Optimal wholesale price and technological innovation under dual credit policy on carbon emission reduction in a supply chain

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The adoption of new energy vehicles (NEVs) can effectively reduce vehicle exhaust emissions and achieve carbon peaking and carbon neutrality goals in the transportation sector. To facilitate the development of NEVs, the Chinese government issued the dual credit policy (DCP). However, whether the DCP can promote the technological innovation of NEVs and effectively reduce carbon emissions in the transportation sector remains to be studied. This study constructed the decision-making model of NEVs under the DCP and obtained the optimal strategy to study the impact of the DCP on carbon emissions. Furthermore, we constructed a bargaining game model based on an alliance strategy to demonstrate the coordination of the NEV supply chain. The results showed that implementing the DCP can effectively reduce carbon emissions in the transportation field. The higher the technological innovation credit coefficient or credit price, the more significant the DCP's incentive effect on reducing carbon emissions. Decentralized decision-making weakens the DCP's incentive effect on reducing carbon emissions. The bargaining game based on alliance negotiation can enable independent companies to achieve carbon emission reduction when making centralized decisions so that the DCP's incentive effect on reducing carbon emissions is optimized. The alliance between manufacturers is not to increase profits but to enhance their product advantages. However, suppliers can gain higher profits by participating in the alliance, which provides a theoretical reference for the alliance's cooperation in decision-making.

KEYWORDS

carbon peaking and carbon neutrality goals, carbon emission reduction, dual credit policy, alliance cooperation, new energy vehicles

1 Introduction

According to the BP World Energy Statistical Yearbook, China is the world's highest carbon emitter. China's carbon emissions increased at an average annual rate of 1.2% from 2016 to 2019, exceeding the global average annual growth rate of 0.8% (Statistical, 2020). China announced, at the 75th session of the United Nations General Assembly, that it aims to peak carbon dioxide emissions before 2030 and achieve carbon neutrality before 2060 (Chen and Chao, 2021). With the rapid development of motor vehicles, carbon emissions in the transportation field account for 15% of the country's terminal carbon emissions and the average annual growth rate in the transportation field has remained above 5% (Yang et al.,

TABLE 1 Optimal strategies for the NEV supply chain.

		Technological innovation				Sales	Carbon reduction
		Supplier 1	Supplier 2	Supplier 3	Supplier 4		
Without policy	Decentralized decision-making	46.66	11.66	15.55	9.33	233	1,788
	Centralized decision-making	310.88	77.72	103.63	62.18	1,554	26,562
With policy	Decentralized decision-making	48.68	12.17	16.23	9.74	243	1,883
	Centralized decision-making	564.71	141.18	188.24	112.94	2,259	59,049

TABLE 2 Profits of suppliers and the manufacturer.

	Supplier 1	Supplier 2	Supplier 3	Supplier 4	Manufacturer	Supply chain
Decentralized decision-making	47,398	56,285	55,298	56,877	243,407	459,265
Non-aligned negotiations	116,501	125,388	124,401	125,980	1,766,550	2,260,000
Alliance negotiations	652,640	319,892	318,905	320,484	648,079	2,260,000

2014). Therefore, reducing the exhaust emissions of motor vehicles is extremely important to achieve carbon peaking and carbon neutrality goals in the transportation sector.

With low-carbon advantages, such as no petroleum fuel consumption and exhaust emissions, new energy vehicles (NEVs) have become the automotive industry's leading choice in achieving carbon peaking and neutrality (Jenn et al., 2019; Bonsu, 2020; Zhao et al., 2021). However, NEVs are currently unable to achieve mass uptake—the low level of technology is the key factor that restricts the continuous growth in the sales of NEVs. To support NEV companies in increasing technological innovation investment and to promote the development of NEVs, the Ministry of Industry and Information Technology and five other ministries and commissions jointly issued the dual credit policy (DCP) (Ministry of Industry and Information Technology, 2020). Under the DCP, each NEV can receive a certain amount of credits, and manufacturers sell credits in the credit market to receive credit revenue. Moreover, the higher the NEVs' technical level, the higher the credits. However, the NEVs' technology improvement depends on technological breakthroughs in parts and components, and therefore, suppliers are required to bear the burden of investment in technological innovation. Facing high technological innovation investment and high risk, suppliers' willingness to innovate is not strong and their enthusiasm is not high. Therefore, how to effectively motivate suppliers to invest in technological innovation under the DCP, improve the NEVs' technological level, and reduce carbon emissions in the transportation sector are urgent problems to resolve.

Under the development concept of coordination, openness, and sharing, the formation of alliances has become an essential method of enterprise cooperation. In the NEV supply chain, Mercedes-Benz and CATL have reached a strategic partnership, in which CATL provides module-less battery packs for Mercedes-Benz passenger car products. Module-less battery packs directly integrate battery cells into the battery pack, saving the traditional module link. The integrated advanced battery system gives Mercedes-Benz cars

better range, charging speed, safety, and sustainability (CATL, 2020). BMW Group and Envision Power have reached a long-term cooperation agreement. The next-generation lithium-ion battery cells developed by Envision Power can enable BMW Group's new models to show outstanding performance with high performance, high safety, and zero carbon emissions (BMW Group, 2022). Enterprise alliances and cooperation help secure the resources needed in the global market and help enhance the market competitiveness of enterprises. However, alliance cooperation between enterprises will cause changes in the NEV supply chain structure, which will usually affect the interests of multiple subjects.

Therefore, this paper constructs a technological innovation decision-making model and a bargaining game model based on an alliance strategy under the DCP in order to study the DCP's impact on technological innovation and carbon emissions. We need to solve three problems: first, whether the DCP can promote the NEVs' technological innovation and effectively reduce carbon emissions in transportation, and how can the policy be adjusted to prompt this effect? Second, how can suppliers be effectively motivated to invest in technological innovation and reduce carbon emissions in transportation, realizing the optimal incentive effect? Third, what impact does alliance cooperation in the NEV supply chain have on enterprises?

There are three main contributions to this paper. First, we develop a game model of the NEV supply chain and demonstrate the DCP's positive incentive effect on reducing carbon emissions in the transportation field through rigorous theoretical deduction, which provides a theoretical basis for the government to achieve carbon peaking and carbon neutrality goals in the transportation sector by adjusting the DCP. Second, we demonstrate that the supplier can be effectively incentivized to increase its investment in technological innovation by centralizing decision-making and profit-sharing mechanisms, making the incentive effect of the DCP on technological innovation and reducing carbon emissions in transportation optimal. Third, we demonstrate that an alliance between the
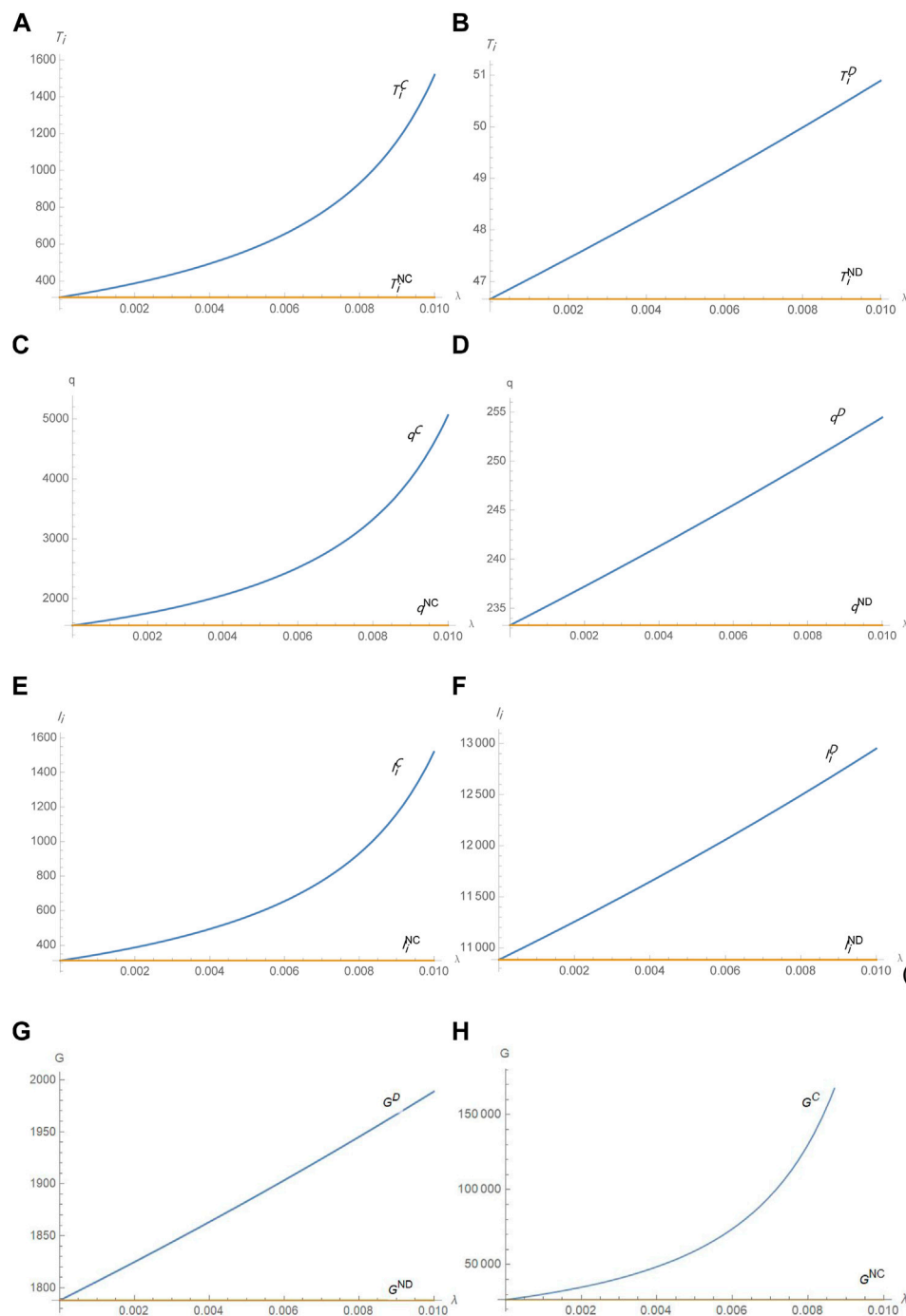
FIGURE 1
Impact of the technological innovation credit coefficient on the optimal strategy.

manufacturer and supplier is not to increase profits but to enhance their product advantages, and suppliers can gain higher profits by participating in the alliance, providing a theoretical reference for decision-making.

The rest of this paper is as follows: Section 2 reviews the related literature, Section 3 introduces the studied problem and builds the model, Section 4 solves the model and analyzes the optimal solution, Section 5 presents the coordination strategy, Section 6 discusses the numerical example and sensitivity analysis, Section 7 is the discussion, and Section 8 outlines the conclusion.

2 Literature review

This research involves two streams of the literature, namely, on dual credit policy and supply chain coordination.
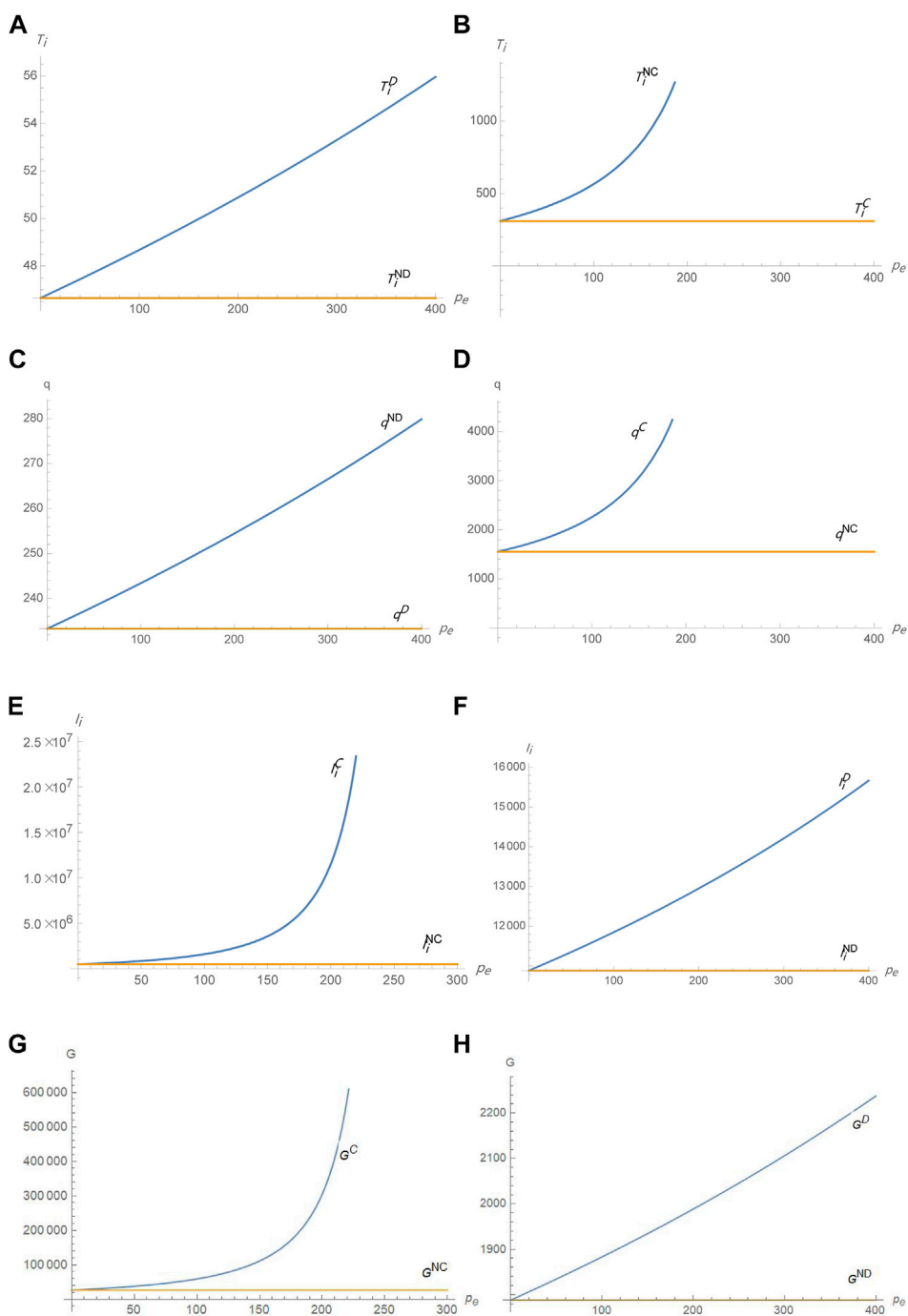
FIGURE 2
Impact of credit prices on the optimal strategy.

2.1 Dual credit policy

Given that China's implementation of the DCP is only recent, research on the DCP is still in its infancy and has inconsistent conclusions.

Some scholars believe that the DCP can positively stimulate the development of NEVs. For example, Dong and Zheng studied the impact of DCP on enterprises' total factor productivity and believed that the policy could significantly improve the technological

productivity of enterprises (Dong and Zheng, 2022). Wang et al. (2020) concluded that the DCP could increase the willingness of enterprises to innovate green technology. Yang et al. (2021) believed that the DCP could positively stimulate NEVs' development, and a moderate credit price could improve the NEVs' technical level. Zhou et al. (2019) found that the DCP raises the green technology threshold for NEVs. Li et al. (2020) studied the impact of DCP on manufacturers' R&D decisions and proved that DCP could effectively replace the subsidy policy to promote NEVs'
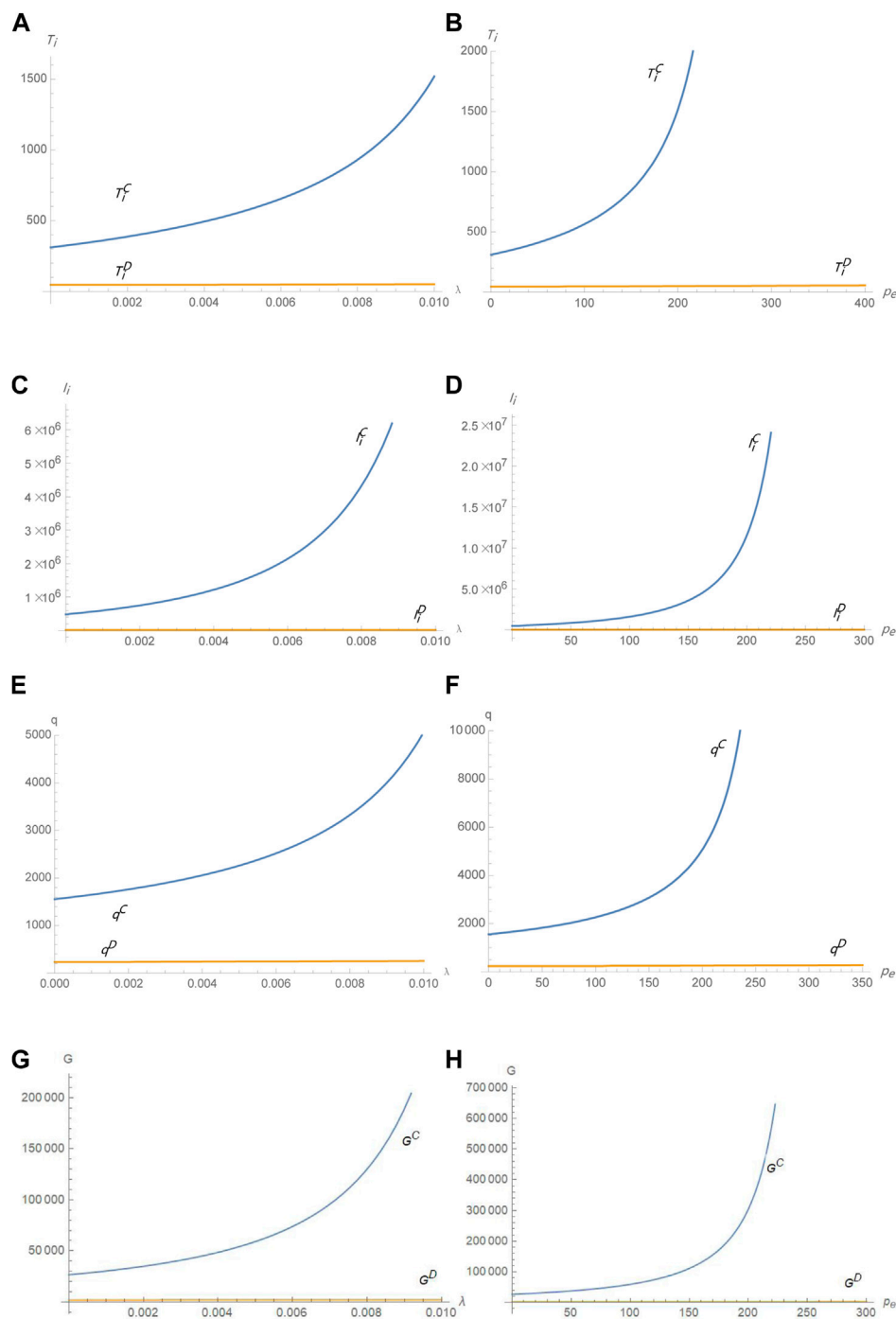
FIGURE 3
Impact of decision-making on the optimal strategy.

development. Ma et al. (2021) found that implementing the DCP could significantly increase the supply chain investment in the NEVs' R&D and improve the NEVs' technical level. Zhou and Shen believed that the DCP incentivizes automakers to develop more NEV modes and improve manufacturers' production capacity (Zhou and Shen, 2020).

Some scholars believe that the DCP cannot achieve the expected incentive effect and needs further revision. For instance, Lou et al.

(2020) found that the DCP might not help manufacturers improve NEVs' technical level. He et al. (2021) believed that the gradual tightening of the DCP would effectively promote electric vehicle R&D intensity. Kong et al. (2022) believed that the DCP could promote the sustainable development of the automobile industry, but the incentive effect on NEVs is limited. Cheng and Fan pointed out that a higher credit price is more conducive to promoting the expansion of NEVs than setting a higher proportion of NEV

FIGURE 4
Impact of alliance cooperation on corporate profits.
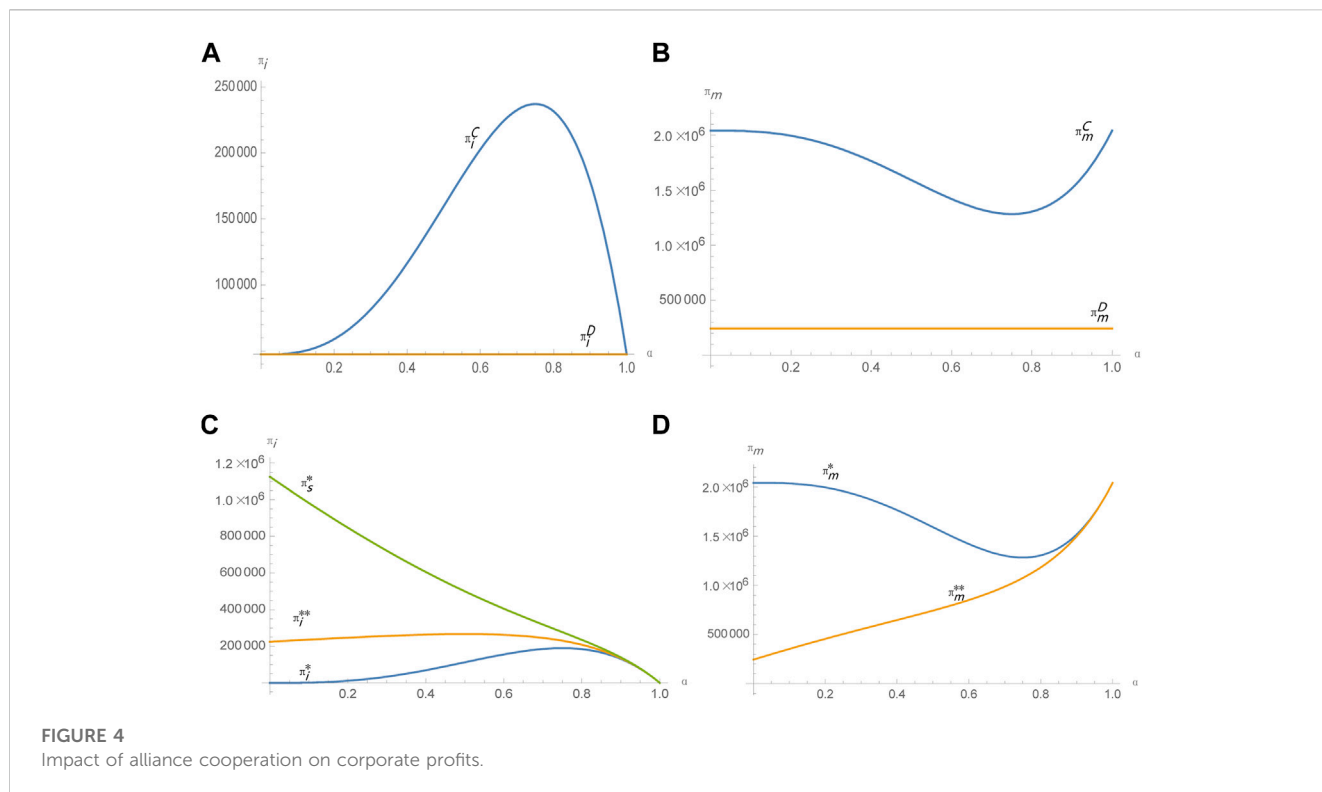
production (Cheng and Fan, 2021). Zhao et al. (2019) believed that the DCP could promote the technological innovation of NEVs but would lose its role in promoting technological innovation in 2025 or earlier. Meng et al. (2022) found that the DCP promotes the development of the NEV industry, whereas the capital constraints weaken the incentive effect of the DCP. Ma et al. (2023) found that when there is information asymmetry in the supply chain, the incentive effect of the DCP is weakened.

Throughout the literature, scholars have not studied much on the impact of the DCP on the NEVs' technological innovation, and the research conclusions are inconsistent. Moreover, there is almost no research on the impact of the DCP on carbon emissions in transportation. Therefore, the impact of the DCP on technological innovation and carbon emission reduction needs to be explored further. Considering the background of the DCP, it combines technology innovation with carbon emission reduction in transportation and provides a new research idea for future research.

2.2 Supply chain coordination

Coordination between manufacturers and suppliers is a crucial issue in supply chain management, and many scholars have studied supply chain coordination by designing a series of contracts. For example, Li et al. (2019) introduced an incentive compatibility mechanism, studied a low-carbon supply chain's emission reduction cooperation mechanism, and explored the impact of cooperative decision-making contracts on supply chain performance. He et al. (2019) studied the online shopping supply chain containing a single online retailer and a third-party logistics enterprise and adopted a bilateral effort cost-sharing contract to

realize coordination. Wang et al. (2017) considered consumers' low-carbon preferences and studied the supply chains' coordination under wholesale price contracts and cost-sharing contracts. Cachon and Lariviere believed that revenue-sharing contracts could coordinate supply chains with a single retailer and distribute supply chain profits arbitrarily (Cachon and Lariviere, 2005). He et al. studied the coordination by various contract types when supply and demand are uncertain, such as the contract of supplier management inventory partnership plus production subsidy, the revenue-sharing contract with advance purchase discount, the contract combining the return policy and wholesale price, and the return policy and sales discount and penalty contract (He et al., 2009; He and Zhao, 2012; He and Zhao, 2016). Dai studied the supply chain coordination contract in the context of retailers' financial constraints (Dai, 2020).

The bargaining model is most commonly used to analyze cooperation between firms (Nash, 1953). For example, Guo and Iyer analyzed the multilateral bargaining problem between manufacturers and retailers, and believed that when the difference in retailer's sales price is insignificant, the manufacturer will choose to negotiate the price simultaneously. When the price difference is significant, the manufacturer will negotiate the price sequentially (Guo and Iyer, 2013). Feng and Lu analyzed outsourcing decisions and contract choices in the supply chain based on a bargaining model (Feng and Lu, 2013a; Feng and Lu, 2013b). Basak (2017) compared and analyzed the competitive model and competitive enterprises that can be used to obtain optimal profits, applying the bargaining model (Basak, 2017). Zhang et al. (2017) demonstrated the impact of enterprises' bargaining power and centralized procurement efficiency on enterprises' willingness to participate in centralized procurement

efficiency on enterprises' willingness to participate in centralized procurement in China's pharmaceutical market. Escapa and Gutierrez quantitatively studied the distribution of the potential benefits between countries based on bargaining models (Escapa and Maria, 1997).

Scholars have studied the supply chain's coordination mechanism from different perspectives, providing a solid theoretical and methodological reference for analyzing the coordination of the NEV supply chain. However, existing research mainly focuses on enterprises' one-on-one cooperation and competition, lacking consideration of reality. In the NEV supply chain, it is common for a manufacturer to cooperate with multiple suppliers, in which case, how the manufacturer incentivizes multiple suppliers to cooperate in technological innovation, realizing supply chain coordination? This paper designs centralized decision-making and profit-sharing mechanisms, which effectively motivate suppliers to increase investment in NEVs' technological innovation, which provides a theoretical frame for future research.

3 Problem description and model

3.1 Problem description

Most of the carbon emissions in the transportation sector come from the exhaust emissions caused by fossil energy such as gasoline and diesel consumed during the operation and use phase of automobiles. In contrast, NEVs do not rely on fossil fuels, significantly reduce vehicle exhaust emissions, and alleviate environmental pollution; therefore, developing NEVs is an effective way to achieve carbon peaking and carbon neutrality goals in transportation. According to statistics, the market share of NEVs will increase by 1% and carbon emissions will reduce by 1.29 million tons. A 1% reduction in the electricity consumption coefficient of pure electric vehicles will reduce carbon emissions by 510,000 tons; however, whether the NEVs' market share increases or the power consumption coefficient of electric vehicles is reduced depends on improvement in NEVs' technical level and investment in technological innovation.

A NEV supply chain consists of one manufacturer and multiple parts suppliers. Suppliers are responsible for investment in the technological innovation of parts, and the technological innovation level determines the technical level of NEVs. The manufacturer procures parts from suppliers and sells the NEVs to customers after the manufacturer completes production.

Under the DCP, each NEV will receive a specific amount of credit and manufacturers sell NEV credits in the credit market to obtain credit revenue. At the same time, the number of credits is related to NEV's technical level, and the higher the technical level, the higher the NEV credits per vehicle. Thus, the DCP will significantly affect the technological innovation investment decisions of the NEV supply chain.

The NEV supply chain companies can choose decentralized and centralized decision-making modes to decide on technological innovation investment. When the NEV supply chain chooses to make decentralized decisions, the manufacturer and supplier determine technological innovation investments and prices

through the Stackelberg game to maximize their profits. When the NEV supply chain chooses to make centralized decisions, supply chain companies decide NEVs' technological innovation investments and sales prices together to maximize supply chain profits.

Furthermore, the manufacturer may form alliances with suppliers to participate in profit distribution negotiations. The decision-making process is as follows: the manufacturer decides to align with the supplier. Manufacturers and suppliers then make decisions to maximize total profit, including decisions on technological innovation, sales prices, and negotiation sequence. If the manufacturer does not align with the supplier, the manufacturer bargains with the supplier sequentially, determines the supplier's profit, and signs a contract. If the manufacturer and a supplier ally, the alliance first negotiates with the supplier sequentially, then the alliance will determine the parties' profits and a contract will be signed according to the agreed profit distribution rules. Finally, the NEV supply chain will conduct technological innovation, procurement, production, and sales based on the cooperation contract to achieve their respective profits.

3.2 Model

The NEV market demand function is $q = a - p + \theta \sum_{i=1}^{n} T_i$ (Ma et al., 2018; Wang and Huang, 2021), where a is the potential demand, p is the NEV sales price, θ is the sensitivity coefficient of market demand, and the greater θ is, the more significant the impact of the supplier's technical level on market demand. $T_i (i = 1, 2, \cdots, n)$ is the technological innovation of supplier i.

Under the DCP, the profits of NEV manufacturers are affected by the revenue from NEV credit trading. Each NEV at the current level of technology T_0 can earn NEV credit ε. Furthermore, considering the supplier's investment in technological innovation to raise the technical level of NEV to $\sum_{i=1}^{n} T_i$, the NEV credits that can increase $\lambda(\sum_{i=1}^{n} T_i - T_0)$, where λ is the NEV technology innovation credit coefficient and $\lambda > 0$. Each vehicle can earn NEV credits $\varepsilon + \lambda(\sum_{i=1}^{n} T_i - T_0)$ (Liu et al., 2022). For simplicity and generality, let $T_0 = 0$ and $\varepsilon = 0$.

Suppose the credit price is p_e; then, the manufacturer's credit revenue for the production of NEVs is $p_e q \lambda(\sum_{i=1}^{n} T_i)$.

Considering that the technological innovation investment of the component supplier is $I_i = \frac{1}{2} k_i T_i^2$ (Gurnani and Erkoc, 2008; Zheng et al., 2019), $k_i > 0 (i = 1, 2, \cdots, n)$, k_i is the technological innovation cost coefficient. Both the manufacturer and the supplier's production costs are zero.

The NEVs' carbon emission reduction comes from two aspects: the replacement of fuel vehicles by NEVs and the reduction of carbon emissions brought about by the technological innovation of NEVs, such as the lower electric energy consumption. Considering each fuel vehicle's carbon emissions is G_0, assuming that each NEV can replace fuel vehicles μ and can reduce carbon emissions μG_0 (Cheng and Fan, 2021), and $\mu > 0$, μ is the replacement rate of NEVs. Considering the technological innovation of NEVs is $\sum_{i=1}^{n} T_i$ and carbon emission reduction is $\delta \sum_{i=1}^{n} T_i$ (Cao and Wu, 2020; Hao and Li, 2020), and $\delta > 0$, δ is the technological innovation emission reduction coefficient. Therefore, producing q NEVs can reduce carbon emissions $(\mu G_0 + \delta \sum_{i=1}^{n} T_i)q$.

Thus, the profit function of the supplier i is

$$\pi_i = w_i q - \frac{1}{2} k_i T_i^2. \tag{1}$$

The manufacturer's profit consists of NEV sales revenue and credit revenue, and the profit function is

$$\pi_m = \left(p - \sum_{i=1}^{n} w_i \right) q + p_e \lambda q \left(\sum_{i=1}^{n} T_i \right), \tag{2}$$

where $p = \omega + \sum_{i=1}^{n} w_i$ and $w_i\,(i = 1, 2, \cdots, n)$ are the parts price of supplier i, and ω is the manufacturer's markup.

4 Model solving and analysis

4.1 Optimal strategy for the NEV supply chain under the DCP

4.1.1 Optimal solution for decentralized decision-making

Under the DCP, when the NEV supply chain makes decentralized decisions (labeled D), the manufacturer and parts supplier use the Stackelberg game to determine technological innovation investment and NEV sales prices, aiming to maximize their profits.

We adopt the reverse induction method in this section to solve the optimal solution.

First, suppliers decide the technological innovation investment and parts price to maximize their profits.

Derive Eq. 1 from w_i and T_i. Let $\frac{\partial \pi_i}{\partial w_i} = 0$ and $\frac{\partial \pi_i}{\partial T_i} = 0$, and by solving it jointly, we obtain $w_i^{D*} = \frac{N(a-\omega)}{(n+1)N - \theta^2 M}$ and $T_i^{D*} = \frac{N(a-\omega)\theta}{k_i((n+1)N - \theta^2 M)}$, where $M = \sum_{\delta=1}^{n} \frac{\prod_{i=1}^{n} k_i}{k_\delta}$ and $N = \prod_{i=1}^{n} k_i$.

Then, the manufacturer decides on NEV sales prices intending to maximize its profits. Substituting w_i^{D*} and T_i^{D*} into π_m, and deriving π_m to ω, let $\frac{\partial \pi_m}{\partial \omega} = 0$; the solution yields $\omega^{D*} = \frac{a((n+1)N - \theta(\theta+2\lambda)M)}{2N(n+1) - 2\theta(\theta+\lambda)M}$ and $p^{D*} = \frac{a((2n+1)N - \theta(\theta+2p_e\lambda)M)}{2N(n+1) - 2\theta(\theta+p_e\lambda)M}$.

Furthermore, we obtain the optimal strategy under decentralized decision-making: $T_i^{D*} = \frac{a\theta N}{k_i(2(n+1)N - 2\theta(\theta+p_e\lambda)M)}$, $\pi_m^{D*} = \frac{a^2 N}{4((n+1)N - \theta(\theta+p_e\lambda)M)}$, $q^{D*} = \frac{aN}{2(n+1)N - 2\theta(\theta+p_e\lambda)M}$, $w_i^{D*} = \frac{aN}{2(n+1)N - 2\theta(\theta+p_e\lambda)M}$, $\pi_i^{D*} = \frac{a^2 N^2 (2k_i - \theta^2)}{8k_i((n+1)N - \theta(\theta+p_e\lambda)M)^2}$, $\pi^{D*} = \frac{a^2 N((4n+2)N - \theta(3\theta+2\lambda)M)}{8((n+1)N - \theta(\theta+p_e\lambda)M)^2}$, and $I_i^{D*} = \frac{(a\theta M)^2}{2k_i(2(n+1)N - 2\theta(\theta+p_e\lambda)M)^2}$. The reduction of carbon emissions is $G^{D*} = \left(\mu G_0 + \frac{\delta a\theta N}{k_i(2(n+1)N - 2\theta(\theta+p_e\lambda)M)} \right) \frac{aN}{2(n+1)N - 2\theta(\theta+p_e\lambda)M}$.

4.1.2 Optimal solution for centralized decision-making

Under the DCP, the NEV supply chain makes centralized decisions (marked C). NEV companies aim to maximize profits in the supply chain and jointly decide on technological innovation investments and sales prices for NEVs.

Therefore, the profit of the NEV supply chain is

$$\pi^C = pq + p_e \lambda q \left(\sum_{i=1}^{n} T_i \right) - \frac{1}{2} \sum_{i=1}^{n} k_i T_i^2. \tag{3}$$

Equation 3 is derived from T_i and p; let $\frac{\partial \pi^C}{\partial T_i} = 0$ and $\frac{\partial \pi^C}{\partial p} = 0$; then, we solve them synchronously and obtain $T_i^{C'} = \frac{a(\theta+p_e\lambda)N}{k_i(2N - (\theta+p_e\lambda)^2 M)}$ and $p^{C*} = \frac{aN - \lambda(\theta+p_e\lambda)}{2N - M(\theta+p_e\lambda)^2}$.

Furthermore, we obtain the optimal strategy under centralized decision-making $\pi^{C*} = \frac{a^2 N}{2(2N - (\theta+p_e\lambda)^2 M)}$, $q^{C*} = \frac{aN}{2N - (\theta+p_e\lambda)^2 M}$, and $I_i^{C'} = \frac{(a(\theta+p_e\lambda)N)^2}{2k_i(2N - (\theta+p_e\lambda)^2 M)^2}$. The reduction of carbon emissions is $G^{C*} = \left(\mu G_0 + \frac{\delta a(\theta+p_e\lambda)N}{k_i(2N - (\theta+p_e\lambda)^2 M)} \right) \frac{aN}{2N - (\theta+p_e\lambda)^2 M}$.

4.2 Optimal decision-making without the DCP

4.2.1 Optimal solution for decentralized decision-making

Without the DCP, $p_e \lambda = 0$.

The profit function of the supplier i is

$$\pi_i = w_i q - \frac{1}{2} k_i T_i^2. \tag{4}$$

The profit function of the manufacturer is

$$\pi_m = \left(p - \sum_{i=1}^{n} w_i \right) q. \tag{5}$$

If the NEV supply chain makes decentralized decisions (labeled ND), it aims to maximize its profits and determine technological innovation and price through the Stackelberg game. The decision-making process contains two stages. First, the manufacturer decides the sales price based on the parts price and technological innovation. Then, suppliers decide on their technological innovation investments and component prices.

By solving via reverse induction, we can obtain the optimal strategy $T_i^{ND*} = \frac{a\theta N}{k_i(2(n+1)N - 2\theta^2 M)}$, $w_i^{ND*} = \frac{aN}{2(n+1)N - 2\theta^2 M}$, $p^{ND*} = \frac{a((2n+1)N - \theta^2 M)}{2N(n+1) - 2\theta^2 M}$, $q^{ND*} = \frac{aN}{2(n+1)N - 2\theta^2 M}$, $I_i^{ND*} = \frac{(a\theta M)^2}{2k_i(2(n+1)N - 2\theta^2 M)^2}$, $\pi_m^{ND*} = \frac{a^2 N}{4((n+1)N - \theta^2 M)}$, $\pi_i^{ND*} = \frac{a^2 N^2 (2k_i - \theta^2)}{8k_i((n+1)N - \theta^2 M)^2}$, and $\pi^{ND*} = \frac{a^2 N((4n+2)N - 3\theta^2 M)}{8((n+1)N - \theta^2 M)^2}$. Furthermore, the reduction in carbon emissions is defined as $G^{ND*} = \left(\mu G_0 + \frac{\delta a\theta N}{k_i(2(n+1)N - 2M\theta^2)} \right) \frac{aN}{2(n+1)N - 2\theta^2 M}$.

4.2.2 Optimal solution for centralized decision-making

Without the DCP, $p_e \lambda = 0$. The profit function of the NEV supply chain is

$$\pi^C = pq - \frac{1}{2} \sum_{i=1}^{n} k_i T_i^2. \tag{6}$$

If the NEV supply chain makes centralized decisions (labeled NC), they jointly decide on technological innovation and prices for NEVs to maximize total profits.

Solving Eq. 6, we get the optimal strategy $T_i^{NC*} = \frac{a\theta N}{k_i(2N - \theta^2 M)}$, $q^{NC*} = \frac{aN}{2N - \theta^2 M}$, $I_i^{NC*} = \frac{(a\theta N)^2}{2k_i(2N - \theta^2 M)^2}$, $p^{NC*} = \frac{aN}{2N - M\theta^2}$, and $\pi^{NC*} = \frac{a^2 N}{2(2N - \theta^2 M)}$. Furthermore, the reduction in carbon emissions is defined as $G^{NC*} = \left(\mu G_0 + \frac{\delta a\theta N}{k_i(2N - \theta^2 M)} \right) \frac{aN}{2N - \theta^2 M}$.

Proposition 1: The DCP can stimulate the NEV supply chain to increase technological innovation investment, raise the technical

level and sales of NEVs, and effectively reduce carbon emissions in the transportation field.

Proof. The optimal strategy with and without a DCP is compared. First, let us compare the optimal strategy under decentralized decision-making. Substituting I_i^{D*}, I_i^{ND*}, q^{D*}, q^{ND*}, T_i^{D*}, T_i^{ND*}, G^{ND*}, and G^{D*} into $I_i^{D*} - I_i^{ND*}$, $q^{D*} - q^{ND*}$, $T_i^{D*} - T_i^{ND*}$, and $G^{D*} - G^{ND*}$ yields $I_i^{D*} - I_i^{ND*} = \frac{a^2 MN^2\theta^3 p_e\lambda(2(n+1)N - M\theta(2\theta + p_e\lambda))}{8k_i((n+1)N - \theta(\theta + p_e\lambda)M)^2((n+1)N - \theta^2 M)^2} > 0$, $q^{D*} - q^{ND*} = \frac{aMN\theta\lambda p_e}{((n+1)N - \theta^2 M)((n+1)N - \theta(\theta + p_e\lambda)M)} > 0$, $T_i^{D*} - T_i^{ND*} = \frac{aNM\theta^2 p_e\lambda}{2k_i((n+1)N - M\theta^2)((n+1)N - \theta(\theta + p_e\lambda)M)} > 0$, and $G^{D*} - G^{ND*} = \mu G_0(q^{D*} - q^{ND*}) + \delta(T_i^{D*}q^{D*} - T_i^{ND*}q^{ND*}) > 0$.

Then, we compare the optimal strategy under centralized decision-making. Substituting I^{C*}, I^{NC*}, q^{C*}, q^{NC*}, T_i^{C*}, T_i^{NC*}, G^{NC*}, and G^{C*} into $I^{C*} - I^{NC*}$, $q^{C*} - q^{NC*}$, $T_i^{C*} - T_i^{NC*}$, and $G^{C*} - G^{NC*}$ yields $I^{C*} - I^{NC*} = \frac{a^2 N^2 p_e\lambda(2\theta + p_e\lambda)(4N^2 - (M\theta(\theta + p_e\lambda))^2)}{2k_i(2N - (\theta + p_e\lambda)^2 M)^2(2N - \theta^2 M)^2} > 0$, $q^{C*} - q^{NC*} = \frac{aMN p_e\lambda(2\theta + p_e\lambda)}{(2N - (\theta + p_e\lambda)^2 M)(2N - \theta^2 M)} > 0$, $T_i^{C*} - T_i^{NC*} = \frac{aN p_e\lambda(2N + M\theta(\theta + p_e\lambda))}{k_i(2N - (\theta + p_e\lambda)^2 M)(2N - \theta^2 M)} > 0$, and $G^{C*} - G^{NC*} = \mu G_0(q^{C*} - q^{NC*}) + \delta(T_i^{C*}q^{C*} - T_i^{NC*}q^{NC*}) > 0$. Q.E.D.

Compared to the scenario without the DCP, implementing the DCP stimulates the NEV supply chain to increase technological innovation investment and enhance NEVs' technical level. The DCP will promote the transformation of the NEV supply chain in "relying on technology" to obtain core competitiveness.

Moreover, the continuous improvement of NEVs' technical level, the increasing number of NEVs, and the continuous increase in the NEVs' market share will help the energy upgrading and transformation of the transportation industry, thereby significantly reducing the total carbon emissions from the transportation sector and enabling the carbon peaking and carbon neutrality goals of this sector to be achieved quickly.

Proposition 2: Under the DCP, the higher the technological innovation credit coefficient or credit price, the higher the NEVs' technical level, the higher the NEV sales, and the more significant the incentive effect of the DCP on reducing carbon emissions in the transportation industry.

Proof. Deriving T_i^{C*}, T_i^{D*}, q^{C*}, q^{D*}, G^{D*}, and G^{C*} to p_e yields $\frac{\partial T_i^{C*}}{\partial p_e} = \frac{aN\lambda(2N + M(\theta + p_e\lambda)^2)}{k_i(2N - M(\theta + p_e\lambda)^2)^2} > 0$, $\frac{\partial T_i^{D*}}{\partial p_e} \frac{2a\theta^2 NM\lambda}{k_i(2(n+1)N - 2\theta(\theta + p_e\lambda)M)^2} > 0$, $\frac{\partial q^{C*}}{\partial p_e} \frac{2aNM\lambda(\theta + p_e\lambda)}{(2N - M(\theta + p_e\lambda)^2)^2} > 0$, $\frac{\partial q^{D*}}{\partial p_e} \frac{2a\theta NM\lambda}{(2(n+1)N - 2\theta(\theta + p_e\lambda)M)^2} > 0$, $\frac{\partial G^{D*}}{\partial p_e} = \frac{aMN\theta\lambda(aM\delta\theta + \mu G_0((n+1)N - M\theta(\theta + p_e\lambda)))}{2((n+1)N - M\theta(\theta + p_e\lambda))^3} > 0$, and $\frac{\partial G^{C*}}{\partial p_e} = \frac{aMN\lambda(a\delta(2N + 3M(\theta + p_e\lambda)^2) + 2G_0(\theta + p_e\lambda)(2N - M(\theta + p_e\lambda)^2))}{(2N - M(\theta + p_e\lambda)^2)^3} > 0$.

Deriving T_i^{C*}, T_i^{D*}, q^{C*}, q^{D*}, G^{D*}, and G^{C*} to λ yields $\frac{\partial T_i^{C*}}{\partial\lambda} = \frac{aN p_e(2N + M(\theta + p_e\lambda)^2)}{k_i(2N - M(\theta + p_e\lambda)^2)^2} > 0$, $\frac{\partial q^{C*}}{\partial\lambda} \frac{2aNM p_e(\theta + p_e\lambda)}{(2N - M(\theta + p_e\lambda)^2)^2} > 0$, $\frac{\partial q^{D*}}{\partial\lambda} \frac{2a\theta NM p_e}{(2(n+1)N - 2\theta(\theta + p_e\lambda)M)^2} > 0$, $\frac{\partial T_i^{D*}}{\partial\lambda} \frac{2a\theta^2 NM p_e}{k_i(2(n+1)N - 2\theta(\theta + p_e\lambda)M)^2} > 0$, $\frac{\partial G^{D*}}{\partial\lambda} = \frac{aMN\theta p_e(aM\delta\theta + \mu G_0((n+1)N - M\theta(\theta + p_e\lambda)))}{2((n+1)N - M\theta(\theta + p_e\lambda))^3} > 0$, and $\frac{\partial G^{C*}}{\partial\lambda} = \frac{aMN p_e(a\delta(2N + 3M(\theta + p_e\lambda)^2) + 2G_0(\theta + p_e\lambda)(2N - M(\theta + p_e\lambda)^2))}{(2N - M(\theta + p_e\lambda)^2)^3} > 0$.

Q.E.D.

Proposition 2 shows that the DCP always affects the optimal strategy. With the increase of the credit price or technological innovation credit coefficient, the higher the NEVs' technical

level, the higher the sales. Moreover, by improving their technical level and sales of NEVs, carbon emissions in the transportation field can be reduced more effectively. Therefore, the DCP can not only encourage NEV companies to continuously improve the technological innovation of NEVs and enhance the industry's rapid development but also promote carbon emission reduction in the transportation sector, allowing this sector to achieve its carbon peaking and carbon neutrality goals faster.

The government can promote healthy development of the NEV industry by adjusting the technological innovation credit coefficient or credit price, and reduce carbon emissions in the transportation field by adjusting the DCP.

Proposition 3: The higher the carbon emissions of fuel vehicles, the higher the replacement rate of fuel vehicles by NEVs and the more significant the incentive effect of the DCP on reducing carbon emissions. The higher the emission reduction coefficient of NEV technology innovation, the more significant the incentive effect of DCP on reducing carbon emissions.

Proof. Deriving G^{C*} and G^{D*} to μ, G_0, and δ yields $\frac{\partial G^{C*}}{\partial\mu} = \frac{aNG_0}{2N - (\theta + p_e\lambda)^2 M} > 0$, $\frac{\partial G^{C*}}{\partial G_0} = \frac{aN\mu}{2N - (\theta + p_e\lambda)^2 M} > 0$, $\frac{\partial G^{C*}}{\partial\delta} = \frac{a^2 MN(\theta + p_e\lambda)}{2N - (\theta + p_e\lambda)^2 M} > 0$, $\frac{\partial G^{D*}}{\partial\mu} = \frac{aNG_0}{2(n+1)N - 2\theta(\theta + p_e\lambda)M} > 0$, $\frac{\partial G^{D*}}{\partial G_0} = \frac{aN\mu}{2(n+1)N - 2\theta(\theta + p_e\lambda)M} > 0$, and $\frac{\partial G^{D*}}{\partial\delta} = \frac{a^2 MN\theta}{(2(n+1)N - 2\theta(\theta + p_e\lambda)M)^2} > 0$.

Q.E.D.

Proposition 3 shows that the DCP can motivate NEV companies to increase investment in technological innovation, improve the technical level of NEVs, and increase consumers' intention to purchase them, thereby increasing the replacement rate of fuel vehicles by NEVs and effectively reducing carbon emissions in the transportation field. Moreover, the higher the replacement rate of fuel vehicles by NEVs, the more significant the emission reduction effect.

Meanwhile, the higher the carbon emissions of fuel vehicles, the more significant the incentive effect of the NEVs' development on carbon emission reduction in transportation. Moreover, the higher the emission reduction coefficient of technological innovation of NEVs, the stronger the effect of the DCP on reducing carbon emissions in the transportation field.

Proposition 4: Decentralized decision-making harms the DCP's incentive effect and weakens the DCP's incentive effect on emission reduction in the transportation field.

Proof. We compare and analyze the optimal solution for decentralized and centralized decision-making. Substituting T_i^{C*}, T_i^{D*}, G^{C*}, and G^{D*} yields $T_i^{D*} - T_i^{C*} = -\frac{aN(2Np_e\lambda + 2nN(\theta + p_e\lambda) - M\theta(\theta + p_e\lambda))}{2k_i(N(1+n) - M\theta(\theta + p_e\lambda))(2N - \theta(\theta + p_e\lambda))} < 0$, $G^{D*} - G^{C*} = \mu G_0(q^{D*} - q^{C*}) + \delta(T_i^{D*}q^{D*} - T_i^{C*}q^{C*}) < 0$.

Q.E.D.

Compared to centralized decision-making, under decentralized decision-making, the investment in technological innovation of NEVs is reduced, NEVs' technical level decreases, and the impact of the NEVs' development on carbon emission reduction weakens. Decentralized decision-making harms the DCP's incentive effect, and decentralized decision-making weakens the DCP's incentive effect on emission reduction in the transportation field.

Therefore, it is essential to implement a coordinated strategy to enable independent companies to achieve the optimal strategy under centralized decision-making, encourage the NEV supply chain to increase investment in technological innovation, improve the NEVs' technical level, strengthen the DCP's incentive effect on emission reduction in the transportation field, significantly reduce pollutant emissions in the transportation field, and achieve carbon peaking and carbon neutrality goals in the transportation field faster.

5 The NEV supply chain coordination strategy

Compared to decentralized decision-making, the profit increase is $\Delta\pi = \frac{a^2 N (4nN(nN-\theta^2 M+(p_e\lambda)^2 M)+M(2N(p_e\lambda)^2+M\theta(\theta-2p_e\lambda)(\theta+p_e\lambda)^2))}{8(N(1+n)-\theta M(\theta+p_e\lambda))^2 (2N-M(\theta+p_e\lambda)^2)}$. As long as the NEV enterprises get reasonable profit distribution, the smooth implementation of supply chain cooperation can be effectively guaranteed.

Therefore, the next step will be to discuss distributing the profit increase $\Delta\pi$ after centralized decision-making through bargaining negotiations.

Considering that manufacturers and suppliers negotiate the allocation of the increased profit $\Delta\pi$, the profits of manufacturers and component suppliers are $\Delta\pi_m$, $\Delta\pi_i (i = 1, 2, \cdots, n)$, and $\Delta\pi_m + \sum_{i=1}^{n} \Delta\pi_i = \Delta\pi$.

There are n pairs of negotiations between the manufacturer and the supplier, and each bargaining negotiation is

$$Max\,(\Delta\pi_m - d_m)^{\zeta_i}\,(\Delta\pi_i - d_i)^{\eta_i}, \qquad i = 1, 2, \cdots, n, \qquad (7)$$
$$s.t.\,(\Delta\pi_m, \Delta\pi_i) \geq (d_m, d_i),$$
$$\Delta\pi_m + \Delta\pi_i \leq \Pi_j, \, (j = 1, 2, \cdots, n),$$

where $\Pi_j (j = 1, 2, \cdots, n)$ is the profit available for distribution in the jth round of negotiations, $\Pi_1 = \Delta\pi$ and $\Pi_{j+1} = \Pi_j - \pi_j$. (d_m, d_i) is the point of agreement at which negotiations break down, i.e., when the benefits to be obtained by the negotiating parties are less than (d_m, d_i). To simplify the analysis, consider $d_m = 0$ and $d_i = 0$. $\zeta_i (0 < \zeta_i < 1)$ is the manufacturer's negotiating power, and $\eta_i (0 < \eta_i < 1)$ is the bargaining power of the supplier i.

5.1 Non-alignment between the supplier and manufacturer

Considering that component suppliers provide complementary parts to manufacturers, the importance of these parts is roughly the same and the negotiating power of component suppliers does not differ much. Without losing generality, we further assume that the manufacturer has the same negotiating power for suppliers $\alpha (0 < \alpha < 1)$ and component suppliers have the same bargaining power $\beta (0 < \beta < 1)$, and $\alpha + \beta = 1$.

When the supplier participates in the jth round of negotiation, the profits made by the manufacturer and supplier i are $\frac{\zeta_i}{\zeta_i + \eta_i}\Pi_j$ and $\frac{\eta_i}{\zeta_i + \eta_i}\Pi_j$, and after further substituting $\Pi_1 = \Delta\pi$, the supplier's profit is $\beta\alpha^{j-1}\Delta\pi$ and the manufacturer's profit is $\alpha^j\Delta\pi$.

Therefore, when suppliers and manufacturers negotiate sequentially, component suppliers' profits are affected by both

negotiation power and the negotiation sequence. Negotiating earlier allows the supplier to obtain more profits. Similarly, delays in the sequence of negotiations can also result in a loss of supplier profits. However, when manufacturers participate in the jth round negotiations, the profit is $\alpha^j\Delta\pi$, and the profits obtained are only related to its bargaining power and have nothing to do with the negotiation sequence.

Proposition 5: When the manufacturer does not align with the supplier, the supplier i profit is $\pi_i^* = \beta\alpha^{n-1}\Delta\pi + \pi_i^{D'}$. The manufacturer's profit is $\pi_m^* = (1 - n\beta\alpha^{n-1})\Delta\pi + \pi_m^D$.

Proof. Suppose the supplier participates in the $(j - \varepsilon)^{th}$ round of negotiations $(j = 2, 3, \cdots, n; \varepsilon \in \{1, 2, \cdots, j - 1\})$, its allocated profit is $\beta\Pi_{j-\varepsilon}$; if the supplier participates in the jth round negotiation, its allocated profit is $\beta\Pi_j$. Comparing the profits of suppliers participating in rounds $(j - \varepsilon)^{th}$ and participating in j^{th} round negotiations, we obtain $\Delta\pi_j = \beta(\Pi_{j-\varepsilon} - \Pi_j) = \beta\alpha^{j-\varepsilon-1}(1 - \alpha^\varepsilon) > 0$. Therefore, the supplier's profit from participating in the $(j - \varepsilon)^{th}$ round negotiations is higher than the profit from participating in the jth round negotiations, and the supplier will give the manufacturer a concession to obtain a higher negotiation order. Assume that the supplier's concession strategy is $ST_j = (P_1, P_2, \cdots, P_j).(j = 1, 2, \cdots, n)$, where P_j is the profit that the supplier should give to the automaker to get j^{th} round negotiation. After giving profit to the automaker, the supplier's actual profit is $\beta\alpha^{j-1}\Delta\pi - P_j$. If the supplier bargains in the last round, the supplier's profit is $\beta\alpha^{n-1}\Delta\pi$, which is the lowest supplier's profit by bargaining, where $P_n = 0$. The upper bound on the supplier's transfer profit is the entire profit obtained by bringing the bargaining sequence forward, so the supplier's transfer profit is $P_j^* = \beta(\alpha^{i-1} - \alpha^{n-1})\Delta\pi$. Substituting P_j^* into $\beta\alpha^{j-1}\Delta\pi - P_j$, the profit after the supplier's concession is $\beta\alpha^{n-1}\Delta\pi$, which means that no matter which round of negotiations the supplier participates in, it can only receive the profit from participating in the final round of negotiations, while the final profit of the automaker is $(1 - n\beta\alpha^{n-1})\Delta\pi$, and the manufacturer's profit is the total of its negotiation profit and the concession of all suppliers.

Q.E.D.

After the supplier gives the manufacturer a concession, regardless of which negotiations the supplier participates in, it can only obtain the profit from participating in the final round of negotiations, which is the minimum profit the supplier can obtain by participating in the negotiations. The manufacturer's profit is the total of its negotiated profit and the concession of all suppliers, and the manufacturer obtains a higher profit because of their right to decide the negotiation sequence.

However, compared to decentralized decision-making, a profit distribution strategy can increase the profits of suppliers $\beta\alpha^{n-1}\Delta\pi$ and the manufacturer's profits $(1 - n\beta\alpha^{n-1})\Delta\pi$; each company's profits can be improved and the NEV supply chain coordination can be achieved. Moreover, independent NEV supply chain member companies have achieved the optimal technical level and carbon emission reduction through the coordination mechanism under centralized decision-making. The DCP's incentive effect on carbon emission reduction in the transportation field can be optimized, which is conducive to achieving carbon peaking and carbon neutrality goals in the transportation field.

5.2 Alliances between the manufacturer and supplier

Consider that in an alliance between a manufacturer and a supplier, s^* indicates the supplier participating in the alliance, then the supplier s^* allies with the manufacturer $\mathcal{B}_1 = \{s^*, m\}$, and the negotiation power of the alliance $\mathcal{B}_1$ is the total of the manufacturer and supplier's negotiating power s^*, that is, $\alpha_{\mathcal{B}_1} = \alpha + \beta = 1$, while the negotiation power of suppliers who do not participate in cooperation remains unchanged and remains β.

When the supplier s^* allies with the manufacturer, causing a change in the supply chain structure, the number of suppliers participating in the negotiation decreases from n to $n-1$, and the alliance $\mathcal{B}_1$ needs to conduct $n-1$ rounds of one-by-one negotiations with suppliers. When the alliance $\mathcal{B}_1$ negotiates with suppliers who are not involved in cooperation in the jth round, the profits of the alliance $\mathcal{B}_1$ and suppliers that do not participate in cooperation are $\pi_{\mathcal{B}_1} = \frac{1}{(1+\beta)^j}\Delta\pi$ and $\frac{\beta}{(1+\beta)^j}\Delta\pi$.

Proposition 6: When the manufacturer participates in negotiations after allying with the supplier and reaches equilibrium, the profit of the supplier who does not participate in the alliance is $\pi_i^{**} = \frac{\beta}{(1+\beta)^{n-1}}\Delta\pi + \pi_i^{D*}$. The profit of the alliance $\mathcal{B}_1$ is $(1 - \frac{(n-1)\beta}{(1+\beta)^{n-1}})\Delta\pi + \pi_i^{D*} + \pi_m^{D*}$. The profit of participating alliance suppliers s^* is $\pi_{s^*}^* = \beta(1 - \frac{(n-1)\beta}{(1+\beta)^{n-1}})\Delta\pi + \pi_i^{D*}$. The profit of the manufacturer is $\pi_m^{**} = \alpha(1 - \frac{(n-1)\beta}{(1+\beta)^{n-1}})\Delta\pi + \pi_m^{D*}$.

Proof. It can be seen from the proof of Proposition 5 that when the supplier s^* allies with the manufacturer for negotiations, the negotiation sequence still affects the supplier's profits. Moreover, the supplier with the earlier negotiation sequence can obtain more profit distribution. Suppliers in the supply chain will still give the alliance a concession P_j^* to strive for an earlier negotiation order. Similar to Proposition 5, the maximum limit of the supplier concession is $\beta((\frac{1}{1+\beta})^j - (\frac{1}{1+\beta})^{n-1})\Delta\pi$, which is all the profits obtained in advance due to the negotiation sequence; therefore, the supplier's concession to the alliance is $P_j^{**} = \beta((\frac{1}{1+\beta})^j - (\frac{1}{1+\beta})^{n-1})\Delta\pi$. After the supplier makes a concession, the supplier who does not participate in the cooperation can only receive the final round of negotiations' profit $\frac{\beta}{(1+\beta)^{n-1}}\Delta\pi$, which is the minimum profit a non-cooperative supplier can obtain by participating in the negotiation if the manufacturer allies with a supplier. The profit of the alliance $\mathcal{B}_1$ is $(1 - \frac{(n-1)\beta}{(1+\beta)^{n-1}})\Delta\pi$, which is the sum of the alliance's negotiation profit and supplier concessions; the alliance $\mathcal{B}_1$ obtains excess profits due to the right to decide the negotiation sequence. Furthermore, assuming that within the alliance $\mathcal{B}_1$, the manufacturer and supplier distribute alliance profits through bargaining negotiations; then, by substituting the bargaining power of manufacturers and suppliers α and β, the profits of the manufacturer and supplier s^* are $\alpha(1 - \frac{(n-1)\beta}{(1+\beta)^{n-1}})\Delta\pi$ and $\beta(1 - \frac{(n-1)\beta}{(1+\beta)^{n-1}})\Delta\pi$, respectively.

Q.E.D.

When the manufacturer allies with a supplier, the alliance receives excess profits due to the right to decide the negotiation sequence. The manufacturer and supplier share the alliance profits through bargaining negotiations, and suppliers receive higher profits by participating in the alliance. Suppliers who do not participate in the alliance cooperation can only receive the final round of

negotiations' profit and the minimum profit suppliers can obtain by participating in negotiations.

Proposition 7: When the manufacturer allies with a supplier, the profit of all suppliers increases. The supplier who participates in the alliance receives more profit than the supplier who does not. However, the profit of the manufacturer decreases due to the alliance.

Proof. Substituting $\pi_{s^*}^*$ and π_i^{**} into $\pi_{s^*}^* - \pi_i^{**}$, we obtain $\pi_{s^*}^* - \pi_i^{**} = \beta(1 - (n-1)\beta(\frac{1}{1+\beta})^{n-1})\Delta\pi - \frac{\beta}{(1+\beta)^{n-1}}\Delta\pi = \frac{\beta}{(1+\beta)^{n-1}}((1+\beta)^{n-1} - (n-1)\beta - 1)\Delta\pi$. Because $(1+\beta)^{n-1} = 1 + (n-1)\beta + \binom{n}{2}\beta^2 + o(\beta^2) > (n-1)\beta + 1$, we get $\pi_i^{**} - \pi_i^* = \beta\frac{1}{(1+\beta)^{n-1}}\Delta\pi - \beta\alpha^{n-1}\Delta\pi = \frac{\beta\Delta\pi}{(1+\beta)^{n-1}}(1 - (1-\beta^2)^{n-1}) > 0$. Therefore, we get $\pi_{s^*}^* > \pi_i^{**} > \pi_i^*$.

Q.E.D.

When the manufacturer and supplier form alliances, the profits of all suppliers are improved, suppliers who participate in cooperation can obtain more profits than those who do not participate in cooperation, suppliers will actively cooperate with manufacturers, and manufacturers have the initiative to choose partners.

However, the manufacturer has aligned themselves with the supplier, resulting in lower profits. Therefore, for manufacturers, alliances do not increase profits, although they enhance their products' competitive advantage, and it is necessary to choose partners carefully. The research also explains why the manufacturer partners with component suppliers with advanced technology advantages.

6 Numerical analysis and sensitivity analysis

6.1 Numerical analysis

The following analysis is carried out through an example to visually demonstrate the influence of different parameter values on optimal strategies. For example, we use four suppliers of parts to perform numerical analysis. The parameters are as follows: $k_1 = 10, k_2 = 40, k_3 = 30, k_4 = 50, \theta = 2, \lambda = 0.5, a = 2000, \alpha = 0.6, \beta = 0.4, p_e = 100, and \lambda = 0.005$.

We can obtain the optimal strategy by substituting parameters, as shown in Table 1.

After implementing the DCP, the technical level and sales of NEVs have increased and the carbon emissions in the transportation field have significantly reduced. The DCP can promote the NEV industry's development and reduce carbon emissions.

However, we found that the incentive effect of the DCP on NEV technology innovation, sales, and carbon emission reduction is much lower than that under centralized decision-making. Decentralized decision-making weakens the incentive effect of the DCP. Only by making centralized decisions by NEV supply chain companies can the DCP's incentive effect be optimized.

Therefore, it is essential to design an incentive mechanism to coordinate the NEV supply chain so that independent and decentralized companies can achieve centralized decision-making.

As seen from Table 2, if the supply chain makes centralized decisions, the profits are significantly improved compared to those under the decentralized decision-making. For NEV companies that seek to maximize profits, it is easy to achieve cooperation as long as this can improve profits. By bargaining for the distribution of incremental profits, both suppliers and manufacturers gain more profits than under decentralized decisions. Therefore, the incentive system based on the bargaining game achieves coordination of the NEV supply chain and promotes centralized decision-making by NEV companies.

As seen from Table 2, when suppliers individually negotiate on a one-on-one basis with manufacturers in the order of negotiation, the profits of all suppliers are improved, and all suppliers' profits increase by the same amount. When a given supplier and the manufacturer are aligned to negotiate, all suppliers' profits increase and the given supplier's profits increase by much more than those of other suppliers. Therefore, forming alliances with manufacturers is the best choice for suppliers to obtain more profits. However, manufacturers' profits decline after the formation of such an alliance. Therefore, the purpose of the alliance of manufacturers is different from that for suppliers, i.e., not to increase profits but to cooperate with suppliers with technological advantages to enhance product competitiveness.

6.2 Sensitivity analysis

6.2.1 Influence of the DCP

① The impact of the technological innovation credit coefficient

As seen in Figures 1A, B, NEV technology has improved, regardless of the decision-making mode after implementing the DCP compared to without the DCP. Moreover, the higher the technological innovation credit coefficient, the higher the NEVs' technology level. As seen from Figures 1C, D, implementing the DCP has increased NEV sales under decentralized and centralized decision-making. Moreover, the higher the technological innovation credit coefficient, the higher the NEV sales. As seen from Figures 1E, F, after the implementation of the DCP, regardless of the decision-making mode, the supplier's technological innovation investment increases, and the higher the technological innovation credit coefficient, the higher the supplier's technological innovation investment. As seen from Figures 1G, H, after implementing the DCP, carbon emissions in the transportation field are reduced under decentralized and centralized decision-making. With the improved credit coefficient of technological innovation, the impact of the DCP on carbon emission reduction in the transportation field is more significant.

② The impact of credit prices

As seen from Figures 2A, B, after the DCP's implementation, the NEVs' technology level improves, regardless of the decision-making mode. Moreover, the higher the credit price, the higher the NEVs' technology level. As seen from Figures 2C, D, NEV sales increased after implementing the DCP. Moreover, the

higher the credit price, the higher the NEV sales. According to Figures 2E, F, after the implementation of the DCP, regardless of the decision-making mode, the supplier's technological innovation investment increases, and with the increase in the credit price, the higher the technological innovation investment. As seen from Figures 2G, H, carbon emissions in the transportation sector reduce after the implementation of the DCP. With the increase in credit prices, the impact of the DCP on carbon emission reduction in the transportation field is more significant.

6.2.2 Impact of decision-making methods

As seen from Figures 3A, C, F, G, compared to the decentralized decision-making, the investment in NEV technology innovation increases, the technical level of NEVs increases, NEV sales increase, and carbon emission reduction increases under the centralized decision-making. Moreover, the higher the credit coefficient of technological innovation, the more significant the advantages of centralized decision-making.

As seen from Figures 3B, D, E, H, compared to the decentralized decision-making, the investment in NEV technology innovation increases, NEVs' technical level increases, NEV sales increase, and carbon emission reduction increases under the centralized decision-making. Moreover, the higher the credit price, the more significant the advantages of centralized decision-making.

6.2.3 Impact of alliance negotiations

As seen from Figures 4A, B, the manufacturer and supplier are more profitable under the centralized decision-making than under the decentralized decision-making and obtain incremental profits based on bargaining negotiations. Therefore, the coordination strategy is the optimal strategy for centralized decision-making, improving the technological innovation investment and technical level of NEVs, reducing carbon emissions in the transportation field, and increasing the profits of all companies, thus representing a win--win situation.

As seen from Figure 4C, when a manufacturer engages in alliances with a supplier, all suppliers are profitable, all suppliers benefit from alliances, and the suppliers who participate in cooperation earn more margins than suppliers who do not. As seen from Figure 4D, the manufacturer's profits decrease, proving that the manufacturer is not aligned to improve profits.

7 Discussion

The Chinese government issued the DCP intending to promote the development of NEVs through market incentives. Some researchers believe that the DCP could achieve China's goals in this regard. The DCP can stimulate manufacturers and suppliers to increase investment in NEVs' technological innovation, improve NEVs' technology level, and promote NEVs' large-scale promotion (Zhou and Shen, 2020; Ma et al., 2021; Yang et al., 2021). Our research confirms this view.

Next, we discuss the essential parameters involved in the proposed models.

Under the DCP, as the technological innovation credit coefficient or credit price increases, the DCP's incentive effect on

the development of the NEV industry and the reduction of carbon emissions in transportation become more significant. Therefore, the government can set and adjust the technological innovation credit coefficient to prompt the NEV industry's healthy and sustainable development and achieve the transportation sector's carbon peak and carbon neutrality goals.

The decentralized decision-making weakens the incentive effect of the DCP on technological innovation investment, carbon emission reduction, technology level, and NEV production. With the increase of the technological innovation credit coefficient or credit price, the weakening of the incentive effect of the DCP is more significant. However, the NEV supply chain can achieve one-to-many cooperation through the centralized decision-making and profit-sharing mechanism and could effectively motivate suppliers to increase NEVs' technological innovation investment and optimize the incentive effect of the DCP.

We found that the impact of alliance negotiations on the profits of manufacturers and suppliers differs. Through bargaining negotiations, both manufacturers and suppliers have obtained more profits than under decentralized decision-making. Moreover, as the manufacturer's bargaining power increases, the manufacturer's profit and supplier's profit decreases. Nevertheless, compared to no alliance, when the manufacturer and a supplier form an alliance, the manufacturer's profits decrease and the suppliers' profits increase. The results indicate that the manufacturer's primary purpose in allying is to enhance their products' competitiveness rather than to increase their profits, while suppliers could gain more profits by allying.

8 Conclusion

8.1 Main findings

This paper considers the NEV supply chain consisting of one manufacturer and multiple suppliers, constructs a technological innovation decision-making model under the DCP, and studies the optimal technological innovation strategy and the impact of the DCP on carbon emissions. Furthermore, this paper constructs a bargaining game model based on an alliance strategy to study the coordination of the NEV supply chain. Finally, it verifies the DCP's incentive effect on NEV technology innovation and carbon emission reduction in the transportation field through a numerical example analysis. The main findings of the research are as follows:

① Implementing the DCP can stimulate the NEV supply chain to increase technological innovation investment, improve the technological level and sales of NEVs, and effectively reduce carbon emissions in the transportation sector. Moreover, with the increase of the technological innovation credit coefficient or credit price, the DCP has a significant incentive effect on the technological innovation of NEVs and the reduction of carbon emissions in the transportation sector.

② The decentralized decision-making weakens the incentive effect of the DCP on reducing carbon emissions, and the bargaining game based on alliance negotiation can enable

independent enterprises to achieve the optimal strategy for centralized decision-making so that the incentive effect of the DCP on reducing carbon emissions can be optimized.

③ The purpose of an alliance between manufacturers and suppliers is different. For manufacturers, it is not to increase profits but to enhance their product advantages. However, suppliers can profit more by participating in the alliance, providing a theoretical reference for decision-making.

8.2 Theoretical implications

This study bridges the concepts of the DCP, carbon emission reduction, and NEVs' technological innovation cooperation. The contributions to the existing literature are as follows:

① This paper theoretically further enriched the research content in policy incentive (especially DCP), carbon emission reduction, and technological innovation cooperation of the NEV supply chain, considering the background of the DCP, and combines NEV technological innovation with carbon emission reduction, which provides a new research idea for future research.

② This paper constructs a technological innovation game model of the NEV supply chain under the dual credit policy and a bargaining model considering the alliance. The results show that the NEV supply chain can achieve one-to-many cooperation through centralized decision-making and profit-sharing mechanisms, and could effectively motivate suppliers to increase NEVs' technological innovation investment and optimize the incentive effect of the DCP, which provides a theoretical reference for future research.

8.3 Practical implications

Based on the main findings, we put forward policy implications as follows:

① The DCP can encourage enterprises to increase investment in NEV technological innovation and significantly reduce carbon emissions in transportation. Moreover, the higher the technology innovation credit coefficient or credit price, the more is invested in technology innovation for NEVs and the more significant the effect on reducing carbon emissions in the transportation sector. Therefore, the government can regulate the NEV industry by setting or adjusting the credit coefficient of technological innovation or credit price, promoting the NEV industry's healthy and sustainable development, and realizing the carbon peaking and carbon neutrality goals.

② The alliance cooperation between manufacturers and suppliers can improve the suppliers' profits, enhance the manufacturers' competitiveness, and achieve a win-win scenario for all parties. The government should encourage alliances among companies to rapidly upgrade NEVs and achieve more quickly the carbon peaking and carbon neutrality goals in transportation.

8.4 Future work

This study has some limitations. First, the demand function is linear and random or other demand function forms deserve further investigation. Second, it is assumed that there is only one supplier for one component. However, there may be different suppliers of the same component; therefore, supplier competition should be considered.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding authors.

Author contributions

BH and YL conceived the original idea for the research and established the model. MM and WM performed the model analyses. MM performed the numerical analyses. All authors drafted and revised the draft.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Nomenclature

Abbreviations

NEVs new energy vehicles
DCP dual credit policy

Superscripts

D decentralized decision
ND decentralized decisions without the dual credit policy

Subscripts

m carmaker

Parameters

a potential market demand

θ consumer preference coefficient for NEV technology

w wholesale price of the parts

ε NEV credits with the technical performance T_0

I supplier's technology innovation investment

G_0 each fuel vehicle's carbon emissions

δ technological innovation emission reduction coefficient

C centralized decisions

NC centralized decisions without dual credit policy

i supplier

p NEVs' price

T NEVs' technology innovation

p_e NEV credit price

λ technology innovation credit coefficient

k supplier's technology innovation cost coefficient

μ replacement rate of NEVs