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Research on collaborative R&D decision making of photovoltaic industry supply chain considering green preference under carbon target regulation

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A B S T R A C T

Under the dual carbon target regulation, this article constructs a collaborative research and development carbon reduction model for the photovoltaic industry supply chain from the perspective of carbon tax and consumer green preferences, using differential game theory. Considering three different scenarios of no research and development carbon reduction, independent research and development carbon reduction, and collaborative research and development carbon reduction, the optimal factors and profit values are obtained, and case analysis and sensitivity analysis are conducted. Research has found that: 1) The optimal carbon reduction achieved by photovoltaic industry supply chain entities through cooperative research and development is higher than that achieved through independent research and development. 2) The increase in carbon tax rates has to some extent increased carbon emissions, but at the same time reduced the overall profit of the photovoltaic industry chain. 3) The higher the proportion of research and development costs borne by photovoltaic system manufacturers, the higher the carbon emission reduction of photovoltaic silicon wafer suppliers' research and development. 4) Consumer green preferences are beneficial for increasing carbon emissions reduction in the photovoltaic industry chain.

1. Introduction

After General Secretary Xi Jinping proposed the dual carbon target, China has issued a series of policies and measures around "carbon peak and carbon comprehensive", with the aim of promoting industrial decarbonization, carbon reduction, and low-carbon. The photovoltaic industry is one of the important industries for China's energy structure transformation. In the photovoltaic supply chain, the carbon emissions from silicon wafer manufacturing account for the highest proportion, accounting for more than 40% of the entire photovoltaic lifecycle carbon emissions. Silicon wafer manufacturing involves processes such as purification of polycrystalline silicon materials, production of monocrystalline silicon rods/ingots, and slicing, which require a significant amount of energy consumption. Traditional processes such as the improved Siemens method have extremely high power demands (Wang & Liu, 2024). Under government regulations and consumer green preferences, the photovoltaic industry has begun implementing carbon emission reduction research and development, as well as carbon capture (Yin et al., 2020). Companies such as GCL Technology have already optimized their production processes through research and development to promote carbon reduction. Therefore, it is important to study how the photovoltaic industry supply chain develops carbon reduction decisions from the perspective of government policies (carbon tax) and consumer green preferences.

Scholars both domestically and internationally have conducted a series of studies on R&D decision-making in industrial supply chains. Many researchers have explored these decisions from perspectives such as partner selection, benefit allocation, and innovation strategy. For instance, Fang et al. (2024) constructed a two-tier network comprising decision-making and influencing layers using green patent and operational data from listed power companies between 2009 and 2019, investigating

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the co-evolution of green technological innovation and corporate performance in the power market. Xing et al. (2024) developed a value assessment model for collaborative green product innovation under scenarios with and without minimum shipment guarantees, aiming to maximize the collective benefits of the alliance, and examined profit-sharing decisions among supply chain entities. Lotfipour and Mohtavipour S. (2024) investigated market share decisions in industries using the Multi-criteria decision making (MCDM) model (Dai & Wang, 2025). Yi and Tang (2024) employed differential game theory to explore dynamic improvements and coordination strategies for collaborative product innovation in supply chains, incorporating factors such as product innovation reputation and disappointment aversion into decision-making. Based on these findings, they proposed product innovation subsidy contracts and revenue-sharing adjustment mechanisms.

Scholars have also conducted extensive research on the perspective of low-carbon decision-making in the supply chain. Most scholars study industrial cooperation from the perspectives of fairness preference, contract selection and government participation. For example, scholars have studied sustainable decision-making in low-carbon supply chains from the perspective of fairness preference and risk aversion. Zhong et al. (2022) investigated the optimal decision-making in a low-carbon supply chain composed of manufacturers and leading retailers considering the green investment and fairness preference of member companies, and constructed four Stackelberg game decision-making models to compare and analyze the impact of fairness preference and green investment on the optimal decision-making in a low-carbon supply chain. Song et al. (2025) considered the uncertainty of green technology R&D investment and the fair attention behavior of channel members, and analyzed the optimal decisions of participants under the manufacturer led and retailer led structures. Barman et al. (2025) investigated the production decisions of the supply chain operating within the framework of green financing and carbon cap and trade plan. Some scholars have studied the impact of contracts in supply chain decisions on the decisions of industrial entities, including revenue sharing contracts, cost sharing contracts and carbon contracts. For example, Tang et al. (2023) studied the decision-making of product pricing, social responsibility effort level and recovery rate of closed-loop supply chain in which manufacturers undertake corporate social responsibility and entrust retailers to recycle waste products, and discussed the coordination effect of revenue sharing contract and two pricing contracts based on Nash bargaining on retailers' recycling closed-loop supply chain. Dai and Li (2023) discussed the coordination of revenue sharing contract and repurchase contract in the industrial supply chain. Xu et al. (2025) and others constructed a two echelon marine green fuel supply chain optimization model consisting of green marine fuel suppliers and ports, and compared the supplier's profits and decision changes under four scenarios: no contract, cost sharing contract, revenue sharing contract and revenue sharing+cost sharing contract. Mao et al. (2024) considered the risk sharing model and used the Stackelberg game to calculate the optimal pricing decisions of the supply and demand sides under three different transaction modes. Wang and Gao (2024) considered a closed-loop supply chain composed of a single manufacturer and a single retailer, built a centralized and decentralized decision-making model of government dynamic subsidy blockchain technology, and designed a coordination mechanism to maximize the role of government dynamic subsidies. Hu and Wu (2025) considered the form of carbon sharing contract, and studied the interest decision between upstream new energy vehicle battery suppliers and downstream new energy vehicle manufacturers in the supply chain of the new energy vehicle industry. From the perspective of government participation, scholars believe that government participation in low-carbon R&D decision-making in the industrial supply chain plays an important role. Li et al. (2022) used the differential game method to build a cooperative emission reduction model with the participation of government, manufacturing enterprises and retail enterprises under different power structures, and found that government policies have a driving effect on industrial supply chain decision-making. Liu et al. (2022) based on the theory of bilateral matching and evolution, under the regulation of government rewards and punishments, constructed an evolution model consisting of manufacturers investing in LCT and suppliers providing LCT, and built a profit optimization model of green supply chain from the perspectives of centralized matching (CM), decentralized matching (DM) and mismatch (mm). Rong (2022) deduced the optimal solution of stakeholders by building a Stackelberg game analysis model, and compared it to evaluate the impact of manufacturers' altruistic preference and government subsidies on Transnational green supply chain under dynamic tariffs. Su, C. (2020) discussed the pricing decision model of green supply chain with different forms of subsidies under different power structures in the case of consumers' green preferences and different government subsidies, analyzed the optimal strategies of green supply chain under different modes, and discussed how the government subsidy coefficient affects the optimal decision of green supply chain. Deng et al. (2025) and Sun et al. (2022) both studied the supply chain green technology innovation decision from the perspective of government subsidies. Xuchao et al. (2024) and Zhu (2025) discussed the green innovation decision of the industrial supply chain from the perspective of government tax and fiscal incentives.

In the research of industrial low-carbon supply chains, scholars' research objectives include the field of new energy vehicles, photovoltaic industry, etc. For example, Yu et al. (2025) developed game theory models for four different cooperation frameworks: technology led model, supplier cooperation model, manufacturer led model and joint decision model, and studied the R&D and pricing decision of automobile supply chain. Liu et al. (2025) built a decision-making model for collaborative carbon reduction of the new energy vehicle supply chain under carbon subsidy policy based on carbon footprint. Han et al. (2024) studied the low-carbon decision-making of the photovoltaic industry supply chain. Hayashi (2020) studied the technological innovation of the solar photovoltaic industry. Although the literature on collaborative decision-making of the photovoltaic industry is relatively few, scholars also use differential game theory to study the cooperation, competition, carbon emission reduction, contract and other decisions of the photovoltaic industry supply chain. For example, daidaoming et al. (2025) considered a three-level supply chain composed of two heterogeneous power plants, a single grid company and a single independent power selling company to study the cooperative operation decision of photovoltaic supply chain under the renewable energy consumption responsibility weighting system. Yuan et al. (2023) built a carbon emission accounting system for the photovoltaic industry from capacity construction to market application from the perspective of the whole industry chain. Hu et al. (2022) introduced government competition policy and technological innovation factors into the two-level polysilicon supply chain game model to study the impact of government competition incentives and technological innovation efforts on the optimal profits of manufacturers at all levels under different circumstances. For the research on low-carbon decision-making of the photovoltaic industry, scholars considered the impact of R&D policy, R&D mode and other factors on low-carbon decision-making. For example, Chen et al. (2021) studied the diffusion of green R&D in the photovoltaic industry under different incentive and regulatory scenarios in order to explore the incentive effect of policies on green R&D. Liu and Feng (2023) in order to study the optimal choice of green product R&D mode under different power structures and the impact of power structure on product price, market demand, green level and corporate profits, compared five modes of manufacturer's green product R&D, retailer's green product R&D, retailer's green product R&D outsourcing third party, manufacturer's and retailer's green product R&D, and studied the selection strategy of green product R&D mode in sustainable supply chain.

It can be seen that the research results of domestic and foreign experts and scholars on Collaborative Innovation of photovoltaic industry are fruitful, which provides a useful reference for this paper to study the R&D Decision of photovoltaic industry supply chain with consumers' green preference under carbon target regulation. Previous scholars' research mainly focuses on the impact of government policies, low-carbon and other factors on industrial collaborative innovation. Different from previous studies, this paper studies the R&D Decision of the photovoltaic industry supply chain from the perspective of carbon tax and consumers' green preference under the regulation of double carbon goals. Therefore, this paper analyzes the impact of carbon tax and consumers' green preference on the decision-making of three different industrial supply chain cooperative R&D situations: no R&D carbon emission reduction situation, independent R&D carbon emission reduction situation and cooperative R&D carbon emission reduction situation.

2. Model building

2.1 Model assumptions

Since China explicitly proposed the dual carbon target in September 2020, the standards for carbon emissions in the manufacturing industry have gradually been refined. The carbon tax prevalent in most developed countries around the world may also affect China's carbon tax policy in the future. The supply chain of China's photovoltaic industry has to carry out research and development innovation to reduce carbon emissions. Therefore, under the government's carbon target regulation, this article considers a two-level supply chain system consisting of a single photovoltaic system manufacturer (Z) and a photovoltaic silicon wafer supplier (G), and uses differential game theory to construct a photovoltaic industry supply chain cooperation research and development emission reduction decision model based on carbon tax and green preferences. Based on the actual situation, the following assumptions are made:

Assumption 1: Research and development innovation and innovation costs. Photovoltaic silicon wafer suppliers belong to high carbon emission production in the entire photovoltaic industry supply chain system, so photovoltaic silicon wafer manufacturers need to conduct research and development to reduce emissions under carbon target regulations and carbon tax mechanisms. This article uses H to represent the cost of R&D emissions reduction for Chinese photovoltaic silicon wafer suppliers, that is, the amount of carbon emissions reduced after R&D. Use $C(H)$ to represent the R&D and emission reduction costs of photovoltaic silicon wafer manufacturers. According to the research of previous scholars, the cost of innovation is generally an increasing function of the degree of innovation. Based on the cost model studied (Zhang et al., 2015), this article defines the cost model of R&D emission reduction for photovoltaic silicon wafer manufacturers as $C(H)=\frac{1}{2}kH^2$, where k is the R&D emission reduction cost coefficient.

Assumption 2: Production cost. Both photovoltaic silicon wafer suppliers and photovoltaic system manufacturers need to pay corresponding costs during the production process. This article uses C_g to represent the silicon wafer production cost of photovoltaic silicon wafer suppliers; Use C_z to represent the non raw material cost of photovoltaic system manufacturers.

Assumption 3: Product price. Use W to represent the price of silicon wafer combinations produced by photovoltaic silicon wafer suppliers that can be combined into a photovoltaic system; Use P to represent the price at which a photovoltaic system manufacturer sells a set of photovoltaic systems. Regulation $W \geq C_g + C(H)$; $P \geq C_Z + W$.

Assumption 4: Green preference and carbon emissions. Consumers have a green preference for photovoltaic systems, and when the carbon emissions during the production process are high, consumers will reduce their consumption of the product. Therefore, green preferences influence the quantity of photovoltaic systems consumed by consumers. This article uses γ to represent the sensitivity coefficient of consumer demand for low-carbon products.

Assumption 5: Price elasticity. There is a potential maximum market demand for photovoltaic systems, represented by α as the potential maximum market demand for photovoltaic silicon wafers. Given the instability of the market, the actual demand in the market is influenced by product prices and market supply and demand. The demand price elasticity coefficient is represented by β .

Assumption 6: Actual market demand. The actual market demand is influenced by consumers' green preferences and prices. The actual market demand is $Q=\alpha-\beta P-\gamma(e-H)$, where e represents the carbon emissions during the actual production process of photovoltaic silicon wafers.

Assumption 7: Carbon tax. Photovoltaic silicon wafer suppliers need to eliminate a large amount of carbon when producing silicon wafers. Assuming that the government imposes a tax on carbon emissions, t represents the proportion of carbon tax paid by the government on the carbon emissions during the production process of photovoltaic silicon wafer suppliers.

Assumption 8: R&D investment coefficient. When a photovoltaic system manufacturer collaborates with a photovoltaic silicon wafer supplier for research and development, the R&D investment coefficient borne by the photovoltaic silicon wafer supplier is θ . Therefore, the R&D investment coefficient borne by the photovoltaic system manufacturer is $1-\theta$.

2. Modeling

According to the production and R&D behavior decisions of the photovoltaic industry supply chain, collaborative R&D in the photovoltaic industry supply chain can be analyzed in three situations, including no R&D emission reduction situation, independent R&D emission reduction situation, and collaborative R&D emission reduction situation.

2.1 No research and development emissions reduction situation $(H=0,\ \theta=0)$

When photovoltaic silicon wafer suppliers give up on low-carbon emission reduction research and development innovation due to the huge cost of research and development, the government charges a carbon emission specific tax on pricing. According to the assumed conditions, it can be concluded that the profit functions of photovoltaic system manufacturers and photovoltaic silicon wafer suppliers in the absence of research and development emissions reduction are as follows:

$$\Pi_Z(P)=(P-W-C_Z)(\alpha-\beta P-\gamma e)$$
$$\Pi_G(W)=(W-C_g-te)(\alpha-\beta P-\gamma e)$$

In the absence of research and development to reduce emissions, photovoltaic silicon wafer suppliers should first determine their own silicon wafer prices based on market supply and demand, and photovoltaic system manufacturers should then determine the demand based on the price of photovoltaic silicon wafers and formulate photovoltaic system prices. This article uses reverse induction to solve the optimal decision combination between photovoltaic system manufacturers and photovoltaic silicon wafer suppliers. The calculation process is as follows:

Step 1: Find the optimal product price for the camera of the photovoltaic system manufacturer. According to the profit function $\Pi_Z(P)$ of the photovoltaic system manufacturer, solve the first-order and second-order derivative functions of the photovoltaic system price P . They are:

$$\frac{\partial\Pi_Z(P)}{\partial p}=\alpha-\gamma e+\beta W+\beta C_Z-2\beta P$$
$$\frac{\partial^2\Pi_Z(P)}{\partial p^2}=-2\beta<0$$

Obviously, the profit function $\Pi_Z(P)$ of the photovoltaic system manufacturer must be a concave function with respect to the price of the photovoltaic system, that is, when the first-order derivative is zero, the profit function of the photovoltaic system manufacturer reaches its maximum value. Therefore, $\frac{\partial\Pi_Z(P)}{\partial p}=0$ can be used to obtain the optimal selling price P^* for the photovoltaic system manufacturer, which is:

$$P^*=\frac{\alpha-\gamma e+\beta W+\beta C_Z}{2\beta}$$

Step 2: Find the optimal silicon wafer price for photovoltaic silicon wafer suppliers. First, substitute the obtained optimal sales price P^* of the photovoltaic system into the profit function of the photovoltaic silicon wafer supplier, and the profit function of the new photovoltaic silicon wafer supplier at this time can be obtained as:

$$\Pi_G(W)=(W-C_g-te)(\frac{\alpha-\gamma e-\beta W-\beta C_Z}{2})$$

According to the profit function of the new photovoltaic silicon wafer supplier, solve its first-order and second-order derivative functions regarding the silicon wafer price W, which are:

$$\frac{\partial\Pi_G(W)}{\partial W}=\frac{\alpha-\gamma e-\beta C_Z+\beta C_g+\beta te}{2}-\beta W$$

$$\frac{\partial^2\Pi_G(W)}{\partial W^2}=-\beta<0$$

Obviously, the profit function $\Pi_G(H,W)$ of the photovoltaic silicon wafer supplier must be a concave function of the silicon wafer price W, that is, when the first-order derivative of the silicon wafer price W is zero, the profit of the photovoltaic silicon wafer supplier is maximized. Therefore, $\frac{\partial\Pi_G(W)}{\partial W}=0$ can be used to obtain the optimal silicon wafer price W^* for photovoltaic silicon wafer suppliers, which is:

$$W^*=\frac{\alpha-\gamma e-\beta C_Z+\beta C_g+\beta te}{2\beta}$$

By substituting the obtained optimal silicon wafer price W^* into the optimal sales price P^* of the photovoltaic system manufacturer, the optimal sales price P^* of the photovoltaic system can be obtained as:

$$P^*=\frac{3\alpha-3\gamma e+\beta C_Z+\beta C_g+\beta te}{4\beta}$$

By substituting the obtained optimal silicon wafer price W^* and optimal sales price P^* into the profit functions of the photovoltaic system manufacturer and photovoltaic silicon wafer supplier, the optimal profit function $\Pi_Z^*(P)$ of the photovoltaic system manufacturer and the optimal profit function $\Pi_G^*(W)$ of the photovoltaic silicon wafer supplier can be obtained, which are:

$$\Pi_Z^*(P)=\frac{(\alpha-\gamma e-\beta C_Z-\beta C_g-\beta te)^2}{16\beta}$$

$$\Pi_G^*(W)=\frac{(\alpha-\gamma e-\beta C_Z-\beta C_g-\beta te)^2}{8\beta}$$

At this point, the optimal overall profit of the entire photovoltaic industry supply chain without research and development emissions reduction is:

$$\Pi^*=\frac{3(\alpha-\gamma e-\beta C_Z-\beta C_g-\beta te)^2}{16\beta}$$

2.2 Independent research and development of emission reduction situation（$H\neq0$，$\theta=0$）

According to the assumed conditions, when the photovoltaic silicon wafer supplier chooses to conduct carbon reduction research and development independently, the profit functions of the photovoltaic system manufacturer and the photovoltaic silicon wafer supplier under the scenario of emission reduction research and development of the photovoltaic silicon wafer supplier can be obtained as follows:

$$\Pi_Z(P)=(P-W-C_Z)(\alpha-\beta P-\gamma(e-H))$$

$$\Pi_G(W)=(W-C_g-t(e-H))(\alpha-\beta P-\gamma(e-H))-\frac{1}{2}kH^2$$

In the case of independent research and development to reduce emissions, after photovoltaic silicon wafer suppliers reduce carbon emissions, the sales volume of photovoltaic systems in the market changes, and the profits, innovation costs, and carbon tax paid by photovoltaic silicon wafer suppliers all change. This article uses reverse induction to solve the optimal decision combination between photovoltaic system manufacturers and photovoltaic silicon wafer suppliers. The calculation process is as follows:

Firstly, based on the profit function $\Pi_Z(P)$ of the photovoltaic system manufacturer, solve the first-order and second-order derivative functions of the photovoltaic system price P. They are:

$$\frac{\partial \Pi_Z(P)}{\partial p} = \alpha - \gamma(e-H) + \beta W + \beta C_Z - 2\beta P$$

$$\frac{\partial^2 \Pi_Z(P)}{\partial p^2} = -2\beta < 0$$

Obviously, the profit function $\Pi_Z(P)$ of the photovoltaic system manufacturer must be a concave function with respect to the price of the photovoltaic system, that is, when the first-order derivative is zero, the profit function of the photovoltaic system manufacturer reaches its maximum value. Therefore, $\frac{\partial \Pi_Z(P)}{\partial p}=0$ can be used to obtain the optimal selling price P^{**} for the photovoltaic system manufacturer, which is:

$$P^{**} = \frac{\alpha - \gamma(e-H) + \beta W + \beta C_Z}{2\beta}$$

By substituting the obtained optimal sales price P^{**} of the photovoltaic system into the profit function of the photovoltaic silicon wafer supplier, the profit function of the new photovoltaic silicon wafer supplier at this time can be obtained as:

$$\Pi_G(W) = (W - C_g - t(e-H))(\frac{\alpha - \gamma(e-H) - \beta W - \beta C_Z}{2}) - \frac{1}{2}kH^2$$

According to the profit function of the new photovoltaic silicon wafer supplier, solve its first-order and second-order derivative functions regarding the silicon wafer price W, which are:

$$\frac{\partial \Pi_G(W)}{\partial W} = \frac{\alpha - \gamma(e-H) - \beta C_Z + \beta C_g + \beta t(e-H)}{2} - \beta W$$

$$\frac{\partial^2 \Pi_G(W)}{\partial W^2} = -\beta < 0$$

Let $\frac{\partial \Pi_G(W)}{\partial W} = 0$ determine the optimal silicon wafer price W^{**} for photovoltaic silicon wafer suppliers as follows:

$$W^{**} = \frac{\alpha - \gamma(e-H) - \beta C_Z + \beta C_g + \beta t(e-H)}{2\beta}$$

By substituting the obtained optimal silicon wafer price W^{**} into the optimal sales price P^{**} of the photovoltaic system manufacturer, the optimal sales price P^{**} of the photovoltaic system can be obtained as:

$$P^{**} = \frac{3\alpha - 3\gamma(e-H) + \beta C_Z + \beta C_g + \beta t(e-H)}{4\beta}$$

By substituting the obtained optimal silicon wafer price W^{**} and optimal sales price P^{**} into the profit functions of the photovoltaic system manufacturer and photovoltaic silicon wafer supplier, the optimal profit function $\Pi_Z^{**}(P)$ of the photovoltaic system manufacturer and the optimal profit function $\Pi_G^{**}(W)$ of the photovoltaic silicon wafer supplier can be obtained, which are:

$$\Pi_Z^{**}(P) = \frac{(\alpha - \gamma(e-H) - \beta C_Z - \beta C_g - \beta t(e-H))^2}{16\beta}$$

$$\Pi_G^{**}(W) = \frac{(\alpha - \gamma(e-H) - \beta C_Z - \beta C_g - \beta t(e-H))^2}{8\beta} - \frac{1}{2}kH^2$$

At this point, the optimal overall profit for the entire photovoltaic industry supply chain under the scenario of independent research and development to reduce emissions is:

$$\Pi^{**}=\frac{3(\alpha-\gamma(e-H)-\beta C_Z-\beta C_g-\beta t(e-H))^2}{16\beta}-\frac{1}{2}kH^2$$

It can be imagined that the situation where photovoltaic silicon wafer suppliers choose to make independent research and development decisions will only occur if their profits are higher than those without research and development and emission reduction, that is, $\Pi_G^{**}(W)\geq\Pi_G^{*}(W)$. It can be calculated that:

$$0<H\leq\frac{2(\gamma+\beta t)(\alpha-\gamma e-\beta C_Z-\beta C_g-\beta te)}{4\beta k-(\gamma+\beta t)^2}$$

Only when the carbon emission reduction $H\in\left(0\quad\frac{2(\gamma+\beta t)(\alpha-\gamma e-\beta C_Z-\beta C_g-\beta te)}{4\beta k-(\gamma+\beta t)^2}\right]$ is achieved through independent research and development by the photovoltaic silicon wafer supplier, will they choose to make independent research and development emission reduction decisions. According to the optimal profit function $\Pi_G^{**}(W)$ of photovoltaic silicon wafer suppliers under independent research and development emission reduction decisions, the first-order derivative and second-order derivative functions of R&D carbon emission reduction H are calculated as follows:

$$\frac{\partial\Pi_G^{**}(W)}{\partial H}=\frac{2(\gamma+\beta t)(\alpha-\gamma e-\beta C_Z-\beta C_g-\beta te+(\gamma+\beta t)H)}{8\beta}-kH$$

$$\frac{\partial\Pi_G^{**2}(W)}{\partial H^2}=\frac{2(\gamma+\beta t)^2}{8\beta}-k$$

Only when $\frac{\partial\Pi_G^{**2}(W)}{\partial H^2}$ is present, i.e. $\frac{2(\gamma+\beta t)^2}{8\beta}<k$, and its first-order derivative is zero, can the optimal R&D carbon emission reduction be determined. The optimal carbon reduction amount at this time is:

$$H^{**}=\frac{(\gamma+\beta t)(\alpha-\gamma e-\beta C_Z-\beta C_g-\beta te)}{4\beta k-(\gamma+\beta t)^2}$$

2.3 Collaborative R&D emission reduction situation $(H\neq 0,\ \theta\neq 0)$

Due to the high cost of research and development innovation for carbon reduction, photovoltaic silicon wafer suppliers face great innovation pressure when choosing to reduce emissions without research and development or independently. Moreover, research and development innovation for carbon reduction directly affects market demand due to consumer green preferences. Therefore, the effective participation of photovoltaic system manufacturers in collaborative research and development to reduce carbon emissions can alleviate the research and development pressure on photovoltaic silicon wafer suppliers. According to the assumed conditions, when the photovoltaic system manufacturer and the photovoltaic silicon wafer supplier choose to cooperate in the research and development of carbon emission reduction, the respective profit functions of the photovoltaic system manufacturer and the photovoltaic silicon wafer supplier can be obtained as follows:

$$\Pi_Z(P)=(P-W-C_Z)(\alpha-\beta P-\gamma(e-H))-\frac{1}{2}(1-\theta)kH^2$$

$$\Pi_G(W)=(W-C_g-t(e-H))(\alpha-\beta P-\gamma(e-H))-\frac{1}{2}\theta kH^2$$

This article uses reverse induction to solve the optimal decision combination between photovoltaic system manufacturers and photovoltaic silicon wafer suppliers (the calculation process is the same as the previous text, omitted here):

The optimal silicon wafer price W^{***} obtained from photovoltaic silicon wafer suppliers is:

$$W^{***}=\frac{\alpha-\gamma(e-H)-\beta C_Z+\beta C_g+\beta t(e-H)}{2\beta}$$

The optimal selling price P^{***} for the photovoltaic system is obtained as follows:

$$P^{***}=\frac{3\alpha-3\gamma(e-H)+\beta C_Z+\beta C_g+\beta t(e-H)}{4\beta}$$

By substituting the obtained optimal silicon wafer price W^{***} and optimal sales price P^{***} into the profit functions of the photovoltaic system manufacturer and photovoltaic silicon wafer supplier, the optimal profit function $\Pi_Z^{***}(P)$ of the photovoltaic system manufacturer and the optimal profit function $\Pi_G^{***}(W)$ of the photovoltaic silicon wafer supplier can be obtained, which are:

$$\Pi_Z^{***}(P)=\frac{(\alpha-\gamma(e-H)-\beta C_Z-\beta C_g-\beta t(e-H))^2}{16\beta}-\frac{1}{2}(1-\theta)kH^2$$

$$\Pi_G^{***}(W)=\frac{(\alpha-\gamma(e-H)-\beta C_Z-\beta C_g-\beta t(e-H))^2}{8\beta}-\frac{1}{2}\theta kH^2$$

At this point, the optimal overall profit for the entire photovoltaic industry supply chain under independent emission reduction research and development is:

$$\Pi^{***}=\frac{3(\alpha-\gamma(e-H)-\beta C_Z-\beta C_g-\beta t(e-H))^2}{16\beta}-\frac{1}{2}kH^2$$

It can be imagined that the situation where photovoltaic system manufacturers and photovoltaic silicon wafer suppliers choose to cooperate in research and development to reduce carbon emissions only occurs when their respective profits are higher than those of non cooperative research and development, that is, $\Pi_Z^{***}(W)\geq\Pi_Z^{*}(W)$, $\Pi_G^{***}(W)\geq\Pi_G^{**}(W)$. It can be calculated that:

$$0<H\leq\frac{2(\gamma+\beta t)(\alpha-\gamma e-\beta C_Z-\beta C_g-\beta te)}{8(1-\theta)\beta k-(\gamma+\beta t)^2}$$

$$0<H\leq\frac{2(\gamma+\beta t)(\alpha-\gamma e-\beta C_Z-\beta C_g-\beta te)}{4\theta\beta k-(\gamma+\beta t)^2}$$

Comparatively speaking, when $0<\theta<\frac{2}{3}$, $H\in\left(0\quad\frac{2(\gamma+\beta t)(\alpha-\gamma e-\beta C_Z-\beta C_g-\beta te)}{8(1-\theta)\beta k-(\gamma+\beta t)^2}\right]$;

When $\theta>\frac{2}{3}$, $H\in\left(0\quad\frac{2(\gamma+\beta t)(\alpha-\gamma e-\beta C_Z-\beta C_g-\beta te)}{4\theta\beta k-(\gamma+\beta t)^2}\right]$。

According to the optimal profit function $\Pi_G^{***}(W)$ of photovoltaic silicon wafer suppliers in the context of collaborative R&D emission reduction decisions, the first-order derivative and second-order derivative functions of R&D carbon emission reduction H are calculated as follows:

$$\frac{\partial\Pi_G^{**}(W)}{\partial H}=\frac{2(\gamma+\beta t)(\alpha-\gamma e-\beta C_Z-\beta C_g-\beta te+(\gamma+\beta t)H)}{8\beta}-\theta kH$$

$$\frac{\partial\Pi_G^{**2}(W)}{\partial H^2}=\frac{2(\gamma+\beta t)^2}{8\beta}-\theta k$$

Only when $\frac{\partial\Pi_G^{**2}(W)}{\partial H^2}$ is present, i.e. $\frac{2(\gamma+\beta t)^2}{8\beta}<\theta k$, and its first-order derivative is zero, can the optimal R&D carbon emission reduction be determined. The optimal carbon reduction amount at this time is:

$$H^{***}=\frac{(\gamma+\beta t)(\alpha-\gamma e-\beta C_Z-\beta C_g-\beta te)}{4\theta\beta k-(\gamma+\beta t)^2}$$

That is, when $\theta>\frac{2}{3}$, $\frac{2(\gamma+\beta t)^2}{8\beta}<\theta k$, the photovoltaic system manufacturer collaborates with the photovoltaic silicon wafer supplier to develop the optimal carbon reduction amount for $H^{***}=\frac{(\gamma+\beta t)(\alpha-\gamma e-\beta C_Z-\beta C_g-\beta te)}{4\theta\beta k-(\gamma+\beta t)^2}$.

3. Discussion and Comparison of Results

Table 1 summarizes the optimal photovoltaic system prices, photovoltaic silicon wafer prices, respective optimal profits, and optimal carbon emission reductions for photovoltaic system manufacturers and photovoltaic silicon wafer manufacturers under the scenarios of no research and development emission reduction, independent research and development emission reduction, and collaborative research and development emission reduction.

Table 1
Optimal Factor Values and Profit Values of Photovoltaic Industry Supply Chain Entities under Three Different R&D Scenarios

parameter	No research and development emissions reduction situation*	Independent research and development of emission reduction situation**	Collaborative R&D emission reduction situation***
w	$\frac{\alpha-\gamma e-\beta C_Z+\beta C_g+\beta te}{2\beta}$	$\frac{\alpha-\gamma(e-H^{**})-\beta C_Z+\beta C_g+\beta t(e-H^{**})}{2\beta}$	$\frac{\alpha-\gamma(e-H^{***})-\beta C_Z+\beta C_g+\beta t(e-H^{***})}{2\beta}$
H	/	$\frac{(\gamma+\beta t)(\alpha-\gamma e-\beta C_Z-\beta C_g-\beta te)}{4\beta k-(\gamma+\beta t)^2}$	$\frac{(\gamma+\beta t)(\alpha-\gamma e-\beta C_Z-\beta C_g-\beta te)}{4\theta\beta k-(\gamma+\beta t)^2}$
p	$\frac{3\alpha-3\gamma e+\beta C_Z+\beta C_g+\beta te}{4\beta}$	$\frac{3\alpha-3\gamma(e-H^{**})+\beta C_Z+\beta C_g+\beta t(e-H^{**})}{4\beta}$	$\frac{3\alpha-3\gamma(e-H^{***})+\beta C_Z+\beta C_g+\beta t(e-H^{***})}{4\beta}$
Π_Z	$\frac{(\alpha-\gamma e-\beta C_Z-\beta C_g-\beta te)^2}{16\beta}$	$\frac{(\alpha-\gamma(e-H^{**})-\beta C_Z-\beta C_g-\beta t(e-H^{**}))^2}{16\beta}$	$\frac{(\alpha-\gamma(e-H^{***})-\beta C_Z-\beta C_g-\beta t(e-H^{***}))^2}{16\beta}-\frac{1}{2}(1-\theta)kH^{***2}$
Π_g	$\frac{(\alpha-\gamma e-\beta C_Z-\beta C_g-\beta te)^2}{8\beta}$	$\frac{(\alpha-\gamma(e-H^{**})-\beta C_Z-\beta C_g-\beta t(e-H^{**}))^2}{8\beta}-\frac{1}{2}kH^{**2}$	$\frac{(\alpha-\gamma(e-H^{***})-\beta C_Z-\beta C_g-\beta t(e-H^{***}))^2}{8\beta}-\frac{1}{2}\theta kH^{***2}$
Π	$\frac{3(\alpha-\gamma e-\beta C_Z-\beta C_g-\beta te)^2}{16\beta}$	$\frac{3(\alpha-\gamma(e-H^{**})-\beta C_Z-\beta C_g-\beta t(e-H^{**}))^2}{16\beta}-\frac{1}{2}kH^{**2}$	$\frac{3(\alpha-\gamma(e-H^{***})-\beta C_Z-\beta C_g-\beta t(e-H^{***}))^2}{16\beta}-\frac{1}{2}kH^{***2}$

According to Table 1, the following properties can be obtained:

Property 1: From the optimal carbon emission reduction, it can be found that the cooperation between photovoltaic system manufacturers and photovoltaic silicon wafer suppliers in developing carbon emission reduction is greater than the independent research and development of carbon emission reduction by photovoltaic silicon wafer suppliers.

Proof: Comparing H^{**} with H^{***}, since $\theta\in[0 \quad 1]$, then

$$\frac{(\gamma+\beta t)(\alpha-\gamma e-\beta C_Z-\beta C_g-\beta te)}{4\beta k-(\gamma+\beta t)^2}<\frac{(\gamma+\beta t)(\alpha-\gamma e-\beta C_Z-\beta C_g-\beta te)}{4\theta\beta k-(\gamma+\beta t)^2}.$$

That is, $H^{**}\leq H^{***}$.

Property 2: In terms of the optimal sales price for photovoltaic system manufacturers and photovoltaic silicon wafer suppliers, the optimal sales price for collaborative research and development of carbon reduction is higher than that for independent research and development of carbon reduction, and even higher than that for no research and development of carbon reduction, i.e. $w^*<w^{**}<w^{***}$, $P^*<P^{**}<P^{***}$.

Proof: According to property 1, it can be inferred that $H^{**}\leq H^{***}$, it is evident that:

$$\frac{\alpha-\gamma e-\beta C_Z+\beta C_g+\beta te}{2\beta}<\frac{\alpha-\gamma(e-H^{**})-\beta C_Z+\beta C_g+\beta t(e-H^{**})}{2\beta}<\frac{\alpha-\gamma(e-H^{***})-\beta C_Z+\beta C_g+\beta t(e-H^{***})}{2\beta}$$

$$\frac{3\alpha-3\gamma e+\beta C_Z+\beta C_g+\beta te}{4\beta}<\frac{3\alpha-3\gamma(e-H^{**})+\beta C_Z+\beta C_g+\beta t(e-H^{**})}{4\beta}<\frac{3\alpha-3\gamma(e-H^{***})+\beta C_Z+\beta C_g+\beta t(e-H^{***})}{4\beta}$$

That is, $w^*<w^{**}<w^{***}$, $P^*<P^{**}<P^{***}$ 。

Property 3: When collaborating on carbon reduction research and development, the higher the research and development costs borne by photovoltaic system manufacturers, the higher the enthusiasm of photovoltaic silicon wafer enterprises to research and develop carbon reduction, and the higher the optimal collaborative research and development carbon reduction emissions.

Proof: Calculate the first-order derivative function H^{***} of the optimal R&D carbon reduction amount $\frac{\partial H^{***}}{\partial \theta}$ under the scenario of collaborative R&D carbon reduction.

$$\frac{\partial H^{***}}{\partial \theta} = -\frac{(\gamma+\beta t)(\alpha-\gamma e-\beta C_Z-\beta C_g-\beta te)}{\left[4\theta\beta k-(\gamma+\beta t)^2\right]^2} < 0$$

As the proportion of research and development costs borne by photovoltaic silicon wafer suppliers decreases and the proportion of research and development costs borne by photovoltaic systems increases, the carbon emission reduction of cooperative research and development becomes higher.

Property 4: For the main body of the photovoltaic industry supply chain and the overall situation, the optimal profit of their collaborative research and development on carbon reduction is greater than the profit without research and development on carbon reduction.

Proof: According to the overall profit function of the photovoltaic industry supply chain, if $\Pi_g^{***} - \Pi_g^{**}$ is given, we can obtain:

$$\frac{(\alpha-\gamma(e-H^{***})-\beta C_Z-\beta C_g-\beta t(e-H^{***}))^2}{8\beta} - \frac{1}{2}\theta k H^{***2} - \frac{(\alpha-\gamma e-\beta C_Z-\beta C_g-\beta te)^2}{8\beta}$$
$$= \frac{(\alpha-\gamma e-\beta C_Z-\beta C_g-\beta te)(\gamma+\beta t)H^{***}}{8\beta} > 0$$

Prove it.

Similarly, it can also be proven that $\Pi_Z^{***} - \Pi_Z^{**}$, $\Pi^{***} - \Pi^{**}$.

4. Numerical Case Analysis

4.1 Numerical Calculation

Based on the comprehensive 2024 report from the National Energy Administration of China and related industries, cost data and market size data related to the supply chain of China's photovoltaic industry in 2024 have been analyzed and organized. According to research reports on the development of the photovoltaic industry over the years, a photovoltaic system requires approximately 72 modules and 142857 silicon wafers, with each wafer having a power of about 70000 watts. According to photovoltaic industry reports, the current photovoltaic conversion efficiency can reach 21%. From this, it can be calculated that each silicon wafer can generate 1.47 watts of power, and each photovoltaic system can produce approximately 300000 watts. Based on this, cost data related to the photovoltaic industry supply chain and market size can be calculated. In this way, the relevant data required for this article can be calculated as shown in Table 2.

Table 2

Global Photovoltaic Industry Related Data in 2024

year	parameter	Silicon wafer cost（YUAN/w）	Non silicon wafer cost（YUAN/w）	Market installed capacity（GW）
2024	Before adjustment	0.46	0.98	277.57
	parameter	Silicon wafer cost（YUAN/suite）	Non silicon wafer cost（YUAN/suite）	Market installed capacity（suite）
	After adjustment	65714.22	294000	925233.33

Table 3

Optimal Factor Values and Profit Values of the Photovoltaic Industry Supply Chain under Three Scenarios

Parameter	No research and development emissions reduction situation*	Independent research and development of emission reduction situation**	Collaborative R&D emission reduction situation***
w	4383559.54	4389089.88	4390474.65
H	/	220.33	275.50
p	6935553.53	6943804.98	6945871.09
Π_Z	4.8039E+11	4.8160E+11	4.8153E+11
Π_g	9.6078E+11	9.6199E+11	9.6284E+11
Π	1.4412E+12	1.4436E+12	1.4444E+12

Meanwhile, this article assumes a demand price elasticity of 0.1; The cost coefficient of technological innovation is 50000; The market carbon tax rate is 20%; The consumer demand coefficient for low-carbon products is 5; The initial carbon emissions per unit product are 2500; The innovation cost sharing ratio for photovoltaic silicon wafer suppliers is 0.8. Based on the data in the table above, the optimal parameter values and profit values for the photovoltaic industry supply chain in 2024 can be calculated for the scenarios of no R&D emissions reduction, independent R&D emissions reduction, and collaborative R&D emissions reduction. The calculation results are shown in Table 3. As shown in Table 3, it can be seen from the optimal R&D carbon emission reduction of photovoltaic silicon wafer suppliers that the R&D carbon emission reduction under cooperative R&D is greater than that under independent R&D, which corresponds to property 1. Secondly, in terms of the optimal silicon wafer price for photovoltaic silicon wafer suppliers and the optimal sales price for photovoltaic system manufacturers, both show that collaborative research and development leads to the best emission reduction situation, independent research and development leads to the second best emission reduction situation, and no research and development leads to the smallest emission reduction situation, which corresponds to property 2. From the optimal profits of photovoltaic silicon wafer suppliers, photovoltaic system manufacturers, and the total profit of the photovoltaic industry supply chain, it can be seen that the optimal profit under cooperative research and development is higher than that under no research and development emission reduction, which corresponds to property 4.

4.2 Sensitivity Analysis

Based on the data in the table above, sensitivity analysis will be conducted on parameters such as the carbon emission tax rate collected by the Chinese government, the proportion of research and development carbon reduction costs borne by photovoltaic silicon wafer suppliers during cooperative research and development in the photovoltaic industry supply chain, and the consumer green preference coefficient. The results are shown in Tables 4, 5, and 6.

Table 4
The Impact of Carbon Emission Tax Rates on the R&D and Profit of the Photovoltaic Industry Supply Chain

t	H^{**}	H^{***}	Π^{**}	Π^{***}	$\frac{\Pi^{***}-\Pi^{**}}{\Pi^{**}}$
0.15	220.12	275.23	1.443631E+12	1.444404E+12	0.0535
0.18	220.25	275.39	1.443609E+12	1.444384E+12	0.0537
0.2	220.33	275.50	1.443595E+12	1.444370E+12	0.0537
0.23	220.46	275.67	1.443573E+12	1.444349E+12	0.0538
0.25	220.55	275.77	1.443558E+12	1.444335E+12	0.0538
0.28	220.68	275.94	1.443536E+12	1.444314E+12	0.0539
0.3	220.77	276.04	1.443522E+12	1.444300E+12	0.0539

From Table 4, it can be seen that the carbon tax rate collected by the government has a certain impact on the carbon reduction research and development and profits of the photovoltaic industry supply chain. Obviously, increasing the carbon tax rate by the government can to some extent increase the carbon emissions reduction of the photovoltaic industry supply chain, but the effect is not significant. On the contrary, increasing the carbon tax rate will lead to a decrease in the overall profit of the photovoltaic industry supply chain. Secondly, increasing the carbon tax gradually increases the ratio of the optimal profit of collaborative research and development for carbon reduction to the profit added of independent research and development for carbon reduction. This means that increasing the carbon tax increases the willingness of the photovoltaic industry supply chain to choose collaborative research and development for carbon reduction.

Table 5
The impact of R&D innovation cost allocation ratio on the R&D and profits of the photovoltaic industry supply chain

θ	H^{**}	H^{***}	Π^{**}	Π^{***}	$\frac{\Pi^{***}-\Pi^{**}}{\Pi^{**}}$
0.7	220.33	314.93	1.443595E+12	1.444905E+12	0.0907
0.8	220.33	275.50	1.443595E+12	1.444370E+12	0.0537
0.9	220.33	244.85	1.443595E+12	1.443943E+12	0.0241

From Table 5, it can be seen that as photovoltaic silicon wafer suppliers bear a higher proportion of the cost of collaborative research and development for carbon reduction, their research and development carbon reduction emissions decrease, and the optimal profit of the entire photovoltaic industry supply chain also decreases. On the contrary, the higher the proportion of cooperative research and development gold medal costs borne by photovoltaic system manufacturers, the greater the carbon emission reduction, which corresponds to property 3. From Table 6, it can be seen that consumer green preferences play an important role in reducing carbon emissions in the photovoltaic industry supply chain. As the consumer green preference coefficient increases, the research and development carbon emissions of photovoltaic silicon wafer suppliers steadily increase, and the effect is significantly better than that of carbon taxes. But the increase in consumer green preferences has led to a gradual reduction in the main profits of the photovoltaic industry supply chain, as the increase in carbon emissions requires companies to invest a large amount of research and development costs. But according to Table 6, it can be found that the increase in consumer green preferences has gradually strengthened the willingness of the photovoltaic industry supply chain to choose cooperative research and development.

Table 6
The Impact of Consumer Green Preferences on the R&D and Profit of the Photovoltaic Industry Supply Chain

γ	H^{**}	H^{***}	Π^{**}	Π^{***}	$\frac{\Pi^{***}-\Pi^{**}}{\Pi^{**}}$
5	220.33	275.50	1.443595E+12	1.444370E+12	0.0537
10	435.15	544.63	1.409799E+12	1.412838E+12	0.2156
15	646.93	810.98	1.380899E+12	1.387674E+12	0.4906
20	857.23	1077.04	1.356709E+12	1.368751E+12	0.8876
25	1067.63	1345.41	1.337128E+12	1.356109E+12	1.4195

5. Conclusion

Under the dual carbon target regulation, this article analyzes three research and development decisions on carbon reduction among the main enterprises in the photovoltaic industry supply chain from the perspective of carbon tax and consumer green preferences. Using differential game theory, three decision models are constructed for carbon reduction without research and development, independent research and development, and cooperative research and development. The optimal factor values and optimal profit values of the main enterprises in the photovoltaic industry supply chain are obtained under different situations, and case studies and sensitivity analysis are conducted. The conclusion is as follows:

(1) The optimal carbon reduction achieved by the main enterprises in the photovoltaic supply chain through cooperative research and development should be higher than that achieved through independent research and development. The research and development of carbon reduction in the photovoltaic industry supply chain is beneficial for increasing product market prices. Therefore, under the dual carbon target regulation, in order to achieve carbon reduction in the manufacturing process of photovoltaic silicon wafers, the main enterprises of the photovoltaic industry supply chain should actively seek cooperation channels, build cooperation contracts and mechanisms. The government should also actively provide a platform and environment to promote good cooperation among the main bodies of the photovoltaic industry supply chain.

(2) The increase in carbon tax rates has to some extent increased carbon emissions, but at the same time reduced the overall profit of the photovoltaic industry chain. Therefore, when implementing carbon tax rates, the government should focus on examining the development and trends of the entire supply chain of the official clothing industry, and implement a dynamic mechanism for carbon tax rates.

(3) The higher the proportion of research and development costs borne by photovoltaic system manufacturers, the higher the carbon emission reduction of photovoltaic silicon wafer suppliers' research and development. The main body of the photovoltaic industry supply chain should actively cooperate and jointly research and develop. At the same time as photovoltaic system manufacturers are willing to bear the research and development proportion, corresponding compensation mechanisms can be established to compensate for their loss of profits; At the same time, the government should actively establish mechanisms and measures to encourage their collaborative research and development.

(4) Consumer green preferences are conducive to improving the carbon reduction of the photovoltaic industry chain, and the effect is significant. Therefore, the photovoltaic industry supply chain should actively understand the market, grasp consumer dynamics, and adjust its research and production strategies in a timely manner with changes in consumer willingness to consume.

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References

Barman, A., Sarkar, P., Kalisz-Szwedzka, K., & Weber, G. W. (2025). Maximizing efficiency in low-carbon sustainable supply chain under yield uncertainty and risk-averse flexibility. International Journal of Production Research, 1-19.

Chen, F., Wu, B., & Lou, W. (2021). An evolutionary analysis on the effect of government policies on green R & D of photovoltaic industry diffusion in complex network. *Energy Policy, 152*, 112217.

Dai, D., & Wang, Y. (2025). Cooperation and operational decision-making of photovoltaic supply chain under the responsibility weight system of renewable energy consumption. *Chinese Management Science*, *1–18*.

Dai, J. S., & Li, G. (2023). Financial constraint supply chain cooperation advertising coordination model. *Chinese Management Science*, *31*(9), 83–93.

Deng, Q., Li, Y., Feng, L., & Li, W. (2025). Research on the incentive effect of government preferential policies on enterprises' green technology innovation decisions. *Chinese Management Science*, *1–28*.

Fang, D., Wang, P., & Cao, G. (2024). The collaborative evolution mechanism of green innovation and performance in electricity under social networks. *Journal of Management Science*, *27*(10), 35–52.

Han, X., Lv, F., Li, J., & Zeng, F. (2024). Flexible interactive control method for multi-scenario sharing of hybrid pumped storage-wind-photovoltaic power generation. *Journal of Energy Storage, 100*, 113590.

Hayashi, D. (2020). Green Innovation in China and India: Technological Learning, Technology Transfer, and Public Policies in the Wind Power and Solar Photovoltaic Industries (Doctoral dissertation, University of Zurich).

Hu, J., & Wu, J. (2025). Research on collaborative innovation decision making of new energy vehicle industry chain considering carbon quota sharing contract. *International Journal Of Industrial Engineering Computations*, 16(2), 261-274.

Hu, J., Wu, J., Wu, J., Sheng, Y., & Shi, Q. (2022). Research on competition and cooperation in the photovoltaic industry supply chain driven by innovation: Based on government competition policy. *Chinese Management Science*, *30*(10), 256–264.

Li, N., Deng, M., Mou, H., Tang, D., Fang, Z., Zhou, Q., ... & Wang, Y. (2022). Government participation in supply chain low-carbon technology R&D and green marketing strategy optimization. *Sustainability, 14*(14), 8342.

Liu, J., Dong, J., Chen, Y., & Huang, B. (2025). Design of a carbon footprint-based carbon subsidy impact mechanism for collaborative carbon reduction in new energy vehicle supply chains. *Applied Economics*, 1-16.

Liu, L., Wang, Z., Li, X., Liu, Y., & Zhang, Z. (2022). An evolutionary analysis of low-carbon technology investment strategies based on the manufacturer-supplier matching game under government regulations. Environmental Science and Pollution Research, 29(29), 44597-44617.

Liu, T., & Feng, Q. (2023). R&D mode and coordination of green products in sustainable supply chain considering power structures. Plos one, 18(11), e0291351.

Mao, J., Lu, J., Song, J., & Zhu, P. (2024). Research on the resilience assessment and enhancement method of cloud manufacturing service supply and demand relationship considering risk allocation. *Chinese Management Science*, 1–13.

Rong, L., & Xu, M. (2022). Impact of altruistic preference and government subsidy on the multinational green supply chain under dynamic tariff. Environment, Development and Sustainability, 24(2), 1928-1958.

Song, H., Wang, R., Mao, X., Tao, J., Zhang, M., Wang, X., & Sang, X. (2025). Green supply chain strategy considering participant fairness concern and uncertainty of research and development. *Scientific Reports, 15*(1), 28898.

Su, C., Liu, X., & Du, W. (2020). Green supply chain decisions considering consumers' low-carbon awareness under different government subsidies. Sustainability, 12(6), 2281.

Sun, C., Li, X., & Yu, H. (2022). The path selection of government subsidy exit strategy for cross-border two-way supply chain. *Chinese Management Science*, *30*(11), 127–136.

Tang, J., Li, B., Gong, B., Liu, Z., & Zhu, X. (2023). Research on decision-making and coordination of retail recycling closed-loop supply chain considering corporate social responsibility. *Chinese Management Science*, *31*(11), 228–237.

Wang, F., & Liu, W. (2024). The current status, challenges, and future of China's photovoltaic industry: A literature review and outlook. *Energies, 17*(22), 5694.

Wang, Y., & Gao, J. (2024). Research on closed-loop supply chain decision-making and coordination based on government dynamic subsidies for blockchain technology. *Systems Engineering Theory and Practice, 44*(3), 1053–1068. https://doi.org/10.12011/SETP2023-1468

Xing, Q., Ren, Y., & Deng, F. (2024). Decision on the distribution of benefits for collaborative innovation of green products under the guarantee of minimum shipment volume. *Management Review*, *36*(2), 80–91.

Xing, Q., Ren, Y., & Deng, F. (2024). Decision on the distribution of benefits for collaborative innovation of green products under the guarantee of minimum shipment volume. *Management Review*, *36*(2), 80–91.

Xu Chao, Cai Yaoqin, Bai Tianlei&Zhou Cai (2024). Tax revenue sharing, fiscal incentives, and corporate green innovation: evidence from the "55% share" reform of value-added tax Nankai Economic Research, (12), 206-226.

Xu, C. Y., Wang, Y. Q., Yao, D. L., Qiu, S. Y., & Li, H. (2025). Research on the coordination of a marine green fuel supply chain considering a cost-sharing contract and a revenue-sharing contract. *Frontiers in Marine Science, 12*, 1552136..

Yi, H., & Tang, L. (2024). Research on differential strategies for collaborative product innovation in supply chain under disappointment avoidance of decision makers. *Control and Decision*, *39*(1), 271–280.

Yin, C., Gu, H., & Zhang, S. (2020). Measuring technological collaborations on carbon capture and storage based on patents: A social network analysis approach. *Journal of Cleaner Production, 274*, 122867.

Yu, H., & Song, F. (2025). R&D and pricing strategies in the intelligent vehicle supply chain under cross-organizational cooperative models. PloS one, 20(4), e0321903.

Yuan, C., Hu, L., & Zhang, Y. (2023). Scenario analysis of emission reduction in China's photovoltaic industry based on EBC framework. *Systems Engineering*, *41*(6), 52–61.

Zhang, H., Zhang, J., & Lai, M. (2015). Analysis of government behavior and supply chain cooperative R&D game under low carbon background. *Chinese Management Science*, *23*(10), 57–66.

Zhong, H., Huo, H., Zhang, X., & Zheng, S. (2022). Sustainable decision-making in a low-carbon supply chain: Fairness preferences and green investment. *IEEE Access, 10,* 48761-48777.

Zhu, J., Shi, Y., Wu, Y., & Venkatesh, V. G. (2025). Low carbon policy: a green agriculture supply chain perspective. Annals of Operations Research, 1-33.