scientific reports

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Dynamic optimization and coordination of the new energy vehicle supply chain based on credit trading and green innovation

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This paper incorporates green innovation into a two-tier new energy vehicle supply (NEV) chain under a dual credit policy, in which the NEV manufacturer controls the level of green innovation and wholesale prices, and the NEV retailer controls sales prices. We analyze the pricing and green innovation strategies of the NEV manufacturer and retailer in decentralized and integrated scenarios by constructing differential game models. We then test the performance of the supply chain by comparing the profit, energy efficiency levels and green innovation levels of the NEV supply chain with those in the decentralized scenario. It is found that the profits, energy efficiency levels and green innovation levels of the NEV supply chain in the integrated scenario are higher than those in the decentralized scenario. Therefore, a revenue and investment sharing contract is designed to coordinate the supply chain and several conditions are derived for the contract to be accepted by both members of the supply chain. Numerical calculations are performed and the theoretical results and impacts of the unit credit trading price and the percentage of units of NEV converted into credits on the supply chain coordination are analyzed to further validate the effectiveness of the dual credit policy.

Keywords New energy vehicle supply chain, Differential game, Dual credit policy, Green innovation, Energy efficiency level

With the significant increase in global energy consumption, worsening supply-demand mismatch, and growing environmental concerns related to greenhouse gases, numerous governments have developed new strategies to facilitate energy transition[1,2]. Among them, the energy transition of the automotive industry has become an important breakthrough. Because new energy vehicles (NEVs) offer energy savings, emission reduction and effective environmental protection, they have become the main focus of transformation and upgrading in the global automotive industry[3]. However, since NEVs remain in the early stages of development, compared to traditional fuel vehicles, NEVs have disadvantages such as slow charging time and limited cruising range. Therefore, to promote the development of NEVs, various countries have introduced different incentive policies and measures[4,5]. As the world's largest electric vehicle market, China is also constantly exploring and improving local NEV incentive policies.

In addition to providing policies such as exemptions from purchase taxes and power battery recycling and utilization, a series of programs promoting NEVs have been introduced. These programs include the vigorous construction of NEV charging and swapping facility parking incentives. While these non-market-oriented policies have stimulated the development of the NEV market, long-term fiscal pressure and excessive government intervention have resulted in market failure. As a result, the country has been forced to change its strategy. Therefore, in 2008, China introduced a dual credit policy to promote the sustainable development of NEVs. The policy has played a positive role in guiding the progress of energy-saving technologies in the automotive industry and promoting the development of the NEV industry. According to the specific provisions of dual credit policy, NEV manufacturers generate revenue by selling new energy credits to traditional fuel vehicles. To produce traditional fuel vehicles, traditional fuel vehicle manufacturers are required to purchase new energy credits if they have insufficient credits or if their actual average falls short. In other words, automakers that produce a higher number of fuel vehicles can purchase credits from automakers that produce more NEVs. This

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promotes the transition from traditional fuel vehicles to NEVs and stimulates the growth of the electric vehicle industry.

On the one hand, faced with ever-growing environmental problems, an increasing number of consumers are focusing on environmental protection issues. More consumers are willing to choose a greener way of traveling, so NEV manufacturers are investing more in greening their NEVs and realizing greener NEVs. On the other hand, as customers demand increasing diversity in NEVs, many manufacturers are forced to produce multiple NEVs to meet the various needs of their customers. For example, BYD launched electric cars in 2008 with the goal of reaching \$404.6 billion in revenue by 2024. To achieve this goal, this year, BYD is launching two models of the Qin PLUS Champion Edition EV with a range of 420KM, the leading and surpassing models, and two models with a range of 510KM, the excellent and surpassing models. The two NEVs with the same range have very little difference in model and performance, mainly in price. This creates further difficulties in managing the manufacturer-led NEV supply chain due to the price competition from alternative NEVs.

Considering the background described above, the dual credit policy, and the green innovation efforts on two NEVs, this paper explores the decisions made by NEV supply chain members, including the energy efficiency level, in a dynamic setting. Furthermore, this paper aims to address the following research questions:

1. What are the optimal/equilibrium pricing and green innovation strategies in an integrated/decentralized environment?
2. What is the impact of the trading price of credits and the rate of conversion of NEVs into credits on the supply chain and its members?
3. How can a contract be designed to achieve a perfectly coordinated decentralized supply chain?

The main contributions of this paper are as follows. First, combined with the dual credit policy, this paper studies the long-term equilibrium strategy of producing two kinds of NEVs with the same degree of environmental friendliness in the two-level NEV supply chain under different scenarios by using a differential game model. This study aims to theoretically analyze the impact of sales prices and the level of green innovation on operational decisions in three different scenarios: a decentralized scenario, an integrated scenario, and a decentralized system with a contract. Second, the numerical example section analyzes the impact of the sales price per unit of credit and the percentage of the unit of the NEV converted into credit on the supply chain. Finally, we propose a revenue and cost-sharing (RC) contract to coordinate the supply chain and establish favorable conditions for both sides of the supply chain to accept the RC contract.

The rest of the paper is organized as follows. In "Literature review" section, we briefly review the relevant literature. "Problem and symbol description" and "Model formulation" sections construct models that give optimal pricing and green innovation strategies in the decentralized and integrated scenarios. Strategies are also compared for the integrated scenario and the decentralized scenario. In "Coordination with a revenue- and cost-sharing contract" section, we design an RC contract to coordinate the NEV supply chain. "Numerical experiments" section illustrates the theoretical results with numerical examples and further analyzes the impact of several key parameters on the coordination of the NEV supply chain. The final section presents the conclusions of the paper and research directions for future work.

Literature review

The literature related to the work presented in this paper has two streams: supply chain coordination for NEVs under the dual credit policy and differential game theory.

Supply chain coordination for NEVs under policy

In recent years, many scholars have researched various aspects of NEV incentive policies. Zhang and Cai[6] introduced a signal game model to analyze the equilibrium of the game between the government and NEV enterprises under the subsidy policy, focusing on the subsidy interaction between them under different circumstances. Yu et al.[7] verified that government subsidies before and government subsidies afterwards have different impacts on NEV firms in China through panel regression model analysis of fiscal data from 2013-2017, and gained some managerial insights. Wang et al.[8] explored the effects of adaptive and consistent subsidies in terms of both supply and demand in order to satisfy the maximization of the utility of subsidy policies. Other studies on subsidy policies can be found in Wang et al.[9], Sun et al.[10], and Fan et al.[11]. In contrast to the above literature, which focuses on the impact of subsidy policies on the government and NEV firms, several scholars have examined other policies. Li and Jones[12], Abeng et al.[13], and Jiao et al.[14] explored the effectiveness of policies that limit vehicle ownership, waste battery recycling and CO_2 reduction.

Faced with considerable financial pressure from the government, the subsidy policy entered the post-subsidy era. The dual credit policy was issued by China in 2018. Using an analytical model based on game theory, Li et al.[15] verified that the dual credit policy can significantly increase the number of NEVs and further demonstrate that the implementation of the dual credit policy reduces the effectiveness of green subsidy policies. Li et al.[16] analyzed the impact of production decisions in NEV supply chains and conventional vehicle supply chains under point trading and showed that there is an optimal point trading price that makes the system most profitable. Cheng and Fan[17] established a system of fuel vehicle manufacturers and NEV manufacturers to explore the choice of vehicle production strategies in cooperation and competition. Li et al.[18] considered a monopolistic market consisting of a firm producing fuel cars and NEVs and a NEV firm, analyzed three ways of acquiring NEV credits, namely, self-production, purchase and hybrid strategies, and analyzed the optimal decision behavior of the two car companies under the three strategies. Wang and Liao[3] studied manufacturers that produce only fuel vehicles and those that produce both fuel vehicles and NEVs, focusing on the impact of the dual credit policy on both vehicle manufacturers. Pu et al.[19] used game theory to build a supply chain model composed of suppliers and automobile manufacturers. On the basis of incorporating the impact of double credit policy and vertical spillover effect, it studied how to reduce carbon emissions through vertical spillover under the goal of profit maximization, and further explored the low-carbon strategy of automobile supply chain. Wu et al.[20] built and solved the Stackelberg game model of vehicles under the dual credit policy under two scenarios of sharing and not sharing the perceived quality information of new energy in the supply chain of NEVs (including NEV enterprises, battery manufacturers and fuel vehicle enterprises). By analyzing the results of the model and combining with a numerical example, this study discusses the impact of credit price and information prediction accuracy on enterprise decision-making and profits, and puts forward management enlightenment. Ma et al.[21] discussed the impact of market uncertainty and risk attitude on NEV technology innovation under the dual credit policy, focusing on the role of manufacturers' demand information sharing and blockchain adoption. By constructing a game model based on mean variance theory, the optimal strategies of four scenarios are derived The research shows that the policy can effectively stimulate technological innovation, and the incentive effect increases with the increase of technological innovation credit coefficient or credit price.

While the above literature concentrates on the horizontal competition and cooperation strategies of car manufacturers under the dual credit policy, this paper considers the vertical cooperation of NEV manufacturers and retailers under the dual credit policy, in particular the production of two models by NEV manufacturers to meet consumers' purchasing needs, which has rarely been studied before.

Differential game theory in a green supply chain

Differential game theory, usually used in cooperation and competition in dynamic environments, have been widely used in the study of long-term decision making in supply chains. Recently, several research papers have employed differential game theory to explore the impact of green innovation on green supply chain operational decision-making. De[22] verified that co-maximization incentives increase manufacturers' investment in green efforts. Wei et al.[23] considered green innovation in Stackelberg differential game models and analyzed the dynamic equilibrium of Cournot competition and green innovation using optimal control theory. Mohsin et al.[24] modeled the green secondary supply chain differential game for green technology development. The results of the study show that the level of the green technology and the total profit of green supply chain are higher under centralized than under decentralized decision-making. Ma et al.[25] used differential game models to analyze the carbon reduction behavior of cold chain members and the optimal decision to invest in preservation technologies from a long-term and dynamic perspective. Deng et al.[26] developed a differential game model consisting of local governments and enterprises to investigate the impacts of low-carbon innovation efforts and environmental governance efforts on green technological innovations. Chen et al.[27] developed a differential game model under the social welfare orientation to investigate the effect of the subsidy rate on consumers' environmental awareness using a three-tier green supply chain as the research object. Huang et al.[28] built a differential game model to explore the impact of collection channels on prices and return rates from the perspective of manufacturers, retailers and third parties' respective management of second-hand product collections. Zhang et al.[29] developed a dynamic differential game model to explore whether a single manufacturer and a single retailer should invest in digital applications, and proposed an improved model to encourage manufacturers to invest in digital technology and share information with retailers. Liu et al.[30] introduced blockchain technology, took product freshness and goodwill as state variables, and built a differential game model involving suppliers and e-commerce platforms. The research showed that the introduction of blockchain technology would help to improve the freshness. In order to explore the relationship between blockchain technology and the performance of low-carbon e-commerce supply chain, Yu et al.[31] proposed a dynamic game theory model. The research results show that in the monopoly market, the introduction of blockchain technology has proved to be the best strategy to improve the low-carbon e-commerce supply chain.

Research gap

While existing literature has explored the impact of the dual credit policy on the NEV industry, it exhibits several limitations, thereby providing room for innovation in this study. First, regarding model construction, most prior studies have employed static models to analyze the market for a single type of NEV[18], failing to capture the dynamic interactions among enterprises and the heterogeneity of different NEV types. Distinct from previous research, this paper establishes a dynamic framework under the dual credit policy that incorporates green innovation, two categories of NEVs, and a contractual mechanism. Specifically, we adopt a differential game model to investigate the pricing competition and green innovation level decisions of two NEV variants within the NEV supply chain under the dual credit policy. Second, in terms of supply chain coordination, most existing literature on coordination mechanisms[25] has focused on traditional supply chains, neglecting the uniqueness and complexity of supply chain coordination under the dual pressures of the dual credit policy and NEV competition. To address this gap, this study innovatively designs the RC contract. This contract not only effectively coordinates supply chain profits in the traditional sense but, more crucially, can simultaneously guide competing NEV manufacturers to elevate their green innovation levels to the system-optimal state. It thereby resolves the insufficient incentive issue of existing contracts when coping with the"policy-competition" environment. Finally, in terms of contract feasibility, this paper does not stop at proving the theoretical validity of the contract, but further deduces the key parameter conditions for supply chain members to be willing to accept the RC contract in a dynamic environment. This provides a clear theoretical basis for decision makers to design feasible contract parameters. A summary is provided in Table 1.

Problem and symbol description

In the context of the dual credit policy, consider a supply chain composed of an NEV manufacturer and a retailer. In order to better explore the impact of the dual credit policy on the optimal decisions of the NEV

Researches	Green innovation	Differential game	Dual-credit policy	RC contract	One/Two products
Li et al.[15]	√	√	√	–	One
Wang and Liao[3]	–	–	√	–	Two
Mohsin et al.[24]	√	√	–	–	One
Ma et al.[25]	–	–	–	√	One
Deng et al.[26]	√	√	–	–	One
Zhang et al.[32]	√	√	–	–	One
This study	√	√	√	√	Two

Table 1. Comparisons of our paper and the related literature.

manufacturer and retailer, and to facilitate the initial construction of the model, the NEV manufacturer employs the make-to-order (MTO) strategy to produce two NEVs with an equivalent level of environmental friendliness. This approach aims to attract more consumers to choose NEVs as a mode of transportation. The manufacturer controls the level of green innovation *g*(*t*) and the wholesale prices $\omega_i(t)$ $(i = 1, 2)$. They also sell NEV credits for profit. On the other hand, the retailer sets the sales prices $p_i(t)(i = 1, 2)$ for NEVs. As consumers become more environmentally conscious, an increasing number of people are opting for greener NEVs as a means of transportation. As a result, the NEV manufacturer actively invests in green innovation *g*(*t*) to improve the energy efficiency *m*(*t*) of NEVs to produce more environmentally friendly NEVs.

The continuous development of greening innovative technology has driven energy efficiency levels and the dynamic changes better reflect this reality. However, as technology continues to evolve, so do energy efficiency standards. This can be interpreted as a decay in the level of near greenness over time. On the other hand, as technology continues to develop rapidly, energy efficiency standards are also increasing, making what used to be a highly energy-efficient NEV, relative to today, an inefficient NEV. This is the decay of energy efficiency levels over time. Energy efficiency levels are therefore not only reflected in the green innovation level but also in a dynamic environment that declines monotonically, as evidenced by

$$\dot{m(t)} = \mu g(t) - \eta m(t), m(0) = m_0 \tag{1}$$

Here $\mu > 0$ is the NEV green innovation effectiveness parameter, representing the efficiency of promoting energy efficiency growth through unit green innovation investment. If NEV company has advanced research and development capabilities, mature technology platforms, efficient innovation management systems, and unit green innovation investment can bring greater energy efficiency improvements, $\mu > 0$ will be even greater; Vice versa. $\eta > 0$ represents the rate of decay of energy efficiency levels of NEVs over time. In the NEV industry, with the continuous advancement of innovative technologies and the continuous improvement of industry standards, the energy efficiency level of NEVs is gradually becoming outdated. With the improvement of energy efficiency standards, previously considered advanced energy efficiency levels are gradually unable to meet the new standards. $m(0) = m_0$ represents the initial energy efficiency level of NEVs.

Consumer awareness of the environment influences the choice of vehicle types. Those who are more environmentally conscious are more likely to choose NEVs that are more green and low carbon, so there is a positive correlation between consumer demand and the level of green innovation. Following prior studies, Bolton ang Mattila[33], and Bai et al.[34], we model the market demand for NEVs in a deterministic environment as

$$D_i(t) = \alpha_i + \varphi m(t) - \beta p_i(t) + \gamma p_{3-i}(t), i = 1, 2 \tag{2}$$

where $\alpha_i > 0$ represents the market volume of the NEV $i(i = 1, 2)$, $\varphi > 0$ represents the level of demand expansion for greening innovations in the NEV, $\beta > 0$ represents the price sensitivity coefficient for the NEV, γ represents the cross-price sensitivity coefficient. To ensure that the demand for NEVs is more sensitive to their own prices than to competing NEV prices, it is assumed that $\beta > \gamma$[34].

The improvement of green innovative technologies for NEVs affects the stock of their energy efficiency levels, while additional costs, such as safety and quality costs, are incurred in the production of NEVs. In other words, the higher the level of energy efficiency of an NEV, the more technology investment is required, which in turn has a negative impact on the unit production cost of the NEV manufacturer. For example,"China NEV industry development report" pointed out that the production cost of NEVs equipped with modified batteries is 20%–30% higher than that of ordinary vehicles on average; At the same time, the technology research and development of several leading NEV enterprises (such as Tesla and BYD) showed that the research and development investment and parts cost related to energy efficiency upgrading showed an increasing trend with the improvement of energy efficiency. Therefore, the unit production cost function for the NEV is shown below.

$$C_i(t) = c_i + c_0 m(t), i = 1, 2 \tag{3}$$

where c_i $(i = 1, 2)$ is the initial unit production cost of the NEV. The parameter c_0 represents the marginal cost of production due to the energy efficiency level of the NEV, referred to as the operational inefficiency factor, it indirectly reflects the complexity and technological maturity of the NEV production process. To ensure a positive solution, c_0 should satisfy that $0 < c_0 < \frac{\varphi}{\beta-\gamma}$ and a large value of means high inefficiency in the production process. This linear cost function has been used by many scholars, including Zhang et al.[32] and Anton et al.[35]. In particular, when $c_0 = 0$, the operational inefficiency is disregarded, the unit production cost is therefore fixed.

The greenness of the NEV increases with the greening innovation technology of the NEV manufacturer, and the greening innovation cost of the NEV is influenced by the greening innovation technology, assuming that the green innovation cost is quadratic and the green innovation level of the NEV manufacturer is the same for two type NEVs, i.e.,

$$G(t) = \frac{k}{2}g^2(t) \tag{4}$$

In the context of the dual credit policy, every NEV produced by an NEV manufacturer is converted proportionally to generate a certain number of NEV credits, which the government allows the NEV manufacturer to sell to traditional fuel car companies that need the credits, and thus improve their profitability in this way. In order to quantitatively analyze the impact of the credit trading market on the optimal decision-making of the NEV supply chain, it is assumed that the price of an NEV unit credit is h, and θ represents the percentage an NEV that translates into a unit credit. To ensure positive solutions, the following condition is assumed to be satisfied: $0 < c_1 + c_2 - 2h\theta < \frac{\alpha_1+\alpha_2}{\beta-\gamma}$. The variables and parameters involved in the model are defined as shown in Table 2.

Based on the above analysis, the target profit functions for the NEV manufacturer and retailer in the context of dual credit policy over an infinite time horizon are

$$J_M = \int_0^{\infty} e^{-\rho t}[\sum_{i=1}^{2}(\omega_i(t) - c_i - c_0 m(t))D_i(t) - kg^2(t) + \sum_{i=1}^{2} h\theta D_i(t)]dt \tag{5}$$

$$J_R = \int_0^{\infty} e^{-\rho t}[\sum_{i=1}^{2}(p_i(t) - \omega_i(t))D_i(t)]dt \tag{6}$$

The long-term cumulative profits of the NEV manufacturer includes the profits from wholesale NEVs $(\omega_i(t) - c_i - c_0 m(t))D_i(t)$, the green innovation input costs of two type NEVs $kg^2(t)$ and the profits from selling NEV credits $\sum_{i=1}^{2} h\theta D_i(t)$. The long-term cumulative profit of the retailer includes the profit from the sale of NEV $(p_i(t) - \omega_i(t))D_i(t)$.

Model formulation

This section focuses on two sales channels for the NEV manufacturer and retailer, the decentralized channel and the integrated channel. First, it introduces the decentralized channel in which the NEV manufacturer determines the wholesale price and the level of green innovation of the NEV, while the NEV retailer determines the sales

Decision variables	
$p_i(t)$	Unit sales price of the NEV *i* at time *t*, $i = 1, 2$
$\omega_i(t)$	Unit wholesale price of the NEV *i* at time *t*, $i = 1, 2$
$g(t)$	The green innovation level of the NEV manufacturer at time *t*
State variable	
$m(t)$	The energy efficiency of NEVs at time *t*
Parameters	
μ	The NEV green innovation effectiveness parameter
η	the rate of decay of energy efficiency levels of NEVs
α_i	The market volume of the NEV *i*, $i = 1, 2$
φ	The level of demand expansion for greening innovations in the NEV
β	The price sensitivity coefficient for the NEV
γ	The cross-price sensitivity coefficient
c_i	The initial unit production cost of the NEV, $i = 1, 2$
c_0	The marginal cost of production due to the energy efficiency level of the NEV
k	Green innovation cost coefficient
h	The price of an NEV unit credit
θ	The percentage an NEV that translates into a unit credit
ρ	Discount factor

Table 2. The major parameters and notations.

price. Then, it discusses the integrated channel in which the NEV manufacturer maximizes the benefits of the entire NEV channel by controlling the sales price and the level of green innovation.

Decentralized scenario

In addition to the 4S store sales method, there are retailers that buy NEVs from manufacturers at low prices and sell them to consumers, such as China Grand Automotive Services Group Co., Ltd. and Hanson Automobile Group Co., Ltd. Assuming that the NEV manufacturer is the leader and the NEV retailer is the follower, we use a Stackelberg game to model the relationship between the NEV manufacturer and the retailer. The sequence of events is described as follows: The NEV manufacturer first decides the wholesale price $\omega_i(t)\,(i=1,2)$ and green innovation $g(t)$. Then, the NEV retailer reacts by determining its selling price $p_i(t)\,(i=1,2)$, using backward induction, considering the reaction function of the NEV retailer, solving the decision problem of the NEV retailer first and then recursively solving the decision problem of the NEV manufacturer. The dynamic relationship Eqs. (1), (5) and (6) consisting of the NEV manufacturer and retailer is described differentially as

$$\begin{aligned} &\max_{\omega_1(t),\omega_2(t),g(t)} J_M^D = \int_0^\infty e^{-\rho t}[\sum_{i=1}^{2}(\omega_i - C_i(t))D_i(t) - kg^2(t) + \sum_{i=1}^{2} h\theta D_i(t)]dt \\ &\max_{p_1(t),p_2(t)} J_R^D = \int_0^\infty e^{-\rho t}[\sum_{i=1}^{2}(p_i(t) - \omega_i(t))D_i(t)]dt \\ &s.t. \dot{m}(t) = \mu g(t) - \eta m(t), m(0) = m_0 \end{aligned} \tag{7}$$

where the sales price $p_i(t)\,(i=1,2)$, wholesale price $\omega_i(t)\,(i=1,2)$ and greening innovation level $g(t)$ are the control variables and the level of energy efficiency $m(t)$ is the state variable. Eq. (7) explores the best solution for the NEV manufacturer and retailer in a decentralized situation.

Proposition 1 *Under the decentralized channel structure, the equilibrium sales prices, wholesale prices and green innovation are*

$$p_1^D(m) = \frac{3(\beta\alpha_1 + \gamma\alpha_2)}{4(\beta^2 - \gamma^2)} + \frac{c_1 - h\theta}{4} + \frac{3\varphi + (\beta - \gamma)c_0}{4(\beta - \gamma)}m, \tag{8}$$

$$p_2^D(m) = \frac{3(\beta\alpha_2 + \gamma\alpha_1)}{4(\beta^2 - \gamma^2)} + \frac{c_2 - h\theta}{4} + \frac{3\varphi + (\beta - \gamma)c_0}{4(\beta - \gamma)}m, \tag{9}$$

$$\omega_1^D(m) = \frac{\gamma\alpha_2 + \beta\alpha_1}{2(\beta^2 - \gamma^2)} + \frac{c_1 - h\theta}{2} + \frac{\varphi + (\beta - \gamma)c_0}{2(\beta - \gamma)}m, \tag{10}$$

$$\omega_2^D(m) = \frac{\gamma\alpha_1 + \beta\alpha_2}{2(\beta^2 - \gamma^2)} + \frac{c_2 - h\theta}{2} + \frac{\varphi + (\beta - \gamma)c_0}{2(\beta - \gamma)}m, \tag{11}$$

and

$$g^D(m) = \frac{\mu}{2k}(2A_1 m + A_2). \tag{12}$$

Under the decentralized channel structure, the optimal profit for the NEV manufacturer and retailer are expressed below.

$$J_M^D = e^{-\rho t}\left(A_1 m^2 + A_2 m + A_3\right), \tag{13}$$

$$J_R^D = e^{-\rho t}\left(B_1 m^2 + B_2 m + B_3\right). \tag{14}$$

The optimal profitability of the NEV supply chain is expressed as follows.

$$J^D = e^{-\rho t}\left[(A_1 + B_1)m^2 + (A_2 + B_2)m + (A_3 + B_3)\right]. \tag{15}$$

where $A_1 = \frac{k(\beta-\gamma)(2\eta+\rho)-\xi_1}{2\mu^2(\beta-\gamma)}$,

$$A_2 = \frac{k[\varphi - (\beta - \gamma)c_0]\left[\sum_{i=1}^2 \alpha_i + (\gamma - \beta)\left(\sum_{i=1}^2 c_i - 2h\theta\right)\right]}{2(\rho k(\beta - \gamma) + \xi_1)},$$

$$A_3 = \frac{\mu^2 {A_2}^2}{4k\rho} + \frac{\sum_{i=1}^2 \left\{\left[\beta\alpha_i + \gamma\alpha_{3-i} + (h\theta - c_i)\left(\beta^2 - \gamma^2\right)\right][\alpha_i + \gamma c_{3-i} - \beta c_i + h\theta(\beta - \gamma)]^2\right\}}{8\rho(\beta^2 - \gamma^2)},$$

$$B_1 = \frac{k\left[\varphi - (\beta-\gamma)\,c_0\right]^2}{8\xi_1},$$

$$B_2 = \frac{\left\{\left[\xi_1\left(\rho k(\beta-\gamma)+\xi_1\right)\right](1-\gamma+\beta) + k(\beta-\gamma)\,\mu^2\left[\varphi-(\beta-\gamma)\,c_0\right]^2\right\}}{8\xi_1\left[\rho k(\beta-\gamma)+\xi_1\right]^2} + \frac{k\left[\varphi-(\beta-\gamma)\,c_0\right]\left[\sum_{i=1}^{2}\alpha_i + (\gamma-\beta)\left(\sum_{i=1}^{2}c_i - 2h\theta\right)\right]}{8\xi_1\left[\rho k(\beta-\gamma)+\xi_1\right]^2},$$

$$B_3 = \frac{\sum_{i=1}^{2}\left\{\left[\beta\alpha_i + \gamma\alpha_{3-i} + \left(\beta^2-\gamma^2\right)(h\theta - c_i)\right]\left[\alpha_i + \gamma c_{3-i} - \beta c_i + h\theta(\beta-\gamma)\right]\right\}}{16\rho\left(\beta^2-\gamma^2\right)} + \frac{A_2 B_2 \mu^2}{2k\rho}$$

$$\text{and } \xi_1 = \sqrt{k(\beta-\gamma)\left\{k(\beta-\gamma)(2\eta+\rho)^2 - \mu^2\left[\varphi-(\beta-\gamma)\,c_0\right]^2\right\}}.$$

Moreover, the accumulated energy efficiency level over time is

$$m^D(t) = m_\infty^D + \left(m_0 - m_\infty^D\right)e^{-Q_1 t} \tag{16}$$

where $Q_1 = \frac{\xi_1^2 - \rho^2 k^2 (\beta-\gamma)^2}{2k(\beta-\gamma)\left[\xi_1 + \rho k(\beta-\gamma)\right]} > 0$, $m_\infty^D = \frac{k\mu^2(\beta-\gamma)\left[\varphi-(\beta-\gamma)c_0\right]\left[\sum_{i=1}^{2}\alpha_i + (\gamma-\beta)\left(\sum_{i=1}^{2}c_i - 2h\theta\right)\right]}{2\left[\xi_1^2 - \rho^2 k^2(\beta-\gamma)^2\right]}$ corresponding to the steady-state energy efficiency level.

Proof. Please see Appendix A.

Proposition 1 suggests that the sales price, wholesale price and green innovation for the NEV increase linearly in the state variable, implying that an increase in the level of energy efficiency will lead to an increase in the sales price, wholesale price and green innovation level. From the expressions of the optional sales and wholesale prices, for any value of *m*, the energy efficiency level has a positive effect on the sales price and wholesale price of both NEVs. The level of energy efficiency has a greater impact on sales prices than wholesale prices because $\left(p_i^D(m)\right)' - \left(\omega_i^D(m)\right)' > 0\,(i = 1, 2)$. Moreover, the wholesale price of NEV *i* also plays a positive role in the sales price as Eqs. (10) and (11) show. From Eq.(16), there are two trends in the optimal trajectory of the energy efficiency level of the NEV, determined by the initial and steady-state values of the energy efficiency level. When $m_0 > m_\infty^D$, the energy efficiency level decreases over time, when $m_0 < m_\infty^D$, the energy efficiency level increases over time, and when $m_0 = m_\infty^D$, the energy efficiency level is constant.

Substituting Eq. (16) into Eqs.(8)-(12),we obtain the time path of the equilibrium sales prices, wholesale prices, and green innovation.

Proposition 2 *The optimal sales prices, wholesale prices and green innovation level paths for the two NEVs under the integrated channel are given by*

$$\begin{aligned} p_1^D(t) =& \frac{3(\beta\alpha_1 + \gamma\alpha_2) + \left(\beta^2-\gamma^2\right)(c_1 - h\theta) + (\beta+\gamma)\left(3\varphi + (\beta-\gamma)\,c_0\right)m_\infty^D}{4\left(\beta^2-\gamma^2\right)} \\ &+ \frac{3\varphi + (\beta-\gamma)\,c_0}{4(\beta-\gamma)}\left(m_0 - m_\infty^D\right)e^{-Q_1 t}, \end{aligned} \tag{17}$$

$$\begin{aligned} p_2^D(t) =& \frac{3(\beta\alpha_2 + \gamma\alpha_1) + \left(\beta^2-\gamma^2\right)(c_2 - h\theta) + (\beta+\gamma)\left(3\varphi + (\beta-\gamma)\,c_0\right)m_\infty^D}{4\left(\beta^2-\gamma^2\right)} \\ &+ \frac{3\varphi + (\beta-\gamma)\,c_0}{4(\beta-\gamma)}\left(m_0 - m_\infty^D\right)e^{-Q_1 t}, \end{aligned} \tag{18}$$

$$\begin{aligned} \omega_1^D(t) =& \frac{\gamma\alpha_1 + \beta\alpha_2 + \left(\beta^2-\gamma^2\right)(c_1 - h\theta) + (\beta+\gamma)\left(\varphi + (\beta-\gamma)\,c_0\right)m_\infty^D}{2\left(\beta^2-\gamma^2\right)} \\ &+ \frac{\varphi + (\beta-\gamma)\,c_0}{2(\beta-\gamma)}\left(m_0 - m_\infty^D\right)e^{-Q_1 t}, \end{aligned} \tag{19}$$

$$\begin{aligned} \omega_2^D(t) =& \frac{\gamma\alpha_2 + \beta\alpha_1 + \left(\beta^2-\gamma^2\right)(c_2 - h\theta) + (\beta+\gamma)\left(\varphi + (\beta-\gamma)\,c_0\right)m_\infty^D}{2\left(\beta^2-\gamma^2\right)} \\ &+ \frac{\varphi + (\beta-\gamma)\,c_0}{2(\beta-\gamma)}\left(m_0 - m_\infty^D\right)e^{-Q_1 t}, \end{aligned} \tag{20}$$

and

$$g^D(t) = \frac{\mu}{k}\left(A_1 m_\infty^D + \frac{A_2}{2}\right) + \frac{\mu A_1}{k}\left(m_0 - m_\infty^D\right)e^{-Q_1 t}. \tag{21}$$

Proof. Please see Appendix B.

Proposition 2 shows that the optimal wholesale prices, sales prices and green innovation level of two NEVs exhibit the same monotonicity. If the initial energy efficiency level is higher than the steady-state energy efficiency level, i.e., $m_0 > m_\infty^D$, then the wholesale price, sales price and green innovation level monotonically decrease and eventually stabilize. On the contrary, if $m_0 < m_\infty^D$, the wholesale prices, sales prices and green innovation levels monotonically increase and eventually stabilize.

Equations (17) and (18) show that there are two pricing approaches for the NEV retailer, i.e., skimming pricing and penetration pricing, and the pricing model depends on the relationship between the initial energy efficiency level and the steady-state energy efficiency level. Skimming pricing refers to a monotonically decreasing sales price, which is represented here as $m_0 > m_\infty^D$, and penetration pricing refers to a monotonically increasing price, i.e., $m_0 < m_\infty^D$. In addition, when the initial energy efficiency level is high, both the NEV manufacturer and the retailer use higher prices when wholesaling and selling NEVs. However, when the initial energy efficiency level is low, the pricing strategy shifts to using lower wholesale prices and selling NEVs.

Corollary 1 *When* $0 < c_0 < \frac{\varphi}{\beta-\gamma}$, *we have* $0 < m_0^D < \frac{\varphi\mu^2\left[\sum_{i=1}^2 \alpha_i+(\gamma-\beta)\left(\sum_{i=1}^2 c_i-2h\theta\right)\right]}{8k\eta(\beta-\gamma)(\eta+\rho)-2\mu^2\varphi^2}$.

i. *If* $m_0 > \frac{\varphi\mu^2\left[\sum_{i=1}^2 \alpha_i+(\gamma-\beta)\left(\sum_{i=1}^2 c_i-2h\theta\right)\right]}{8k\eta(\beta-\gamma)(\eta+\rho)-2\mu^2\varphi^2}$, *the NEV manufacturer and retailer choose a skimming pricing strategy for any* $c_0 \in \left(0, \frac{\varphi}{\beta-\gamma}\right)$, *that is, the NEV manufacturer and retailer first set a higher price to sell the two NEVs and then lower the price later.*
ii. *If* $0 < m_0 < \frac{\varphi\mu^2\left[\sum_{i=1}^2 \alpha_i+(\gamma-\beta)\left(\sum_{i=1}^2 c_i-2h\theta\right)\right]}{8k\eta(\beta-\gamma)(\eta+\rho)-2\mu^2\varphi^2}$, *there exists* $\check{c}_0$ *leading to a pricing strategy shift,that is, the strategy switches from price penetration for* $c_0 \in (0, \check{c}_0)$ *to pricing skimming for* $c_0 \in \left(\check{c}_0, \frac{\varphi}{\beta-\gamma}\right)$, *where* $\check{c}_0$ *satisfies* $0 < m_0 < \frac{\varphi\mu^2\left[\sum_{i=1}^2 \alpha_i+(\gamma-\beta)\left(\sum_{i=1}^2 c_i-2h\theta\right)\right]}{8k\eta(\beta-\gamma)(\eta+\rho)-2\mu^2\varphi^2}$.

Corollary 1 suggests that a different c_0 leads to different pricing strategies for the NEV manufacturer and retailer, and that there may be a threshold $\check{c}_0$ that causes manufacturers and retailers to change their pricing strategies. When the initial level of energy efficiency is large, changes in c_0 have no effect on the pricing strategies of the manufacturer and retailer. Both the NEV manufacturer and retailer will always use a skimming pricing strategy. When c_0 is small, the NEV manufacturer and retailer will first adopt a penetration pricing strategy and then shift to a skimming pricing strategy. This implies that the pricing strategies of the NEV manufacturer and retailer are influenced by operational efficiency.

Integrated scenario

Under the integrated distribution model, the NEV manufacturer and the retailer collaborate to make decisions on the sales price and green innovative technology to maximize overall profit. The dynamic optimization problem for the integrated channel is formulated as follows.

$$\begin{aligned} &\max_{p_1(t),p_2(t),g(t)} J^I = \int_0^\infty e^{-\rho t}[\sum_{i=1}^2 \left(p_i\left(t\right) - C_i\left(t\right)\right) D_i\left(t\right) - kg^2\left(t\right) + \sum_{i=1}^2 h\theta D_i\left(t\right)]dt \\ &s.t. \dot{m}\left(t\right) = \mu g\left(t\right) - \eta m\left(t\right), m\left(0\right) = m_0 \end{aligned} \tag{22}$$

where the sales price $p_i\left(t\right)$ $(i = 1, 2)$ and the green innovation level $g\left(t\right)$ are the control variables, and the level of energy efficiency $m\left(t\right)$ is the state variable. The following proposition provides the optimal solution to Eq. (22).

Proposition 3 *Under the integrated distribution model, the optimal sales prices and green innovation for the two NEVs are*

$$p_1^I\left(m\right) = \frac{\gamma\alpha_2 + \beta\alpha_1}{2\left(\beta^2 - \gamma^2\right)} + \frac{c_1 - h\theta}{2} + \frac{\varphi + \left(\beta - \gamma\right)c_0}{2\left(\beta - \gamma\right)}m, \tag{23}$$

$$p_2^I\left(m\right) = \frac{\gamma\alpha_1 + \beta\alpha_2}{2\left(\beta^2 - \gamma^2\right)} + \frac{c_2 - h\theta}{2} + \frac{\varphi + \left(\beta - \gamma\right)c_0}{2\left(\beta - \gamma\right)}m, \tag{24}$$

and

$$g^I\left(m\right) = \frac{\mu}{2k}\left(2M_1 m + M_2\right). \tag{25}$$

The optimal profit for a two-level NEV supply chain is expressed as follows.

$$J^I = e^{-\rho t}\left(M_1 m^2 + M_2 m + M_3\right). \tag{26}$$

where $M_1 = \frac{k(2\eta+\rho)(\beta-\gamma)-\xi_2}{2\mu^2(\beta-\gamma)}$,

$$M_2 = \frac{k\left[\varphi + (\gamma-\beta)\,c_0\right]\left[\sum_{i=1}^{2}\alpha_i + (\gamma-\beta)\left(\sum_{i=1}^{2}c_i - 2h\theta\right)\right]}{\rho k(\beta-\gamma)+\xi_2},$$

$$M_3 = \frac{\mu^2 {M_2}^2}{4k\rho} + \frac{\sum_{i=1}^{2}\left(\beta\alpha_i + \gamma\alpha_{3-i} + (h\theta - c_i)\left(\beta^2-\gamma^2\right)\right)\left(\alpha_i + \gamma c_{3-i} - \beta c_i + h\theta(\beta-\gamma)\right)}{4\rho\left(\beta^2-\gamma^2\right)},$$

$$\text{and } \xi_2 = \sqrt{k(\beta-\gamma)\left\{k(\beta-\gamma)(2\eta+\rho)^2 - 2\mu^2\left[\varphi-(\beta-\gamma)\,c_0\right]^2\right\}}.$$

Moreover, the accumulated energy efficiency level over time is

$$m^I(t) = {m^I}_\infty + \left(m_0 - {m^I}_\infty\right)e^{-Q_2 t}. \tag{27}$$

where $Q_2 = \frac{{\xi_2}^2 - \rho^2 k^2(\beta-\gamma)^2}{2k(\beta-\gamma)[\xi_2+\rho k(\beta-\gamma)]} > 0$, ${m^I}_\infty = \frac{k\mu^2(\beta-\gamma)[\varphi-(\beta-\gamma)c_0]\left[\sum_{i=1}^{2}\alpha_i + (\gamma-\beta)\left(\sum_{i=1}^{2}c_i - 2h\theta\right)\right]}{{\xi_2}^2-\rho^2k^2(\beta-\gamma)^2}$ referring to the steady-state energy efficiency level.

Proof. Please see Appendix C.

Proposition 3 shows that the results in the integrated scenario are similar in nature to those in the decentralized scenario. The sales price and green innovation level of the two NEVs are linearly increasing in the state variable, implying that when the energy efficiency level of the NEVs increases, the decision-maker will increase the sales price and green innovation level of the NEVs to meet consumer preferences.

Proposition 4 *The optimal sales prices and green innovation paths for the two NEVs under the integrated scenario are given by*

$$p_1^I(t) = \frac{\gamma\alpha_1 + \beta\alpha_2 + \left(\beta^2-\gamma^2\right)(c_1 - h\theta) + (\beta+\gamma)\left(\varphi + (\beta-\gamma)\,c_0\right)m_\infty^I}{2\left(\beta^2-\gamma^2\right)} \tag{28}$$

$$+ \frac{\varphi + (\beta-\gamma)\,c_0}{2(\beta-\gamma)}\left(m_0 - m_\infty^I\right)e^{-Q_2 t}, \tag{29}$$

$$\begin{aligned} p_2^I(t) = &\frac{\gamma\alpha_2 + \beta\alpha_1 + \left(\beta^2-\gamma^2\right)(c_1 - h\theta) + (\beta+\gamma)\left(\varphi + (\beta-\gamma)\,c_0\right)m_\infty^I}{2\left(\beta^2-\gamma^2\right)} \\ &+ \frac{\varphi + (\beta-\gamma)\,c_0}{2(\beta-\gamma)}\left(m_0 - m_\infty^I\right)e^{-Q_2 t}, \end{aligned} \tag{30}$$

and

$$g^I(t) = \frac{\mu}{k}\left(M_1 {m^I}_\infty + \frac{M_2}{2}\right) + \frac{\mu M_1}{k}\left(m_0 - {m^I}_\infty\right)e^{-Q_2 t}. \tag{31}$$

Proof. Please see Appendix D.

Similar to the decentralized scenario, Proposition 4 illustrates that the sales prices of the two NEVs are related to m_0 and m_∞^I. When $m_0 > m_\infty^I$, the sales price of the two NEVs decreases monotonically and eventually reaches a steady state, and vice versa. The above results show that when the initial energy efficiency level is large enough, the NEV company attempts to sell both vehicles at a higher price and thus earn higher profits. Over time, the energy efficiency level decreases, eventually forcing the NEV companies to reduce the sales price and vice versa.

Proposition 5 *Restricting the sales price and green innovation path of the two NEVs over time, we can obtain the steady state of the sales price and green innovation, respectively.*

i. *The stable state of the sales price of NEV 1 is*

$$p_{1\infty}^I = \frac{\gamma(\alpha_2 - \gamma c_1) + \beta(\alpha_1 + \beta c_1)}{2\left(\beta^2-\gamma^2\right)} - \frac{h\theta}{2} + \frac{\varphi + (\beta-\gamma)\,c_0}{2(\beta-\gamma)}{m^I}_\infty \tag{32}$$

which is a supermodular function in (θ, μ);

ii. *The stable state of the sales price of NEV 2 is*

$$p_{2\infty}^I = \frac{\gamma(\alpha_1 - \gamma c_2) + \beta(\alpha_2 + \beta c_2)}{2\left(\beta^2-\gamma^2\right)} - \frac{h\theta}{2} + \frac{\varphi + (\beta-\gamma)\,c_0}{2(\beta-\gamma)}{m^I}_\infty \tag{33}$$

which is a supermodular function in (θ, μ);

iii. *The stable state of green innovation in NEVs is*

$$g^I{}_\infty = \frac{\mu}{k}\left(M_1 m^I{}_\infty + \frac{M_2}{2}\right) \tag{34}$$

which is a supermodular function in (h, k).

Proof. Please see Appendix E.

The results of Proposition 5 demonstrate a steady state of the sales price and green innovation for the two NEVs in the integrated scenario. In the long run, their trajectories change from trending to constant values, which enables NEV retailers to align their operational behaviors in the initial phase.

Corollary 2 *When* $0 < c_0 < \frac{\varphi}{\beta-\gamma}$, *we have* $0 < m_0^I < \frac{\varphi\mu^2\left[\sum_{i=1}^2 \alpha_i + (\gamma-\beta)\left(\sum_{i=1}^2 c_i - 2h\theta\right)\right]}{4k\eta(\beta-\gamma)(\eta+\rho)-2\mu^2\varphi^2}$.

i. *If* $m_0 > \frac{\varphi\mu^2\left[\sum_{i=1}^2 \alpha_i + (\gamma-\beta)\left(\sum_{i=1}^2 c_i - 2h\theta\right)\right]}{4k\eta(\beta-\gamma)(\eta+\rho)-2\mu^2\varphi^2}$, *the NEV retailer chooses a skimming pricing strategy for any* $c_0 \in \left(0, \frac{\varphi}{\beta-\gamma}\right)$, *that is, the NEV retailer first sets a higher price to sell the two NEVs and then lowers the price later.*

ii. *If* $0 < m_0 < \frac{\varphi\mu^2\left[\sum_{i=1}^2 \alpha_i + (\gamma-\beta)\left(\sum_{i=1}^2 c_i - 2h\theta\right)\right]}{4k\eta(\beta-\gamma)(\eta+\rho)-2\mu^2\varphi^2}$, *there exists* $\hat{c}_0$ *leading to a pricing strategy shift,that is, the strategy switches from price penetration for* $c_0 \in (0, \hat{c}_0)$ *to pricing skimming for* $c_0 \in \left(\hat{c}_0, \frac{\varphi}{\beta-\gamma}\right)$, *where* $\hat{c}_0$ *satisfies* $0 < m_0 < \frac{\varphi\mu^2\left[\sum_{i=1}^2 \alpha_i + (\gamma-\beta)\left(\sum_{i=1}^2 c_i - 2h\theta\right)\right]}{4k\eta(\beta-\gamma)(\eta+\rho)-2\mu^2\varphi^2}$.

Corollary 2 is similar to Corollary 1 in that a different c_0 will lead to different pricing strategies for retailers of NEVs, and there is likely to be a threshold $\hat{c}_0$ that will cause retailers to change their pricing strategies. When the initial energy efficiency level is large, the change in c_0 has no effect on the retailer's pricing strategy and the retailer will always adopt a skimming pricing strategy. When $\hat{c}_0$ is small, the NEV retailer will first adopt a penetration pricing strategy and then shift to a skimming pricing strategy.

Result comparison

In this section, we compare the steady-state sales price, green innovation, energy efficiency level and channel margins of the two NEVs in both the decentralized and integrated scenarios.

Corollary 3 *The key parameters* μ, c_0 *and* φ *of the decentralized and integrated scenarios* $p_i(t)$, $g(t)$ *and* $m(t)$ *are compared.*

i. $\frac{\partial p_i^z hang2020subsidyzhang2020subsidyD}{\partial\mu} > 0, \frac{\partial p_i^I}{\partial\mu} > 0, \frac{\partial g^D}{\partial\mu} > 0, \frac{\partial g^I}{\partial\mu} > 0, \frac{\partial m^D}{\partial\mu} > 0$ *and* $\frac{\partial m^I}{\partial\mu} > 0$.

ii. $\frac{\partial p_i^D}{\partial c_0} < 0, \frac{\partial p_i^I}{\partial c_0} < 0, \frac{\partial g^D}{\partial c_0} < 0, \frac{\partial g^I}{\partial c_0} < 0, \frac{\partial m^D}{\partial c_0} < 0$ *and* $\frac{\partial m^I}{\partial c_0} < 0$.

iii. $\frac{\partial p_i^D}{\partial\varphi} > 0, \frac{\partial p_i^I}{\partial\varphi} > 0, \frac{\partial g^D}{\partial\varphi} > 0, \frac{\partial g^I}{\partial\varphi} > 0, \frac{\partial m^D}{\partial\varphi} > 0$ *and* $\frac{\partial m^I}{\partial\varphi} > 0$.

Proof. Please see Appendix F.

Corollary 3 shows that the steady-state sales price, green innovation and energy efficiency levels of the two NEVs increase with increasing μ and φ and decrease with decreasing c_0. The results indicate that the larger μ is, the greater the manufacturer's green investment in the NEV, which in turn leads to increasing greening innovations, subsequently increasing levels of energy efficiency and sales prices. As energy efficiency levels and sales prices increase, the increased sensitivity of energy efficiency to demand stimulates the growth of green innovation. However, the operational inefficiency coefficient c_0 has a negative impact on the optimal solution for NEVs in both decentralized and integrated scenarios, suggesting that higher operational inefficiencies create barriers to green investment, ultimately leading to lower levels of energy efficiency and lower sales prices.

Corollary 4 *The steady-state sales price under the decentralized and integrated settings are related as follows*:

i. *If* $c_1 - c_2 > \frac{3(\alpha_1-\alpha_2)}{\beta+\gamma}$, $p_{1\infty}^D > p_{2\infty}^D$; *if* $c_1 - c_2 = \frac{3(\alpha_1-\alpha_2)}{\beta+\gamma}$, $p_{1\infty}^D = p_{2\infty}^D$; *if* $c_1 - c_2 < \frac{3(\alpha_1-\alpha_2)}{\beta+\gamma}$, $p_{1\infty}^D < p_{2\infty}^D$.

ii. *If* $c_1 - c_2 > \frac{\alpha_1-\alpha_2}{\beta+\gamma}$, $p_{1\infty}^I > p_{2\infty}^I$; *if* $c_1 - c_2 = \frac{\alpha_1-\alpha_2}{\beta+\gamma}$, $p_{1\infty}^I = p_{2\infty}^I$; *if* $c_1 - c_2 < \frac{\alpha_1-\alpha_2}{\beta+\gamma}$, $p_{1\infty}^I < p_{2\infty}^I$.

Proof. Please see Appendix G.

Corollary 4 compares the sales prices of two NEVs in the decentralized and integrated scenarios. Let $\Delta = \frac{\alpha_1-\alpha_2}{\beta+\gamma}$. It can be shown that the difference in the sales prices of the two NEVs is related to the difference in their initial costs and Δ. When $c_1 - c_2 > 3\Delta$ in the decentralized scenario, the sales price of NEV 1 is higher than that of NEV 2 and when $c_1 - c_2 > \Delta$ in the integrated scenario, vice versa.

Corollary 5 *The steady-state green innovation, energy efficiency levels and channel profitability relationships for the NEVs in the decentralized and integrated settings are:* $g_\infty^D < g_\infty^I$, $m_\infty^D < m_\infty^I$, $J^D < J^I$.

Proof. Please see Appendix H.

Corollary 5 demonstrates that the integrated channel yields a higher steady-state level of green innovation, energy efficiency level, and channel profitability for NEVs compared to the decentralized channel. This suggests that the centralized scenario is more favorable for promoting the green innovation level of NEVs. The above phenomenon occurs because the objective of maximizing the benefits of individual NEV supply chain members differs from the objective of maximizing the benefits of the entire supply chain. In other words, there is a dual marginal effect in the decentralized scenario.

Coordination with a revenue- and cost-sharing contract

In the RC contract, as the leader, the NEV manufacturer charges a lower wholesale price of $\omega_i(t)\,(i = 1, 2)$ to the retailer and allocates a fraction $\delta\,(0 < \delta < 1)$ of the investment in green innovation technology and the proceeds from the sale of the credits. In exchange, the retailer of the NEV gives the manufacturer $(1 - \delta)$ of the total revenue generated from the sales of the two NEVs in return. The profit functions for the NEV manufacturer and retailer are as follows:

$$\begin{aligned}
&\max_{\omega_i(t),\omega_2(t),g(t)} J_M^{RC} = \int_0^\infty e^{-\rho t}[\sum_{i=1}^{2}(\omega_i(t) - C_i(t) + (1-\delta)p_i(t))D_i(t) - k(1-\delta)g^2(t) + (1-\delta)\sum_{i=1}^{2} h\theta D_i(t)]dt \\
&\max_{p_1(t),p_2(t)} J_R^{RC} = \int_0^\infty e^{-\rho t}[\sum_{i=1}^{2}\left(\delta p_i(t) - \omega_i(t)\right)D_i(t) - k\delta g^2(t) + \delta\sum_{i=1}^{2} h\theta D_i(t)]dt \\
&s.t.\dot{m}(t) = \mu g(t) - \eta m(t),\ m(0) = m_0
\end{aligned} \tag{35}$$

Solving Eq. (35) using the coordination conditions of the RC contract leads to the following conclusions.

Proposition 6 *The decentralized supply chain of the NEV can be coordinated through RC contracts when* $m^{RC}(t) = m^I(t)$ *and* $p_i^{RC}(t) = p_i^I(t)\,(i = 1, 2)$. *Moreover, the sales price of another NEV is* $p_{3-i}^{RC}(t) = p_{3-i}^I(t)\,(i = 1, 2)$,*andthewholesalepricesofthetwoNEVsare*$\omega_i^{RC}(t) = \delta\left(c_i + c_0 m^I(t)\right)(i = 1, 2)$.

Proof. Please see Appendix I.

Proposition 6 suggests that the NEV manufacturer, as the leader, should set the wholesale price of both NEVs below the corresponding unit subscription cost to incentivize the NEV retailer to fulfill the RC contract, and the manufacturer should implement its own optimal operational decision, which is consistent with the optimal operational decision in the integrated scenario. Under the stated assumptions, the decentralized NEV supply chain is coordinated through the RC contract. In addition, we obtain the following results.

Proposition 7 *For a decentralized NEV supply chain with the RC contract, the following holds.*

i. *The NEV manufacturer and retailer accept the RCcontract if and only if* $\frac{J_R^D}{J^I} \leq \delta \leq 1 - \frac{J_M^D}{J^I}$.
ii. $J_M^{RC} + J_R^{RC} = J^I$ *and* $m^{RC}(t) = m^I(t)$.

Proof. Please see Appendix J.

Proposition 7(i) represents the feasible range of contract scores δ for each member of the NEV chain to accept the RC contract. The existence of this feasible range implies that the contract can produce a win-win outcome. Proposition 7(ii) demonstrates that the optimal system profit and efficiency level for an integrated system are the same as for a decentralized model with the RC contract.

Numerical experiments

To enhance the comprehensibility of the aforementioned theoretical results, we perform a numerical analysis in this section. The purpose of this analysis is to examine the influence of various key parameters on the sales price, energy efficiency level, trajectory of green innovation, and system effectiveness of the two NEVs. The goal is to obtain valuable insights for managers.

In light of Li et al.[16], Li et al.[18] and Cheng et al.[36] on the research on parameter settings related to the effectiveness of the dual credit policy, and Yang et al.[37] on the research on green innovation, the initial values of the parameters are set as follows: $\alpha_1 = 20$, $\alpha_2 = 18$ $\varphi = 1$, $\beta = 2$, $\gamma = 1$, $\mu = 1$, $\eta = 0.5$, $c_1 = 1$, $c_2 = 2$, $c_0 = 0.5$, $k = 2$, $\rho = 0.1$, $h = 5$, $\theta = 0.2$ and $m_0 = 15$.

The NEV supply chain is coordinated through RC contracts. Using the numerical example above, when $t = 0$, we observe that the profits of the NEV retailers under the RC contract are higher than in the decentralized case when δ is greater than or equal to 0.25. When δ is less than or equal to 0.50, the profits of the NEV manufacturer under the RC contract will be higher than those under the decentralized scenario. When δ lies within the range [0.25, 0.50], both the NEV manufacturer and the retailer accept the RC contract. The detailed calculation to determine the range of δ is shown in Fig. 1. In addition, the same level of profit and energy efficiency for the NEV

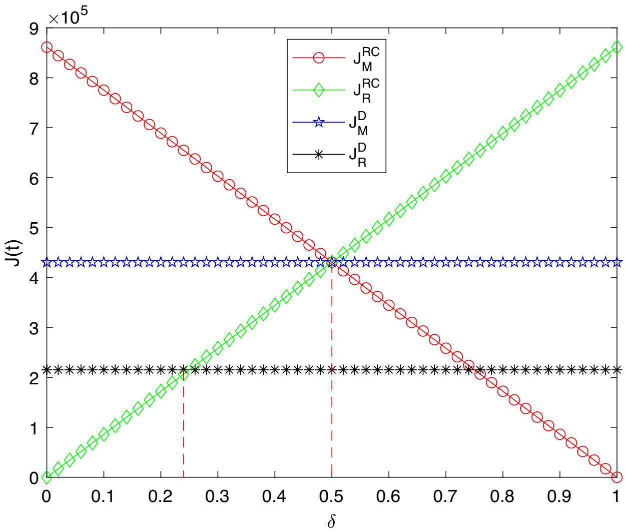
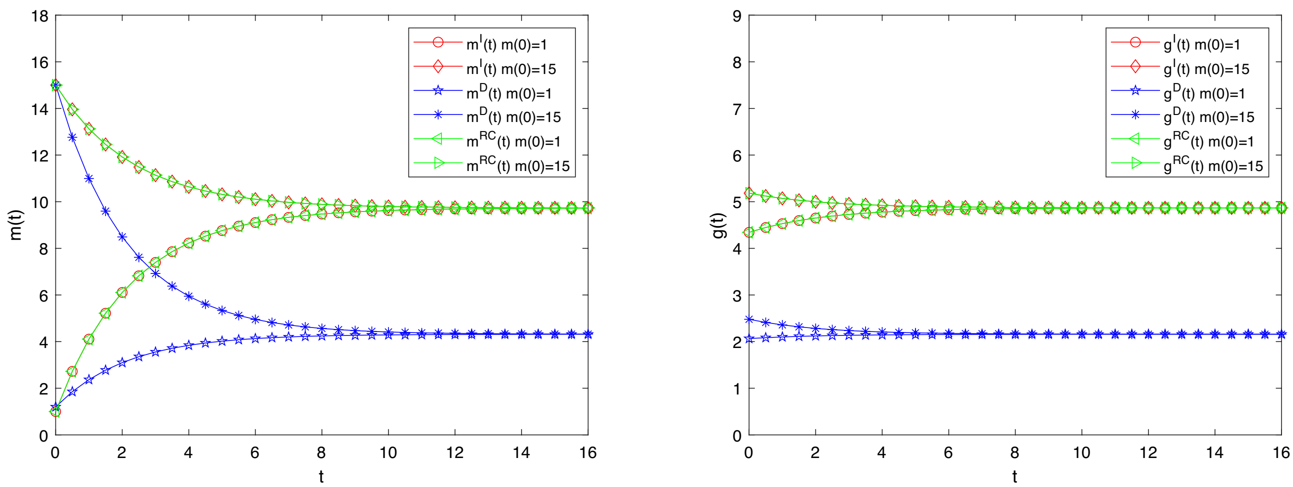


Fig. 1. Scope of RC contracts accepted by manufacturer and retailer of the NEV.



(a) Optimal trajectory energy efficiency level

(b) Optimal trajectory green innovation level

Fig. 2. Optimal trajectory energy efficiency level and green innovation level.

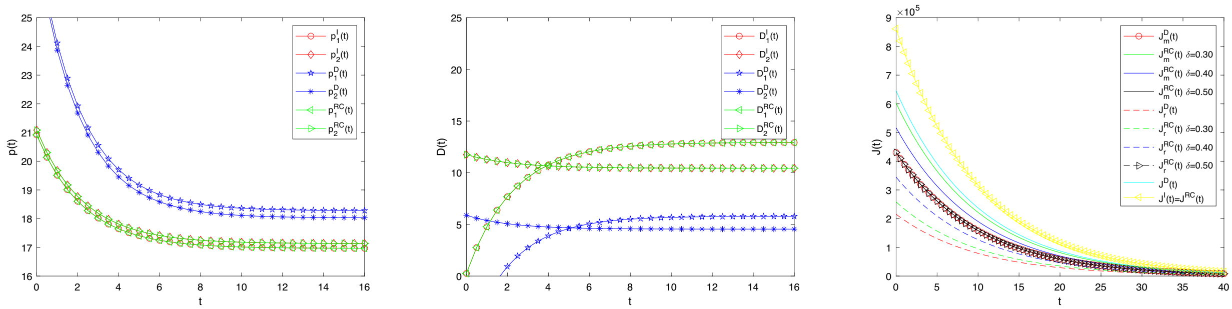
supply chain and the integration supply chain under the RC contract means that the decentralized supply chain is perfectly coordinated through the RC contract.

Effects of time *t*

Next, we examined the trajectory of the energy efficiency level and green innovation level of NEVs over time. Figure 2 shows that the optimal energy efficiency level $m\left(t\right)$ and the green innovation level $g\left(t\right)$ of the NEV tend to be stable as *t* tends to infinity (the unit of *t* is one month). Figure 2a shows that the final stability value is the same under the integrated scenario, the decentralized scenario and the RC contract, regardless of the initial energy efficiency level, and that the following condition holds: $m^{RC}\left(t\right)=m^{I}\left(t\right)>m^{D}\left(t\right)$. Similarly, the change in $g\left(t\right)$ also has this characteristic, as shown in Fig. 2b. Figure 2a and b are monotonic as shown in Proposition 1, and their monotonicity is related to m_0 and m_∞. When $m_0>{m^{I}}_{\infty}$ ($m_0>{m^{D}}_{\infty}$ or $m_0>{m^{RC}}_{\infty}$) monotonically decreases with time *t*, and when $m_0<{m^{I}}_{\infty}$ ($m_0<{m^{D}}_{\infty}$ or $m_0<{m^{RC}}_{\infty}$) monotonically increases with time *t*.

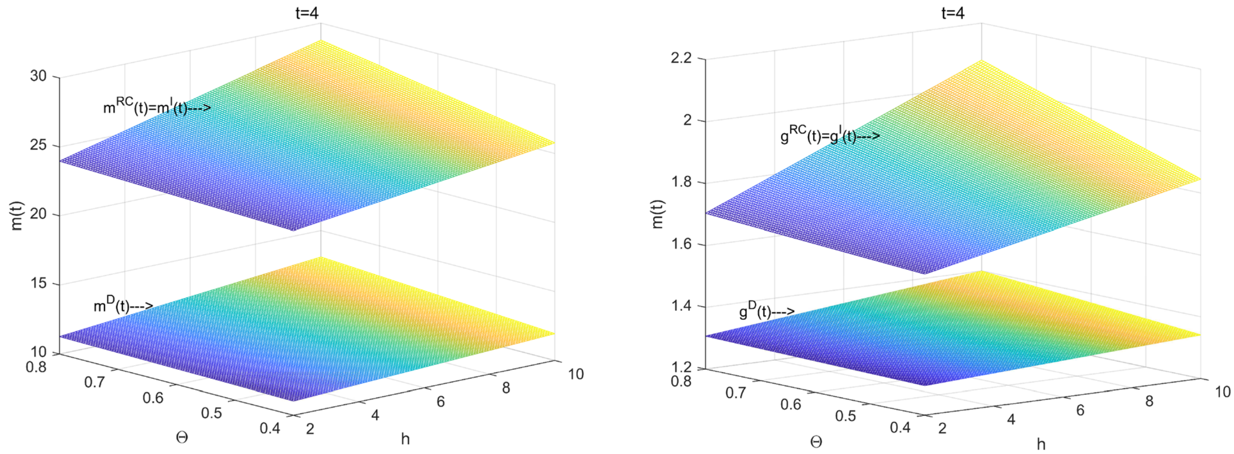
Selecting $m_0=15$ and using the parameter values given in the above example, we plot the image of the sales price, market demand and profit of the NEV for the decentralized scenario, the integrated scenario and the RC contract decentralized scenario.

Figure 3 shows the comparison of market demand, price and profit of NEV supply chain under three scenarios. Figure3a shows that the sales price of NEVs under integrated decision making is always lower than the sales price of NEVs in decentralized scenario, while Fig. 3b and c show that the market demand and profit



(a) Price comparison of two NEVs (b) Comparison of market demand for NEV (c) Comparison of total profits for the NEV manufacturer, retailer and system in three scenarios

Fig. 3. Comparison of market demand, prices and profits in the NEV supply chain under three scenarios.



(a) Effects of h and θ on the energy efficiency level (b) Effects of h and θ on the green innovation

Fig. 4. Effects of h and θ on the energy efficiency level and green innovation.

of NEVs under integrated scenario is always higher than the market demand and profit under the decentralized scenario. In the decentralized scenario, NEV1, NEV2, their respective market demand and overall NEV supply chain profit are 20.59, 20.31, 2.746, 4.866 and 478,400, respectively, while in the integrated scenario, NEV1, NEV2, their respective market demand and overall NEV supply chain profit are 18.02, 18.19, 9.548, 10.78 and 638,100. This result indicates that when the NEV manufacturer and retailer cooperate, the sales prices of the two NEVs are reduced by 12.48% and 10.44%, respectively, which in turn increases the number of consumers by 247.70% and 121.54%, and the NEV supply chain profit by 33.38%. This result means that the partnership between the NEV manufacturer and retailer will lead to more consumers and higher profits.

Figure 3a–c show that the same sales price, the same market demand and the same total system profit are achieved under the RC contract, indicating that under the above assumptions, the RC contract achieves perfect coordination of the NEV supply chain and higher profits and higher levels of green innovation are achieved through the RC contract. This means that the decision-making of each subject of the supply chain under the RC contract is highly collaborative, eliminating the loss of efficiency caused by decentralized decision-making, thus promoting a higher level of green innovation and higher supply chain profits, reflecting the advantages of the RC contract in optimizing the operation of the supply chain and promoting green development. Figure 3c further shows that the RC contract makes the sum of the profits of the NEV manufacturer and supplier in the decentralized scenario equal to the total profits in the integrated scenario, and that the RC contract makes the profits of the NEV manufacturers and retailers in the decentralized scenario consistently higher than the profits of the NEV manufacturer and retailer in the decentralized scenario. This illustrates the extent to which the RC contract increases the economic benefits of the members of the NEV supply chain. In other words, the supply chain as a whole has reached equilibrium, but the distribution of profits in each link of the supply chain is different. The manufacturer's profit increase is slow, but relying on the negotiated supply chain can achieve more stable sales and long-term technology iteration space. Retailers have more power to expand the market

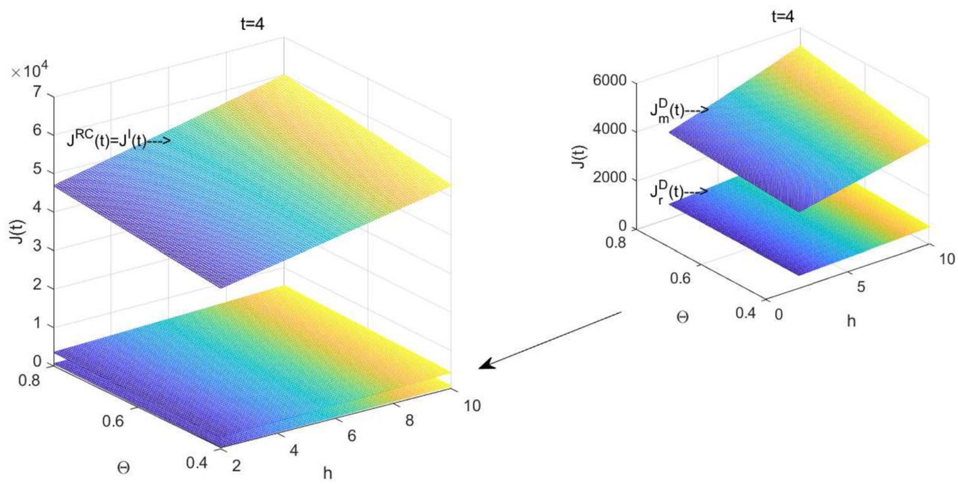


Fig. 5. Effects of *h* and θ for the NEV manufacturer, retailer and system profits under three scenarios.

and optimize services due to the rapid profit increase, and ultimately promote the sustainable development of the entire NEV industry.

Effects of θ and *h*

Figure 4a and b examine the impact of the price per unit of NEV credit h and the proportion of the NEV converted into credits per unit θ on the energy efficiency level $m\left(t\right)$ and green innovation technology $g\left(t\right)$ of the NEV under three different scenarios. To make this comparison more obvious, we use $t=4$ as an example for our analysis.

Figure 4a shows that the energy efficiency level $m\left(t\right)$ of the NEV increases with the increase of the price per unit of the NEV credits *h* and the proportion of units of the NEV converted into credits θ. The energy efficiency level under RC contract coordination is the same as that under the integrated scenario, and the energy efficiency level under the integrated scenario is always higher than that under the decentralized scenario. The green innovation technology $g\left(t\right)$ of the NEV increases with the increase in the price per unit of NEV credit *h* and the ratio of conversion into credit per unit of NEV θ. The green innovation technology in the integrated scenario is always higher than that in the decentralized scenario, and the RC contract largely improves the green innovation technology of the NEVs, as shown in Fig. 4b. This demonstrates that increasing the price and conversion ratio of the NEV credits per unit in the NEV supply chain is beneficial to the level of green and innovative technology and energy efficiency of the NEV, thus making consumers more inclined to buy them. The improvement of energy efficiency and the progress of green innovation can directly reduce the use cost of NEV and improve the competitiveness of NEV. The manufacturer' green innovation and energy efficiency improvement due to the incentive of the dual credit policy will be transmitted to all links of the supply chain. The retailer will also be easier to expand the market due to NEV's green environmental protection, and ultimately promote the rapid development of the entire NEV supply chain.

Figure 5 investigates the impact of the unit price of NEV credits *h* and the percentage of conversion of NEV into credits θ on the supply chain and members of the NEV catalogue under three different scenarios. Figure 5 shows that the NEV supply chain and members increase with the increase in the unit price of NEV credits *h* and the percentage of conversion of the NEV into credits θ under the integrated scenario, the decentralized scenario or RC contract coordination, which can promote the development of the NEV supply chain. This shows that the unit price of NEV credits *h* and the percentage of conversion of NEV into credits θ, as important policy and market regulation tools, have a significant positive effect on NEV supply chain and its members. Similarly, it is of great practical significance to reasonably set the trading price of credits to stimulate the development of NEV supply chain industry.

Conclusions and managerial insights

In this study, we examine a secondary supply chain that includes a single NEV manufacturer and a single retailer. The focus is on the dual credit policy, where the NEV manufacturer sells two NEVs to the retailer. The manufacturer aims to enhance energy efficiency by investing in green innovation technology. The objective is to analyze the decision-making behavior of the NEV supply chain members regarding green innovation cooperation and determine the optimal approach. By comparing the profitability and level of green innovation in the NEV supply chain with those in an integrated scenario, the RC contract is proposed as a means to coordinate the NEV supply chain and achieve perfect coordination conditions for NEVs. Finally, the aforementioned theory is validated through numerical analysis, and the analysis also examines the influence of various key parameters on supply chain coordination.

Conclusions

The main conclusions of this research are as follows. (i) The dual credit policy can effectively increase the profitability of the supply chain and its members. The policy can effectively promote the green innovation level of the NEV supply chain; (ii) Under the integrated scenario, NEVs exhibit a higher steady-state green innovation level, energy efficiency and channel profitability than the decentralized scenario; and (iii) When condition $\omega_i^{RC}(t) = \delta\left(c_i + c_0 m^I(t)\right)(i = 1, 2)$ is met, the RC contract allows for perfect coordination of the NEV supply chain. Moreover, under the above assumptions, when the RC contract achieves perfect coordination, a range of contract parameters can be obtained; (iv) Under RC contract coordination, an increase in the price per unit of the NEV credits and the proportion of NEV converted to credits per unit will lead to an increase in green innovative technologies and an increase in supply chain and member profits; and (v) The pricing strategy of NEVs is closely related to the initial energy efficiency level. In other words, when the initial energy efficiency level is large, the NEV supply chain adopts a skimming pricing strategy and vice versa.

Managerial insights

Some managerial implications are provided for NEV chain members and governments to improve the long-term performance of the NEV chain. The implications are as follows. (i)NEV enterprises should actively comply with the double integral policy, improve the supply chain and their own performance with the help of the policy, and increase green innovation investment to promote the development of enterprises in green technology research and development, production process improvement and other aspects; (ii)NEV enterprises should strive to build or participate in an integrated supply chain scenario. Under the integrated mode, NEV can achieve a higher level of green innovation, energy efficiency and profit, which helps enterprises to occupy advantages in long-term development and achieve sustainable development; (iii)In the actual operation process, enterprises should formulate appropriate RC contract terms according to the satisfaction conditions of the RC contract and the range of relevant parameters, so as to optimize the cooperation of each link of the supply chain and improve the overall operation efficiency and efficiency.

Limitations and prospects

This study has several limitations, which can provide further development direction for subsequent research. First, the model is based on the monopoly market structure, without considering the competitive behavior of other NEV supply chains, and the competitive environment may have an important impact on the optimal pricing and green innovation strategy. Secondly, assuming that the demand is a deterministic linear function, it fails to capture the uncertainty of market demand and consumer preferences, and the stochastic factors in reality may significantly change the decision-making effect. In addition, this study assumes that the green innovation efficiency of the two models is the same, without considering the heterogeneity between models (such as the difference in technical basis and cost structure). In the future, the green innovation investment brought by the difference of models can be taken as the key direction of follow-up research. Finally, the model assumes that green innovation investment can always bring positive returns, ignoring the law of diminishing marginal returns and the constraints that may be brought by technological limits. Subsequent studies can more comprehensively describe the relationship between green innovation investment and performance. These limitations provide valuable directions for future research.

Data availability

The data presented in this study are available on request from the corresponding author. The data are not publicly available due to the need for further research.

Received: 18 February 2025; Accepted: 4 November 2025
Published online: 12 December 2025

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Author contributions

Lili Zhao: Methodology, Investigation, Writing–original draft, Writing–review and editing. Xiuli Bao: Software, Investigation, Supervision. Jizi Li: Data curation, Methodology. All authors have read and agreed to the published version of the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1038/s41598-025-27557-x.

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