called the main body of the vehicle.

As one of the main components of electric vehicles, motors are mainly composed of steel, cast aluminum and copper. Research shows that the environmental impact of the life cycle of electric vehicle motors is mainly related to materials and weight. Therefore, this study classifies it as the main body of automobiles. to facilitate subsequent research [57].

$$E_{V1,e} = \sum_{t} (M_{V1,t} * F_{t,e}) \tag{19}$$

Among them:

e: The e-th type of environmental impact(kg CO_2-eq);

$F_{t,e}$: Environmental impact factor of the t-th material for the e-th type of environmental impact(kg CO_2-eq);

$M_{V1,t}$: Mass of the t-th automotive material in the vehicle body(kg);

$E_{V1,e}$: Amount of the e-th type of environmental impact caused by the production of the vehicle body(kg CO_2-eq).

The rest of the variables are the same as previously defined.

(2) battery production

The calculation formula for the environmental impact of the battery production process is as follows [57]:

$$E_{V2,e} = E_e^{Bs} + E_e^{Bp} \tag{20}$$

Among them:

Bs: Starter battery(kWh);

Bp: Power battery(kWh);

E_e^{Bs}: The *e*-th environmental impact caused by the production of the starter battery(kg CO_2-eq);

E_e^{Bp}: The *e*-th environmental impact caused by the production of the power battery(kg CO_2-eq);

$E_{V2,e}$: The *e*-th environmental impact caused by the production of electric vehicle batteries(kg CO_2-eq).

(3) Production of Automotive Fluids

In this study, automotive fluids mainly include engine oil, brake fluid, transmission fluid, powertrain coolant, windshield washer fluid, and additives. Since current GICEVs and HEVs generally use electric power-assisted steering systems without fluid, power steering fluid is not included in the automotive fluids in this work. The calculation for the environmental impact of fluid production is as follows [57]:

$$E_{V3,e} = \sum_t E_{t,e}^{V3} \tag{21}$$

Among them:

$E_{t,e}^{V3}$: The *e*-th environmental impact caused by the production of the t-th type of automotive fluid(kg CO_2-eq);

$E_{V3,e}$: The e-th environmental impact caused by the production of fluids(kg CO_2-eq).

(4) Assembly Process of Electric Vehicles

The assembly process mainly includes: paint production and coating, HVAC and lighting assembly, heat treatment, material handling and welding, compressed air, etc. For different vehicle types (GICEV, HEV, PHEV, and BEV), the energy consumption of each process in the vehicle assembly process is proportional to the mass. The environmental impact of the assembly process is recorded as $E_{V4,e}$。

(5) Distribution and Delivery

After the vehicles leave the factory, they need to be delivered to distributors, of which process the environmental impact is proportional to the mass, and the environmental impact of the delivery process is recorded as $E_{V5,e}$。

（6）Vehicle Maintenance

The environmental impact of the vehicle maintenance process is denoted as $E_{V6,e}$, in this text. Only the environmental effects caused by the production of the replaced parts during this stage are considered. These environmental impacts can be calculated based on the analysis of the vehicle parts production stage and the replacement checklist.

（7）Scrap Processing Stage

The main steps of vehicle scrapping include disassembly, cutting, separation, and transportation to the landfill. Due to the significant environmental impact of vehicle battery scrapping, this work separately investigates the environmental impacts of both the vehicle body and the scrapping process of vehicle batteries. The environmental impact of the scrapping process is denoted as $E_{V7,e}$. This study only considers the final scrapping and recycling of vehicle batteries when the vehicle is scrapped, without considering the replacement batteries.

The first step in vehicle life cycle assessment is to evaluate the weight of vehicle components. The second step involves considering the material composition of major components in the vehicle life cycle model. The third step involves creating a replacement checklist for components that need to be replaced during the vehicle's lifespan. In the fourth step, for the scrap processing and recycling stage, this work considers the energy requirements and gas emissions generated during the recycling of waste materials back into raw materials. Finally, energy consumption estimates from raw material acquisition to vehicle assembly processes (such as iron ore mining and processing into stamped steel plates) will be used in the vehicle life cycle simulation.

Based on the above analysis, the total environmental impact of the vehicle cycle can be obtained [57].

$$VC_e = \frac{\sum_{i=1}^{7} E_{Vi,e}}{d} \tag{22}$$

Among them:

VC_e:The e-th environmental impact amount under the vehicle cycle functional unit(kg CO_2-eq);

$E_{Vi,e}$: The e-th environmental impact amount of each component of the vehicle chain, including vehicle body (V1), battery (V2) fluid (V3), vehicle assembly (V4), distribution, distribution and transportation (V5), Maintenance (V6), scrap processing (V7);

d : Vehicle life mileage(km).

4. Car life cycle

Combining the environmental inventory results of the fuel cycle with the inventory results of the vehicle cycle, the environmental impact results under the functional unit of the vehicle's full life cycle (each vehicle travels per kilometer) can be obtained. The formula is as follows [57]:

$$T = \big((r_1+r_2) * UF\big) + \big((b_1+b_2) * (1 - UF)\big) + VC \tag{23}$$

Among them:

r_1: Environmental impact in the upstream stage of power generation(kg CO_2-eq);

r_2: The environmental impact of the downstream stage of electricity, that is, the vehicle driving stage(kg CO_2-eq);

b_1: Environmental impact of the upstream stage of gasoline(kg CO_2-eq);

b_2: Environmental impact in the downstream stage of gasoline and vehicle driving stage(kg CO_2-eq);

VC: Environmental impact of vehicle chains(kg CO_2-eq);

UF: Utility factor, which refers to the average mileage of a PHEV driven in pure electric mode as a percentage of the total mileage(dimensionless);

4.1.3 Life cycle cost analysis of electric vehicles

(1) Purchase cost

The purchase cost is the cost that consumers need to spend in the short term or once when purchasing an electric vehicle. It consists of two parts: the purchase price of an electric vehicle and the related expenses incurred during the purchase process. The purchase price of electric vehicles is the cost that consumers pay to car manufacturers to buy electric vehicles. The costs generated in the purchase process are mainly used to support consumers to use the purchased cars smoothly, including vehicle transportation costs, vehicle quality inspection fees and license plate purchase fees. Its calculation model is shown in equation (24) [58]:

$$CA = P + C \tag{24}$$

Among them,

CA: The total cost of acquiring the vehicle(CNY);

P: The initial price of the vehicle(CNY);

C: The additional costs involved in the purchase process(CNY).

(2) Use cost

Usage costs occur after the consumer has purchased the car, and it is mainly used to support the daily running of the electric vehicle. The operating cost includes two parts: the operating cost and the vehicle maintenance cost, of which the operating cost is mainly the charging cost, depending on the electricity price and mileage, the vehicle maintenance cost includes the vehicle maintenance and maintenance costs, and the use cost accounts for a relatively high proportion of the life cycle cost of electric vehicles, generally between 50% and 60%. The calculation logic of the use cost of electric vehicles is to calculate the operating cost and vehicle maintenance cost respectively, and then sum up to form the calculation formula of the use cost, as shown in equation (25) [58].

$$CM = CO + CM1 + CM2 \tag{25}$$

Among them,

CM: The overall cost of the vehicle, including operating and maintenance costs(CNY);

CO: The cost of operating the vehicle(CNY);

CM1: The cost associated with maintaining the vehicle's battery(CNY);

CM2: The cost associated with general maintenance for the electric vehicle(CNY).

(3) Operating costs

The operating costs of electric vehicles include two parts: charging costs and battery costs, and formula (26) is its calculation models [58]:

$$CO = D_{CD} * L/T \tag{26}$$

Among them,

CO: operating cost;

D_{CD}: unit charge electricity price (yuan/KWH);

L: vehicle charge per 100 kilometers (degrees);

T: Battery charging efficiency.

(4) Maintenance costs

The calculation of vehicle maintenance costs is to calculate battery maintenance costs and other parts maintenance costs separately. Battery maintenance is key. Battery reliability mainly depends on the efficient operation of the power battery, and only the efficient operation of the battery can provide enough kinetic energy to ensure the effective work of the electric vehicle. The power battery of the BYD series of electric vehicles studied in this work is guaranteed for life, so the maintenance cost of its battery can be ignored, and only the maintenance cost of other components can be considered.

(5) scrap disposal cost

The Cost of Disposal and Recycle (CDR) mainly refers to the cost of various disposal activities after the electric vehicle has been scrapped due to its service life. When consumers scrap electric vehicles, they will have a certain amount of equipment residual value recovered, which can be used to make up for the relevant expenses paid for scrapping. Therefore, the scrapping cost accounts for a relatively small proportion of the total cost of electric vehicles. In the calculation model of electric vehicle scrapping disposal cost, as shown in Formula 27, scrapping disposal cost and recovery equipment salvage value are regarded as an overall cost CDR [58].

$$CDR = (CA - CS)/R \tag{27}$$

Among them,

CDR: The cost associated with scrapping or recycling the vehicle(CNY);

R: The total distance driven before scrapping, typically measured in 10,000 kilometers (km);

CA: The initial purchase price of the vehicle(CNY);

CS: The residual value recovered at the time of scrapping (CNY).

(6) Environmental cost analysis

The production stage, driving stage and scrapping stage of electric vehicles will produce materials that cause damage to the environment, aggravate environmental pollution and ecological damage, and the cost paid to compensate for this series of environmental pollution and damage is called environmental cost. There are always environmental costs in the life cycle of a car. The environmental costs borne by consumers are mainly incurred during the vehicle use phase. Since the power of traditional gasoline vehicles is fossil fuels, it will produce a large number of environmental pollutants during the driving process, while the power of electric vehicles is electric energy, and the emission of polluting gases during the driving process is much smaller than that of traditional gasoline vehicles, so the environmental cost that consumers have to bear when buying traditional gasoline vehicles is significantly higher than the purchase of electric vehicles.

Environmental costs take the form of energy and environmental taxes levied on consumers and car producers. Some countries have begun to levy environmental taxes and energy taxes on personal vehicles, including not only carbon dioxide and sulfide emissions, but also engine oil. The purpose of levying energy tax and environmental tax is to achieve energy conservation and emission reduction of polluting gases. The environmental tax is mainly levied on car manufacturers, but the car manufacturers will pass the increase in the cost of the environmental tax to the car consumers, which will make the car purchase price of consumers. It can be said that the collection of energy tax and environmental tax will increase the cost of car consumers. Since China has not yet implemented the collection of energy tax and environmental tax, this work uses Denmark's relevant measures on energy tax collection to build an environmental cost model, as shown in equation (28) [58].

$$CE = r * N \tag{28}$$

Among them,

CE: The total environmental cost associated with fuel consumption (CNY).

r: The tax rate applied to fuel or energy use, typically expressed in currency units per unit of fuel consumed (CNY).

N: The amount of fuel consumed per 100 kilometers (in liters per 100 kilometers, L/100 km).

Since the power source of pure electric vehicles is electric energy, there is no pollution gas emissions during the vehicle driving, so there is no need to consider environmental costs. Noise pollution from electric vehicles and conventional gasoline vehicles is not considered in this work.

Electric vehicle life cycle cost model, such as equation (does not consider the time value of money) [58].

$$LCC = CA + CM + CDR + CE \tag{29}$$

Among them,

LCC: Life cycle cost of electric vehicles(CNY).

4.2 GREET Model

This section introduces the GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model, a key tool used to assess the environmental impacts and energy consumption of transportation technologies. The following sub-chapters will provide an overview of the GREET model, including its introduction, the core components that make up the model, its simulation capabilities, and various applications of the model in analyzing the life cycle impacts of electric vehicles and other transportation technologies.

4.2.1 Introduction to GREET Model

The GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model is an assessment tool developed by the Argonne National Laboratory in the United States for studying the energy consumption and gas emissions throughout the life-cycle of vehicles. This model has been widely utilized in the field of automotive life-cycle assessment. General Motors, for instance, applied the GREET model in the context of the United States to analyze and evaluate energy consumption and greenhouse gas emissions for various vehicle technologies and fuel pathways. The GREET model boasts an extensive database covering the production, transportation, and usage pathways of various fuels, as well as information on transportation modes. It enables researchers to assess the emissions and energy consumption across the entire life-cycle under different transportation technology scenarios by modifying boundary conditions and parameters. The framework of the GREET model is illustrated in Figure 2.

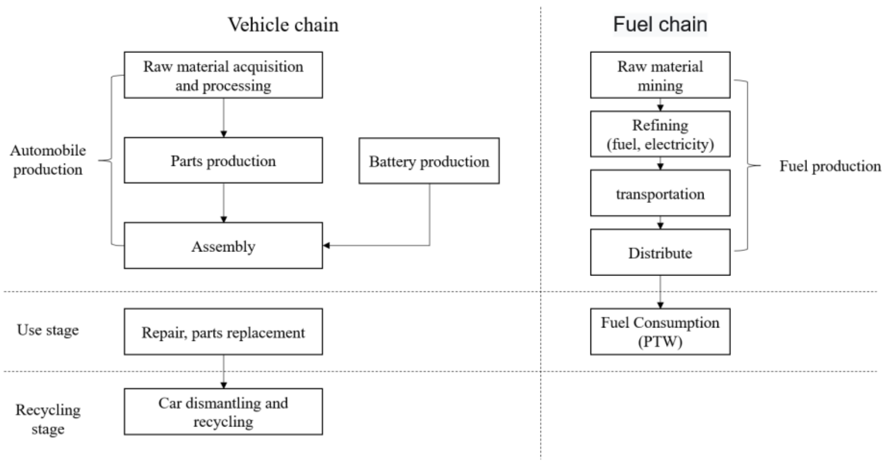

Fig.2 GREET Model Framework[85]

For the energy utilization aspect, the GREET model includes calculations for three different categories of energy: total energy, fossil energy, and petroleum-based energy. For the emissions aspect, the model covers three main greenhouse gases (GHGs), namely CO_2, CH_4, and N_2O, as well as five standard emissions (VOC, CO, NO_x, PM10, SO_x). In the GREET model, the emissions of the three greenhouse gases are calculated comprehensively into equivalent carbon dioxide emissions using the Global Warming Potential (GWP) values. In the GREET model, according to the recommendations of the Intergovernmental Panel on Climate Change (IPCC), the GWP values are set as follows: carbon dioxide is 1, methane is 21, and nitrous oxide is 310.

4.2.2 Core Components of GREET Model

According to this template, the energy generation process in the GREET software is divided into four stages: raw material extraction and processing, energy processing and conversion, energy transportation and distribution, and energy end-use. Based on this framework, an energy structure can be designed to represent each stage of energy utilization, as illustrated in Figure 3.

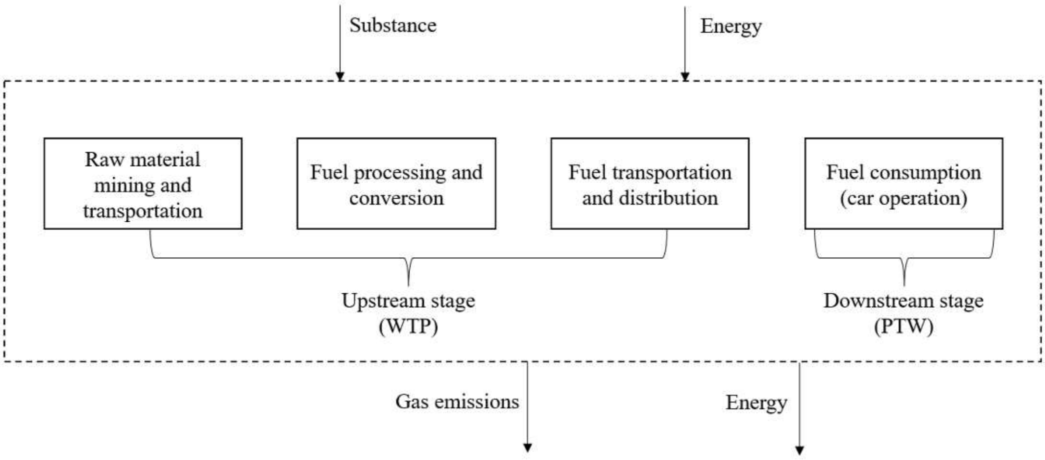

Fig.3 Energy production process[2] [85]

The energy consumed per unit of product output can be calculated from the energy efficiency(η) of the process. When all raw materials are consumed through combustion in the production of fuel, the total energy consumption (E_{in}) is calculated as [59]:

$$E_{in} = \frac{1}{\eta} \tag{30}$$

[2] WTP: Well-to-Pump
PTW: Pump-to-Wheelsr

When raw materials are burned as process fuels, emissions are inevitable. In order to divide the input raw material energy into raw material energy and process fuel energy, three situations must be considered during the research process:

(1) In the first case, all input raw materials are consumed to produce the required fuel, such as electricity production;

(2) In the second case, (in most cases) part of the input raw materials is used as raw material to produce the required fuel, and the remaining raw materials are used as process fuel to generate the necessary heat in the production process together with other process fuels, steam, etc.

(3) In the third case, there is no chemical reaction during the fuel production process. Each unit of energy of fuel product output requires one unit of energy of raw material input.

Emissions in the upstream stage of the fuel cycle originate mostly from the combustion of process fuels, with a smaller amount originating from non-combustion processes such as evaporation or leakage. Each type of emission corresponds to process fuel type, consumption and equipment. The calculation formula for the i-th emission produced by the combustion process of process fuel is [59]:

$$M_i = M_{uc,i} + \sum_j \sum_k F_{i,j,k} * E_{p,j,k} \tag{31}$$

In the formula: $M_{uc,\ i}$ is the i-th emission emitted by the non-combustion process (g); $F_{i,\ j,\ k}$ is the emission factor of the k-th equipment using the j-th process fuel (g/MJ); $E_{p,\ j,\ k}$ is the k-th equipment using the j-th process fuel(MJ). The consumption of j process fuels is calculated as [59]:

$$E_{p,j,k} = E_{in} * \alpha_j * \beta_{k,j} \tag{32}$$

Among them, E_{in} is the total energy consumption, calculated by formula (30) and formula (31),α_j is the proportion of the j-th process fuel in the total process fuel consumption(dimensionless),$\beta_{k,\ j}$ is the proportion of the j-th process fuel in all uses Proportion of the k-th type of equipment among the equipment for the type of process fuel(dimensionless).

It should be noted that in addition to the combustion consumption, the total energy consumption and total emissions in the upstream of the fuel cycle should also be taken into consideration in the upstream stages of the life cycle of process fuels, because process fuels, as a kind of fuel, have also experienced a series of the same production methods. In summary, the calculation formulas for the total energy consumption (E_{total}) and total emissions ($M_{total,\ i}$) upstream of the fuel cycle are [59]:

$$E_{total} = E_{in} + \sum_{j=1}^{n} (E_{up,in,j} * E_{p,j}) \tag{33}$$

$$M_{total,i} = M_i + \sum_{j=1}^{n} (M_{up,i,j} * E_{p,j}) \tag{34}$$

In the formula: $E_{up,\ in,\ j}$ is the energy consumption in the upstream stage of the j-th process fuel itself (MJ); $M_{up,\ i,\ j}$ is the amount of emission i in the upstream stage of the j-th process fuel itself (MJ); $E_{p,j}$ is the j-th process fuel consumption (MJ).

4.2.3 Simulation Capabilities of GREET Model

There are tools for stochastic simulation in the GREET model. GREET is a comprehensive model for full fuel cycle energy and emissions evaluation of a variety of different transportation fuels and vehicle technologies. GREET integrates a large number of input parameters and output results. Many input parameters are assumed to include some uncertain quantities, and these uncertainties require probability distribution functions to characterize the specific range of the uncertain parameters. Because some parameters of GREET are uncertain, the output results must be described in the form of distribution functions. Stochastic simulation tools incorporate different sampling methods to characterize these uncertainties. The stochastic simulation tool has been made as an attachment to Microsoft EXCEL to describe the probability distribution and complete the sampling of input parameters. The add-on can be run at any time to complete a stochastic simulation of GREET. Broadly speaking, the software's add-on tools allow:

(1) Assign the probability distribution function to the input variable;

(2) Determine the required sampling volume and the sampling method used;

(3) Define predictor variables (simulation tools provide different options to choose from approximately 3000 predictor variables to reduce parameter selection);

(4) Reduce errors;

(5) Perform statistical analysis on the output results.

Figure 4 is a more detailed overview of stochastic simulation using the EXCEL add-on:

The GREET model stochastic simulation process involves 11 probability distribution functions such as Beta distribution, normal distribution, lognormal distribution, uniform distribution, triangular distribution, Weibull distribution, Gamma distribution, extreme value distribution, exponential distribution, Pareto distribution and Logistic distribution.

In addition, the GREET model also involves Monte Carlo Sampling (MCS), Median Latin Hypercube Sampling (MLHS), Hammersley Sequence Sampling (HSS), Latin Four sampling methods including Latin Hypercube Hammersley Sampling (LHHS, Latin Hypercube Hammersley Sampling).

Monte Carlo sampling is one of the most widely used sampling methods in probability distribution. It is an experimental mathematical method based on random sampling for solving probabilistic or deterministic problems in natural sciences, engineering, and control management. It is also known as statistical experimentation and stochastic sampling technique. In current structural reliability calculations, it is considered a relatively accurate method, which refers to: the probability of an event can be estimated using the frequency of occurrence of that event in a large number of experiments. When the sample size is large enough, the frequency of occurrence of the event can be considered as its probability, therefore, a large number of random samples of random variables affecting its reliability can be first taken, and then these sampled values are substituted into the functional equations group by group to determine whether the structure fails. Finally, the failure probability of the structure is calculated from them. The Monte Carlo method is based on this approach for analysis.

Suppose independent random variables $X_i(i=1, 2, 3, \cdots, k)$ with corresponding probability density functions $fx_1, fx_2, \cdots, fx_k$, and a functional equation $Z=g(x_1, x_2, \cdots, x_k)$.

First, according to the respective distributions of each random variable, N sets of random value $x_1, x_2, \cdots, x_k$ are generated, and the functional values $Z_i=g(x_1, x_2, \cdots, x_k)(i=1, 2, \cdots, N)$ are calculated. If among these, there are L sets of random values corresponding to functional values $Z_i \leqslant 0$, then as $N \rightarrow \infty$, according to the Bernoulli large number theorem and the properties of normal random variables, we have: the probability of structural failure, reliability index. From the perspective of the Monte

Carlo method, this approach avoids the mathematical difficulties in structural reliability analysis. Regardless of whether the state function is nonlinear or the random variables are non-normally distributed, as long as the number of simulations is large enough, a relatively accurate failure probability and reliability index can be obtained.

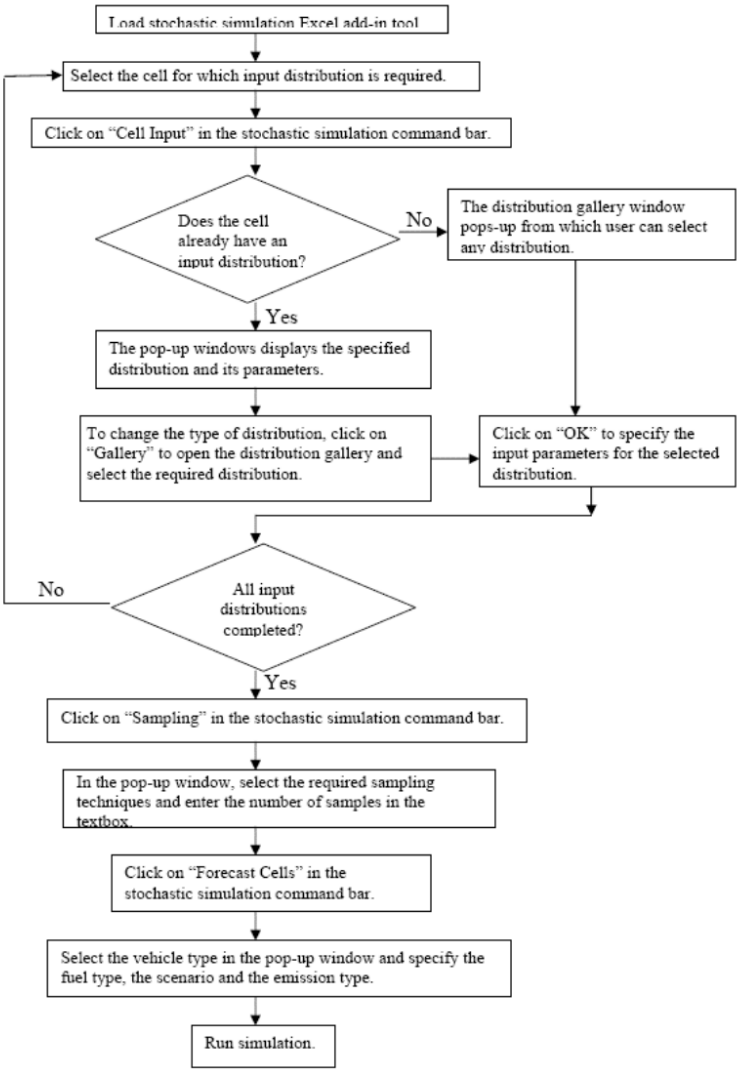

Fig.4 GREET Stochastic Simulation Overview [60]

4.2.4 Application of GREET Model

The applicability of the GREET model to the rail transit industry is demonstrated as follows.

(1) The GREET model can analyze the energy consumption of different types of rail transit systems and compare the efficiency of different vehicles, routes and energy configurations.

(2) The GREET model can estimate greenhouse gas emissions related to rail

transit systems, such as carbon dioxide, nitrogen oxides, and particulate matter emissions. This helps assess the impact of rail transport on air quality and climate change and supports related policy and decision-making.

(3) The GREET model can help evaluate the impact of different energy configuration solutions on the rail transit system, and then guide the energy transformation and sustainable development of the rail transit system.

4.3 Goals and Scope of LCA for Electric Vehicles

Research Objectives:

The overall objective of this study is to conduct a life cycle analysis and environmental impact assessment of electric vehicles (EVs) in the context of China, analyzing the environmental benefits (energy and emissions) of EVs' widespread adoption. The specific objectives are as follows:

1.Utilize a hybrid life cycle assessment method to establish life cycle assessment models for electric passenger vehicles and conventional gasoline engine passenger vehicles in the context of China, collecting and processing relevant data.

2.Analyze the energy consumption and gas emissions of the fuel cycles of electric vehicles and conventional gasoline engine vehicles in China.

3.Analyze the environmental impacts generated during the manufacturing and scrapping processes of electric vehicles and their key components in the context of China, and compare them with the environmental impacts of the fuel cycle (WTW) counterparts.

4.Analyze the consumption of various types of energy and gas emissions throughout the life cycle of electric vehicles and conventional gasoline engine vehicles.

5.Conduct a comparative analysis of the environmental impacts of electric vehicles and conventional gasoline engine vehicles throughout their life cycles under different technological pathways, evaluating the environmental benefits of electric vehicles in the context of China.

6.Further characterize the life cycle environmental impacts of electric vehicles under various technological pathways and conduct comparative analysis.

7.Perform sensitivity analysis to identify key influencing factors in the life cycle of electric vehicles.。

Environmental Impacts:

This study examines the electric vehicles energy consumption, greenhouse gas emissions, and conventional air pollutants (volatile organic compounds, carbon monoxide, nitrogen oxides, sulfur dioxide, particulate matter). Specifically:

Energy Consumption: Total primary energy, total fossil energy, including coal and petroleum.

Greenhouse Gas (GHG) Emissions: Mainly carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), which contribute to global climate change.

Conventional Air Pollutants:

1.Volatile Organic Compounds (VOCs): These are chemical substances that volatilize spontaneously from liquids or solids at normal temperature and pressure, posing hazards to human health and the environment, like irritating the eyes, nose, and throat, causing acute poisoning with symptoms like headaches, dizziness, and nausea, damage the liver, kidneys, and central nervous system, and even leading to cancer. VOCs react with NO to produce ground-level ozone through photochemical reactions.

2.Carbon Monoxide (CO): It is a product of incomplete combustion of carbon-based fuels. It forms carboxyhemoglobin in the blood, reducing the capacity of red blood cells to carry oxygen.

3.Nitrogen Oxides (NOx): Reacts with VOCs under sunlight to form ground-level ozone (O3). O3 can damage lung tissue and exacerbate respiratory diseases, causing long-distance migration and affecting health far from the original source. NOx also causes acid deposition, increases ammonia loading in water bodies, disrupts the chemical and nutrient balance of ecosystems, and reacts with general organic chemicals in the atmosphere to produce toxic substances.

4.Sulfur Dioxide (SO2): SO2 affects respiration, leading to respiratory diseases, weakening lung defenses, and exacerbating pulmonary and cardiovascular diseases. SO2 emitted into the air deposits on the earth's surface in the form of gas molecules or dissolves in rainwater or fog as typical sulfuric acid (H2SO4). It is particularly harmful to plants and wildlife in water.

5.Particulate Matter (PM): PM is a complex mixture of small particles and liquid droplets. The particulate matter of concern typically refers to those with an aerodynamic diameter equal to or less than 10μm, as these particles can enter the lungs through the throat and nose, also known as inhalable particulate matter. Particulate matter is divided into two categories: coarse particles PM10 and fine particles PM2.5.

Different particle sizes have different ways of entering the lungs and blood and different transmission characteristics. Human exposure to particulate matter can cause respiratory difficulties, exacerbate respiratory diseases such as asthma, bronchitis, and arrhythmia, and lead to premature death.

4.4 Integration of TCO and LCA Calculations

4.4.1 Data Integration

Establish a unified data collection and management system to ensure the consistency and accuracy of data. LCA requires detailed product lifecycle data, while TCO requires all relevant cost data, including purchase costs, installation costs, and operational costs. By creating a unified data platform, data redundancy and conflicts can be avoided, enhancing the efficiency of data management.

4.4.2 Method Integration

Early Integration: In the product design phase, combine the assessment methods of TCO(assess their economic costs, selecting the optimal design solution) and LCA(evaluate the environmental impacts of different design options) to identify and optimize the environmental and economic performance of the product in advance.

Mid-term Integration: During the product production and operation phase, regularly conduct TCO and LCA assessments to monitor the environmental and economic performance of the product, and promptly identify and address issues. For example, use LCA to identify high environmental impact areas in the production process and combine TCO to assess their cost-effectiveness, implementing corresponding improvement measures such as optimizing energy use and reducing waste emissions.

Late Integration: In the product disposal phase, use LCA to assess the environmental impact of disposal and combine TCO to assess the costs, selecting the optimal disposal solution. For example, use LCA to evaluate the environmental impact of different disposal methods and combine TCO to assess their costs, choosing a disposal method that can reduce environmental impact and is economically feasible.

4.4.3 Indicator System Integration

Establish a comprehensive indicator system that combines the key indicators of

TCO and LCA. For example, integrate the environmental impact indicators of LCA (such as global warming potential, codification potential, etc.) with the cost indicators of TCO (such as total ownership cost, operational cost, etc.) to form a comprehensive assessment indicator system. Through this integrated indicator system, the environmental and economic performance of the product can be assessed more comprehensively, providing a more scientific basis for corporate decision-making.

4.5 Data and Materials

This work takes electric vehicles as the research object, takes each vehicle's mileage as the functional unit, considers its life cycle process from production, distribution, use, maintenance to scrap disposal, and comprehensively evaluates the energy consumption and gas emissions of the electric vehicle's life cycle.

4.5.1 Basic Parameters

Any life cycle assessment study is based on the LCA results of the upstream phase of the fuel. According to the fuel chain algorithm analysis, LCA evaluation of electric vehicle fuel (gasoline and electric power) production stage involves energy sources, including coal, crude oil, natural gas, fuel oil, traditional diesel, traditional gasoline, etc., whose characteristic parameters are shown in Table 1 below.

Table 1 Energy characteristic parameters

Energy density	LHV	Carbon content		Sulfur content	
	g/L	MJ/kg	wt%	gC/MJ	Wt ppm
Coal		22.7	60.0	26.4	34000
Oil	847	42.7	85.3	20.0	16000
Natural gas	0.78	47.1	75.0	15.9	7
Fuel	991	39.5	86.8	22.0	5000
Conventional diesel	837	42.8	86.5	20.2	200
Conventional gasoline	745	43.4	86.3	19.9	50

Raw material mining mainly involves the mining of coal, crude oil and natural gas. According to the "China Energy Statistical Yearbook 2021", the energy conversion efficiency and process fuel consumption can be calculated, as shown in Table 2 [64].

Table 2 Energy consumption

Energy	Energy conversion efficiency	Process fuel ratio						
		Raw coal	crude oil	natural gas	gasoline	fuel	diesel	electricity
Coal	97.5%	80.1	0.0	0.4	0.5	0.1	3 5	15.6
Crude oil	95.7%	6.0	52.6	0.0	1.9	2.5	14.4	22.7
Natural gas	88.5%	2.1	0.0	83.4	0.7	0.9	5.0	7.9

According to the ,China Coal Industry Development Research Report 2021 [65], China Transportation Statistical Yearbook 2021 [66] and China Energy Statistical Yearbook 2021 [67] and other documents, the status of China's primary energy transportation can be obtained as shown in Table 3

Table 3 Status of primary energy transportation in China

Proportion of primary energy transported by various modes of transport				
	Railway	road	water transport	pipeline
Coal	70.6	10.3	19.1	--
Crude oil	14.7	0.0	51.9	33.4
Natural gas	--	--	--	100
Average haul				
	Railway	road	water transport	pipeline
Coal	640	179	255	0
Crude oil	917	0	1806	428
Coal	--	--	--	428

4.5.2 Vehicle Production

In the raw material production stage, the required raw materials include steel, cast iron, cast aluminum, forged aluminum, copper, glass, average plastics, rubber, nickel, cobalt, manganese, graphite, adhesives, electrolytes, carbon fibers, lead, sulfuric acid, fiberglass, liquids (including brake fluid, transmission fluid, powertrain coolant, and windshield washer fluid), etc. The energy consumption factors and carbon emission factors are sourced from the Argonne National Laboratory's GREET model [68] . The carbon emission factors of energy sources such as coal, electricity, natural gas, coke, crude oil, gasoline, diesel, blast furnace gas, and coke oven gas are obtained from literature [61]. In the parts manufacturing stage, this study only considered the three energy consumptions of natural gas, coal and electricity. The energy consumption of parts manufacturing was calculated based on the research of Kim et al. [70] and Wang et al. [71] (Table 4). During the vehicle assembly process, except for the heating process, which uses coal to provide thermal energy, all other processes use electrical energy. The consumption of electrical energy and thermal energy are 6. 86 MJ/kg and 2. 03 MJ/kg respectively. Based on this, the energy consumption of vehicle assembly is calculated. (Table 5).

Table 4 Energy consumption of parts manufacturing and vehicle assembly

Different Stages	Energy Type	GICEV	HEV	PHEV	BEV	FCV
Component Manufacturing	Natural Gas(MJ)	6043	6467	6991	7388	7674
	Coal(MJ)	3936	3478	3760	3314	4127
	Electricity(MJ)	4344	4707	5088	5429	5585
Vehicle Assembly	Coal(MJ)	2741	2883	3116	3248	3421
	Electricity(MJ)	9261	9741	10530	10976	11559

If heavy-duty diesel trucks are used as the transportation mode, the energy consumption coefficient is 0. 6 kJ kg-1 km-1[72] . In the vehicle production stage, indirect carbon emissions are directly related to the carbon emission factors of different energy sources. Due to data availability reasons, this study only considered the changes in carbon emission factors of electricity (Table 2) when calculating carbon emissions for the year 2035.

Table 5 Carbon emission factors and power structures of different power supplies [35][47][55]

Power Source Types	carbon emission factor / （g/kW·h）	2023 (%)	2035 (%)
Coal-fired power generation	960. 0	64. 1	41. 6
Natural gas-fired power generation	440. 0	3. 2	9. 7
Nuclear power	7. 4	4. 8	8. 0
Hydropower	7. 4	17. 8	15. 0
Biomass power generation	27. 8	1. 5	2. 7
Wind power	12. 5	5. 5	11. 5
Solar power	42. 7	3. 1	11. 5
Line loss rate		5. 9	4. 40

4.5.3 Vehicle Usage

During vehicle operation, indirect carbon emissions are generated due to fuel consumption. The five categories of passenger cars in the study require the use of three transportation fuels: gasoline, electricity and hydrogen. The gasoline life cycle includes crude oil extraction, refining, gasoline processing, transportation and refueling. The gasoline in this study is assumed to be fuel ethanol-based gasoline (E10) containing 10% fuel ethanol. In 2019, 27 cities in 10 provinces in China have started to supply E10 gasoline [74] . Considering that gasoline fuel technology is relatively mature, this study assumes that the gasoline emission factor in 2019 and 2035 is 2747 g/L [68] . The power life cycle includes raw material mining, transportation, power generation, grid transmission and other links. The power structure data in 2023 and 2035 come from China Statistical Yearbook, China Energy Statistical Yearbook, China Electric Power Statistical Yearbook [67], etc. Currently in China, the mainstream hydrogen production technologies mainly include hydrogen production from coal (with CCS installed), hydrogen production from industrial by-product purification and hydrogen production from renewable energy electrolysis of water. The carbon emission factors of the three technologies are 2. 97、15. 92、2. 31 respectively[68] . the three technologies accounted for 67%, 30% and 3% respectively in 2019, and will account for 45%, 15% and 40% respectively by 2035[75]. In order to comply with the reality in China, this study uses the average energy consumption of the passenger car industry as the energy consumption parameter of the selected vehicle model[76][77] (Table 6). The charging menefficiency of electric vehicles is generally 85%~95%, and this study took 90% [79] . During the operation of PHEV, the driving mileage using electricity and gasoline account for 80% and 20% respectively, and the slow charging method is used; the driving mileage of BEV fast charging and slow charging account for 20% and 80% respectively[79][80]。

Table 6 Energy consumption of five categories of passenger vehicles in 2023 and 2035 [67]

years	GICEV/（L/100km）	HEV/（L/100km）	PHEV/(L/100 km;kWh/100 km）	BEV/（kWh/100km）	FCV/（kg/100km）
2019	6. 3	4. 8	4. 7;20. 0	15. 2	1. 1
2035	4. 5	3. 5	3. 6;3. 0	11. 0	0. 8

During the vehicle maintenance phase, the study only considered the replacement of components such as lead-acid batteries, fluids and tires that are replaced more frequently. During the entire life cycle, lead-acid batteries and tires need to be replaced 4 times and 1 time respectively[78] . Liquid power system coolant, transmission fluid, brake fluid and windshield fluid need to be replaced 4 times, 2 times and 2 times respectively. 7 times and 11 times[53][61] . According to calculations in the literature [68] , the carbon emissions of lead-acid batteries, power system coolant, transmission fluid, brake fluid, windshield fluid and tire replacement are 73. 1 kg, 50. 2 kg, 7. 2 respectively. kg, 7. 2 kg, 3. 3 kg and 239. 4 kg.

4.5.4 Vehicle Disposal

In this study, the economic assessment methods related to the vehicle scrapping process have been comprehensively examined, with particular attention given to future changes in carbon emission factors. The scrapping process has been analyzed by considering key aspects such as energy consumption during both the dismantling of the vehicle and the handling of the battery. The energy consumption factor is 0.37 MJ/kg and 31 MJ/kg respectively [67]. In addition, the proceeds from the sale of recycled metals will also be calculated, which requires detailed data on current and future metal market prices. Compare the differences between current technologies and those expected in 2035 by building different scenarios, including advances in recycling technologies, more efficient end-of-life technologies and greener energy use, as well as the economic impacts under different regulatory change scenarios, such as stricter emission standards or subsidies for the use of green recycling technologies. This comprehensive model is developed to include not only direct costs (such as energy consumption, labor, equipment depreciation) and the benefits of recycled materials, but also indirect costs or savings from environmental impacts, thereby guiding policy decisions and business strategies to drive the automotive industry towards more sustainable practices.

5. Results

This part first analyzes the life cycle carbon emissions of five types of passenger cars, then compares the carbon emission results of passenger cars under different power structure scenarios, and finally compares the carbon emissions of passenger cars in different provinces.

5.1 Life Cycle Carbon Emissions

From Table 7, it can be observed that in 2021, the life-cycle carbon emissions of the five types of passenger vehicles, from highest to lowest, are as follows: PHEV, GICEV, BEV, HEV, and FCV. FCVs have the best emission reduction effect, with a reduction of 8.0 tons compared to GICEVs. This is primarily because FCVs have relatively low carbon emissions during the operational stage, being 15.2 tons less than GICEVs during this stage (equivalent to 47%). Despite an increase of 6.1 tons of carbon emissions during the production stage due to the manufacturing of fuel cells, the overall emission reduction effect remains optimal.PHEVs have a carbon emission level 1.7 tons higher than GICEVs (equivalent to 4%). The main reason is that PHEVs have two sets of driving systems, internal combustion engines and electric motors, resulting in 3.3 tons higher carbon emissions during the production stage compared to GICEVs (equivalent to 28%). Although there is a reduction in carbon emissions during the operational stage, the overall emissions are slightly higher than GICEVs.BEVs have a carbon emission reduction of 1.5 tons compared to GICEVs. This is mainly due to higher vehicle efficiency and lower electricity carbon emission factors. With the continuous maturation of electric vehicle technology, improvements in efficiency, and the decrease in carbon emission factors brought about by the promotion of renewable energy sources, the emission reduction effect of electric vehicles will become more significant in the future.

Due to the lack of consideration for structural changes in vehicle models over time in this study, the differences between 2035 and 2021 primarily reflect changes in emissions due to variations in power generation structures, hydrogen production methods, and changes in fuel consumption. In 2035, from a life-cycle perspective, carbon emissions from all types of passenger vehicles have decreased to varying degrees compared to 2021 (Table 7). The largest reduction is observed in PHEVs, decreasing from 39.4 tons to 26.8 tons, a decrease of 32%. This shift also places

PHEVs from having the highest carbon emissions in 2021 to the second highest, only exceeding FCVs. The main contribution to the decrease in carbon emissions comes from the reduction in carbon emissions generated by fuel combustion, which is primarily due to the significant decrease in the amount of electricity and gasoline consumed by PHEVs, as well as the decrease in electricity carbon emission factors resulting from adjustments in power generation structures. With the optimization of power generation structures, the emission reduction advantage of electric vehicles will gradually become more apparent. By 2035, GICEVs become the type of passenger vehicle with the highest carbon emissions, indicating that all types of electric vehicles have emission reduction effects. Among them, FCVs still exhibit the most significant carbon reduction effect, reducing emissions by 6.3 tons compared to GICEVs. Looking at the proportion of emissions in each stage, the proportion of emissions during the operational stage in 2035 has decreased, with electric vehicles showing the most significant decline, primarily due to adjustments in power generation structures.

Table 7 Comparison of carbon emission contributions of various aspects of different types of passenger vehicles (1) [69](kg)

Category		2021				
		GICEV	HEV	PHEV	BEV	FCV
Production Stage	Raw Material Production	8288	9221	11117	13263	13526
	Component Manufacturing	1559	1606	1737	1780	1906
	Vehicle Assembly	1937	2037	2202	2295	2417
	Vehicle Distribution	84	88	95	99	104
Usage Stage	Fuel Consumption	25032	21993	21084	16022	10117
	Vehicle Maintenance	761	761	761	761	761
Scrap Stage	Vehicle Scrappage	90	177	788	1763	1156
life-cycle Overall		38795	38795	37749	35883	37783

Table 7 Comparison of carbon emission contributions of various aspects of different types of passenger vehicles [69](2)(kg)

Category		2035				
		GICEV	HEV	PHEV	BEV	FCV
Production Stage	Raw Material Production	8118	9021	10843	12890	13215
	Component Manufacturing	1353	1384	1496	1524	1642

	Vehicle Assembly	1499	1577	1704	1776	1871
	Vehicle Distribution	84	88	95	99	104
Usage Stage	Fuel Consumption	18542	14422	11271	8784	5578
	Vehicle Maintenance	761	761	761	761	761
Scrap Stage	Vehicle Scrappage	66	131	581	1 301	853
life-cycle Overall		30423	27383	26750	27134	24024

In the production stage， the main carbon emissions of various types of passenger cars come from the production of raw materials, accounting for as high as 68% to 80%. Among them, the carbon emissions of electric vehicles are higher than those of GICEV, mainly because the manufacturing process of electric vehicles is more complex, and the carbon emissions from the production of power batteries (including fuel cells) are relatively high. In the operation stage, in 2021 and 2035, the carbon emissions of GICEV account for over 62% of the entire life-cycle carbon emissions, far higher than those of BEV and FCV, mainly because the efficiency of GICEV during the operation stage (16% to 20%) is much lower than that of BEV (63% to 84%) and FCV (37% to 46%); FCV has the smallest proportion of carbon emissions, accounting for only 36% and 25% of the life-cycle carbon emissions in 2021 and 2035, respectively, much lower than other types of passenger cars, mainly due to the lower carbon emission factor of hydrogen energy (coal hydrogenation with CCS reduces carbon emissions). In the scrappage stage, due to the assumptions made regarding the energy consumption factors of vehicle bodies and power batteries in this study, the emissions of electric vehicles with power batteries will be relatively higher.

5.2 Comparison of Carbon Emissions under Different Power Structures

To investigate the impact of different power structures on the life-cycle carbon emissions of automobiles, this study designed three scenarios: baseline scenario, marginal power structure scenario and high renewable energy scenario. Baseline scenarios represent the current or recent power structure. The marginal power mix scenario considers which sources of electricity will meet the additional or marginal power demand. The high renewables scenario assumes a significant shift in the future electricity mix to renewables. In this study, the baseline scenario and the marginal electricity scenario used the average electricity structure of China in 2021 and the structure of newly added generating capacity, respectively. The high renewable energy scenario used estimates of future electricity structure from the Energy Research Institute of the National Development and Reform Commission[82] , in which renewable energy would account for 86% of China's electricity consumption (Table 8).

Table 8 China's power structure in different scenarios [82] (%)

Scenarios	Coal-fired power	Natural gas power	Nuclear power	Hydropower	Biomass power generation	Wind power	Photovoltaic power generation
Baseline Scenario	64. 1	3. 2	4. 8	17. 8	1. 5	5. 5	3. 1
Marginal Electricity Scenario	41. 9	5. 8	16. 4	8. 4	3. 0	11. 7	12. 8
High Renewable Energy Scenario	6. 9	3. 1	4. 3	14. 5	7. 3	35. 4	28. 5

Figure 5 shows the carbon emissions of five types of passenger vehicles under different power structures. The arrows indicate the degree of change in carbon emissions caused by changes in the power structure. From the baseline scenario to the marginal scenario and the high renewable energy scenario, the electricity carbon emission factor decreases from 673 g/kWh to 465 g/kWh and 106 g/kWh respectively. Generally speaking, the impact of changes in the power structure on BEVs and PHEVs is much greater than that of the other three types of passenger vehicles, mainly because the emission factors of the electricity consumed by these two types of passenger vehicles during the operation phase have dropped significantly, while the other three types of passenger vehicles Passenger-like vehicles only consume electricity during the production stage, resulting in a reduction in indirect emissions.

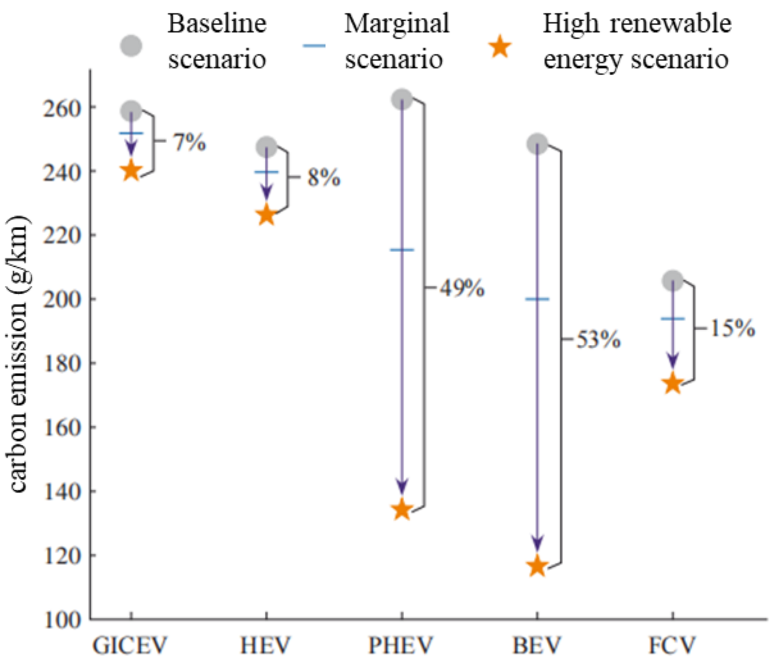

Fig.5 Comparison of carbon emissions from five types of passenger vehicles under different power structures [69]

Note: The % value in the figure represents the proportion of carbon emissions reduction from the baseline scenario to the high renewable energy scenario.

For GICEV, HEV, and FCV, the carbon intensity decreased by 7%, 8%, and 15%, respectively, from the baseline scenario to the high renewable energy scenario, mainly due to the decrease in indirect emissions resulting from electricity consumption during the vehicle production stage. For BEV and PHEV, from the baseline scenario to the high renewable energy scenario, their CO2 emissions will decrease from 248 g/km and 262 g/km to 117 g/km and 134 g/km, respectively, representing reductions of 53% and 49%. In the baseline scenario, except for PHEV, the carbon emissions of other types of electric vehicles are lower than GICEV, with HEV, BEV, and FCV reducing emissions by 4%, 4%, and 21%, respectively. In the marginal electricity scenario and high renewable energy scenario, all types of electric vehicles have emission reduction effects. In the marginal electricity scenario, compared to GICEV, HEV, PHEV, BEV, and FCV reduce emissions by 5%, 14%, 21%, and 23%, respectively. In the high renewable energy scenario, the emission reduction effects of electric vehicles further increase, with HEV, PHEV, BEV, and FCV reducing emissions by 6%, 44%, 51%, and 28%, respectively. Thus, it can be seen that different electricity structures have different impacts on the carbon emissions of various types of vehicles. Changing the national electricity structure in the short term may be very difficult. However, these findings are very useful for regions with different electricity structures. Therefore, based on the existing electricity structure in these regions, electric vehicle types with lower emissions can be selected.

5.3 Analysis of Energy Consumption over the Full Life Cycle of Vehicles

GICEV, PHEV, and BEV have energy consumptions of 803 GJ, 575 GJ, and 510 GJ respectively throughout the entire fuel cycle. According to Figure 6, PHEV and BEV, the two new types of electric vehicles, have reduced energy consumption to varying degrees compared to GICEV: PHEV reduced by 28.35%; BEV exhibited the most significant energy-saving effect, with a reduction of 36.45%. During the WTT stage, compared to traditional vehicles, both PHEV and BEV consume more energy, with BEV having the highest energy consumption, 64.94% higher than GICEV. This is mainly due to the substantial consumption of primary energy required for electricity production, as China primarily relies on coal-fired power generation, which has an efficiency of only about 40%, resulting in the loss of most of the energy during conversion. During the PTW stage, the energy consumptions of PHEV and BEV are 56.15% and 31.56% respectively compared to GICEV, highlighting a significant energy-saving advantage. This is because the energy loss during gasoline combustion is severe, while the fuel economy of electricity is superior to gasoline, with a higher energy conversion efficiency. Therefore, using electric vehicles during the vehicle driving stage is beneficial for energy conservation and environmental protection.

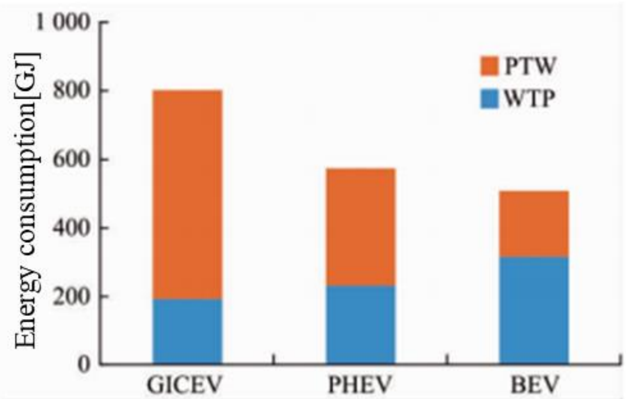

Fig. 6 Energy consumption of fuel cycle stages[69]

The energy consumption of GICEV, PHEV, and BEV over the entire vehicle life-cycle is 113 GJ, 167 GJ, and 183 GJ, respectively. As shown in below, the energy consumption of the vehicle body is the highest, the is the battery and fluids. Energy consumption of each part of the vehicle life-cycle increases with mass.

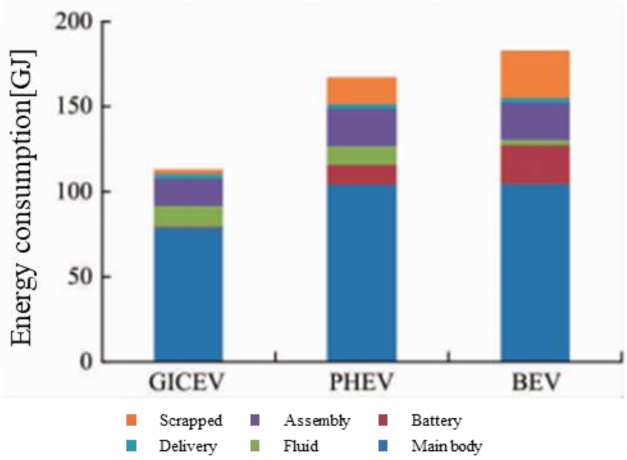

Fig. 7 energy consumption of vehicle cycle[69]

At the same time, the energy consumption during battery production and disposal stages increases significantly with the level of vehicle electrification. The total energy consumption over the vehicle life-cycle includes both the fuel cycle and the vehicle cycle energy consumption, with GICEV, PHEV, and BEV having total energy consumptions of 916 GJ, 742 GJ, and 693 GJ, respectively. As shown in Figure 8, both PHEV and BEV have lower total energy consumption than GICEV, with reductions of 18.94% and 24.27%, respectively, indicating that electric vehicles can reduce energy consumption to a certain extent. Regardless of the type of vehicle, the fuel cycle accounts for over 70% of the total life-cycle energy consumption. This suggests that the bottleneck limiting further development of traditional vehicles is the low conversion efficiency of gasoline. To better leverage the energy-saving advantages of electric vehicles, it is crucial to improve the conversion efficiency of primary energy generation.

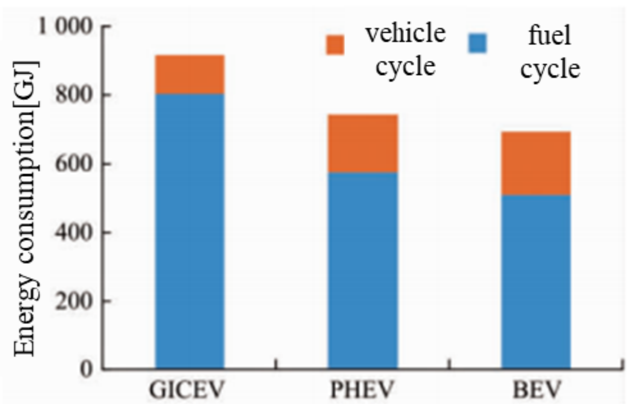

Fig. 8 Energy consumption of vehicle life-cycle[69]

5.4 Analysis of Pollutant Emissions over the Full Life Cycle of Vehicles

From Figure 9, it can be observed that for BEV, PHEV achieves more significant reductions in CO and VOC emissions, with reductions of 90.34% and 44.39%, respectively. CO_2 and NOx emissions also decrease by 19.17% and 25.67%, respectively. However, SOx emissions increase significantly to 2.57 times that of GICEV, and particulate matter emissions also increase by 43.92%. This indicates that with the increase in vehicle electrification, emissions of CO and VOC, primarily from incomplete combustion and fuel evaporation, decrease. At the same time, SO_x emissions increase with the increase in electricity usage, as China's coal-based power generation still produces a considerable amount of sulfur oxides even with desulfurization technologies in place. Because electricity is a clean energy source, the zero emissions achieved by BEV during the PTW stage are the key factors driving the reduction of CO_2 and NO_x emissions over its entire life-cycle. This also indicates that BEV concentrates its greenhouse gas emissions (mainly CO_2) in the WTT stage (electricity production stage), which not only facilitates centralized emission control in coal-fired power plants but also helps alleviate the urban heat island effect, thereby improving the quality of life for local residents. In terms of particulate matter emissions, both types of electric vehicles emit more than traditional vehicles, with no advantage, mainly due to dust generated during coal mining and transportation processes.

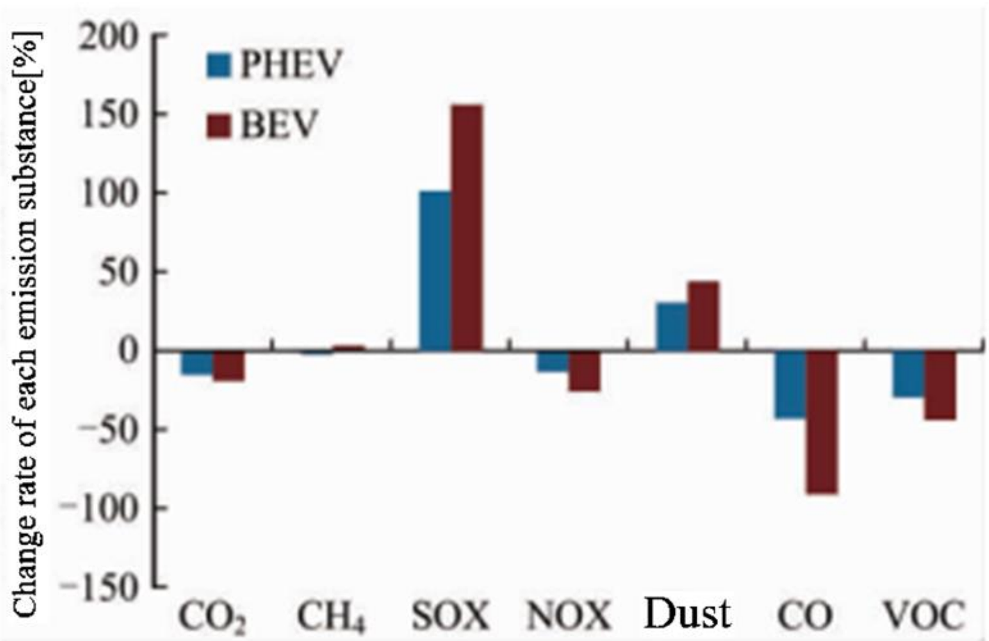

Fig. 9 Pollution emission changes of two EVs compared with GICEV[69]

5.5 Environmental Impact Assessment of the Full Life Cycle of Vehicles

The five environmental impacts involved, along with their corresponding pollutants, are global warming (CO_2 and CH_4), acidification (SO_x and NO_x), photochemical ozone formation (VOC, CO, and CH_4), and particulate matter (dust). Based on the environmental inventory classification, using the equivalency model as a characterization model, internationally recognized characterization factors are selected to calculate the potential impact values of the five environmental impacts. Subsequently, standardization and weighting processes are carried out, resulting in the Environmental Impact Load (EIL). The calculated environmental impact loads for GICEV, PHEV, and BEV are shown in Table 6.

The environmental impact load for GICEV is 58.40 person equivalents, meaning that the environmental impact of a traditional car's entire life-cycle is 58.40 times the comprehensive environmental impact potential per capita in 1990. Similarly, the environmental impact load for PHEV is 44.24 person equivalents, and for BEV, it is 34.62 person equivalents. For GICEV, the largest contribution to environmental impact comes from photochemical ozone formation, accounting for 79.81%, followed by global warming, acidification, and eutrophication, accounting for 12.35%, 4.95%, and 1.63%, respectively. The impact of particulate matter is the smallest, accounting for only 1.27%, which is because gasoline combustion generates a large amount of volatile organic compounds that participate in photochemical reactions, while emitting significant amounts of greenhouse gases that contribute to global warming. With the increase in electrification level, the impact of acidification becomes more significant. For BEV, acidification accounts for 16.96% of the total impact, second only to photochemical ozone formation, indicating that vehicles with higher levels of electrification involve more processes that utilize electricity in fuel production and vehicle manufacturing, leading to the generation of large amounts of sulfur and nitrogen oxides, thereby causing acidification.

Table 9 Environmental impact load of GICEV，PHEV，BEV[59]

Substance Name	Equivalent Factor	Impact Potential/ kg	Standardization Baseline	Standardized Value	Weight	Environmental Load		
						GICEV	PHEV	BEV
CO2	1. 00	75603. 17	8700 kg	8. 69	0. 83	7. 21	6. 09	5.

			CO2-eq					85
CH4	25. 00							
SOx	1. 00	142. 43	36 kg SO2-eq	3. 96	0.73	2. 89	4. 86	5. 87
NOx	0. 70							
NOx	1. 35	80. 32	62 kg NO3-eq	1. 30	0.73	0. 95	0. 82	0. 70
VOC	0. 60	57. 16	0. 65 kg C_2H_4-eq	87. 94	0.53	46. 61	31. 50	21. 13
CO	0. 03							
CH4	0. 01							
DUST	1. 00			1. 22	0.61	0. 74	0. 98	1. 07
Total	-	-	-	-	-	58. 40	44. 24	34. 62

5.6 Life cycle cost analysis of electric vehicles

In this work, four models of BYD Auto will be compared, mainly BYD E6 pure electric vehicle, BYD Qin hybrid electric vehicle, BYD F3DM plug-in hybrid electric vehicle and BYD F3 fuel car. Their performance parameters are shown in Table 10. Data from BYD's website

Table 10 Performance parameters of four BYD vehicles

Vehicle type		Pure electric vehicle Byd E6	Hybrid electric vehicle Byd Qin	Plug-in hybrid electric vehicles Byd F3DM	Fuel car Byd F3 (2013)
Performance index[3]	Maximum speed (km/h)	140	185	150	170
	Motor rated power (kW) Or engine capacity (l)	90	113	125	80
	Drive on a single charge	300	70(BEV mode)	100(BEV mode)	550

[3] Source: https://www.dongchedi.com/auto/auto_compare/params?carIds=24289%2C21779%2C4256%2C4218

	or refueling Mileage (km)				
	Energy consumption per 100 km	19.5kwh	2L[4]	2.7L	6.2L
	Battery replacement or refueling takes time (minutes)	3	3	3	5
	Car life (10,000 km)	30 (Battery life is 150,000 Km)	30 (Battery life is 150,000 Km)	30 (Battery life is 150,000 Km)	30

Based on the above analysis of the life cycle cost of electric vehicles and the performance parameters of BYD's four vehicles, the following vehicle cost comparison table 11 can be obtained.

As can be seen from the data in Table 11, the total cost of BYD hybrid electric vehicles and plug-in hybrid electric vehicles is lower than that of fuel vehicles, while BYD E6 pure electric vehicles have a higher purchase price100km costs more than a petrol car. Further analysis of the data leads to the following conclusions:1. In the case of electric vehicle technology is still to be perfected, the cost of HEV and PHEV is already lower than that of fuel vehicles. If electric vehicle technology can be breakthroughs, the cost of electric vehicles will also be reduced, and it is expected to achieve the full life cycle cost of BEV is lower than that of fuel vehicles. Therefore, the most critical thing to develop electric vehicles is to break through electric vehicle technology and reduce its total cost.

2. With the reduction of fossil fuels such as oil and the shortage of resources, on the one hand, the state will levy energy tax on consumers, on the other hand, the state will increase the environmental tax levied on automobile companies, and the

[4] L:litre

enterprises will pay for the increased environmental tax by consumers, so consumers need to bear double taxation, therefore, the life cycle cost of consumers buying fuel vehicles will increase.

3. When consumers consider the high cost of electric vehicles, they will choose to buy GICEV, which will increase energy consumption and pollution gas emissions and exacerbate the negative impact on the environment.

4. From the perspective of scale effect and technical learning effect, with the support of the state, electric vehicles will become more and more popular, and their technical level will become higher and higher, so the price of electric vehicles will decrease, whether it is BEV or HEV, or the full life cycle cost of PHEV will be reduced. From a cost perspective, consumers will be more willing to buy electric vehicles to save energy and reduce emissions.

Table 11 Life cycle cost comparison of 4 types of vehicles[83]

	BYD E6	BYD Qin	BYD F3DM	BYD F3 (2013)
Purchase cost	310000yuan	200000yuan	170000yuan	60000yuan
Use cost	12 yuan/100 kilometers	16 yuan/100 kilometers	20 yuan/100 kilometers	41 yuan/100 kilometers
Disposal cost	87 yuan/100 kilometers	50 yuan/100 kilometers	40 yuan/100 kilometers	67 yuan/100 kilometers
Environmental cost	0	2r	2.7r	6.2r
The national policy subsidy	60000yuan	35000yuan	50000yuan	0yuan
The life cycle cost of electric vehicles	183 yuan/100 kilometers	（121+2r） yuan/100 kilometers	（101+2.7r） yuan/100 kilometers	（128+6.2r） yuan/100 kilometers

Note: r is for energy and environmental tax rate.

6. Conclusion

The rapid development of automobile industry increases the consumption of oil, which leads to the greater risk and threat of China's petroleum energy. In addition, the rapid development of the automobile industry has also led to the intensification of environmental pollution, and the government and the public have turned their attention to the development of electric vehicles with the goal of energy saving and emission reduction.

In this study, the life cycle assessment method was used to study the carbon emission impact of five types of passenger vehicles. In this study, the author not only analyzed the carbon emissions of the whole life cycle of the vehicle (including raw material production, parts manufacturing, vehicle assembly, vehicle distribution, vehicle operation, vehicle maintenance and vehicle scrapping), but also considered the impact of changes in the power structure on the carbon emissions of electric vehicles and the economic benefits of electric vehicles. Based on the above analysis, the following conclusions can be drawn.

1.In the context of China's energy structure, compared with GICEV, the environmental benefits of electric vehicles are not obvious. This is mainly because most of our electricity comes from coal power generation, and the process of coal power generation will produce a lot of energy consumption and pollution emissions. BEV is effective in reducing oil consumption, which is in line with the current situation of "lacking oil and rich coal" in China.

2.Under the same energy structure background, the total energy consumption of electric vehicles throughout their life-cycle is lower than that of traditional gasoline vehicles. Compared to internal combustion engine vehicles (GICEV), plug-in hybrid electric vehicles (PHEV) and battery electric vehicles (BEV) reduce total energy consumption by 18.94% and 24.27%, respectively. This is mainly due to the efficient conversion of electric energy during the driving stage. However, when considering only the fuel cycle upstream, coal-fired power generation results in significant energy consumption for BEVs, 64.94% higher than that of GICEVs.

3.Electric vehicles have the best emission reduction effect on CO and VOC, which mainly come from incomplete combustion and fuel evaporation, followed by CO2. However, due to the substantial increase in electricity use, the emissions of SOx have significantly increased. From the perspective of comprehensive environmental impact caused by pollutant emissions, the environmental impact loads of PHEVs and BEVs are 24.25% and 40.72% lower, respectively, than that of GICEVs.

4.Compared to traditional vehicles, both types of electric vehicles can reduce environmental costs to a certain extent, with BEVs having the lowest environmental cost, reducing pollution costs by 31.28% compared to GICEVs. Promoting electric vehicles is conducive to emission reduction.

5. If the goal is to save energy and reduce pollution gas emissions, PHEV can be chosen as the main development object. If the goal is to reduce the consumption of petroleum energy, BEV is the most suitable choice.

6. The life cycle cost of HEV and PHEV is lower than that of GICEV, and the 100 km life cycle cost of BEV is higher than that of GICEV due to the high purchase cost of BEV. Government price subsidies have a big impact on which models consumers buy.

For fossil fuel dominated countries like China, whether it is coal, oil or natural gas, the total pollution emissions of electric vehicles may be greater than that of traditional cars. In order to fundamentally change the environmental problem, we must first change the energy structure or reduce pollution by increasing the source of fuel raw materials. Only in this way can the development and promotion of new energy vehicles achieve a multiplier effect on environmental protection. At the same time, it is necessary to support the development of new energy vehicles, especially electric vehicles, because electric vehicles for China is in line with the "energy conservation and emission reduction" policy requirements, can save energy, reduce CO_2 and other greenhouse gas emissions, and alleviate the air pollution of cities with net electricity input. In addition, vigorously developing electric vehicles can also change the development pattern of today's Chinese automobile industry and seize opportunities for automobile companies.

In conclusion, electric vehicles have energy-saving advantages throughout their life-cycle, but the overall effect is somewhat diminished due to significant energy loss during upstream power generation. If clean energy develops vigorously in the future and replaces coal-fired power generation, the energy-saving potential of electric vehicles will be further realized. At that time, sulfur oxides will also be effectively reduced, and the environmental benefits of promoting electric vehicles will be significant.

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Appendix

Eq1:

Parameter	Description	Unit	Source
a	Any unit process in the upstream phase of the fuel chain	(dimensionless)	[57]
E_{out}	Total energy input required to produce the output energy E_{out} for any unit process a in the upstream phase	(g/MJ)	
E_{in}^{a}	Total energy input required per unit of energy product output for any unit process a in the upstream phase, i.e., total energy consumption	(MJ/MJ)	

Eq2:

Parameter	Description	Unit	Source
E_{in}^{a}	Total energy input required per unit of energy product output for any unit process a in the upstream phase, i.e., total energy consumption	(g/MJ)	[57]
η^{a}	Energy efficiency of any unit process a in the upstream phase	(dimensionless)	

Eq3:

Parameter	Description	Unit	Source
E_{feed}^{a}	Energy of the feed stock required for any unit process a in the upstream phase	(g/MJ)	[57]
$E_{process}^{a}$	Energy required for the process fuel in any unit process a in the upstream phase	(g/MJ)	

Eq4:

Parameter	Description	Unit	Source
$E_{process}^{a}$	refers to the energy of the process fuel required to produce a unit energy product in any unit process a	(MJ/MJ)	[57]
η	refers to the energy efficiency of unit process a	(dimensionless)	

Eq5:

Parameter	Description	Unit	Source
MC_{out}^{a}	Carbon content in the output energy product of unit process a	(g/MJ)	[57]
MC_{in}^{a}	Carbon content in the input feed stock energy of unit	(g/MJ)	

	process *a*		
MC_{out}^{a-1}	Carbon content in the output energy product of the previous unit process *a*-1	(g/MJ)	

Eq6:

Parameter	Description	Unit	Source
$EM_{c,i}^{a}$	Emissions of combustion pollutant *i* from any unit process *a*	(g/MJ)	[57]
$EF_{i,j,k}$	Emission factor of pollutant *i* for process fuel *j* used in energy device *k*	(g/MJ)	
$E_{process,j,k}^{a}$	Consumption of process fuel *j* in energy device *k* for any unit process *a*	(g/MJ)	

Eq7:

Parameter	Description	Unit	Source
E_{in}^{a}	Total energy consumption for unit process *a*	(MJ/MJ)	[57]
α_j	Proportion of total process fuel consumption that is process fuel *j*	(dimensionless)	
$\beta_{k,j}$	Proportion of energy device *k* among all devices consuming process fuel *j*	(dimensionless)	

Eq8:

Parameter	Description	Unit	Source
C	Sulfur		[57]
O_2	Oxygen gas		
CO_2	Sulfur dioxide, the product of the reaction.		

Eq9:

Parameter	Description	Unit	Source
$EF_{SO_2,j}$	Emission factor of SO_2 for the combustion of process fuel *j*	(g/MJ)	[57]
D_j	Density of process fuel *j*	(g/Lfor liquid fuels, g/m³ for gaseous fuels)	
LHV_j:	Lower heating value of process fuel *j*	(MJ/L for liquid fuels, MJ/m³ for gaseous fuels, MJ/ton for solid fuels)	
$r_{s,j}$	Sulfur mass ratio in process fuel *j*	(dimensionless)	
64	Molar mass of SO_2	(g/mol)	
32	Molar mass of sulfur	(g/mol)	

Eq10:

Parameter	Description	Unit	Source
C	Carbon		[57]
O_2	Oxygen gas		
CO_2	Carbon dioxide, the product of the reaction.		

Eq11:

Parameter	Description	Unit	Source
$EF_{CO_2,j,k}$	Emission factor of CO_2 for the combustion of process fuel *j* in combustion device *k*	(g/MJ)	[57]
D_j	Density of process fuel *j*	(g/L for liquid fuels, g/m³ for gaseous fuels, MJ/ton for solid fuels)	
LHV_j	Lower heating value of process fuel *j*	(MJ/L for liquid fuels, g/m³ for gaseous fuels, MJ/ton for solid fuels)	
$r_{c,j}$	Carbon mass ratio in process fuel *j*	(dimensionless)	
$E_{voc,j,k}$	Emission factor of VOC for the combustion of process fuel *j* in combustion device *k*	(g/MJ)	
0.85	Average carbon mass ratio in VOC emissions	(dimensionless)	
$EF_{CO,j,k}$	Emission factor of CO for the combustion of process fuel *j* in combustion device *k*	(g/MJ)	
0.43	Carbon mass ratio in CO emissions	(dimensionless)	
$EF_{CH_4,j,k}$	Emission factor of CH_4 for the combustion of process fuel *j* in combustion device *k*	(g/MJ)	
0.75	Carbon mass ratio in CH_4 emissions	(dimensionless)	
44	Molar mass of CO_2	(g/mol)	
12	Molar mass of carbon	(g/mol)	

Eq12:

Parameter	Description	Unit	Source
EF_{GHG}	GHG emission factor	(g/MJ)	[57]
EF_{CO_2}	CO_2 emission factor	(g/MJ)	
EF_{CH_4}	CH_4 emission factor	(g/MJ)	
EF_{N_2O}	N_2O emission factor	(g/MJ)	

Eq13:

Parameter	Description	Unit	Source
EM_i^a	Emissions of pollutant *i* from unit process *a*	(g/MJ)	[57]
$EM_{c,i}^a$	Combustion emissions of pollutant *i* from unit process *a*	(g/MJ)	
$EM_{nc,i}^a$	Non-combustion emissions of pollutant *i* from unit process *a*	(g/MJ)	

Eq14:

Parameter	Description	Unit	Source
EU_i^a	life-cycle energy consumption of process *a* for energy type *i*	(MJ/MJ)	[57]
E_{in}^a	Direct energy consumption of process *a* for energy type *i*	(MJ/MJ)	
$E_{up,in,j}$	Upstream energy consumption of process fuel *j*	(MJ/MJ)	

Eq15:

Parameter	Description	Unit	Source
EMU_i^a	life-cycle emissions of pollutant *i* from process *a*	(g/MJ)	[57]
EM_i^a	Direct emissions of pollutant *i* from process *a*	(g/MJ)	
$EF_{up,in,j}$	Upstream emissions of pollutant *i* from the production and distribution of process fuel *j*	(g/MJ)	

Eq16:

Parameter	Description	Unit	Source
EU_i^a	life-cycle energy consumption of process *a* for energy type *i*	(MJ/MJ)	[57]
E_{in}^a	Direct energy consumption of process *a* for energy type *i*	(MJ/MJ)	
$EF_{up,in,j}$	Upstream emissions of pollutant *i* from the production and distribution of process fuel *j*	(g/MJ)	
$E_{process,j}^a$	Consumption of process fuel *j* in process *a*	(MJ/MJ)	

Eq17:

Parameter	Description	Unit	Source
E_{up}	life-cycle energy consumption in the upstream phase of the fuel cycle	(MJ/MJ)	[57]
$EM_{up,i}$	Mass of the *i*-th type of emissions in the life-cycle of the upstream phase of the fuel cycle	(g/MJ)	
The rest of the variables are the same as previously defined.			

Eq18:

Parameter	Description	Unit	Source
E_{op}	Energy consumption during the vehicle operation phase	(MJ/km)	[57]
B	Vehicle fuel economy	(L/100 km or kW/100 km)	
LHV	Lower heating value of the fuel	(MJ/L)	
LS	Fuel loss rate during the vehicle operation phase	(%)	

Eq19:

Parameter	Description	Unit	Source
e	The *e*-th type of environmental impact	(kg CO_2-eq)	[57]
$F_{t,e}$	Environmental impact factor of the *t*-th material for the *e*-th type of environmental impact	(kg CO_2-eq)	
$M_{V1,t}$	Mass of the *t*-th automotive material in the vehicle body	(kg)	
$E_{V1,e}$	Amount of the *e*-th type of environmental impact caused by the production of the vehicle body	(kg CO_2-eq)	

Eq20:

Parameter	Description	Unit	Source
Bs	Starter battery	(kWh)	[57]
Bp	Power battery	(kWh)	
E_e^{Bs}	The *e*-th environmental impact caused by the production of the starter battery	(kg CO_2-eq)	
E_e^{Bp}	The *e*-th environmental impact caused by the production of the power battery	(kg CO_2-eq)	
$E_{V2,e}$	The *e*-th environmental impact caused by the production of electric vehicle batteries	(kg CO_2-eq)	

Eq21:

Parameter	Description	Unit	Source
$E_{t,e}^{V3}$	The *e*-th environmental impact caused by the production of the t-th type of automotive fluid	(kg CO_2-eq)	[57]
$E_{V3,e}$	The e-th environmental impact caused by the production of fluids	(kg CO_2-eq)	

Eq22:

Parameter	Description	Unit	Source
VC_e	The *e*-th environmental impact amount under the vehicle cycle functional unit	(kg CO_2-	[57]

		eq)	
$E_{Vi,e}$	The *e*-th environmental impact amount of each component of the vehicle chain, including vehicle body (V1), battery (V2) fluid (V3), vehicle assembly (V4), distribution, distribution and transportation (V5), Maintenance (V6), scrap processing (V7)	(kg CO_2-eq)	
d	Vehicle life mileage	(km)	

Eq23:

Parameter	Description	Unit	Source
r_1	Environmental impact in the upstream stage of power generation	(kg CO_2-eq)	[57]
r_2	The environmental impact of the downstream stage of electricity, that is, the vehicle driving stage	(kg CO_2-eq)	
b_1	Environmental impact of the upstream stage of gasoline	(kg CO_2-eq)	
b_2	Environmental impact in the downstream stage of gasoline and vehicle driving stage	(kg CO_2-eq)	
VC	Environmental impact of vehicle chains	(kg CO_2-eq)	
UF	Utility factor, which refers to the average mileage of a PHEV driven in pure electric mode as a percentage of the total mileage	(dimensionless)	

Eq24:

Parameter	Description	Unit	Source
CA	The total cost of acquiring the vehicle	(CNY)	[58]
P	The initial price of the vehicle	(CNY)	
C	The additional costs involved in the purchase process	(CNY)	

Eq25:

Parameter	Description	Unit	Source
CM	The overall cost of the vehicle, including operating and maintenance costs	(CNY)	[58]
CO	The cost of operating the vehicle	(CNY)	
CM1	The cost associated with maintaining the vehicle's battery	(CNY)	
CM2	The cost associated with general maintenance for the electric vehicle	(CNY)	

Eq26:

Parameter	Description	Unit	Source
CO	Operating cost	(CNY)	[58]

D_{CD}	Unit charge electricity price	Yuan/kWh	
L	Vehicle electricity consumption per 100 km	kWh/100 km	
T	Battery charging efficiency	Percentage or fraction	

Eq27:

Parameter	Description	Unit	Source
CDR	The cost associated with scrapping or recycling the vehicle	(CNY)	[58]
R	The total distance driven before scrapping, typically measured in 10,000 kilometers	km	
CA	The initial purchase price of the vehicle	(CNY)	
CS	The residual value recovered at the time of scrapping	(CNY)	

Eq28:

Parameter	Description	Unit	Source
CE	The total environmental cost associated with fuel consumption	Currency units (e.g., yuan)	[58]
r	The tax rate applied to fuel or energy use, typically expressed in currency units per unit of fuel consumed	(e.g., USD/L, EUR/L, CNY/L)	
N	The amount of fuel consumed per 100 kilometers	L/100 km	

Eq29

Parameter	Description	Unit	Source
LCC	Life cycle cost of electric vehicles	Currency units (e.g., yuan)	[58]

Eq30:

Parameter	Description	Unit	Source
E_{in}	Total energy input required per unit of energy product output for any unit process a in the upstream phase, i.e., total energy consumption	(g/MJ)	[59]
η	Energy efficiency of any unit process a in the upstream phase	(dimensionless)	

Eq31:

Parameter	Description	Unit	Source
$M_{uc,\ i}$	The i-th emission emitted by the non-combustion process	(g)	[59]

$F_{i,\,j,\,k}$	The emission factor of the k-th equipment using the j-th process fuel	(g/MJ)	
$E_{p,\,j,\,k}$	The *k*-th equipment using the *j*-th process fuel	(MJ)	

Eq32:

Parameter	Description	Unit	Source
α_j	The proportion of the *j*-th process fuel in the total process fuel consumption	(dimensionless)	[59]
$\beta_{k,\,j}$	The proportion of the *j*-th process fuel in all uses Proportion of the *k*-th type of equipment among the equipment for the type of process fuel	(dimensionless)	

Eq33:

Parameter	Description	Unit	Source
E_{total}	Total energy consumption, measured in megajoules	(MJ)	[59]
$E_{up,\,in,\,j}$	The proportion of the *j*-th process fuel in the total process fuel consumption	(MJ)	
$M_{up,\,i,\,j}$	The proportion of the *j*-th process fuel in all uses Proportion of the *k*-th type of equipment among the equipment for the type of process fuel	(MJ)	
$E_{p,j}$	The j-th process fuel consumption	(MJ)	

Eq34:

Parameter	Description	Unit	Source
$M_{total,i}$	Total emissions of pollutant *i*	(g)	[59]
M_i	Emissions of pollutant *i* from the current process	(g)	
$M_{up,i,j}$	Amount of pollutant *i* emitted in the upstream stage for the *j*-th process fuel	(g)	