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Research article

Life cycle assessment of atmospheric environmental impact on the large-scale promotion of electric vehicles in China

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ABSTRACT

Decarbonizing the transportation sector emerges as a pivotal step in addressing climate change. In recent years, rapid growth in China's new energy automotive industry has significantly contributed to transportation decarbonization. However, environmental challenges in producing and recycling electric vehicles (EVs) may limit emission reduction benefits. In this study, we establish a comprehensive life cycle assessment model for vehicles to analyze the gap in air pollutant and greenhouse gas emissions between electric vehicles and internal combustion engine vehicles (ICEVs). Based on this model, the environmental benefits of further promoting electric vehicles in China are evaluated. Results reveal that, compared to ICEVs, EVs reduce life cycle emissions of CO_2 by 12%, NO*x* by 69%, and VOCs by 9%. Primary constraints on EVs in emission reduction are traced to raw material and component production, notably lithium batteries. By 2025, under the low carbon EVs policy scenario, widespread EV production and sales could cut lifecycle emissions by 3.55 million tons of CO_2, 3,6289 tons of NO*x*, and 4315 tons of VOCs. During the driving stage, these indicators contribute 495%, 124%, and 253%, respectively, to total emission reduction throughout the lifecycle. This study conducts a comprehensive lifecycle analysis of greenhouse gases and various air pollutants for Chinese EVs. It integrates the latest market trends, application progress, and policy guidelines into scenario design, identifying key sources and indicators of atmospheric pollution in the EV production chain. The findings offer valuable policy insights into China's role in the global emission reduction process.

1. Introduction

Transportation activities serve as a vital medium within the global economic system (Fleming and Hayuth, 1994; Lenzen et al., 2018; Ibn-Mohammed et al., 2021). As global production activities and trade connections continue to expand, decarbonization of the transportation sector emerges as a pivotal step in addressing climate change globally (Pan et al., 2018; van der Zwaan et al., 2013; Wang et al., 2022). Nations worldwide are implementing robust measures to build sustainable and eco-friendly smart city transportation, such as accelerating the adoption of electric vehicles (EVs) (Lopez-Carreiro and Monzon, 2018; Solaymani, 2019). In recent years, the number of EVs around the world has developed rapidly, reaching 1.26 million units in 2015 (Kim et al., 2019). As the world's second-largest economy, China is in the stage of high-quality and rapid development (Jahanger, 2021). The transportation activities in China are highly dependent on highways, and thus there exists substantial untapped potential for future growth in highway transportation demand (Wang et al., 2020; Xu et al., 2021). Therefore, promoting new energy vehicles in China can not only accelerate the decarbonization of the transportation sector, but also synergistically promote the reduction of air pollutants such as nitrogen oxides (NOx), sulfur dioxide (SO_2), fine particulate matter ($PM_{2.5}$), etc. Simultaneously, it provides more diversified energy resource options to promote the country to achieve climate change goals, address energy challenges, and promote the intelligent upgrading of the automotive and transportation industry (Zhang and Bai, 2017; Su et al., 2021; Duan et al., 2023).

Numerous studies have discussed carbon dioxide (CO_2) or atmospheric pollutant emissions related to passenger cars (Chavez-Baeza and Sheinbaum-Pardo, 2014; Duan et al., 2021). Most of the results highlight EVs' substantial emission reduction benefits in the driving stage and the entire life cycle compared to internal combustion engine vehicles (ICEVs). However, when extending to the production stage of the entire life cycle, there emerge disparities in research conclusions. Shen et al. (2019) discovered that in 2012, fuel vehicles and pure EVs generated 229 and 129–205 g CO_2 eq/km respectively, and in 2015, these figures decreased to 199 and 91–171 g CO_2 eq/km. Ke et al.

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Abbreviations:

EVs	electric vehicles
ICEVs	internal combustion engine vehicles
CO_2	carbon dioxide
NOx	nitrogen oxides
VOCs	volatile organic compounds
SO_2	sulfur dioxide
$PM_{2.5}$	fine particulate matter
BAU	business as usual scenario
LCE	low carbon EVs policy scenario
PCELC	production and consumption enhanced low carbon EVs policy scenario

(2017) found that promoting EVs in Beijing can reduce CO_2 emissions by 32% and 46% compared to ICEVs. The pivotal differentiating factor between EVs and ICEVs is the power battery, which may pose many ecological risks in the production, recycling, utilization, and disposal of various industrial links throughout its life cycle (Huo et al., 2010; Xia and Li, 2022). Franzò and Nasca (2021) identified that the geographical location of carbon emissions from EV manufacturing significantly impacted the life-cycle emissions, with the use stage, car and battery manufacturing having the main impact. Meng et al. (Cui et al., 2011; Meng et al., 2017) constructed a GHG accounting evaluation model for urban public transportation systems and found that upstream and downstream emissions have a significant impact on the GHG emissions of urban public transportation systems. The greenhouse gas emissions from operation and maintenance, vehicle materials and fuel production, and transportation and construction stages in the BRT system account for 14%, 3%, and 2% of the total, respectively. McManus (2012) found that critical materials required for lithium battery production is the main contributor to greenhouse gas, with 12.5 kg CO_2 emitted per kg of lithium battery production.

Regarding other pollutant emissions, studies show that EVs have lower carbon emissions and nitrogen oxide than gasoline vehicles, while particulate matter and sulfur dioxide emissions are higher (Yang et al., 2021). Li et al. (2019) used the "well-to-wheel" framework to assess the regional marginal effects of implementing EVs. The results showed that in 2017, NOx emissions could be reduced in all provinces that implemented EVs, but SO_2 emissions could only be reduced in the southern region of the Yangtze River. Overall, although variations exist in the pollutant and carbon emission reduction effects across different types of EVs throughout their entire life cycle, there is a consensus on whether EVs can achieve emission reduction during their entire life cycle depends on the cleanliness of energy consumption and vehicle material production and manufacturing (Nordelöf et al., 2014; Verma et al., 2022). Due to the higher emission factors of particulate matter and acidic gases in China's power production at this stage, compared to fuel oil, there is a potential risk of increased emissions during the entire life cycle of EVs (Andersson and Börjesson, 2021; Lai et al., 2022; Zheng and Peng, 2021).

Contemporary LCA studies predominantly emphasize greenhouse gas emissions as a means of evaluating the environmental impact of EVs, with little consideration of the impact of EVs on air pollutant emissions. In addition, there is a lack of research based on production status, especially to identify the main emission types in the manufacturing process of lithium batteries, components, and complete vehicles, in order to develop emission reduction strategies for EV's production (Dey and Mehta, 2020; Andersson and Börjesson, 2021; Salemdeeb et al., 2021) Many existing studies primarily focus on the life cycle analysis of specific internal combustion engine, electric, and hybrid vehicle models, often without conducting comprehensive and systematic assessments of market size and application conditions (Onat et al., 2016). Additionally, limited research has been devoted to investigating the medium- and long-term atmospheric environmental benefits associated with the large-scale promotion of electric passenger vehicles, particularly within the context of policy and market influences. This study aims to address these issues by verifying the medium- and long-term impacts of greenhouse gas and air pollutant resulting from the promotion of EVs in China under varying levels of low-carbon policies, and provide options for countries to develop policy tools to promote the production and consumption of EVs.

In this study, we select typical internal combustion engines and electric passenger vehicles in China as objects and establish a 'cradle-to-grave' life cycle assessment model. Based on this model, we compare pollutant and carbon emissions differences between the two types of vehicles across four stages: Raw material stage, Production stage, Driving stage, and Recycling stage. Considering policy objectives and the current state of market promotion, this study also forecasts the medium- and long-term production and consumption scale. It evaluates the ecological and environmental benefits that will result from the further expansion of the production and consumption scale of new energy vehicles in the future. Compared to previous studies, we have conducted a cross-sectional analysis of greenhouse gases and multiple atmospheric pollutants specific to the current situation in China, highlighting China's contribution to global emissions reduction. Furthermore, we conducted scenario design based on the latest market scale, application progress, and policy directions to identify the emissions-intensive stages and indicators in the production chain of EVs. This assessment is conducted to provide policy recommendations for achieving a carbon peak in transportation and promoting the green and low-carbon development of new energy vehicles.

2. Methods and data

2.1. Object and boundary

This study selects two of China's best-selling EV and ICEV models with similar specifications. Specifically, the EV is BYD Qin plus EV2021, and the ICEV is Volkswagen Lavida, which ranked 2nd and 3rd, respectively, in China's A-class car sales in 2022. Parameters of two vehicles are from the "Catalog of New Energy Vehicle Models Exempted from Vehicle Purchase Tax" issued by the Ministry of Industry and Information Technology of China and public data of enterprises (Table 1).

The functional unit of this study is the transportation service provided by a vehicle traveling 1 km during its lifecycle. According to the general parameters of automotive products, we assume that the lifespan of the two vehicle models is 150000 km, with a lifespan of 10 years. The evaluation indicators include atmospheric pollutant emission indicators such as CO_2, NOx, volatile organic compounds (VOCs), SO_2, and $PM_{2.5}$. The production behavior and emission information of the entire lifecycle system mainly considered in this study are shown in Table 2. Life cycle system boundary of this study is shown in Fig. 1.

2.2. Life cycle inventory analysis

When evaluating the 'cradle to grave' life cycle impact of the two types of vehicles, we consider the energy consumption level, production behavior, and other activities across the four stages of raw materials, production, driving, and recycling. We also clarify the emission factors for each activity to assess the air pollutants and greenhouse gas emissions of EVs and ICEVs per function unit. The calculation method of life cycle environmental impact is as follows:

$$F_i = \sum_{1}^{j} AD_j BD_{i,j} \tag{1}$$

where: F_i is the total output of environmental impact at each stage of the life cycle; i refers to the impact category, which is reflected in

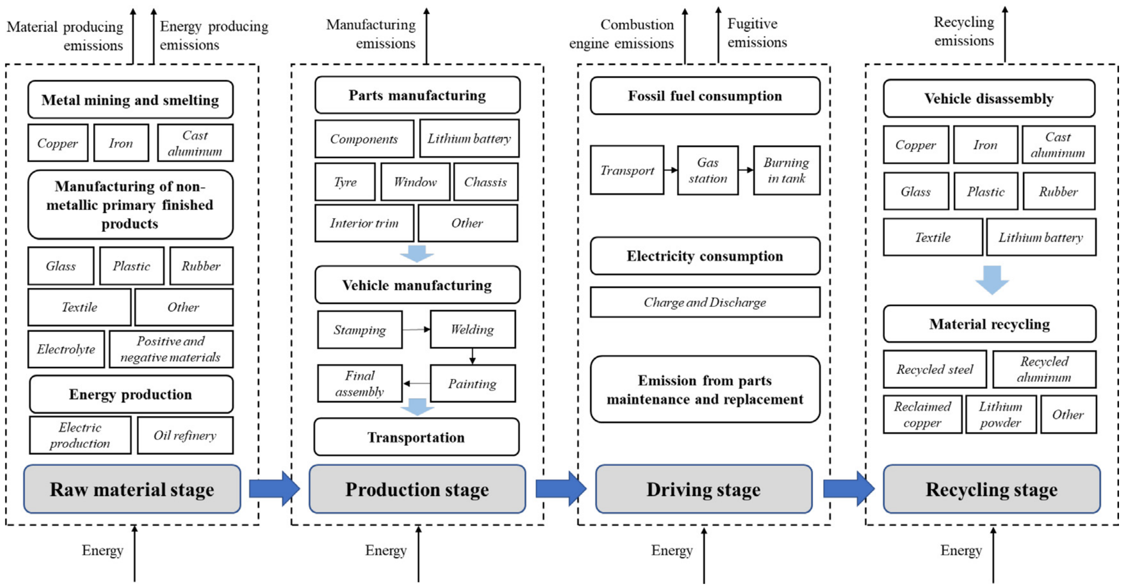

Fig. 1. Life cycle system boundary of this study.

Table 1
Parameters of the vehicle model studied.

Parameter	EV	ICEV
Maximum speed (km/h)	130	190
Maximum horsepower (kW)	100	84
Length/width/height (mm)	4765*1837*1515	4678*1806*1474
Wheelbase (mm)	2718	2688
Curb weight (kg)	1640	1295
Fuel consumption per 100 km (L)	–	5.92
Mileage (km)	150 000	150 000
Battery type	Lithium iron phosphate battery	–
Battery capacity (kWh)	57.6	–
Endurance mileage (km)	510	–
Power consumption per 100 km (kWh)	12.3	–
Total mass of battery pack (kg)	387.6	–

atmospheric emission indicators such as CO_2, NOx, VOCs, PM, SO_2; j refers to a certain stage in the life cycle of EV and ICEV, which is the raw material, production, driving and recycling stage in this study; AD_j refers to the activity data of EV and ICEV at j life cycle stage; $BD_{i,j}$ refers to the class i impact factor data of EV and ICEV at stage j, which is obtained from literature and database. More details are shown in Appendix A.

2.3. Scenario design

The medium-term scenario is set from the present to 2025, while the long-term scenario extends to 2035. Based on the trend of rapid growth in sales and penetration of China's new energy vehicle market, this study sets up business as usual scenario (BAU), low carbon EVs policy scenario (LCE) and production and consumption enhanced low carbon EVs policy scenario (PCELC). In the BAU scenario, the government does not adopt any EV promotion policy, and the market penetration level of EVs will remain around 25.0% in the future. LCE scenario is a low-carbon policy scenario, which refers to a series of new energy vehicle promotion measures planned by the Nation's new energy vehicle industry planning (2021–2035). It is assumed that the market penetration rate of EVs will reach 30.0% and 50.0% by 2025 and 2035. PCELC scenario refers to adopting a series of measures to strengthen the production and consumption of new energy vehicles, such as expanding the application in the public transportation system, exempting purchase tax, and promoting the intelligent upgrade of EV products. It is assumed that the market penetration rate of EVs will reach 40.0% and 60.0% by 2025 and 2035. More detailed descriptions of the scenario are shown in Table 3.

2.4. Limitations in methods

The limitations of method and data are as follows: This study only selected one type of vehicle with the highest sales proportion, while the passenger cars are diverse in sizes, and their materials may be different. Due to limitations in data availability, the selection of production process parameters for lithium batteries and vehicle materials may overlook the rapidly developing manufacturing technologies and the different types of manufacturing methods used in the same manufacturing process, which may result in different carbon footprints. Finally, energy production and consumption may have a significant impact on the conclusions of this study, and this study has not considered the impact of Chinese rapidly use of renewable energy on the model results.

3. Results

3.1. Total emissions of life cycle

The total emissions of air pollutants and GHG (CO_2 equivalent) per mileage in the whole life cycle of ICEVs and EVs are shown in Fig. 2. The results show that the promotion of EVs has significant CO_2, NOx and VOCs emission reduction benefits in the whole life cycle. The life cycle CO_2 emissions of EVs and ICEVs are 199.6 g and 226.1 g per kilometer, respectively, which means EV's life cycle CO_2 emissions are reduced by 12% compared with ICEVs. EV's life cycle NOx and VOCs emissions are 124.9 mg/km and 334.7 mg/km, respectively, 69% and 9% lower than ICEVs. However, LCA results show that the emissions of SO_2 and $PM_{2.5}$ in the EV's life cycle are 76% and 21% higher than those of ICEVs. This increase is primarily attributed to direct emissions from the production of EV materials, energy consumption emissions during power batteries' manufacturing and driving stages.

As for each stage, one of the most restriction of EV's life cycle GHG emission reduction is the production of primary products such as metals, plastics and rubber. The CO_2 emissions of EVs and ICEVs in the raw material stage are 179.7 g/km and 78.7 g/km. The EVs are 128% higher than ICEVs, accounting for 90% and 35% of the CO_2 emissions in their life cycles. The upstream carbon reduction of the supply chain in the development of EVs should be focused on. Every emission indicators

Table 2
EV and ICEV life cycle system boundaries.

Stage	Production behavior	Input material/energy	Emissions considered in this study
Raw material stage	Metal ore mining, mineral processing and metal smelting	Diesel and gasoline for machinery	Carbon Dioxide (CO_2), Nitrogen Oxides (NOx), Particulate Matters (PMs), etc
	Manufacturing of rubber, glass, plastics, lithium chemicals and other primary products	Relevant auxiliary materials; On grid power	CO_2, PM, (volatile organic compounds) VOCs, etc
	Electricity production	Coal, natural gas, etc;	CO_2, PM, (Sulfur Dioxide) SO_2, NOx, etc
	Gasoline and diesel refining	Related accessories	VOCs, NOx, PM, SO_2, etc
Production stage	Casting, rolling, stamping and wire drawing process (from raw materials to products) of general body parts	Natural gas, coal and other related auxiliary materials; On grid power	Metal dust, VOCs, CO_2, NOx, SO_2, etc
	Manufacturing of core parts and components of power system (mainly drive motor and lithium battery for EVs, engine and gearbox for ICEVs)	Natural gas; On grid power	Metal dust, VOCs, CO_2, NOx, SO_2, etc
	Vehicle manufacturing and assembly (stamping, painting, welding and assembly processes)	Natural gas and other related auxiliary materials; On grid power	VOCs, CO_2, NOx, SO_2, etc
Driving stage	Energy consumed during vehicle driving	Vehicle gasoline; On grid power	CO_2, NOx, PM, VOCs, etc
	Vehicle repair, maintenance and parts replacement	Lubricating oil, refrigerant, etc	VOCs fugitive
Recovery stage	Disassembly and shredding of vehicle body	Diesel oil, liquefied petroleum gas and other related auxiliary materials; On grid power	CO_2, NOx, PM, VOCs, etc
	Body material recycling	Coal, gasoline, diesel, natural gas and other related auxiliary materials; On grid power	CO_2, NOx, PM, VOCs, etc
	Lithium-battery material recycling	Natural gas and other related auxiliary materials; On grid power	CO_2, NOx, PM, VOCs, etc

Note: 1. In this study, emissions from the production of secondary energy (mainly electricity, diesel, and gasoline) are included in the raw material stage, while emissions from the consumption of primary energy (coal, natural gas, etc.) are included in each stage.
2. The direct emission of environmental pollutants during the manufacturing process of components is relatively low, which was ignored in this study (Hu and Li, 2019; Shen et al., 2019). This study only considers the emissions caused by energy consumption during the vehicle body disassembly process, and the direct emissions are ignored.
3. This study assumes that all manufacturing processes use common technologies, and ignore the differences in pollutants generated by different manufacturing processes.

Table 3
Policy scenario design.

Scenario	Description
BAU	The government will not adopt any EV promotion policy. By 2025 and 2035, the proportion of EVs in new vehicle sales will remain at 25.0%.
LCE	According to the measures of the New Energy Vehicle Industry Planning (2021–2035), the government will promote EVs to become the mainstream of new sales vehicles by 2035. By 2025, the proportion of EVs in new car sales will be 30.0%, and by 2035, it will reach 50.0%.
PCELC	On the basis of the New Energy Vehicle Industry Plan (2021–2035), the government will introduce measures to stimulate production and consumption, such as electrification pilot, application on the public transportation, exempting purchase tax, and promoting the intelligent upgrade of EV products. By 2025, the proportion of EVs in new car sales will be 40.0%, and by 2035, it will reach 60.0%.

of EVs in the raw material stage are higher than those of EVs, with NOx and $PM_{2.5}$ being 139% and 121% higher than those of ICEVs. In the production stage, the manufacturing of lithium batteries generate more energy consumption and emissions that makes EV's five indicators higher than ICEV. For example, the EV's production CO_2 emissions are 45% higher than that of ICEVs. Other contaminants such as VOCs, NOx, $PM_{2.5}$ and SO_2 of EVs are 1.1, 1.3, 1.4, 1.6 times higher than those of ICEV's.

During the driving stage, the EV's emissions are significantly lower than those of ICEVs because the emissions of EVs related to energy consumption are zero. In this stage, EV's CO_2, VOCs, NOx and $PM_{2.5}$ emissions are reduced by 95%, 87%, 97% and 79% respectively. ICEV's pollutant emissions are most concentrated on the driving stage with the highest proportion of GHG emissions accounting for 61%. While the contribution of NOx and $PM_{2.5}$ emissions of ICEVs is as high as 87% and 49% in the whole life cycle, further indicating that the promotion of EVs has significant environmental emission reduction benefits during this stage.

In the recycling stage, the main emission sources in the recycling stage are vehicle disassembly, body materials, and lithium battery material regeneration. The five atmospheric emission indicators of EVs are higher than those of ICEV. The proportion of air pollutant emission indicators in the life cycle is relatively low, ranging from 0.1% to 0.6% for EVs and 0.1% to 0.5% for ICEVs. The main reason for the differences in emission level is the increased energy consumption and production emissions during the regeneration of EV lithium battery materials into metals.

3.2. Stage distribution of five emission indicators

(1) CO_2 emissions

The emission distribution in stages for the two vehicles is shown in Fig. 3. The CO_2 emissions of EVs are mainly distributed in the raw material stage of the life cycle, and emissions from energy production are 144.8 g/km, accounting for 73% of the total life cycle emissions. The EV's life cycle contribution of CO_2 emissions related to raw material production is more than 90%, while the CO_2 emissions of ICEVs are mainly distributed in the driving stage, accounting for 58% of its life cycle. In general, the usage of EVs has significant CO_2 emission reduction benefits in the driving stage, but the increase in

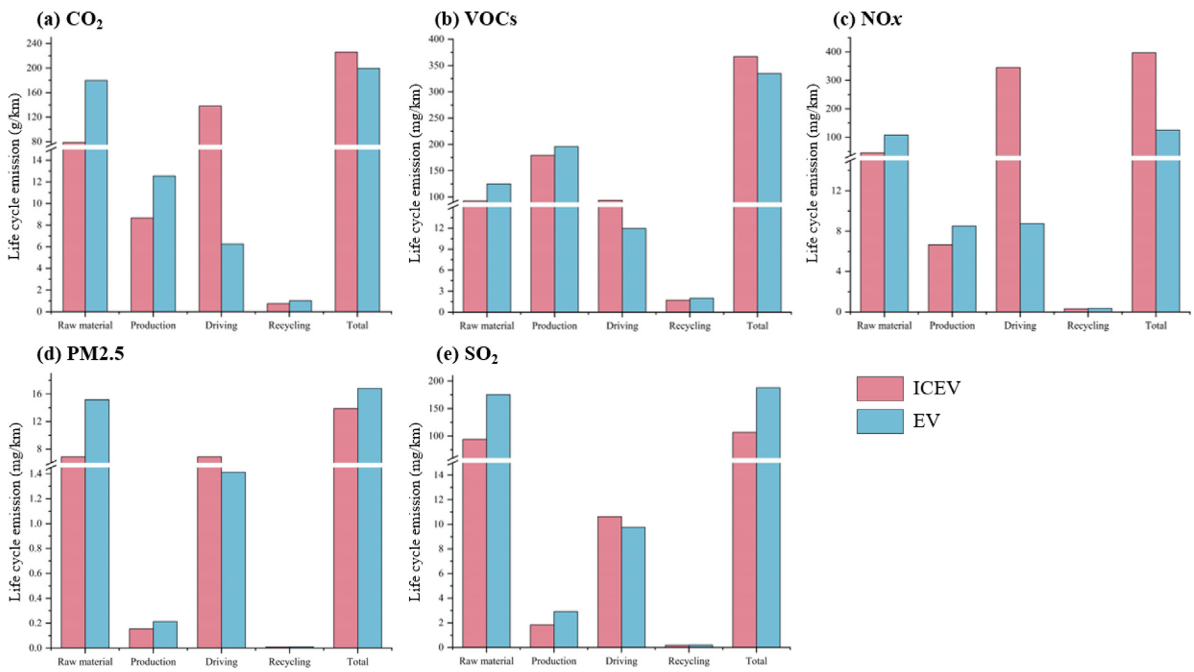

Fig. 2. Life cycle emissions of EVs and ICEVs.

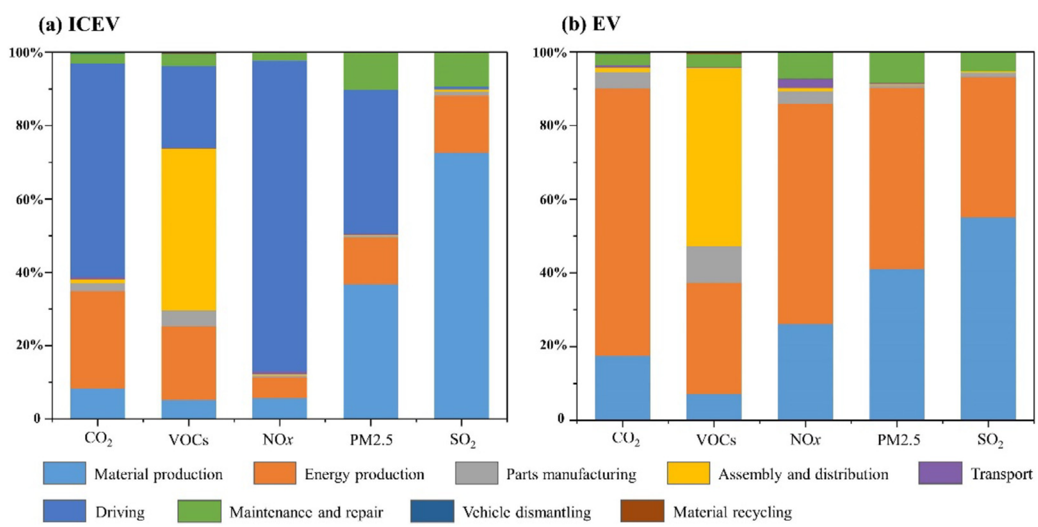

Fig. 3. Distribution of emission stages in the life cycle of EVs and ICEVs.

emissions from the production of upstream raw materials and energy may restrict the CO_2 emission reduction benefits in the whole life cycle. The main processes with high impact are the production of raw materials for vehicles, energy production, and parts manufacturing. These three processes of EVs are 86%, 141% and 78% higher than that of ICEVs, respectively. The main reason is that a series of activities such as mineral mining, raw material manufacturing, battery cells and modules production are required for the production and manufacturing of lithium batteries.

(2) VOCs emissions

Most of the life cycle VOCs emissions of EVs and ICEVs come from the production chain, and the total proportion of the raw material and production stage is 96% and 74%, respectively. The whole vehicle manufacturing process involves the coating and welding process, resulting in a large number of direct VOCs emissions. As a result, the VOC emissions of EV and ICEV in the whole vehicle manufacturing process account for the highest proportion in the life cycle, reaching 48% and 44%, respectively. The second VOCs emission source is energy production, with EV and ICEV reaching 30% and 20%, respectively in their life cycle. The promotion of EVs brings significant VOCs emission reduction benefits, which is mainly reflected in the driving stage. The VOCs emissions of ICEVs at this stage are 81.89 mg/km, constituting 22% of its life cycle emissions. In contrast, EVs exhibit zero emissions during the driving stage. VOCs emissions associated with material production, transportation, disassembly and distribution are minimal, ranging from 0.1% to 7%.

(3) NO*x* emissions

The NO*x* emissions of ICEVs are concentrated in the driving stage, mainly from the combustion of gasoline fuel, accounting for 85% of its life cycle. In contrast, the main NO*x* emissions of EVs come from the energy production and vehicle raw material production, which contribute 60% and 26% to EV's life cycle. The main reason for this difference is still energy production. Given that China's current energy structure dominated by thermal power, the large-scale promotion of EVs may lead to an increase in NO*x* emissions due to energy consumption.

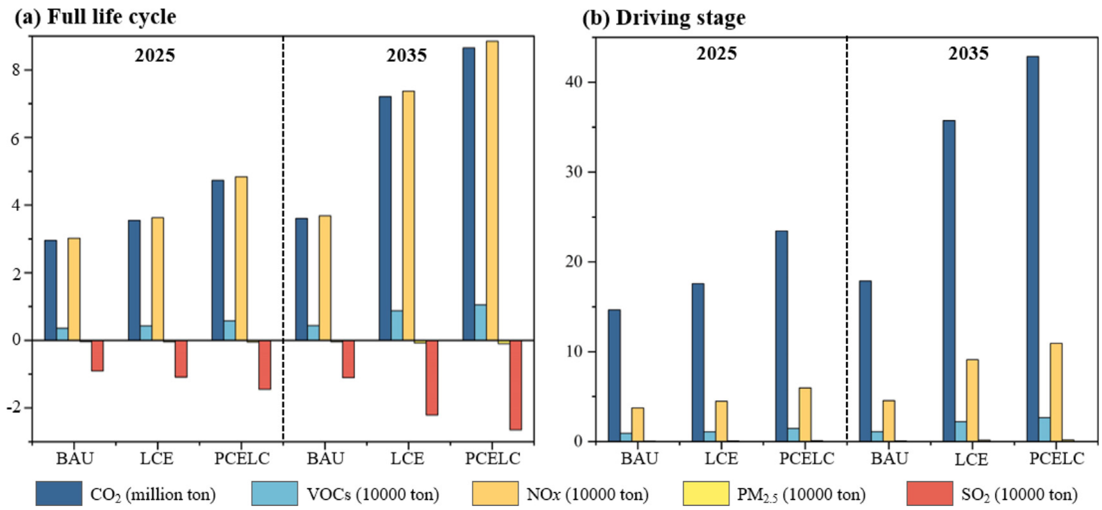

Fig. 4. Life cycle and driving stage emission reduction of EV's large-scale promotion.

Secondly, an increase in upstream NO*x* emissions due to the production of vehicle materials, especially lithium batteries, can largely offset the NO*x* emission reduction during the driving stage brought about by the promotion of EVs.

(4) $PM_{2.5}$ emissions

The $PM_{2.5}$ emissions from the raw material production of EVs and ICEVs are 6.9 mg/km and 5.1 mg/km, respectively, contributing 41% and 37% to their respective life cycles, mainly from the development of mineral resources such as iron and steel, and from the acquisition of lithium iron phosphate and other lithium battery related raw materials. For EVs, $PM_{2.5}$ emissions related to energy production contribute 49% to the life cycle. In the driving stage, ICEVs generate 5.5 mg/km of $PM_{2.5}$ emissions, accounting for 39% of the life cycle, which means the promotion of EVs in the driving stage has obvious $PM_{2.5}$ emission reduction benefits.

(5) SO_2 emissions

The SO_2 emissions of EVs and ICEVs are mainly concentrated in the material and energy production stage, with the contribution of their whole life cycle is 93% and 88%, respectively. The SO_2 emissions of EVs in the process of vehicle raw material production and energy production were 103.5 mg/km and 71.5 mg/km, which are 34% and 332% higher than that of ICEVs, mainly due to the production of steel, aluminum, plastics and lithium iron phosphate materials, as well as the production of EV's electric consumption in the driving stage. It should be noted that the SO_2 emission during the maintenance of the vehicles reached 9.8 mg/km, accounting for 5% and 9% of the life cycle of EVs and ICEVs, mainly due to the SO_2 emission during the maintenance and replacement of lead–acid batteries.

3.3. Environmental benefits under different scenarios

Chinese automobile market has maintained an average growth rate of 3.4% in the past decade. Assuming that the growth rate maintain 3.4% in the medium term (2023–2025), and will slow to 2.0% in the long term (2026–2035), Chinese vehicle sales will expected to be 29.66 and 36.16 million by 2025 and 2035. This study assume that the newly sold EVs replace the ICEVs in equal quantities, and assessed the environmental benefits, as shown in Fig. 4. The results show that under the BAU scenario, by 2025, the promotion and replacement of EVs can reduce the emissions of CO_2, NO*x* and VOCs in the whole life cycle by 2.9583 million, 30.2 and 3.6 thousand tons, among which the contribution in the driving stage will be 495.42%, 123.67% and 253.31%. By 2035, new energy vehicles will become the mainstream of production and sales in China. Under PCELC scenario, It can achieve 42.88 million, 109.4 and 26.6 thousand tons of CO_2, NO*x* and VOCs emissions reduction in the whole life cycle, which the CO_2 emissions is equivalent to 6.0% of China's total vehicle emissions at the driving stage in 2020. Under the trend of low-carbon transformation, this emission reduction effect will be further improved. With the strengthening of the promotion policy of EVs, the life cycle CO_2, NO*x* and VOCs emission reduction benefits under these three scenarios will improve. Under the LCE scenario, through the implementation of the EVs development plan and low-carbon policies, the medium and long-term life cycle CO_2 emission reductions reached 3.55 and 7.21 million tons. In the driving stage, the five indicators under all scenarios can achieve emission reduction, which is the most significant under the PCELC scenario. Under this scenario, the CO_2 emission reduction in the medium and long term at the driving stage is equivalent to 3.26% and 5.96% of China's total CO_2 emissions of vehicles in 2020. In addition, China's rapidly growing new energy installed capacity will help strengthen the environmental effect, which may further enhance the five air pollutant emission reduction benefits of the three policy scenarios.

4. Discussion and policy implications

4.1. Comparison with other studies

This study established the LCA emission inventory of EVs and ICEVs, identified the main environmental impact stages and specific processes from ''cradle to grave'', and analyzed the key pollutant indicators of environmental impact in each stage. Compared with other studies, this study not only focused on greenhouse gas emissions, but also focused on NO*x*, VOCs, PM, SO_2 and other types of air pollutants, and carried out a comprehensive analysis. In addition, in the context of the rapid global development of new energy vehicles, the latest policy scenarios were designed to systematically evaluate the environmental emission reduction of road traffic and the environmental impact of the upstream production stage that the large-scale promotion of EVs may bring about. This provides a robust methodological framework and data support for achieving the synergistic reduction of carbon emissions and other pollutants within the automotive industry. The differences between the research focusing on both GHG and other emissions and this research are shown in Table 4. The EV emission reduction ratios of CO_2, NO*x*, and VOCs range from 12%–32%, 6%–69%, and 9%–95%, while in this study, they are 6%, 69%, and 11%. The reason for the differences in results are the selection of vehicle models and emission parameters, as well as technological updates, and the differences between these studies are not statistically significant. In general, although there are differences in the study models and emission reductions, the conclusion that

Table 4
Comparative analysis of research results.

Author	Vehicle type	Life boundary	Indicator evaluated	Life cycle assessment results
This study	EV, ICEV	Well to wheel	CO_2, VOCs, NO*x*, $PM_{2.5}$, SO_2	Compared with ICEV, EV reduced CO_2 emissions by 11.8%, VOCs emissions by 8.8% and NOx emissions by 69.1%, but increased $PM_{2.5}$ and SO_2 emissions by 21.2% and 76.3%.
Yang et al. (2021)	EV, ICEV, PHEV	Well to wheel	CO_2, VOCs, NO*x*, $PM_{2.5}$, SO_2	Compared with PHEV, BEV reduced CO_2 emissions by 18% and 1%, VOCs emissions by 24% and 16%, NO*x* emissions by 6% and 3%, but increased $PM_{2.5}$ emissions by 159% and 79%, and SO_2 emissions by 111% and 56%.
Ke et al. (2017)	EV, HEV, ICEV	Well to wheel	CO_2, VOCs, PM, SO_2	Pure EVs are expected to achieve 32% and 46% CO_2 emission reduction in Beijing. Compared with ICEV, EV has achieved 95% VOCs emission reduction in 2015, but the NO*x*, $PM_{2.5}$ and SO_2 emissions are higher than ICEV, but they are expected to be significantly reduced in the future.
Lang et al. (2013)	HEV, EV	Well to wheel	SO_2, NO*x*, VOCs, CO, NH_3, PM_{10}, $PM_{2.5}$, CO_2, N_2O, CH_4, Pb, Hg	EV can reduce the emissions of many VOCs and CO_2, but the emissions of SO_3, NO*x* and particulate matter increased by 2.2-10.8 times, 13.0-2.7 times and 2.9-3.6 times respectively.
Huo et al. (2013)	EV, ICEV, CNGV	Well to wheel	GHG, $PM_{2.5}$, PM_{10}, NO*x*, SO_2	EVs can reduce GHG emissions by 20%, but increase PM_{10}, $PM_{2.5}$, NO*x*, and SO_2 emissions by approximately 360%, 250%, 120%, and 370%, respectively.

Note: PHEV stands for Plug-in hybrid EV, HEV stands for hybrid EV, CNGV stands for compressed natural gas vehicle.

EV can significantly reduce CO_2 and VOCs emissions in the life cycle and activities in the raw material production may increase particulate matter and SO_2 emissions can reach a consensus. This conclusion is supported by some other studies (Lang et al., 2013; Ke et al., 2017; Yang et al., 2021), which further confirms the robustness of the model constructed in this study and the reliability of the conclusion.

4.2. Limitations

This study focuses on a representative passenger vehicle to carry out an environmental impact assessment, and selects one mainstream sales model as representative to carry out large-scale promotion scenario analysis. While new energy vehicle technology and product innovation are accelerating, there is some limitations on comparing just one EV and ICEV model given diversity of vehicle types emerging. Under the trend of vehicle electrification expanding beyond passenger vehicles to trucks, buses and other types of automobiles, the manufacturing process of different models can be completely different. Given the future trend toward comprehensive electrification of various vehicle types, there is a need for further improvement in order to achieving comprehensive environmental impact assessments in this model. In addition, this model does not consider the impact of changes in new energy installed capacity and energy structure adjustment on the results. Presently, China is taking solid measures to promote the development of clean energy, which will have a particular impact on the results of pollutant emissions in the raw material stage. The impact of geographical differences in the production and consumption of EVs and ICEVs on the results cannot be ignored. For example, the production of lithium ore in China is mainly concentrated in Jiangxi, Qinghai provinces, while production and consumption of EVs are distributed throughout the country. There are also significant differences in fossil fuels and electricity production and consumption regions. From a methodological perspective, the model established in this study lacks flexibility in parameter adjustment. It is necessary to introduce dynamic evaluation models with more parameters, considering future changes in application scope and technological breakthroughs. In addition, it is necessary to consider spatial consistency in combination with regional grid emission factors. Given the above limitations, future research can be improved through data refinement, considering energy structure and vehicle types in scenario design, and other methodological improvements.

4.3. Policy implications

Driven by technological progress and low-carbon automobile policies, China has contributed to the world's largest EV production and sales market. In this study, we conducted a lifecycle analysis of greenhouse gases and multiple air pollutants based on the Chinese context, an analysis that has received limited attention in previous literature. As China's EVs have entered a phase of large-scale market promotion, the EV life cycle model established in this study will help to systematically assess the environmental impact brought by the large-scale production of EVs, so as to deal with the possible transfer risks of mineral development, resource waste and emissions to the upstream of the supply chain. Countries worldwide have accelerated the adoption of subsidies, financial incentives and other measures to promote the production of local new energy vehicles. For example, the United States adopted a federal tax credit policy for the EVs and requires that 40% of the important minerals needed for battery production come from the United States or North American Free Trade Partners. European countries adopted policies such as car purchase subsidies and car tax incentives to stimulate the consumption of new energy vehicles. These may exacerbate the environmental impact on the production side. In conjunction with the latest market scale, application progress, and policy directions, our research conducted scenario design, identifying the primary atmospheric pollution sources and indicators in the production chain of EVs. This is done to enhance the reference value for the formulation of future policies. The model established in this study, along with the environmental impact assessment findings and scenario analysis, can also provide support for countries in formulating low-carbon promotion strategies for new energy vehicles.

From the perspective of policymakers, the medium and long-term pollutant emission reduction benefits brought by accelerating the usage of EVs in the driving stage are very significant. In the future, the government should further introduce incentive consumption policies such as consumer finance, carbon inclusion and road priority to expand the consumption of EVs in light trucks, small and medium-sized buses and other fields. At the same time, combined with the intelligent and networked advantages of EVs, the smart management platform should be established by using big data technology to regulate and optimize the operation energy consumption of EVs, so as to achieve a greater emission reduction in the driving stage. Under BAU, LCE, and PCELC policy scenarios, the medium and long-term PM and SO_2 emissions will increase in the whole life cycle, and the emission reduction benefits of VOCs are also restricted by the production process. Therefore, in the future, we should focus on strengthening the green development of lithium and iron ore, energy saving in lithium battery manufacturing, and VOCs management in the automotive coating process. To minimize the risk of particulate matter and SO_2 emission increase in the life cycle of EVs, it is essential to promote initiatives like environmentally friendly design and production in the automotive industry. Furthermore, the transformation of clean energy and the development of distributed energy should be encouraged.

While considering the difference in environmental impact between upstream and downstream of EVs, one issue that should be noted is the geographical location of EV production and consumption, such as EVs are produced in China but sold in large quantities to the European and Southeast Asian markets. Therefore, future research should fully consider the spatial differences of pollutant emissions caused by different geographical locations of EV production and consumption from a larger regional perspective, so as to provide support for countries around the world to formulate low-carbon transformation policies for automobiles.

CRediT authorship contribution statement

Haoran Shang: Writing – original draft, Methodology, Conceptualization. **Yutong Sun:** Writing – review & editing, Visualization. **Desheng Huang:** Resources, Data curation, Supervision. **Fanxin Meng:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.resenv.2024.100148.

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