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Carbon Footprint throughout the Life Cycle of Electric Vehicles and Its Influence on Transport Sector Decarbonization

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ABSTRACT

To assess the carbon footprint of new energy vehicles, a comprehensive life cycle analysis is essential. This study develops a unified carbon emission calculation model for electric vehicles, addressing all phases from raw material acquisition, component manufacturing, and usage to recycling. Using the BYD E6 (a specific EV car model) as a case study, life cycle carbon emissions were calculated based on the associated data released in 2022. Carbon emissions from material extraction and recycling, component production and assembly, battery production and recycling, as well as energy consumption during vehicle usage and maintenance, are all considered. The results reveal that battery manufacturing accounts for the largest share of carbon emissions, representing 76.85% of the total. Notably, when second-life utilization technologies for power batteries are employed, the recycling rate increases significantly, leading to a substantial reduction in overall carbon emissions. Additionally, this study analyzes sales trends and market share dynamics of new energy vehicles over the past decade and forecasts their future development, while also considering the financial and ecological benefits derived from the financial value of carbon emissions.

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Introduction

The automotive industry is a major contributor to global greenhouse gas emissions. As vehicle ownership in China continues to increase, reducing carbon emissions within the automotive sector has become a pivotal element in achieving the nation's climate goals. With increasing global awareness of environmental protection and emissions, the automotive industry, which is a significant contributor to human carbon emissions, is undergoing an unprecedented transformation. The rise of new energy vehicles (NEVs) is revolutionizing the present and future of the global automotive sector. Promoting the transition from fuel vehicles to NEVs is a key strategy for reducing carbon emissions in this sector [1]. Low-carbon development has gained worldwide consensus, and China has set the 'carbon peak' and 'carbon neutrality' as national goals [2]. According to the New Energy Vehicle Industry Development Plan (2021–2035) issued by the Ministry of Industry and Information Technology, the number of electric vehicles in China reached 10.45 million by 2022, reflecting a 63% year-on-year increase [3]. In light of the rapid growth of electric vehicles, it is crucial to establish a lifecycle carbon footprint tracking and monitoring system for EVs to gain a deeper understanding of carbon emissions in China's automotive sector. This approach will provide valuable insights and support for the sustainable and low-carbon development of China's new energy vehicle industry.

Many scholars worldwide have conducted lifecycle assessment (LCA) studies on electric vehicles (EVs). Applied LCA in Australia to evaluate the CO2 emissions throughout the lifecycle of EVs [4]. Analyzed and compared the environmental emissions of EVs and fuel-powered vehicles across the manufacturing, use, and recycling stages in Europe [5]. conducted an LCA of fuel cell, electric, and hybrid vehicles in the United States, concluding that hybrid vehicles provide the greatest environmental benefits [6]. Assessed the carbon emissions of various new energy vehicle types, and [7]. Proposed a method for calculating carbon emissions during the manufacturing stage by analyzing the energy consumption and carbon emissions associated with different processes [8]. Given that conclusions may vary across nations due to differences in industrial development, diversity, and strengths, studying the carbon footprint of electric vehicles in China is particularly important.

In summary, while some research has explored carbon emissions across the raw material extraction, manufacturing, usage, and recycling stages of EVs, a gap remains in developing a comprehensive lifecycle carbon emissions model specific to Chinese EVs. Furthermore, the impact of emissions from individual vehicles on the future EV market in China, along with forecasts regarding this influence, remains unquantified. To address these gaps, this study divides the EV lifecycle into four stages—raw material acquisition, manufacturing, usage, and recycling—and develops a unified, user-friendly model for calculating lifecycle carbon emissions, specifically tailored for China.

The Life Cycle of an Electric Vehicle (EV)

Almost all automakers worldwide are advocating for the transition to EVs. Many claim that since EVs rely entirely on electricity during operation, their CO2 emissions are effectively zero. However, from a full cycle perspective, CO2 emissions still occur during electricity generation. Before the automotive industry achieves carbon neutrality, pure EVs cannot be considered zero-carbon vehicles. Moreover, assessing a vehicle's carbon emissions should not only focus on direct emissions during use but also account for its entire lifecycle [9]. This study aims to examine the carbon footprint of EVs in China throughout their lifecycle and assess their environmental and economic impacts. To this end, the lifecycle of an EV is divided into four stages: raw material acquisition, manufacturing and assembly, operation and use, and end-of-life recycling. The system boundary is illustrated in Figure 1. This study uses the BYD E6 as a case study, which is one of the earliest electric vehicles produced in China and holds a significant market share. Its comprehensive lifecycle data provides a valuable reference for understanding the carbon emission patterns and influencing factors of EVs in China.

Raw Material Acquisition Phase

The raw material acquisition phase involves a diverse range of materials. The main raw materials for EVs include steel, iron, aluminum, copper, magnesium, glass, plastics, and rubber. However, due to the relatively small proportion of materials such as magnesium, glass, plastics, and rubber, this study will exclude them from consideration.

The system boundary for the raw material acquisition stage extends from mining to the smelting and refining stages. The carbon emissions in this phase are primarily derived from the emissions generated during the material acquisition process. The consumption of raw materials and related carbon emission factors for manufacturing electric vehicles are summarized in Table 1.

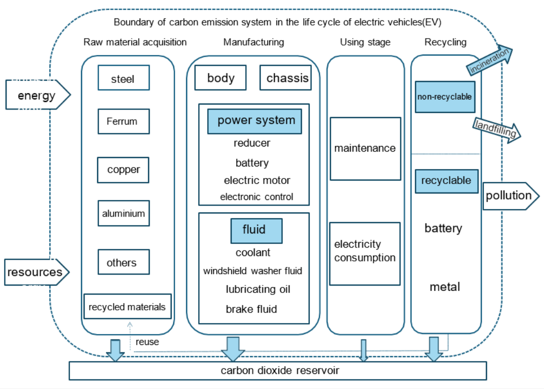

Figure 1: Boundary of carbon emission system in the life cycle of EV

Table 1: List of Consumed Metal Materials and Carbon Emission Factors for EVs

Metal types	Quality/kg	Carbon emission factor /[kg(CO2)/kg]
Steel	926.23	2.458
Iron	37.24	2.05
Aluminum	27.04	4.1
Copper	48	16.4

Note: The data on carbon emission factors corresponding to raw materials is sourced from the China Products Carbon Footprint Factors Database.

Manufacturing Phase

The assembly of a vehicle is a highly complex process that involves significant energy consumption in procedures such as painting, welding, heating, and lighting [11]. The total energy consumption is approximately 4973.85 MJ per vehicle, which includes the manufacturing of the body components, chassis, motor, electronic control system, reducer, etc. Notably, this stage also includes the manufacturing of batteries. Currently, commonly used power batteries for EVs include lithium iron phosphate ($LiFePO_4$), lithium manganese oxide (LMO), and ternary lithium batteries. In the production process of power batteries, the acquisition and processing of battery materials are the primary sources of carbon emissions. The material consumption and carbon emission factors for manufacturing power batteries are presented in Table 2, while energy consumption and quality for the production of various EV components are provided in Table 3.

Table 2: Statistics of Raw Material Consumption in Power Battery Production

Material types	Consumption/kg	Carbon emission factor /[kg(CO2)/kg]
Lithium Nickel Cobalt Manganese Oxide (NCM)	6,076.530 72	17
Polyvinylidene Fluoride	62.318 88	3.95
N-Methyl-2-pyrrolidone	889.761 6	0.553
Conductive Carbon Black	62.03808	1.82
Carbon Nanotubes	1,558.084 32	2.81
Graphite	3,696.507 36	5.48
Sodium Carboxymethyl Cellulose (CMC)	49.420 8	3.568
Styrene-Butadiene	212.228 64	0.12

Table 3: Energy Consumption in the Production and Manufacturing of Various Components of Electric Vehicles

Components	Quality/kg	Electric energy/ (MJ/kg)
Body	717.62	107.91
Chassis	620.40	6.58
Power Battery	481.9	42.13
Motor	93.12	5.03
Reducer	44	6.93
Electronic Control	79	1.37
Fluids	26	66.92

Usage Phase

The usage phase primarily involves electricity consumption and maintenance. In terms of maintenance, the focus is mainly on the replacement of fluids, like brake fluid, lubricating oil, coolant, windshield washer fluid, and refrigerant, resulting in a total carbon emission of 605.72 kg [10-14]. Regarding electricity consumption, key factors such as battery capacity, vehicle type, energy consumption per 100 kilometers, charging efficiency, and the total mileage must be considered. According to data from BYD's official website, the energy consumption of the BYD E6 is 20.5 kilowatt-hours (kWh) per 100 kilometers.

Recycling Phase

The end-of-life recycling phase of vehicles involves battery recycling and metal recovery, primarily involving the remanufacturing and reuse of power batteries and vehicle components, along with processes such as material recovery, incineration, and landfilling. Metal recovery is primarily achieved through smelting for reuse. Given that vehicles experience wear and tear during use, a mass loss of 2% is assumed for vehicle recycling [15]. The focus is on the recovery of metals such as steel, aluminum, iron, and copper. The corresponding recovery rates and energy consumption for recycling are presented in Table 4

Table 4: List of Metal Recovery Data

Metal types	Recovery rates/%	Recovery quality/kg	Electric energy /MJ
Body	90	816.935	3,356.89
Chassis	80	29.196	76.50
Power Battery	92	24.379	29.36
Motor	90	42.336	307.09

Different recycling technologies are employed for power batteries, resulting in variations in recovery rates and energy consumption. Currently, the principal recycling techniques for LiFePO4 batteries include cascade utilization and hydrometallurgical recovery. The cascade utilization method is primarily used for battery recycling, with a carbon emission of 84.99 kg [10]. Therefore, the offset ratio for the battery production phase of recycled products is 96.63% [16].

EV Carbon Emission Calculation Method

The total carbon emission over the full life cycle of an EV is the sum of emissions from four phases. Figure 2 illustrates the flow chart for EV carbon emission calculation, with the corresponding carbon calculation formula as follows:

$Ct = CRMA + CM + CU + CR$ (1)

where Ct represents the total life cycle carbon emissions, measured in kilograms (kg). CRMA, CM, CU, and CR represent carbon emissions during the raw material acquisition, manufacturing, usage, and recycling stages, respectively, also measured in kg.

Carbon Emission in Raw Material Acquisition

Carbon emissions in this phase arise from mining, processing, and related activities.

The calculation formula can be expressed as:

$$C_{\mathrm{RMA}} = \sum_{i=1}^{n} k_i \times m_i \qquad (2)$$

where CRMA is the carbon emissions in the raw material acquisition phase, measured in kg, k_i represents the carbon emission factor for the i^{th} material, measured in units of kg (CO2)/kg, mi represents the mass of the i^{th} material, measured in kg, and n represents the number of types of raw materials.

The total carbon emissions during the raw material acquisition phase of BYD E6, calculated using equation (2), amount to 3251.08 kg.

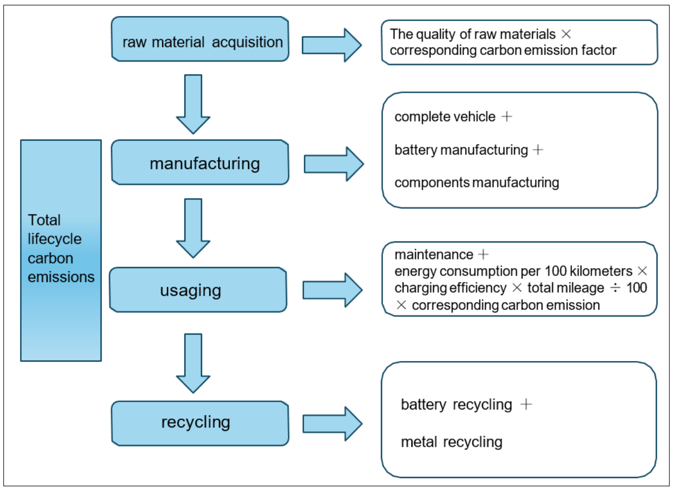

Figure 2: Flow Chart of Carbon Emission Calculation

Manufacturing Carbon Emission

Carbon emissions in this phase arise from three aspects: vehicle assembly, battery manufacturing, and the production of vehicle components. The corresponding formula is:

$$C_M = C_{assembly} + C_{battery} + C_{components} \qquad (3)$$

where Cassembly, Cbattery, and Ccomponents represent the carbon emissions generated in vehicle assembly, battery manufacturing, and components manufacturing, respectively, measured in kg.

$C_{assembly}$ =4973.85 MJx0.1614 kg(CO_2) /MJ=802.77939 kg (4)

Note: According to data from the Ministry of Ecology and Environment of the People's Republic of China in the *"Notice on Key Tasks for Managing Corporate Greenhouse Gas Emission Reporting in 2022*," the national grid emission factor in 2022 was 0.5810 kg(CO2)/(KW·h), with 1 KW·h = 3.6MJ.

$$C_{\mathrm{battery}} = \sum_{i=1}^{z} f_i \times q_i \qquad (5)$$

where f_i represents the carbon emission factor for the i^{th} material, measured in units of kg (CO2)/kg, q_i represents the mass of the i^{th} material, measured in kg, and z represents the number of types of battery materials.

$$C_{\text{components}} = \sum_{i=1}^{x} w_i \times E_i \times \mu \qquad (6)$$

where w_i represents the mass of the i^{th} material, measured in kg, E_i represents the electrical energy consumed in the production of the i^{th} component, measured in MJ, x represents the quantity of vehicle components, μ represents the carbon emission factor of electricity. The total carbon emissions for BYD E6 during the manufacturing phase, calculated using equations (4)-(6), amount to 146,649.14 kg.

Usage Phase Carbon Emission

Carbon emissions in the usage phase stem mainly from two key aspects: materials invested for maintenance and electrical energy consumed during vehicle charging. The calculation formula for this carbon emission is:

$$C_U = C_{\text{maintenance}} + C_{\text{charging}} \qquad (7)$$

where $C_{\text{maintenance}}$ and C_{charging} represent the carbon emissions generated by maintenance and charging, respectively, measured in kg.

$$C_{\text{maintenance}} = \sum_{i=1}^{o} \alpha_i \times \phi_i \qquad (8)$$

where α_i represents the mass of the i^{th} material, measured in kg, ϕ_i is the carbon emission factor for the i^{th} material, measured in units of kg (CO2)/kg, o denotes the quantity of material substitution.

$$C_{\text{charging}} = \frac{\delta \times \theta \times L \times \mu}{100} \qquad (9)$$

where δ represents the energy consumption per 100 kilometers, measured in KW·h /100km, θ represents the charging efficiency, L represents the total mileage of the electric vehicle.

Assuming the total mileage of an EV is 200,000 km, with a charging efficiency of 90% and an energy consumption of 20.5 KW·h per 100 km, the total carbon emissions in the usage phase, calculated using equations (7)-(9), amount to 15309.648 kg.

Recycling Phase Carbon Emission

Carbon emissions in the recycling phase arise from the energy required for battery recycling and metal recovery. The corresponding calculation formula can be written as:

$$C_R = C_{\text{battery recycling}} + C_{\text{meta recycling}} \qquad (10)$$

where C_{battery} recycling and C_{metal} recycling represent the carbon emissions produced in battery recycling and metal recycling, respectively, measured in kg.

$$C_{\text{battery recycling}} = r \times \mu \qquad (11)$$

where r represents the electrical energy consumed per unit mass in the recycling. μ is the carbon emission factor

$$C_{\text{metal recycling}} = \sum_{i=1}^{n} p_i \times \mu \qquad (12)$$

where p_i represents the electrical energy consumed in the metal recycling of the i^{th} material, measured in MJ. Similarly, μ is the corresponding carbon emission factor. The total carbon emissions for BYD E6 during the recycling stage, calculated using equations (10)-(12), amount to 693.442 kg.

Recycling and Reuse Offsetting

Disregarding recycling and reuse, the carbon emissions per EV, as calculated using
equation (1), are as follows:

$$Ct = 165{,}903.31 \text{ kg} \qquad (13)$$

Regarding recycling and reuse, the carbon emissions per EV, as calculated using equation (1), are as follows:

$$Ct = 38{,}399.09 \text{ kg} \qquad (14)$$

In summary, recycling and reuse result in a total reduction of 127,504.22 kg in carbon emissions. Notably, battery manufacturing represents the largest share of carbon emissions in the lifecycle of an EV, accounting for approximately 76.85%. Therefore, recycling and reuse are crucially helpful in lowering the lifecycle carbon emissions of EVs. Furthermore, the reduction of carbon dioxide can alleviate environmental issues such as the greenhouse effect and rising sea levels, while also economically reducing the funds required for carbon emission management.

Comparison with Internal Combustion Engine Vehicle (ICEV)

By comparing the carbon emissions across different phases of the lifecycle, this study calculates the variations in carbon emissions associated with pure EVs in versus fuel-powered vehicles in each phase. This comparison highlights the advantages of low carbon emissions inherent to EVs throughout their lifecycle. For illustrative purposes, the Volkswagen Lavida is used as a representative traditional vehicle. The lifecycle for a conventional fuel vehicle is also divided into four phases, and during the recycling phase, the carbon emissions of new energy vehicles and traditional vehicles are similar [18]. The detailed carbon emissions for each lifecycle phase of the internal combustion engine vehicle (ICEV) are provided in Table 5. Since the referenced literature does not consider the issue of recycling and reuse, only the total life cycle carbon emissions of electric vehicles, excluding recycling and reuse, should be considered. The detailed carbon emissions for each lifecycle phase of the EV are presented in Table 6.

Table 5: The Carbon Emission in the Life Cycle of the ICEV [17]

Stage	Value/kg
Raw material acquisition stage	4,830
Manufacturing stage	220
Usage stage	313,100
Recycling stage	693.442

Table 6: The Carbon Emission in the Life Cycle of the EV

Stage	Value/kg
Raw material acquisition stage	3,251.08
Manufacturing stage	146,649.14
Usage stage	15,309.648
Recycling stage	693.442

In conclusion, the total carbon emissions over the entire life cycle of an ICEV and EV amount to 318,843.442 kg and 165,903.31kg, respectively. Comparing Table 5 and Table 6, the carbon emissions during the manufacturing stage of an EV are higher than those of an ICEV, primarily due to battery production. However, during the usage stage, an EV has lower carbon emissions since it does not emit CO2 in a direct manner. Over the life cycle, an EV reduces carbon emissions by approximately 47.97% compared to an ICEV. If the electricity used is sourced from renewable energy, the life cycle carbon emissions of an EV could be reduced to as low as 20% of those of an ICEV or even lower. Overall, the total carbon emissions of an EV are significantly lower than those of an ICEV. This underscores the importance of promoting EVs as replacements for conventional vehicles to reduce CO2 emissions and mitigate the greenhouse effect.

EV Sales And Market Share Analysis

Compared to conventional fuel vehicles, new energy vehicles significantly reduce greenhouse gas emissions, decrease dependency on oil, and effectively mitigate urban pollution. Therefore, the development of new energy vehicles in China is expected to be rapid. Driven by strong national policies and market mechanisms, the sales and market share of NEVs in China have shown year-on-year growth from 2013 to 2024, as illustrated in Figure 3. This paper will also analyze and forecast future sales trends and market share dynamics.

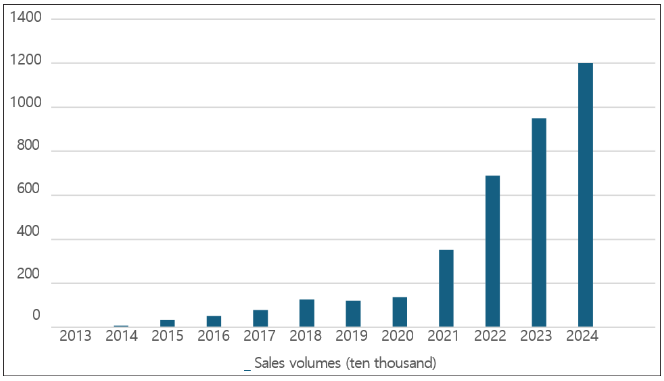

Figure 3: Historical Sales of EVs in China from 2013 to2024

Annual Market Size Growth Assumption

Assuming the market size grows by 5% each year:

$$s_t = s_{t-1} \times (1+y) \tag{15}$$

where S_t represents the market size in year t, S_{t-1} represents the market size in the previous year, and *y* represents the market growth rate.

Market Penetration Rate

If the market penetration rate increases linearly by 0.7% each year beginning in 2024, the market penetration rate for each subsequent year can be expressed as follows:

$$P_t = P_{2024} + 0.007 \times (t - 2024) \tag{16}$$

where *Pt* represents the market penetration rate in year *t*.

Sales Calculation Formula

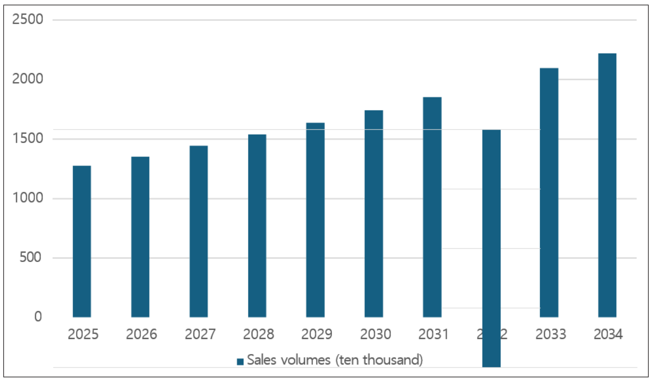

Figure 4: Predicted Sales of EVs in China from 2025 to 2034

The sales of new energy vehicles are calculated based on market size and market penetration rate:

$$v_t = s_t \times P_t \tag{17}$$

where *vt* represents the sales volume of new energy vehicles in year t. Through the calculations above, the sales forecast for new energy vehicles from 2025 to 2034 has been obtained, as detailed in Figure 4.

Hypothesis Testing

Hypothesis testing is a statistical method to make inferences about a population based on sample data. This study employs the t-test method to determine whether the forecasted sales of NEVs from 2025 to 2034 will be significantly higher than the sales value of 12 million units for 2024.

(1) Formulate Hypotheses
Null Hypothesis (H0):H0 = 12 million units
Alternative Hypothesis (H1 or Hα) : H1 : 12 million units

(2) Calculate test statistics

t-test method	Test statistics
Sample mean ($\bar{x}$)	1,737.3 ten thousand
TSS	934,581.09
Sample standard deviation	322.13 ten thousand
t-statistics	5.28
Degrees of freedom (n-1)	9
Significance level	α=0.05

(3) Make decision
The critical value for a significance level of α = 0.05 and degrees of freedom of 9 in the t-distribution table is approximately 1.833 (for a one-tailed test).

$$t = \frac{\bar{x} - \mu}{s/\sqrt{n}} \approx 5.28 > 1.833 \tag{18}$$

Based on the result, we abandon the hypothesis, indicating that there is sufficient evidence to suggest that the predicted average sales from 2025 to 2034 will significantly exceed the forecasted 12 million units for 2024.

Results and Discussion

In the previous sections, we have compared the total lifecycle carbon emissions of an EV and an ICEV, along with the annual market sales data for EVs. This allows us to get a deep understanding of the total carbon emissions generated by EVs and ICEVs in China, and subsequently calculate the yearly reduction in carbon emissions resulting from the replacement of ICEVs with EVs. The historical data is presented in Figure 5, while the predicted values are shown in Figure 6. From 2013 to the present, and in the forecast for the next decade, carbon emissions from ICEVs have remained the highest, far exceeding those of EVs. Notably, whether electric vehicles (EVs) are recycled plays a significant role in the growing disparity in carbon emissions. Therefore, prioritizing the development of EVs is essential. Advanced technology, optimized markets, and rational policies are vital for fostering growth.

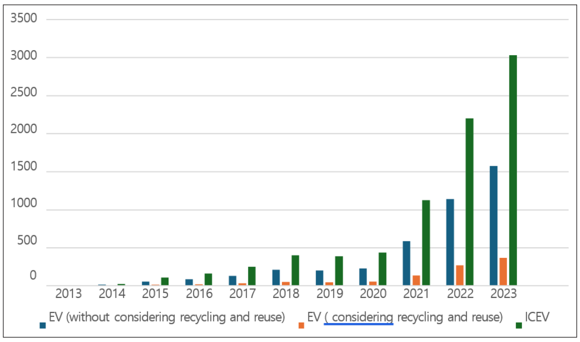

Figure 5: Annual total carbon emissions data for automobiles from 2013 to 2023 (unit: million)

Moreover, the carbon neutrality benefits brought by EVs, alongside their expanding market sales, should not be overlooked, as they contribute significantly to global economic and ecological development without incurring additional mitigation costs. Furthermore, the establishment of national carbon trading markets is a valuable policy tool that enables countries to control and reduce greenhouse gas emissions through market mechanisms. By internalizing the negative externality of carbon emissions, carbon markets incentivize enterprises to reduce their emissions. In the pursuit of carbon neutrality, enterprises that exceed government allocation limits must purchase carbon credits to offset their deficits, while emission-reducing entities or projects can profit by selling credits. As of October 2024, the price of compliance carbon emission allowances (CEA) in the EU carbon market is approximately €83/ton, while in China's carbon market, the price is around RMB 83.33/ton (approximately USD 11.74/ton), marking a historic high. This increase is primarily driven by upcoming regulations that impose higher fines on companies failing to meet emission obligations. Thus, in a future dominated by the NEV market, carbon finance also presents substantial revenue opportunities for both enterprises and nations [17,18].

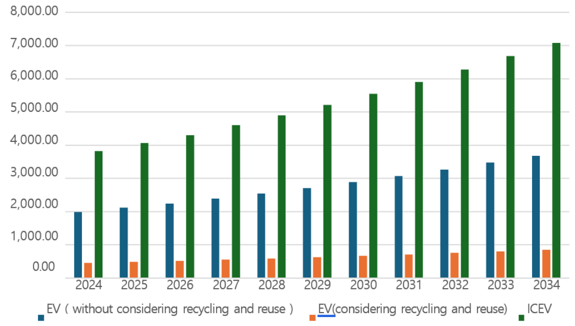

Figure 6: Predicted annual total carbon emissions data for automobiles from 2024 to 2034 (unit: million)

Conclusion

This study has established a lifecycle carbon emission calculation model for an electric vehicle (EV) to investigate its carbon footprint. The four phases of EVs—raw material acquisition, manufacturing, usage, and recycling—are thoroughly examined. Based on the real-world data calculation, the results indicate that carbon emissions from battery manufacturing account for the highest proportion at 76.85%. Subsequently, the study also examined the role of carbon emission offsetting through the recycling of raw materials and batteries. Recycling and reuse reduce a total of 127,504.22 kg in carbon emissions. This highlights the advantages of NEVs. Additionally, a comparison with conventional ICEVs was conducted to further emphasize the benefits of EVs. The total carbon emissions over the entire life cycle of an ICEV and EV amount to 318,843.442 kg and 165,903.31 kg, respectively. This further underscores that EVs play a crucial role in mitigating the substantial carbon dioxide pollution generated by the global automotive market, thereby contributing to environmental improvement. Based on the historical data, linear regression was used to predict the sales trends and market share of NEVs over the next decade. A t-test hypothesis test was then conducted to verify the feasibility and reliability of these predictions, providing that there is sufficient evidence to suggest that the predicted average sales from 2025 to 2034 will significantly exceed the forecasted 12 million units for 2024. Finally, discussions are offered to highlight that EVs will also bring benefits for both economic and environmental development.

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