Hao *et al. Carbon Footprints* 2024;3:15
DOI: 10.20517/cf.2024.24

Carbon Footprints

Original Article

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Electrification pathways for light-duty logistics vehicles based on perceived cost of ownership in Northern China

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How to cite this article: Hao X, Zhou D, Zhong R, Li S, Meng X, Liu B. Electrification pathways for light-duty logistics vehicles based on perceived cost of ownership in Northern China. *Carbon Footprints* 2024;3:15. https://dx.doi.org/10.20517/cf.2024.24

Received: 5 Aug 2024 **First Decision:** 8 Oct 2024 **Revised:** 22 Oct 2024 **Accepted:** 25 Oct 2024 **Published:** 31 Oct 2024

Academic Editor: Feng Dong **Copy Editor:** Fangling Lan **Production Editor:** Fangling Lan

Abstract

Urban decarbonization and environmental mitigation necessitate the electrification of light-duty logistics vehicles (LDLVs), including battery electric, plug-in hybrid, and hydrogen fuel cell variants. Although the market uptake of electric LDLVs is ecologically imperative, it is impeded by range anxiety and charging infrastructure limitations, particularly pronounced in Northern China's cold climates. This paper employs a system dynamics model to assess the Perceived Cost of Ownership of electric LDLVs, integrating both direct expenses - initial investment and energy costs - and indirect factors like energy replenishment, vehicle substitution, and lifecycle carbon emissions. This analysis reveals that, notwithstanding higher upfront costs, electric LDLVs offer substantial economic and environmental advantages, with significant energy and maintenance savings projected by 2030 under various electrification scenarios. This paper predicts that policy incentives, electricity pricing, and technological progress will significantly influence the market dynamics and industry output of new energy vehicles in Northern China. Notably, the findings indicate that by 2030, electric LDLVs could achieve substantial cost savings and environmental benefits, with market penetration and industry output contingent on the interplay of policy support and technological advancements. The baseline scenario forecasts a 48.17% market share and CNY 60.015 billion in industry output, whereas the high-speed electrification scenario projects the most optimistic outcomes, with a 75.29% market share and CNY 306.087 billion in output.

Keywords: Electrification of logistics vehicles, economic analysis, sustainable urban logistics, Northern China, climate impact, system dynamics model, perceived cost of ownership

INTRODUCTION

Climate change has emerged as one of the most pressing global challenges of the 21st century, necessitating urgent action across all sectors of the economy[1]. As nations worldwide grapple with the imperative to reduce greenhouse gas emissions, China, the world's largest carbon emitter, has set ambitious targets to peak carbon emissions by 2030 and achieve carbon neutrality by 2060[2]. This commitment underscores the critical role of sustainable development in urban areas, where the concentration of economic activities and population growth intensifies environmental pressures[3].

Within the broader context of urban sustainability, the logistics sector stands out as a significant contributor to carbon emissions and air pollution. In China, the rapid growth of e-commerce and urban delivery services has led to a substantial increase in light-duty commercial vehicles, exacerbating air quality issues and hindering decarbonization efforts[4]. The logistics industry's vehicle emissions not only contribute to climate change but also pose immediate health risks to urban populations, making the transition to cleaner transportation solutions an urgent priority[5].

Electrification of light-duty logistics vehicles (LDLVs) presents a promising pathway to address these challenges. Battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), and hydrogen fuel cell vehicles offer the potential to significantly reduce both carbon footprints and operational costs in the logistics sector[6]. The adoption of these alternative energy vehicles aligns with global trends toward sustainable urban mobility and has garnered support from policymakers and industry stakeholders alike[7].

However, the transition to electric light-duty commercial vehicles (ELCVs) faces substantial barriers that impede widespread market integration. Range anxiety, stemming from limited battery capacity and inadequate charging infrastructure, remains a primary concern for potential adopters[8]. These challenges are particularly pronounced in regions with extreme climatic conditions, such as Northern China, where cold winters significantly impact vehicle performance and energy efficiency[9]. In these areas, low temperatures can reduce battery capacity by up to 40%, increase charging times, and necessitate more frequent charging stops, thereby intensifying the inconvenience and operational challenges associated with ELCVs[10].

Current research lacks a comprehensive assessment framework that incorporates both tangible and intangible costs associated with electric vehicle adoption in diverse climatic conditions. This study fills this gap by introducing a Perceived Cost of Ownership (PCO) model, a novel approach that evaluates the economic viability of electric light-duty commercial vehicles in comparison to traditional counterparts. The PCO model considers costs from the perspective of logistics companies and fleet managers, who are the primary decision-makers in the adoption of ELCVs. The model's innovation lies in its consideration of spatial heterogeneity and the integration of intangible costs, offering unprecedented insights into the true economic implications of electric vehicle adoption across varying geographic and climatic settings. By examining the economic benefits through this PCO lens, the paper forecasts market penetration trends and assesses the influence of regional economic, social, and environmental factors on the adoption of electric vehicles by 2030. The findings are pivotal for deciphering the barriers to market penetration and for crafting policies that foster sustainable urban logistics solutions. The findings from this research may inform future studies on electric vehicle adoption in regions with similar challenging environments, potentially contributing to a more nuanced understanding of electrification processes in diverse geographical contexts.

The paper is structured as follows: The "Introduction" outlines the motivation for the PCO model. The "Literature Review" critiques existing cost calculation models and underscores the study's innovative contributions. The "Modeling and Methodology" section elucidates the model's framework and analytical approach. The "Model Results and Analysis" presents findings and explores their implications for market trends and policy. Finally, the "Conclusion and Policy Implications" synthesizes the study's insights and suggests avenues for future research.

LITERATURE REVIEW

The traditional framework for assessing the economic viability of new energy commercial vehicles has predominantly relied on the Total Cost of Ownership (TCO) model[7-10], facilitating a quantitative comparison of different vehicle types under various operational scenarios[11-13]. However, this approach has methodological limitations, often focusing on direct monetary costs[11] and lacking a comprehensive assessment of intangible factors[12,13].

In the realm of light commercial vehicles, an influx of literature has emerged, employing diverse analytical techniques such as the Analytic Hierarchy Process (AHP)[14], Data Envelopment Analysis (DEA)[7,15], and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)[16-18]. A comparative analysis of freight electric vehicle schemes across several European countries by Taefi *et al*. (2014) provides valuable insights into policy frameworks, infrastructure development, and operational challenges relevant to LDLV electrification in various contexts[19]. These methods have been adept at revealing the multifaceted benefits of adopting electric vehicles, including social and environmental impacts. Yet, they frequently fall short in integrating the broader spectrum of economic and environmental costs, particularly those influenced by regional and climatic disparities.

The element limitations are evident in the undervaluation of intangible time costs associated with electric light commercial vehicles (ELCVs)[19-23], such as the time spent on charging[11,23] and the anxiety of range limitations[12,24,25]. While studies have begun to address the economic[26] and environmental costs[27-30], including the lifecycle assessment of carbon emissions, there remains a disconnect in quantifying the true impact of spatial heterogeneity and regional climate on ELCV performance and cost-effectiveness.

Regional limitations have been highlighted by the oversight of cold climate challenges in existing system models[31,32], which are especially pertinent in regions like Northern China[33,34]. The cold temperatures significantly affect battery performance[35], yet there is a dearth of research on the economic implications of these technical hurdles[6] and the potential for policy[36] and technological interventions[37] to overcome them.

This comprehensive review of existing literature reveals several critical research gaps in the economic assessment of ELCVs. Traditional TCO models, while valuable, often fail to capture the full spectrum of costs associated with ELCV adoption, particularly intangible factors such as range anxiety and charging time. Current models largely overlook the impact of regional variations, especially in terms of climate and infrastructure, on ELCV performance and economic viability. The unique challenges posed by cold climates, particularly relevant in regions like Northern China, are underrepresented in existing economic models. Furthermore, there is a notable gap in research that comprehensively evaluates the potential of policy interventions and technological advancements to address ELCV adoption barriers.

To address these gaps, our study introduces the PCO model, a novel extension to the TCO model that incorporates both tangible and intangible costs, providing a more holistic assessment of ELCV economic viability. This model accounts for regional variations in climate, infrastructure, and economic conditions, offering insights into the geographically diverse challenges of ELCV adoption. We provide an in-depth examination of the economic implications of cold climate challenges on ELCV performance and adoption, and evaluate the potential of various policy interventions and technological advancements to mitigate adoption barriers, particularly in challenging climatic conditions. By synthesizing these factors, our research offers valuable projections of ELCV market penetration trends, considering the interplay of economic, technological, and policy factors. This multifaceted approach not only addresses the limitations of existing models but also provides a comprehensive framework for understanding and promoting ELCV adoption across diverse geographic and climatic contexts. Our findings have significant implications for policymakers, industry stakeholders, and researchers working toward sustainable urban logistics solutions. Table 1 summarizes the key contributions and limitations of existing cost calculation models, highlighting the need for the PCO model.

METHODOLOGY AND MODELLING

Research scenario definition

Electric LDLVs encompass a diverse array of vehicles tailored for a multitude of applications and can be differentiated under various classification criteria. This study categorizes electric LDLVs into three principal types based on their energy sources: BEVs, PHEVs, and Hydrogen Electric Vehicles (HEVs). The research focus is specifically on BEVs, which are commercial vehicles designed and intended for urban settings. These vehicles are characterized by their compact size, lightweight construction, and efficient powertrain systems. Over a typical service life of five years, BEVs are predominantly utilized for intra-urban freight transportation and logistics distribution, highlighting their agility in maneuvering and their proficiency in short-haul transport. Urban LDLVs are commonly recognized for their excellent fuel efficiency, stringent emission standards, and substantial cargo capacity, aligning well with the demands of urban logistics. They serve as a critical component in various sectors, including urban delivery, e-commerce logistics, food service distribution, courier services, supply chain support for supermarkets and retail outlets, and cold chain logistics. Comparative analysis is conducted with traditional logistics vehicles, exemplified by diesel-powered light-duty trucks, as detailed in Table 2.

LDLV electrification: economic assessment

PCO model proposed in this paper encompasses the tangible vehicle costs that can be directly monetized, as included in the traditional TCO model. These tangible costs include purchase price, energy costs, maintenance costs, taxes, and insurance costs. Additionally, the model takes into account the intangible costs incurred by users during the usage phase, which are defined in this paper as time costs. Both tangible and intangible costs together constitute the economic costs of LDLVs, as detailed in Figure 1.

Tangible costs module

In this comprehensive study, the economic evaluation of electrified LDLVs reveals a nuanced picture of cost dynamics that significantly impact the total cost of ownership. The analysis focuses on three primary cost components: vehicle purchase cost, energy expenditure, and maintenance, each playing a crucial role in determining the long-term economic viability of electric LDLVs. The initial purchase price of pure electric LDLVs presents a notable financial hurdle, with these vehicles typically commanding a premium over their conventional diesel counterparts. However, the implementation of strategic fiscal and tax policies has substantially alleviated this barrier. These policy interventions have effectively reduced the upfront cost by approximately 26,800 yuan, a significant decrease that narrows the price gap between electric and diesel options. This reduction not only makes electric LDLVs more accessible to fleet operators but also shortens the payback period for the initial investment. Over a five-year period with an annual mileage of 93,000 km, the total energy cost for a pure electric logistics vehicle is projected to be 627,800 yuan, a substantial saving of 250,700 yuan compared to diesel vehicles, which have a total energy cost of 878,500 yuan. Additionally,

Table 1. Literature review summary table

Ref.	Methodology	Key contributions	Limitations	Consideration of intangible costs	Regional/Climatic impacts
[7-10]	TCO	Direct cost comparison, operational scenario analysis	Limited intangible cost assessment	-	No
[14]	AHP	Multi-criteria decision support	Qualitative focus, less on direct costs	Partial	No
[15]	DEA	Efficiency and performance evaluation	Lacks environmental cost integration	No	Yes
[16-18]	TOPSIS	Comprehensive ranking of alternatives	Does not account for regional differences	No	Yes
[19-22]	-	Time cost analysis for ELCVs	Isolated from broader economic analysis	Yes	No
[22]	-	Charging time valuation	-	Yes	No
[23,24]	-	Range anxiety impact assessment	-	Yes	No
[25]	-	Economic cost studies	-	Yes	No
[26-30]	-	Environmental cost studies	-	No	Yes
[31,32]	-	Cold climate impact on battery performance	-	No	Yes
[33,34]	-	Regional challenges in Northern China	-	No	Yes
[35,36]	-	Technical hurdles in cold climates	-	No	Yes
[37,38]	-	Economic implications of cold climate on ELCVs	-	Yes	Yes

Table 2. Research scenario definition

Research subject	Research elements	Usage elements
Traditional light-duty logistics vehicles	Range (km)	800.00
	rated load capacity (tons)	1.74
	Service life (years)	5.00
	Annual mileage (km)	93,000.00
	Daily business operating mileage (km)	127.88
Electric light-duty logistics vehicles	Range (km)	323.54
	Rated load capacity (tons)	1.31
	Service life (years)	5.00
	Annual mileage (km)	93,000.00
	Business day mileage (km)	122.38

electric vehicles exhibit lower maintenance and repair costs, further enhancing their economic viability. These insights suggest that the higher initial investment in electric LDLVs is offset by significant operational and energy cost savings, making them an increasingly attractive option in the transition toward sustainable transportation solutions. The tangible costs module, as detailed in Table 3, provides a comprehensive overview of these financial considerations, highlighting the long-term economic benefits of electrification in the logistics sector.

Intangible costs module

In this study, we extend the traditional TCO model to incorporate intangible costs, introducing the PCO. This innovative approach captures not only the direct expenses but also the inconvenience fees associated with charging and the potential costs of vehicle replacement[38]. The PCO model acknowledges the time

Table 3. Tangible costs module[38]

2022	Tangible costs (Yuan)					
	(1) Purchase cost		(2) Energy cost		(3) Maintenance, taxes, and insurance costs	
Pure electric logistics vehicle	List price	233,800	Annual mileage	93,000.00 (km)	Maintenance	10,300
	Policy subsidies	26,800	Electricity consumption	90 (kWh/100 km)	Insurance	15,000
	Actual price	206,00	Electricity price	1.5 (Yuan/kWh)	Vehicle and vessel tax	600
			Annual electricity cost	125,500	Calculation period	5 (years)
			Calculation period	5 (years)	Total cost	129,600
			Total energy cost	627,800		
Diesel logistics vehicle	Purchase price	126,900	Diesel price	7.36	Maintenance	12,000
			Urea price	2.46	Insurance	15,000
			Fuel consumption	25 (kg/100 km)	Vehicle and vessel tax	500
			Urea consumption	2 (kg/100 km)	Calculation period	5 (years)
			Mileage	93,000.00 (km)	Total cost	137,700
			Annual fuel cost	171,100		
			Annual urea cost	4,600		
			Total energy cost	175,700		
			Calculation period	5 (years)		
			Total energy	878,500		
Electrification of logistics vehicles	Difference	7.91	Difference	-250,700	Difference	-8,100

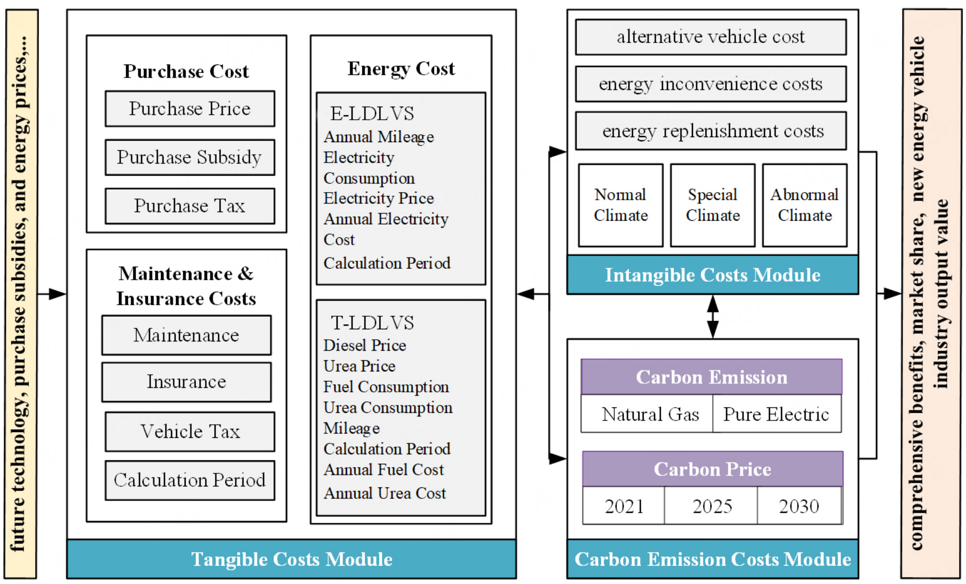

Figure 1. The structure of economic cost evaluation.

value lost due to charging and the impact of regional climate conditions on electric logistics vehicle performance, which can limit operational efficiency and affect the bottom line for logistics operators.

$$C_I = C_F * C_e * C_R \quad (1)$$

where C_I represents intangible costs, C_F represents energy replenishment costs, C_R represents alternative vehicle cost, and C_e represents energy inconvenience costs.

This study segments intangible costs into three components: energy replenishment costs, energy inconvenience costs, and alternative vehicle costs. Energy replenishment costs are calculated based on the time spent locating charging stations, influenced by the distribution of charging infrastructure, road network length, and urban average speed. This is compounded by the total number of charging cycles over the vehicle's life cycle[39].

$$C_F = (S/N_S) * V_a * N_e * V_t \quad (2)$$

where C_F represents energy replenishment costs, S represents road network length, N_S represents the distribution of charging stations, V_a represents urban average speed, N_e represents the number of charging times in the entire life cycle of the vehicle, and V_t represents the time cost of logistics workers.

Charging time costs reflect the waiting period during each charging session, a significant consideration given the longer charging times for electric vehicles compared to traditional counterparts. This waiting time can curtail the operational window and, consequently, the earning potential of logistics practitioners.

$$C_e = T_e * N_e * V_t \quad (3)$$

where T_e represents the single charging time, N_e represents the number of charging times in the entire life cycle of the vehicle, and V_t represents the time cost of logistics workers.

Lastly, the alternative vehicle cost accounts for the expenses incurred when electric vehicles cannot meet service demands due to climate constraints or limited range. This cost represents the strategy of logistics companies to maximize profitability by utilizing traditional vehicles as a fallback option when electric ones falter.

$$C_R = M_3 * C_{Ecv} \quad (4)$$

where M_3 represents the entire life cycle mileage that cannot be normally completed by the electric logistics vehicle under abnormal climate conditions and must be completed by the traditional logistics vehicle, and C_{Ecv} represents the energy cost of the alternative traditional logistics vehicle.

Carbon emission costs module

This study estimates the lifecycle carbon emission costs of traditional LDLVs and electric LDLVs in urban distribution logistics scenarios, considering direct vehicle emissions (weighted carbon emissions of the vehicle), upstream and downstream carbon emissions caused during vehicle production, and the average price of carbon emission allowances in China's carbon emission trading market.

As shown in Table 4, the lifecycle carbon emissions of diesel vehicles in 2022 are 107,360.40 kg, while the carbon emissions of pure electric vehicles are only 9,890.14 kg, nearly 1/11th of that of diesel vehicles. By 2030, the carbon emissions of pure electric vehicles will be only 6,155.20 kg, indicating a significant carbon emission advantage for pure electric vehicles.

Table 4. Lifecycle carbon emission of light-duty urban logistics vehicles

Light-duty urban logistics	2022	2025	2030	2040	2050
Diesel	107,360.40	94,365.88	88,302.36	80,674.38	77,819.32
Natural gas	98,053.53	89,002.43	81,459.85	69,348.79	64,826.04
Pure electric	9,890.14	7,749.75	6,155.20	2,988.53	958.17

Total vehicle carbon emission cost

Table 5 presents a comprehensive analysis of the costs and profits associated with the electrification of LDLVs. The total economic profit, which is the net result of all cost elements, indicates a saving of 76.300 yuan for each vehicle electrified, suggesting that electrification is economically advantageous. The findings suggest that despite initial higher purchase costs, the long-term operational and maintenance savings associated with electric vehicles, along with the environmental benefits of reduced carbon emissions, make electrification a financially viable and environmentally friendly option for the logistics industry. The slight negative total economic profit may indicate areas where costs could be further optimized or where policy interventions, such as subsidies or incentives for electric vehicle adoption, could make electrification even more attractive economically.

Electrification simulation: LDLV simulation model

Model parameter settings

This study takes Beijing as an example and selects urban economic, social, and natural climate conditions as the boundary conditions for the system model baseline area. The year 2021 is set as the start of the simulation, with a simulation period of 10 years and a step length of 1 year.

Macroeconomic elements mainly include regional GDP, GDP growth rate, new energy industry output value, the proportion of new energy industry output value in GDP, new energy automobile output value, the proportion of automobile output value in the industry output value, permanent resident population, natural population growth rate, fixed asset investment in the transportation industry, motor vehicle stock, highway operation freight volume, total retail sales of social consumer goods, *etc*. The macroeconomic data of Beijing from 2018 to 2022 are shown in Table 6.

As shown in Table 7, through channels such as the China Society of Automotive Engineers and the China Federation of Logistics and Purchasing, and in combination with big data crawlers and GIS vector map verification, the supporting environmental information for electric logistics vehicles in the main urban area of Beijing is organized.

Additionally, field research has shown that climate conditions have a significant impact on the range and charging time of electric logistics vehicles. Under normal climate conditions (temperature above 10 °C), electric logistics vehicles can usually operate at rated parameters; between -10 and 10 °C, the operation of electric logistics vehicles will be affected to some extent, with the range of electric vehicles reduced by 50% and the charging time at charging stations increased by 70%, referred to as special climate conditions in this study; at temperatures below -10 °C, electric logistics vehicles cannot operate normally, and using them forcibly carries great vehicle damage risks and safety hazards. Traditional logistics vehicles are usually used to complete the set work, referred to as abnormal climate conditions in this study.

Table 5. Economic profit of light-duty logistics vehicle electrification in 2022

Cost type	Cost element	Cost (Yuan)
Tangible costs	Purchase cost	79,100
	Energy cost	-250,700
	Maintenance cost	-8,100
intangible costs	Search & energy inconvenience costs	105,400
	alternative vehicle cost	2,400
Carbon emission costs	Carbon emission cost	-4,400
Economic cost for electrification	Total	-76,300

Table 6. Macroeconomic situation of Beijing from 2018 to 2022

Economic element	2018	2019	2020	2021	2022
Regional GDP (100 million yuan)	33,106	35,445	35,943	41,045	41,611
GDP growth rate (%)	6.70	6.10	1.10	8.80	0.70
New energy industry output value (100 million yuan)				276.80	341.50
Proportion of new energy industry output in GDP (%)				0.67	0.82
New energy automobile output value (100 million yuan)				77.90	184.40
Proportion of automobile output in industry output (%)				0.28	0.54
Permanent resident population (ten thousand people)	2,192	2,190	2,189	2,189	2,184
Natural population growth rate (%)	-0.03	-0.07	-0.05	-0.02	-0.20
Fixed asset investment in transportation (100 million yuan)	1,283	1,085	983	949	877
Motor vehicle stock (ten thousand vehicles)	608	637	657	685	713
Highway operation freight volume (ten thousand tons)	20,278	22,325	21,789	23,075	18,549
Total retail sales of consumer goods (100 million yuan)	14,422	15,064	13,716	14,868	13,794

Note: In 2021, new energy and new energy automobiles were identified as strategic emerging industries.

Table 7. Supporting environment of electric logistics vehicles in Beijing in 2022

Social element	Value
Road length (km)	8,681.35
Road network area (ten thousand square meters)	15,374.80
Total number of public charging and battery swap stations	3,990
Distance between gas stations (km)	1.60
Refueling time (h)	0.08
Average urban speed (km/h)	22.10
Distance between charging and battery swap stations (km)	2.18
Time value (yuan/h)	32.00
Number of charging stations	3,922
Number of battery swap stations	68.00
Average charging time (h)	1.50

This study organizes and statistically analyzes the average daily temperature of Beijing from 2019 to 2023 for five years, using three indicators: the proportion of normal climate, the proportion of special climate, and the proportion of abnormal climate, to form a climate factor that measures the level of natural conditions in Beijing. The statistical results are shown in Table 8.

Table 8. Climate factors in Beijing

Climate proportion in Beijing	Proportion
Normal climate proportion (above 10 °C)	62.79%
Special climate proportion (-10 to 10 °C)	36.94%
Abnormal climate proportion (below -10 °C)	0.27%

Model assumptions

This paper primarily investigates the impact of policy environment, energy prices, and automotive technology changes on the benefits, market share, and industry output value of the electrification of LDLVs in the northern region of China. The main assumptions are as follows: (1) The model simulation step is 1 year, with the total model cycle spanning from 2021 to 2030; (2) In the process of constructing the model, some relatively minor factors, such as personnel, management, and administrative costs, will be excluded; (3) Within the simulation time frame, except for the period of the pandemic in 2021-2022, the economy maintains stable growth. The output value of new energy vehicles promotes the growth of the regional economy's total output value, and its positive drive leads to an increase in total traffic freight volume. The demand for electric logistics vehicles will grow with the increase in highway operational freight volume; (4) Investment in R&D and infrastructure may affect production costs, charging time, and the range capability of new energy logistics vehicles, contributing to the improvement of technological levels and the perfection of supporting facilities; (5) The calculated prices used in the model are based on current prices, without considering future price changes; and (6) The model does not consider the specific profits or losses of market operators unrelated to the process of logistics vehicle electrification.

Comprehensive benefit model causal relationship diagram

Building upon the previously defined scope of the systematic research and the basic assumptions for model construction, this study has created a causal relationship diagram for the electrification path of LDLVs. The diagram allows researchers to visually identify the causal logic between key elements in the market system and the corresponding systemic feedback mechanisms. The specific causal relationship diagram is shown in Figure 2.

Model stock and flow diagram

Based on the causal loop diagram, a system dynamics stock and flow diagram are constructed using Vensim software. In this model, the output value of the new energy vehicle (NEV) industry, the number of permanent residents, the stock of electric logistics vehicles, and the number of charging stations are the level variables, while the increments of new energy, population increments, stock increments, scrapping amounts, and supporting facility increments are the rate variables of this model. Direct input variables such as purchase subsidies, unit supporting costs, supporting facility investment ratios, the stock of traditional logistics vehicles, and scrap rates are constants, and the rest are auxiliary variables. As shown in Figure 3, under the interconnection and joint action of the above variables, a stock and flow diagram of the electrification path of LDLVs is formed.

As shown in Figure 4, the Economic Benefit Subsystem flow diagram of the economic benefit subsystem includes one level variable, namely the number of charging stations (*NS*), and its corresponding rate variable is the increment of supporting facilities (*IS*). Auxiliary variables include investment in electric logistics vehicle supporting facilities (*FIS*), search time (*TF*), the number of lifecycle replenishment times (*Ne*), range (*SE*), replenishment time (*Te*), replacement cost (*CR*), intangible cost (*CI*), purchase cost (*CP*), energy cost (*CE*), and economic benefits of logistics vehicle electrification (*EF*); constants include the supporting facility investment ratio (*QI*), the proportion of normal climate (*QW1*), and the proportion of special climate (*QW2*).

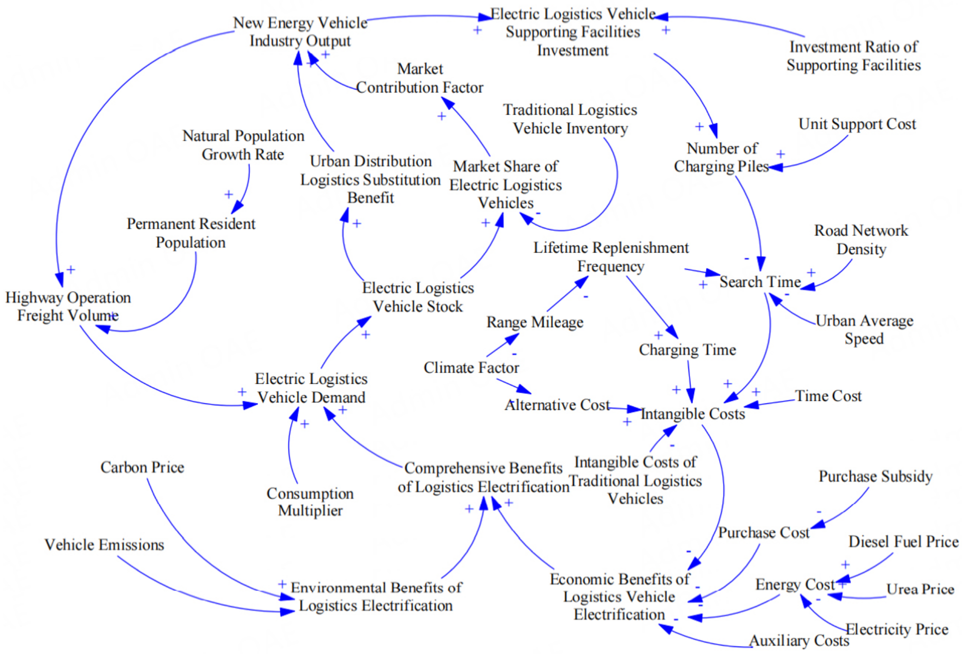

Figure 2. Causal relationship diagram of the comprehensive benefit model for logistics vehicle electrification.

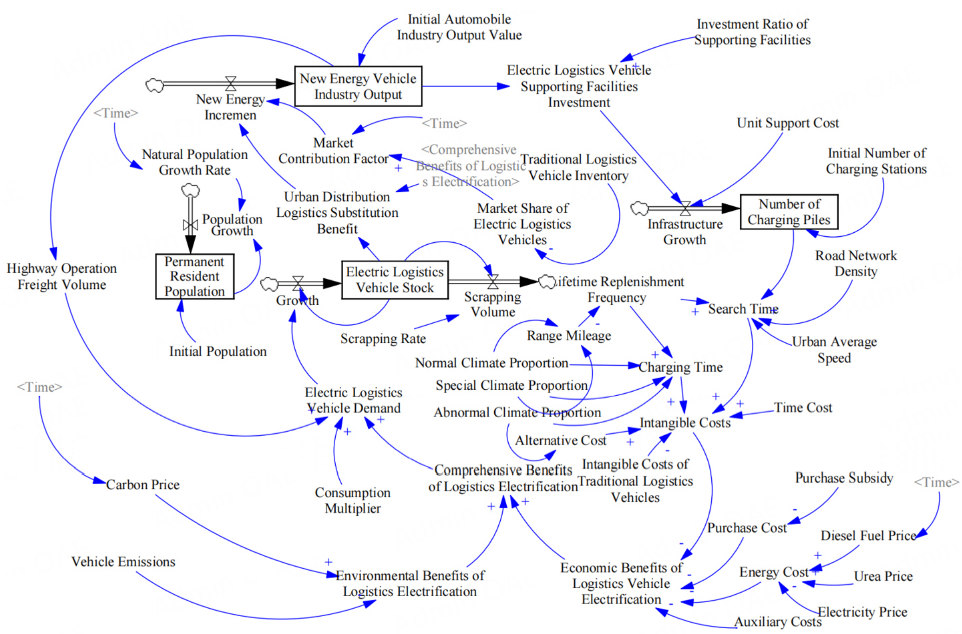

Figure 3. Flow diagram of the benefit evaluation model system for logistics vehicle electrification.

In the environmental benefit subsystem, there are two auxiliary variables: carbon price (*Pc*) and the environmental benefit of logistics vehicle electrification (*EE*), with the whole vehicle carbon emissions of electrified logistics vehicles (*Nc*) being a constant. The purpose of establishing the environmental benefit subsystem is to evaluate the environmental management cost savings that can be achieved by replacing

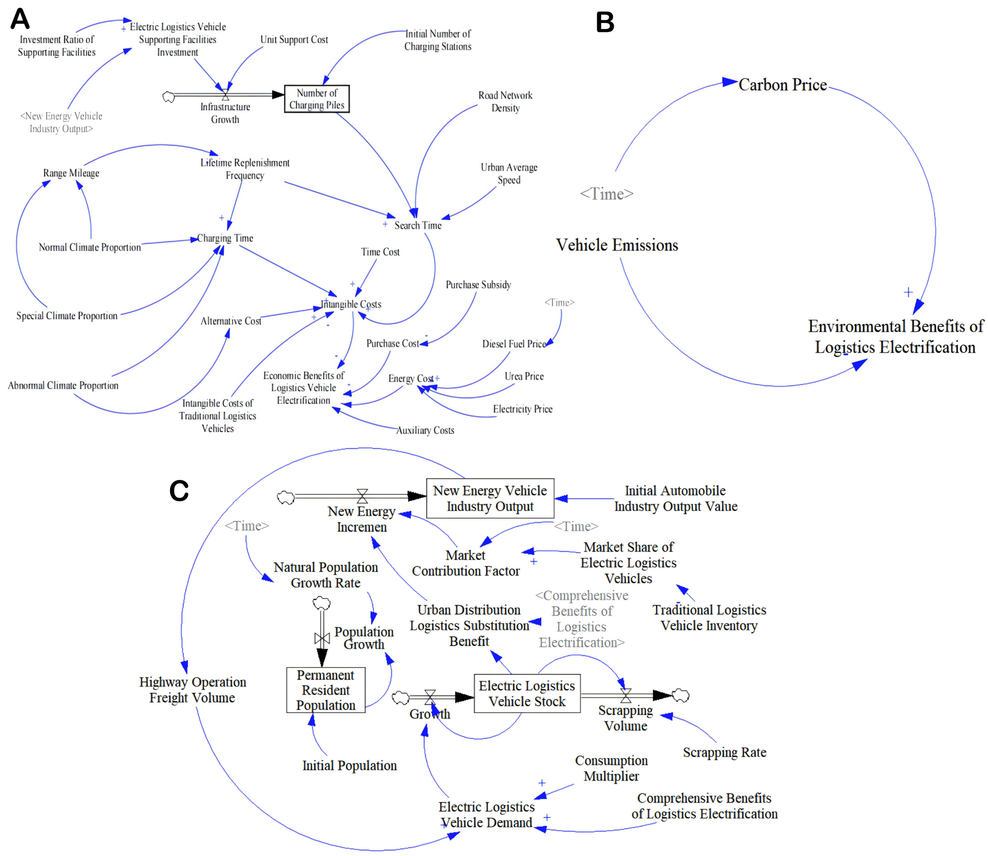

Figure 4. Flow diagram of subsystem (A) Flow diagram of economic benefit subsystem, (B) Flow diagram of environmental benefit subsystem, (C) Flow diagram of market efficiency subsystem.

traditional logistics vehicles with electric logistics vehicles during the process of electrification. Additionally, environmental benefits play a key role in the comprehensive benefits of logistics vehicle electrification and are an indispensable part of the overall assessment.

In the market efficiency subsystem, there are three level variables: New Energy Vehicle Industry Output Value (*NEVPV*), Permanent Resident Population (*PRP*), and Electric Logistics Vehicle Inventory (*ELVI*); the rate variables for these level variables are New Energy Increment (*NEI*), Population Increment (*NPGR*), Electric Logistics Vehicle Increment (*ELVG*), and Electric Logistics Vehicle Scrapping (*ELVS*); the Traditional Logistics Vehicle Inventory (*DLVI*) and the Scrapping Rate (*DLVSR*) are constants, with the rest being auxiliary variables. The market benefit model reflects the impact of the increase in the comprehensive revenue of the whole vehicle brought by the electrification of logistics vehicles on the new energy logistics vehicle industry and the new energy industry. At the same time, the increase in the output value of the new energy industry also plays an important role in the process of electrification of logistics vehicles.

Model validity test

This research has identified three pivotal indicators for evaluating the model's validity: Beijing's new energy industry output value, the permanent resident population, and the number of charging stations. The temporal scope of our validity assessment encompasses the period from 2021 to 2023. The assessment is conducted annually, thus covering a three-year period. A meticulous analysis of the data presented in the table yields a test conclusion. The simulation error for the permanent resident population is a negligible

0.013%, which is attributed to the model's reliance solely on the natural growth rate to predict population changes, thereby ensuring a high degree of accuracy between the estimated and actual values. The specific test results are shown in Table 9.

Scenario settings

Recent studies indicate that electricity prices, vehicle technology advancements, and policy support are critical factors influencing the electrification rate of logistics vehicles, particularly in regions with distinct climatic challenges, such as Northern China[40,41]. The cold climate in this region significantly impacts battery performance and charging efficiency, making these factors even more crucial. Key parameters for these scenarios were derived from projections by the International Energy Agency[42], China's 14th Five-Year Plan (2021-2025)[43], and Bloomberg New Energy Finance (BNEF, 2023)[44], with special attention to their implications for Northern China. The IEA report projects a doubling of China's renewable energy capacity by 2030, which could lead to reduced electricity costs, crucial for offsetting the higher energy consumption in colder climates. BNEF's analysis shows an 89% reduction in battery pack prices from 2010 to 2022, supporting projections for improvements in range and cold-weather performance. The Five-Year Plan outlines targets for new energy vehicle adoption and infrastructure development, which this study interpreted in the context of Northern China's unique challenges.

To analyze and simulate the dynamic impacts of policy optimization adjustments, technological measures, and energy price fluctuations, Gillingham *et al.* (2020) divided policy scenarios into a baseline scenario, accelerated electric energy substitution, and low-speed electric energy substitution to simulate the effects of policy changes on the implementation of new energy vehicle electrification[45]. This paper selects three policy variables: purchase subsidies, range mileage, and electricity price fluctuations for comparative analysis.

Baseline Scenario: This scenario is calibrated to mirror current conditions, with the subsidy phase-out rate set at a moderate 10% per annum. It represents a stable evolution of the market, reflecting the status quo of policy support and technological capabilities. The range mileage for LDLVs is benchmarked at 323.54 km, and the electricity price is anchored at the prevailing rate of 1.5 yuan/kW·h. This scenario offers a reference point to gauge the incremental impacts of the other, more dynamic scenarios.

Low-Speed Electrification Scenario: In this scenario, we explore a more conservative trajectory of electrification, characterized by the absence of purchase subsidies, reflecting a scenario where initial policy support has ceased. The range mileage is projected to increase by a modest 5% annually, acknowledging a slower pace of technological advancement. Electricity pricing is expected to hover at 1 yuan/kW·h[46], representing a gradual adjustment in line with market conditions. This scenario examines the resilience and self-sustainability of the LDLV market in the face of reduced policy incentives.

High-Speed Electrification Scenario: Conversely, this scenario envisions an aggressive push toward electrification, with subsidies phasing out at an accelerated rate of 5% per annum, indicative of a market gaining momentum and requiring less fiscal support. Technological progress is anticipated to be robust, with range mileage increasing by 10% each year, underscoring the potential of breakthroughs in battery technology and energy efficiency. The electricity price is optimistically projected to drop to 0.7 yuan/kW·h[46], reflecting anticipated economies of scale in renewable energy production and grid modernization. This scenario aims to capture the potential for rapid market expansion and industry transformation with strong policy and technological tailwinds.

The model scenario settings are as shown in the Table 10.

Table 9. Validity test results of comprehensive benefit model of logistics vehicle electrification

Time (Year)	2021	2022	2023
Permanent resident population (ten thousand people): estimated value	2,188.60	2,184.59	2,180.30
Permanent resident population (ten thousand people): actual value	2,188.60	2,184.30	2,180.00
Permanent resident population (ten thousand people): error value	0	0.0001	0.0001
New energy vehicle industry output value (billion yuan): estimated value	77.90	178.09	205.39
New energy vehicle industry output value (billion yuan): actual value	77.90	184.40	206.53
New energy vehicle industry output value (billion yuan): error value	0	-0.0342	-0.0055
Number of charging stations (units): estimated value	3,990	5,472	6,956
Number of charging stations (units): actual value	3,990	5,500.000	6,700
Number of charging stations (units): error value	0	-0.0050	0.0383

RESULTS

Sensitivity analysis under single scenarios

The core analysis of this study focuses on electricity prices, vehicle range, and policy subsidies as primary factors influencing LDLV electrification in Northern China. An expanded sensitivity analysis was conducted to address a broader range of variables relevant to Northern China's unique context.

Sensitivity analysis of purchase subsidy variations

As shown in Figure 5, Uncertainty in the NEV sector, particularly surrounding purchase subsidy adjustments, is scrutinized through the lens of this study. The pace of technological innovation, the stringency of policy enforcement, and the unpredictability of market demands are pivotal factors that sway the course of vehicle electrification. This analysis reveals a nuanced relationship between subsidy policies and the projected growth of the NEV industry. The Baseline Scenario, with a gradual subsidy phase-out, forecasts a steady 9.23% growth in comprehensive benefits by 2030. In stark contrast, the High-Speed Electrification Scenario, with an ambitious reduction in subsidies, anticipates a more robust growth rate of 15.55%, suggesting an industry primed for swift technological adoption. Conversely, the Low-Speed Electrification Scenario, devoid of subsidies, foresees a decline, illustrating the market's reliance on policy support. These insights, depicted in this comparative analysis, underscore the significance of balanced policy mechanisms and the imperative for technological advancements to align with market responsiveness. The study's findings advocate for strategic policy formulation that considers the interplay of these uncertainties, ensuring the NEV sector's sustainable progression.

Uncertainty analysis of range mileage variation

As shown in Figure 6, this paper explores the uncertainty surrounding range mileage variations and their impact on the NEV industry's growth, set against a Baseline Scenario with an initial electric light-duty logistics vehicle (LDLV) range of 323.54 km. The analysis juxtaposes a Low-Speed Electrification scenario, with a 5% annual range increase, against a High-Speed scenario, with a 10% increase. The Low-Speed scenario forecasts a measured growth in comprehensive benefits, reaching 4.89% by 2030, indicative of a more tempered advancement in technology. Conversely, the High-Speed scenario, with its accelerated range improvements, projects a markedly higher growth rate of 19.53%, signifying the potential for swift market adoption of LDLVs. This delineated the NEV industry's sensitivity to technological progress. The Baseline Scenario serves as a reference, while the variance in range mileage underscores the critical role of innovation in shaping market trajectory.

Table 10. Model scenario settings

Scenario	Purchase subsidy phase-out rate	Range mileage (km)	Electricity price (yuan/kW·h)
Baseline	10% per year	323.54	1.5
High-speed electrification	5% per year	Annual increase of 10%	0.7 (expected future price)
Low-speed electrification	No subsidy	Annual increase of 5%	1.0 (expected future price)

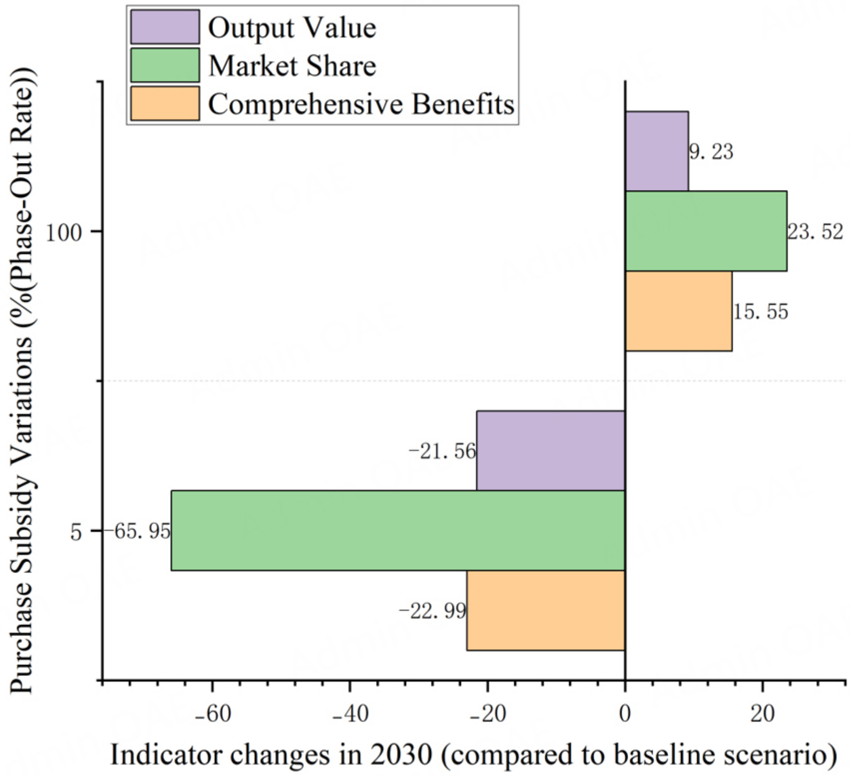

Figure 5. Sensitivity analysis of purchase subsidy variations.

Uncertainty analysis of different electricity prices

As shown in Figure 7, this paper investigates the uncertainty associated with different electricity prices and their impact on the NEV industry, particularly focusing on comprehensive benefits by 2030 in comparison to the baseline scenario. It is worth noting that our current electricity price model uses the actual charging costs at commercial charging stations, which include both the electricity price and service fees. The analysis examines the effects of varying electricity prices on the industry's growth, efficiency, and overall economic viability. The study considers a range of electricity prices, with 0.7 yuan/kWh representing a scenario of low electricity costs, indicative of potential economies of scale in renewable energy production and advancements in grid infrastructure. This pricing strategy is projected to result in a substantial increase in comprehensive benefits, with an impressive 299.5% growth by 2030, highlighting the significance of affordable electricity in accelerating the adoption of electric LDLVs. Conversely, a higher electricity price scenario of 0.7 to 1.0 yuan/kWh is also explored, reflecting potential market conditions where electricity costs are less subsidized or where renewable energy production has not yet achieved the same economies of scale. This scenario still anticipates an increase in comprehensive benefits, albeit at a moderated rate of 30.71%, suggesting that even moderate pricing can support growth in the NEV sector.

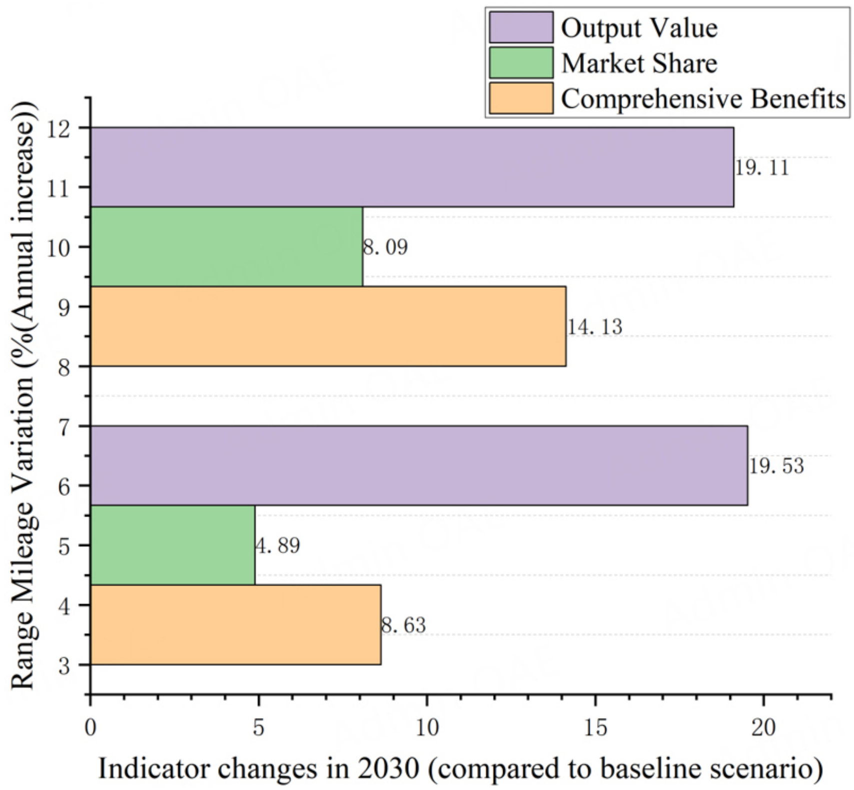

Figure 6. Sensitivity analysis of range mileage variation.

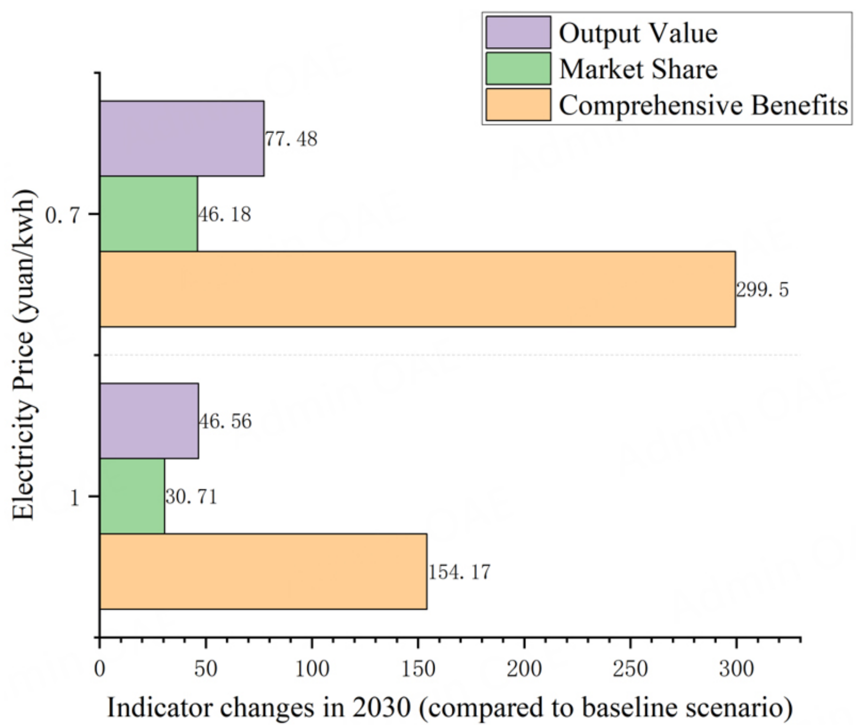

Figure 7. Sensitivity analysis of electricity price changes.

Expanded sensitivity analysis

Findings indicate that charging infrastructure improvements could significantly impact adoption rates, with a 20% increase in charging station density, potentially leading to a 5%-10% increase in LDLV adoption. Advancements in cold weather battery performance, such as a 15% increase in low-temperature range, could result in a 7%-12% increase in market penetration. Grid reliability and renewable energy integration also play crucial roles, with combined improvements potentially enhancing LDLV adoption by 3%-6%. Regional economic growth above average could drive 8%-13% higher adoption rates, while stricter emissions standards in urban areas could boost LDLV adoption by 10%-15%.

To address the impact of excluding minor factors such as administrative costs, a sensitivity analysis was conducted. Administrative costs, estimated at 1%-3% of total vehicle ownership costs, were incorporated into the model. Results showed that including these costs led to a marginal increase in the overall perceived cost of ownership, ranging from 0.8% to 2.5%. This slight increase did not significantly alter the comparative advantage of electric LDLVs over conventional vehicles in most scenarios. However, in cases where the cost difference between electric and conventional LDLVs was already narrow, the inclusion of administrative costs could delay the break-even point by 3-6 months.

In addition to the aforementioned factors, considering the economic and environmental impacts of battery recycling is crucial for a comprehensive understanding of the total cost of ownership and environmental footprint of electric LDLVs, especially given the shorter lifespan of commercial vehicles in this study (5 years). Based on recent studies, we estimate that EV battery recycling value could offset about 20% of initial battery costs, reducing total ownership costs by 2%-3% and potentially decreasing lifecycle carbon emissions by 10%-15%[47]. In the high-speed electrification scenario, economic benefits from recycling were slightly lower (1.5%-2.5% cost reduction) due to lower initial battery costs, while in the low-speed scenario, benefits were more pronounced (2.5%-3.5% reduction). These findings highlight the importance of considering the full EV lifecycle, particularly in regions like Northern China, where EV adoption is rapidly increasing.

Simulation results under combined scenarios

As shown in Figure 8, the combined scenarios for the development of electrified LDLVs project a comprehensive benefit of 4.499 million yuan for the whole vehicle, a market share of 48.17% for electric LDLVs, and an industry output value of 60.015 billion yuan by 2030 under the baseline electrification scenario. This reflects a steady increase in market penetration and gradual expansion of the industry's output value due to current policies and technological conditions. The convergence of policy support and market acceptance propels this trend, laying a foundation for sustainable industry growth. The low-speed electrification scenario further estimates a comprehensive benefit increase to 5.749 million yuan, a market share increase to 54.18%, and an industry output value of 68.465 billion yuan by 2030. In contrast, the high-speed electrification scenario demonstrates even more pronounced growth, with comprehensive benefits expected to reach 9.183 million yuan, a market share of 75.29%, and an industry output value leaping to 306.087 billion yuan. These projections highlight the catalytic role of technological advancements and policy initiatives in accelerating electrification, particularly in enhancing range mileage and optimizing cost-effectiveness.

The market and industry progression of electrified LDLVs is subject to a confluence of factors, including technological innovation, policy support, market demands, and competitive industry strength. Key drivers of electrification include advancements in range mileage, reductions in battery costs, development of charging infrastructure, and supportive government policies. As environmental consciousness grows and the need for sustainable transportation solutions intensifies, so does the market demand for electric vehicles.

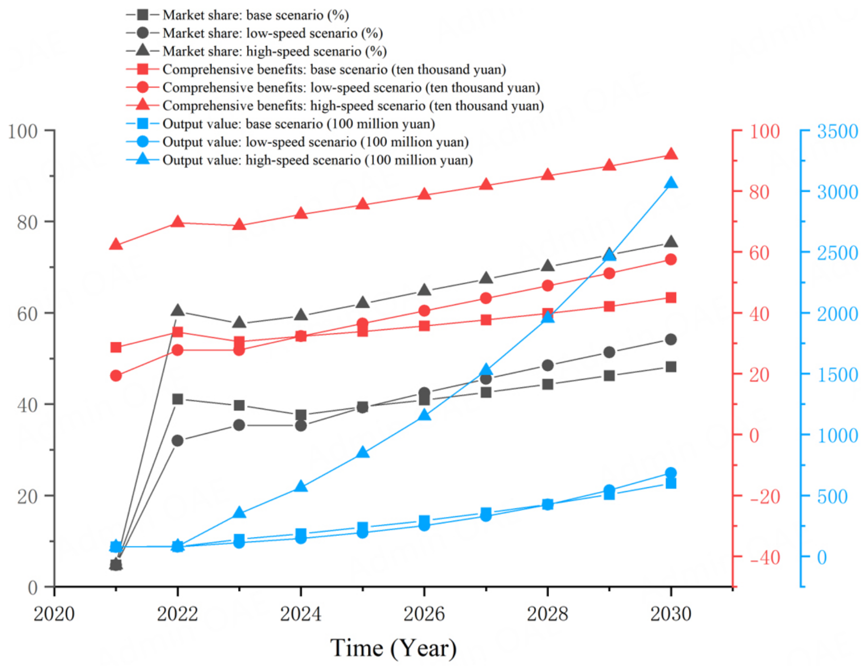

Figure 8. Simulation results of combined scenarios for LDLV electrification.

The expansion of industry output value signifies not only a broadening market scale but also an ascent in the industry's global competitiveness.

Comparative analysis of predicted market share

This study presents a comparative analysis of the predicted market share for new energy light trucks by 2030, featuring forecasts from a range of sources. Figure 9 offers a visual juxtaposition of these predictions, including those from "Made in China 2025," the "Automotive Industry Green Low-Carbon Development Roadmap 1.0," and Marianna Rottoli's 2021 study, alongside the scenarios modeled in this paper: Baseline, Low-Speed Electrification, and High-Speed Electrification. The estimates from this study project a market share of 48.17% for the Baseline scenario, with the Low-Speed and High-Speed Electrification scenarios forecasting increases to 54.18% and 75.29%, respectively. To assess the consensus and variance among these forecasts, this paper calculates and presents the normalized average of the scenarios as a red dashed line in Figure 9, indicating the general trend of the predictions. Together, these data points and the trend line provide a comprehensive view of the industry's potential, as forecasted by different models.

CONCLUSION AND POLICY IMPLICATION

This study provides a comprehensive analysis of the electrification of LDLVs in Northern China, based on the PCO model. Our findings reveal several key insights: (1) Economic viability: Despite higher initial purchase and intangible costs, electrified LDLVs demonstrate significant economic advantages. The overall cost benefit reaches 76,300 CNY, primarily driven by substantial energy cost savings; (2) Impact of electricity pricing: Energy pricing emerges as a critical factor influencing future market dynamics. Compared to the baseline electrification scenario, market share projections for 2030 increase by 30.71% and 46.19% in low and high-speed electrification scenarios, respectively, under varying electricity prices. Notably, electricity pricing is identified as a key economic lever that could accelerate the transition to electric vehicles; and (3) Promising future for LDLV electrification: Even in the face of an inevitable decline in government financial and economic policy support, our projections indicate a positive trajectory for

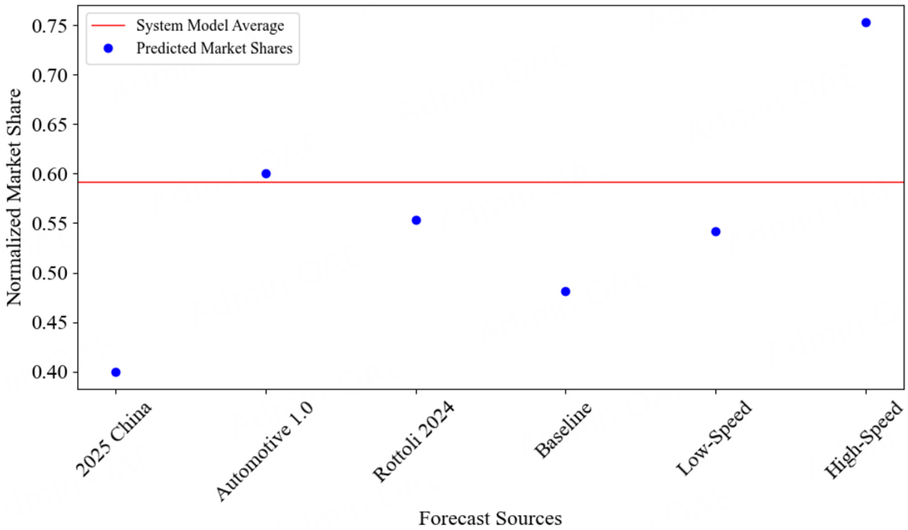

Figure 9. Side-by-side comparison of market share predictions for new energy light trucks by 2030[48].

electrified LDLVs. Considering scenarios of energy price fluctuations and technological breakthroughs, market share is expected to reach 54.18% and 75.29% by 2030 in low and high-speed electrification scenarios, respectively.

To capitalize on these benefits, we recommend that governments implement targeted policies. Specifically, subsidy phasing-out should be gradual to sustain market growth. Electricity pricing must be competitive to reduce operational costs for LDLVs. Additionally, governments should incentivize the rapid deployment of charging infrastructure to mitigate range anxiety and bolster consumer confidence in electric vehicles. These measures will not only expedite the transition to sustainable urban logistics but also stimulate the new energy vehicle sector's development.

The research opens avenues for future studies to delve into the long-term economic impacts of vehicle electrification, encompassing lifecycle costs and battery degradation effects. It is essential to continue monitoring the evolution of electric vehicle technologies and their influence on performance and cost. Additionally, tracking market dynamics, including consumer preferences and competitive industry shifts, will provide valuable insights into consumer adoption patterns. Evaluating the effectiveness of existing and forthcoming policies on electrification adoption rates and usage is crucial for refining strategic approaches. Furthermore, assessing the comprehensive environmental footprint of electric vehicles throughout their lifecycle will contribute to the holistic understanding of their sustainability profile.

Limitations of the study

While this study provides valuable insights into LDLV electrification in Northern China, several limitations should be acknowledged. The geographic focus on Northern China may limit the generalizability of our findings to regions with different climatic and policy environments. Our projections for 2030 may not capture long-term technological breakthroughs or policy shifts. Additionally, the PCO model, while comprehensive, necessarily simplifies some complex real-world interactions and decision-making processes.

Expanding on the limitations, it is important to note that our analysis did not account for the nuances of peak/off-peak electricity pricing, which could significantly impact the operational costs and charging strategies for LDLVs. The economic model could be further refined by incorporating these pricing variables to provide a more accurate representation of cost implications. Moreover, the study's scope did not extend to the end-of-life management of batteries, including recycling and disposal, which are critical factors in the overall environmental and economic assessment of LDLV electrification. The omission of these aspects may underestimate the long-term costs and environmental burdens associated with battery usage in LDLVs. Despite these limitations, our study provides a robust foundation for understanding LDLV electrification in Northern China and offers valuable insights for policymakers and industry stakeholders.

DECLARATIONS

Authors' contributions

Made substantial contributions to the conception and design of the study, and performed data analysis and interpretation: Hao X, Zhou D
Performed data acquisition and analysis: Zhong R, Li S
Provided crucial input in refining the study's assumptions and enhancing the methodology: Meng X
Provided administrative, technical, and material support, and substantively revised the work: Liu B
All authors have read and approved the final manuscript.

Availability of data and materials

The datasets used and analyzed during the current study are available from the corresponding author upon reasonable request.

Financial support and sponsorship

This study was supported by the National Key R&D Program of China (2022YFB2503504), the National Natural Science Foundation of China for Young Scholars (72304031), and Fundamental Research Funds for the Central Universities in China (FRF-TP-22-024A1). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Conflicts of interest

Meng X is affiliated with China Automotive Technology and Research Center Co., Ltd. The authors declared that this affiliation does not influence the research. The other authors have declared that they have no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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