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Collaborative decision making of photovoltaic industry chain considering carbon quota sharing contract

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From the perspective of carbon quota policy, we consider integrating carbon quota sharing contracts into the collaborative decision-making model of the photovoltaic industry chain and compare and explore the collaborative decision-making of the photovoltaic industry chain under decentralized decision-making and considering carbon quota sharing contracts. Research has found that carbon quota sharing contracts can effectively promote green innovation among the main body of the photovoltaic industry chain; In the case of carbon quota sharing contracts, the pricing between photovoltaic system suppliers and photovoltaic power plant enterprises is lower; Under the carbon quota sharing contract, the profits, and overall profits of each entity in the photovoltaic industry chain are better than the optimal profits under decentralized conditions.

1. Introduction

The EU carbon tariffs are about to take effect, making carbon emitting giants seeking carbon reduction measures and building photovoltaic power plants a new necessity (Zhang & Zhang, 2022). However, for the photovoltaic industry chain, except for photovoltaic power plant enterprises, the carbon emissions of other industry chain entities are still relatively high. With the soaring carbon prices in the EU trading market, how upstream enterprises in the photovoltaic industry chain make decisions to balance carbon costs and innovation costs is a key challenge faced by the photovoltaic industry (Zhao & Zhang, 2021). Therefore, based on global carbon quota trading policies, studying the impact of carbon quota sharing on collaborative decision-making in the photovoltaic industry chain has practical significance (Ghosh & Shah, 2012).

In recent years, many international scholars have conducted extensive research on collaborative innovation decision-making in industries, proposing cost sharing contract models and revenue sharing contract models to promote innovation among industry chain entities and achieve collaborative innovation among industry chain entities (Han et al., 2021). For example, supply chain collaborative decision-making was studied based on revenue sharing contracts (Shafiq et al., 2021Cui et al., 2021). A supply chain coordination strategy was studied based on cost sharing contracts (Zhu et al., 2021; Xiao et al., 2019; Hongguang & Jianwen, 2015; Shi, 2023). A few scholars have studied the cost sharing contract and revenue sharing contract models for the photovoltaic industry (Chen et al., 2011; Hu et al., 2020，2022), studying the impact of revenue sharing and cost sharing on the collaborative decision-making of the two-level photovoltaic industry chain.

Considering global carbon emissions and the current state of the carbon market, some scholars have also studied the impact of carbon emissions, carbon trading, and other factors on industrial chain collaborative innovation. Research on the impact of carbon trading policies on supply chain collaborative innovation (Kumar et al., 2021), including carbon reduction decisions

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in closed-loop supply chains (Yan et al., 2023), low-carbon differential decisions in supply chains (Wu & Xia, 2023), and supply chain collaborative decisions under carbon quota and carbon trading policies (Xia et al., 2022; Zou et al., 2022; Wang et al., 2021a, 2021b).

Previous studies by scholars have provided useful references for this article's research on collaborative decision-making in the photovoltaic industry chain under carbon quota sharing contracts. Previous studies have mainly focused on the impact of revenue sharing contracts and cost sharing contracts on collaborative decision-making in the industry chain. Secondly, the introduction of carbon policies is often based on carbon trading scenarios. Unlike previous studies, this study considers the impact of carbon quota sharing contracts on the decentralized decision-making of the photovoltaic system industry chain based on carbon quota trading policies. Based on this, this article constructs a differential game model between photovoltaic system suppliers and photovoltaic power plant enterprises based on carbon quota sharing contracts, obtains the optimal factor solution and optimal profit of the model, discusses and compares the impact of key factors on member decision-making, and empirically analyzes the impact of carbon quota sharing contracts on collaborative innovation decision-making in the photovoltaic industry.

2. Basic Assumptions of the Model

“Carbon quota” refers to the total amount of greenhouse gas emissions by enterprises into the atmosphere within a certain period, approved by government regulatory authorities; Carbon trading "refers to the trading and buying of greenhouse gas emissions reduction by enterprises. However, in the photovoltaic industry chain, almost all entities such as silicon wafer manufacturers and photovoltaic system manufacturers are high carbon emitting enterprises, while only photovoltaic power plant enterprises are low carbon emitting enterprises. Photovoltaic power stations can sell the remaining carbon quotas to earn profits, and photovoltaic system suppliers can also reduce their carbon emissions through technological innovation, while leveraging the priority purchase rights of photovoltaic power station carbon quotas.

Considering the current heat of the carbon market, this article studies the impact of carbon quota trading policies on collaborative innovation decision-making in the photovoltaic industry chain. Therefore, this article establishes a photovoltaic industry chain consisting of photovoltaic silicon wafer manufacturers, photovoltaic system manufacturers, and photovoltaic power station enterprises. For the convenience of research, this article combines photovoltaic silicon wafer manufacturers and photovoltaic system manufacturers as photovoltaic system suppliers to form a secondary photovoltaic industry chain dominated by photovoltaic system suppliers (g) and photovoltaic power plant enterprises (z). Considering that the technological innovation of photovoltaic system suppliers in silicon wafer manufacturing can not only promote their own carbon reduction, but also improve the efficiency of photovoltaic conversion, improve the power generation efficiency of photovoltaic power plants, and reduce carbon emissions. Therefore, driven by carbon quota trading policies, photovoltaic power station enterprises will inevitably provide corresponding contracts to photovoltaic system suppliers to promote their technological innovation.

The basic assumptions of this study are as follows:

H1: Production cost: Photovoltaic system suppliers will pay corresponding costs when producing photovoltaic systems and building photovoltaic power station enterprises, such as silicon wafer costs, assembly costs, wages, etc. We use C_g to represent the basic cost of a photovoltaic system supplier producing a set of photovoltaic systems, and eT to represent the excess carbon emission cost of a photovoltaic system supplier producing a set of photovoltaic systems, where e represents the unit price of excess carbon emissions. We also use C_z to represent the total cost paid by the photovoltaic power plant (excluding the carbon emission cost of the photovoltaic power plant enterprise).

H2: Innovation cost: Photovoltaic system suppliers need to pay a certain amount of research and development costs when conducting technological innovation. The technological innovation of photovoltaic system suppliers mainly focuses on improving the photoelectric conversion efficiency of silicon wafers and reducing carbon emissions. Therefore, this article uses H to represent the technological innovation level of photovoltaic system suppliers. The study also uses $C(H)$ to represent the technological innovation cost of photovoltaic system suppliers. To accurately measure the cost of innovation, a cost model is introduced to construct a technology innovation cost function for photovoltaic system suppliers, where $C(H)=\frac{1}{2}kH^2$ represents the innovation cost coefficient.

H3: Product price: w represents the wholesale price at which a photovoltaic system supplier sells a set of photovoltaic systems; The study also uses p to represent the electricity price of photovoltaic power plant enterprises.

H4: Service life: The study uses t to represent the service life of each photovoltaic system.

H5: Carbon quota: Carbon quota refers to the legal carbon emissions owned by photovoltaic system suppliers and photovoltaic power plant enterprises, and the excess can be obtained through trading. We use T to indicate that the photovoltaic system supplier exceeds the specified carbon emissions when producing a set of photovoltaic systems.

H6: Market size: There is the greatest potential demand for any product in the market, denoted by a as the potential demand for photovoltaic power; If b represents the elasticity coefficient of demand price, then the demand function for photovoltaic power is: $Q=a-bp$. Let S be the power generation of each photovoltaic system in a photovoltaic power plant, the market demand for photovoltaic systems is: $\frac{Q}{S}=\frac{a-bp}{S}$.

H7: Carbon quota trading policy: The calculation method for carbon quota trading policy is: $R=eN$, where e is the transaction unit price of the market carbon quota, and N is the carbon quota generated by a photovoltaic system of a photovoltaic power plant enterprise. Considering the impact of technological innovation on carbon quotas, this article modifies the calculation method of carbon quota trading to $R=e(1+H)N$.

3. Model Analysis and Solution

3.1 Decentralized Decision Model

In the context of decentralized decision-making, both photovoltaic system suppliers and photovoltaic power plant enterprises, as rational entities, will pursue the maximization of their own profits. According to the assumed conditions, the profit functions of photovoltaic system suppliers and photovoltaic power plant enterprises in this situation are:

$$\prod_g(H \quad w)=(w-C_g-e(1-H)T)\frac{(a-bp)}{S}-\frac{1}{2}kH^2. \tag{1}$$

$$\prod_z(H \quad p)=(ptS-w-C_z+e(1+H)N)\frac{(a-bp)}{S}. \tag{2}$$

Under decentralized decision-making, the game order between photovoltaic system suppliers and photovoltaic power plant enterprises is: first, the photovoltaic system supplier determines the wholesale price, then the photovoltaic power plant enterprise determines the wholesale quantity and wholesale price, and finally determines the optimal decision solution. This article uses the reverse induction method to solve the optimal strategy combination, and the calculation process is as follows.

Firstly, based on the profit function $\prod_z(H \quad p)$ of the photovoltaic power plant enterprise, we solve its first-order derivative function and second-order derivative function respect to product prices p, which are:

$$\frac{\partial \prod_z(H \quad p)}{\partial p}=at+b(\frac{w+C_z-e(1+H)N}{S})-2btp.$$

$$\frac{\partial^2 \prod_z(H \quad p)}{\partial p^2}=-2bt<0.$$

Since $\frac{\partial^2 \prod(H \quad p)}{\partial p^2}<0$, the profit function $\prod_z(H \quad p)$ of photovoltaic power plant enterprises is a concave function regarding product prices, which takes its maximum value when the first-order derivative function is zero. Therefore, let $\frac{\partial \prod(H \quad p)}{\partial p}=0$ we determine the optimal product price p^* for a photovoltaic power plant enterprise in this situation as follows:

$$p^*=\frac{at+b(\frac{w+C_z-e(1+H)N}{S})}{2bt}. \tag{3}$$

By replacing Eq. (3) into Eq. (1), it can be concluded that the profit function of the photovoltaic system supplier is:

$$\prod_g(H \quad w)=(w-C_g-e(1-H)T)\frac{at-b(\frac{w+C_z-e(1+H)N}{S})}{2tS}-\frac{1}{2}kH^2 \tag{4}$$

However, according to Eq. (4), the profit function $\prod_g(H \quad w)$ of the photovoltaic system supplier is solved by solving its first-order and second-order derivative functions regarding product wholesale price w and innovation level H, which are:

$$\frac{\partial \prod(H \quad w)}{\partial w}=-\frac{b}{tS^2}w+\frac{(C_g+e(1+H)N+e(1-H)T)b+atS-bC_z}{2tS^2}$$

$$\frac{\partial^2 \prod(H \quad w)}{\partial w^2}=-\frac{b}{tS^2}<0$$

$$\frac{\partial \prod(H \quad w)}{\partial H}=\frac{(w-C_g-eT)beN+eT(atS-b(w+c_z)+beN)}{2tS^2}-(k-\frac{be^2NT}{tS^2})H$$

$$\frac{\partial^2 \prod(H \quad w)}{\partial H^2}=-(k-\frac{be^2NT}{tS^2})<0$$

Since $\frac{\partial^2 \prod(H \quad w)}{\partial w^2}<0$ and $\frac{\partial^2 \prod(H \quad w)}{\partial H^2}<0$, the profit function $\prod_g(H \quad w)$ of the photovoltaic system supplier is a concave function related to the wholesale price w and innovation level H of the product, taking its maximum value when the first-order derivative function is zero. Therefore, for $\frac{\partial \prod(H \quad w)}{\partial w}=0$ and $\frac{\partial \prod(H \quad w)}{\partial H}=0$, the optimal wholesale price w^* and the optimal innovation level H^* of photovoltaic system suppliers in this situation can be obtained, respectively:

$$w^*=\begin{Bmatrix} \frac{(C_g-C_z+eN+eT)b+atS}{2b}+\frac{(eN-eT)}{2} \\ \frac{(eN+eT)(atS-bC_g-bC_z)+((eN)^2-(eT)^2)b+4be^2NT}{4tS^2k-b(eN+eT)^2} \end{Bmatrix}$$

$$H^*=\frac{(eN+eT)(atS-bC_g-bC_z)+((eN)^2-(eT)^2)b+4be^2NT}{4tS^2k-b(eN+eT)^2}$$

By incorporating the optimal wholesale price w^* into Eq. (3), the optimal product price p^* for photovoltaic power plant enterprises can be obtained as:

$$p^*=\begin{Bmatrix} \frac{(C_g+C_z-eN+eT)b+3atS}{4btS}-\frac{(eN+eT)}{4tS} \\ \frac{(eN+eT)(atS-bC_g-bC_z)+((eN)^2-(eT)^2)b+4be^2NT}{4tS^2k-b(eN+eT)^2} \end{Bmatrix}$$

Based on the obtained optimal wholesale price w^* of photovoltaic system suppliers and the optimal product price p^* of photovoltaic power plant enterprises, the optimal profits of photovoltaic system suppliers and photovoltaic power plant enterprises can be obtained by introducing Eq. (1) and Eq. (2), which are:

$$\prod{}^*_g(H \quad w)=\begin{Bmatrix} \begin{bmatrix} (atS-(C_g+C_z-eN+eT)b+b(eN+eT)((eN+eT)(atS-bC_g-bC_z)+ \\ ((eN)^2-(eT)^2)b+4be^2NT)/\left[4tS^2k-b(eN+eT)^2\right])^2 \end{bmatrix}/8btS^2 \\ -\frac{1}{2}k(\frac{(eN+eT)(atS-bC_g-bC_z)+((eN)^2-(eT)^2)b+4be^2NT}{4tS^2k-b(eN+eT)^2})^2 \end{Bmatrix}$$

$$\prod{}^*_z(H \quad p)=\begin{Bmatrix} (atS-(C_g+C_z-eN+eT)b+b(eN+eT)((eN+eT)(atS-bC_g-bC_z) \\ +((eN)^2-(eT)^2)b+4be^2NT)/(4tS^2k-b(eN+eT)^2))^2/16btS^2 \end{Bmatrix}$$

So, the overall optimal profit of the entire photovoltaic industry chain system under decentralized decision-making is:

$$\prod{}^*_g(H \quad w)=\begin{Bmatrix} \begin{bmatrix} (3atS-(C_g+C_z-eN+eT)b+b(eN+eT)((eN+eT)(atS-bC_g-bC_z)+ \\ ((eN)^2-(eT)^2)b+4be^2NT)/\left[16tS^2k-b(eN+eT)^2\right])^2 \end{bmatrix}/8btS^2 \\ -\frac{1}{2}k(\frac{(eN+eT)(atS-bC_g-bC_z)+((eN)^2-(eT)^2)b+4be^2NT}{4tS^2k-b(eN+eT)^2})^2 \end{Bmatrix}$$

Property 1: According to the optimal product price p^*, the optimal sales price of photovoltaic power plant enterprises increases with their own costs and the cost of photovoltaic system suppliers.

Property 2: According to the optimal wholesale price w^* of the product, the wholesale price of photovoltaic system suppliers increases with the increase of their production costs, as well as with the improvement of the lifespan and power generation efficiency of individual photovoltaic systems.

Property 3: According to the optimal innovation level H^*, the optimal innovation level of photovoltaic system suppliers is influenced by the carbon emission factors of photovoltaic system manufacturing. The more carbon emissions, the higher the carbon emission cost, and the lower the innovation level.

Property 4: According to the optimal profit function ($\prod^*_g(H \quad w)$, $\prod^*_z(H \quad p)$) of photovoltaic system suppliers and photovoltaic power plant enterprises, as well as the overall profit function $\prod^*(H \quad p)$ of the photovoltaic industry chain, it can be seen that the profits of photovoltaic system suppliers and photovoltaic power plant enterprises are both increasing functions of the lifespan of the photovoltaic system and decreasing functions of various costs. But the difference is that for photovoltaic system suppliers, the costs arising from technological innovation will reduce the profits of photovoltaic system suppliers but will increase the profits of photovoltaic power stations due to the sale of carbon quotas.

3.3 Carbon Quota Sharing Contract Model

In the context of decentralized decision-making, the existence of double marginal effects causes photovoltaic system suppliers to neglect the improvement of photovoltaic silicon wafer innovation level to achieve high profits and low innovation costs. In order to reduce the cost of photovoltaic silicon wafers and improve the photoelectric conversion rate and achieve the overall technological development and progress of photovoltaic systems, photovoltaic power station enterprises can share some benefits to compensate for the innovation costs of photovoltaic system suppliers, which may effectively promote the improvement of photovoltaic system innovation level. There are many ways to share benefits, and research on collaborative decision-making in the relevant supply chain, such as innovation cost allocation and revenue sharing contracts, has yielded fruitful results. This article will not repeat the research here. Based solely on the carbon quota trading policy, consider the impact of carbon quota sharing contracts on the decentralized decision-making of the photovoltaic system industry chain.

Although carbon quota sharing contracts, cost sharing contracts, and revenue sharing contracts are all benefit contracts, they are different from pre contract or post contract, and carbon quota sharing is more like industrial integration and carbon emission methods. As is well known, in the entire photovoltaic system industry chain, except for photovoltaic power plant enterprises, all other chain entities are carbon emitting giants. Faced with high carbon emission costs, the increase in carbon emission costs invisibly weakens the cost share of enterprises for technological innovation. If the photovoltaic system industry chain is integrated for emissions, that is, photovoltaic power station enterprises are willing to share some carbon quotas with photovoltaic system suppliers in order to encourage innovation at the source of photovoltaic systems, achieve carbon reduction in photovoltaic system manufacturing, and disruptive innovation in photovoltaic system photovoltaic technology. This will enable photovoltaic system suppliers to no longer consider carbon emission costs, thereby increasing funding for technological innovation.

Under the carbon quota sharing contract, this article assumes that photovoltaic power plant enterprises will share a portion of their carbon emissions quota with photovoltaic system suppliers, with a sharing ratio of θ. So, the proportion of carbon emissions borne by photovoltaic power station enterprises to photovoltaic system suppliers is θ, while the proportion of carbon emissions borne by photovoltaic system suppliers is $1-\theta$. Therefore, in this case, the profit functions of photovoltaic system suppliers and photovoltaic power plant enterprises are:

$$\prod_g(H \quad w) = (w - C_g - e(1-H)T + e(1+H)\theta T)\frac{(a-bp)}{S} - \frac{1}{2}kH^2 \tag{5}$$

$$\prod_z(H \quad p) = (ptS - w - C_z + e(1+H)N - e(1-H)\theta T)\frac{(a-bp)}{S} \tag{6}$$

This article still uses the reverse induction method to solve the optimal strategy combination.

Firstly, based on the profit function $\prod_z(H \quad p)$ of the photovoltaic power plant enterprise, let $\frac{\partial \prod(H \quad p)}{\partial p} = 0$ be the optimal product price p^* of the photovoltaic power plant enterprise in this situation as follows:

$$p^* = \frac{at + b(\frac{w + C_z - e(1+H)N + e(1-H)\theta T}{S})}{2bt} \tag{7}$$

By applying Eq. (7) into Eq. (5), it can be concluded that the profit function of the photovoltaic system supplier is:

$$\prod_g(H \quad w)=\left\{\begin{matrix}(w-C_g-e(1-H)T+e(1+H)\theta T)\\ \dfrac{at-b(\dfrac{w+C_z-e(1+H)N+e(1-H)\theta T}{S})}{2tS}-\dfrac{1}{2}kH^2\end{matrix}\right\} \tag{8}$$

However, according to Eq. (8), the profit function $\prod_g(H \quad w)$ of the photovoltaic system supplier can be obtained by taking $\dfrac{\partial\prod(H \quad w)}{\partial w}=0$ and $\dfrac{\partial\prod(H \quad w)}{\partial H}=0$, respectively, to obtain the optimal wholesale price w^* and the optimal innovation level H^* of the photovoltaic system supplier in this situation:

$$w^*=\left\{\begin{matrix}\dfrac{(C_g-C_z+eN+eT-2e\theta T)b+atS}{2b}+\\ \dfrac{(eN-eT)}{2}\dfrac{(eN+eT+2e\theta T)(atS-bC_g-bC_z+beN-beT)}{4tS^2k-4b(eN+e\theta T)(eT+e\theta T)-b(eN-eT)^2}\end{matrix}\right\}$$

$$H^*=\frac{(eN+eT+2e\theta T)(atS-bC_g-bC_z+beN-beT)}{4tS^2k-4b(eN+e\theta T)(eT+e\theta T)-b(eN-eT)^2}$$

By incorporating the optimal wholesale price w^* into Eq. (7), the optimal product price p^* for photovoltaic power plant enterprises can be obtained as:

$$p^*=\left\{\begin{matrix}\dfrac{(C_g+C_z-eN+eT)b+3atS}{4btS}-\dfrac{(eN+eT+2e\theta T)}{4tS}\\ \dfrac{(eN+eT+2e\theta T)(atS-bC_g-bC_z+beN-beT)}{4tS^2k-4b(eN+e\theta T)(eT+e\theta T)-b(eN-eT)^2}\end{matrix}\right\}$$

Based on the obtained optimal wholesale price w^* of photovoltaic system suppliers and the optimal product price p^* of photovoltaic power plant enterprises, the optimal profits of photovoltaic system suppliers and photovoltaic power plant enterprises can be obtained by introducing Eq. (5) and Eq. (6), respectively:

$$\prod{}^*_g(H \quad w)=\left\{\begin{matrix}\left[\begin{matrix}(atS-(C_g+C_z-eN+eT)b+b(eN+eT+2e\theta T)\\ \dfrac{(eN+eT)(atS-bC_g-bC_z)+((eN)^2-(eT)^2)b+4be^2NT}{4tS^2k-b(eN+eT)^2})^2\end{matrix}\right]/8btS^2\\ -\dfrac{1}{2}k(\dfrac{(eN+eT)(atS-bC_g-bC_z)+((eN)^2-(eT)^2)b+4be^2NT}{4tS^2k-b(eN+eT)^2})^2\end{matrix}\right\}$$

$$\prod{}^*_z(H \quad p)=\left\{\left[\begin{matrix}(atS-(C_g+C_z-eN+eT)b+b(eN+eT+2e\theta T)\\ \dfrac{(eN+eT)(atS-bC_g-bC_z)+((eN)^2-(eT)^2)b+4be^2NT}{4tS^2k-b(eN+eT)^2})^2/16btS^2\end{matrix}\right]\right\}$$

So, considering the carbon quota sharing contract, the overall optimal profit of the entire photovoltaic industry chain system is:

$$\prod{}^*_g(H \quad w)=\left\{\begin{matrix}\left[\begin{matrix}(3atS-(C_g+C_z-eN+eT)b+b(eN+eT+2e\theta T)\\ \dfrac{(eN+eT)(atS-bC_g-bC_z)+((eN)^2-(eT)^2)b+4be^2NT}{4tS^2k-b(eN+eT)^2})^2\end{matrix}\right]/16btS^2\\ -\dfrac{1}{2}k(\dfrac{(eN+eT)(atS-bC_g-bC_z)+((eN)^2-(eT)^2)b+4be^2NT}{4tS^2k-b(eN+eT)^2})^2\end{matrix}\right\}$$

Property 5: According to the optimal product price p^*, optimal product wholesale price w^*, and optimal innovation level, the optimal sales price of photovoltaic power station enterprises, wholesale price of photovoltaic system suppliers, and optimal innovation level are basically consistent with properties 1, 2, and 3.

4. Empirical Analysis

Based on the "Report on the Current Status and Future Trends of Carbon Pricing Mechanism Development" released by the World Bank in 2023, the development data of the photovoltaic industry from 2022 to 2023 prepared by the China Photovoltaic Industry Association, and relevant data from various securities research institutes, global cost data and carbon data related to the photovoltaic industry were analyzed and organized (with 2023 being the predicted data in each report). The detailed data table is shown in Table 1.

Table 1
Global Photovoltaic Industry Cost Data and Carbon Data from 2021 to 2023

parameter	2021	2022	2023e
Photovoltaic system cost（yuan/w）	1.9	1.43	1.13
Cost of photovoltaic power plants（yuan/w）	4.15	3.74	3.42
Market installed capacity（GW）	170	230	258
Carbon quota trading price（USD/t）	49.78	80	95

According to the research report on the development of the photovoltaic industry, the power of each photovoltaic system is approximately 24W, and its lifespan is about 30 years. Based on this, the cost of each photovoltaic system and the cost data of each photovoltaic system in the photovoltaic power plant are calculated; Secondly, theoretically, 1MW of photovoltaic energy can generate 1.896 million kilowatt hours of electricity per year. Considering losses, this article sets 1MW of photovoltaic energy to generate 1.5 million kilowatt hours of electricity per year, totaling 36 kilowatt hours per photovoltaic system; According to reports on the global carbon market, producing 200GW of photovoltaic systems requires about 10.5 million tons of carbon emissions, while 1MW photovoltaic power plants can reduce carbon emissions by about 1200 tons per year. It can be calculated that the carbon emissions per photovoltaic system produced by photovoltaic system suppliers are 0.00126 tons, and each photovoltaic system in photovoltaic power plants can reduce emissions by about 0.0288 tons. Meanwhile, due to the large demand and amplitude in the international electricity market, this article stipulates a price demand elasticity of 150000000 and an innovation cost coefficient of 10000000000. From this, the compiled data and carbon data related to the global photovoltaic industry chain from 2021 to 2023 can be obtained, as shown in Table 2.

Table 2
Compiled Global Photovoltaic Industry Chain Related Data and Carbon Data for 2021-2023

parameter	2021	2022	2023e
Photovoltaic system cost（USD/cover）	6.61	4.97	3.93
Cost of photovoltaic power plants（USD/cover）	14.43	13.01	11.9
Market installed capacity（kwh）	2.55E+11	3.45E+11	3.87E+11
Carbon quota trading price（USD/t）	49.78	80	95

pour：S=36；b= 1.50E+10；t=30；k= 1.00E+10；N=0.0288；T=0.00126。

Based on the data in Table 2, the optimal parameter values and profit values of the photovoltaic industry chain can be calculated for decentralized decision-making situations. The results are shown in Table 3.

Table 3
Optimal Parameter Values and Optimal Profit Values in the Case of Decentralized Decision Making (USD)

parameter	years		
	2021	2022	2023e
w^*	915.0159	1239.8180	1391.6474
p^*	1.2795	1.7283	1.9376
H^*	0.2637	0.5746	0.7661
$\prod^*_g(H \quad w)$	5.9496E+12	1.0943E+13	1.3794E+13
$\prod^*_z(H \quad p)$	2.9512E+12	5.4078E+12	6.8026E+12
$\prod^*(H \quad p)$	8.9009E+12	1.6350E+13	2.0597E+13

In the decision-making situation of considering carbon quota sharing contracts, this article selects three types of carbon quota sharing coefficients for calculation and sensitivity analysis to compare the impact of carbon quota sharing coefficients on the decision-making results. The calculation results are shown in Table 4.

Table 4
Optimal Parameter Values and Optimal Profit Values under Carbon Quota Sharing Contracts (USD)

θ	**parameter**	**years**		
		2021	**2022**	2023e
0.1	w^*	915.0118	1239.8146	1391.6452
	p^*	1.2795	1.7283	1.9375
	H^*	0.2669	0.5806	0.7736
	$\Pi^*_g(H \quad w)$	5.9496E+12	1.0943E+13	1.3795E+13
	$\Pi^*_z(H \quad p)$	2.9750E+12	5.4722E+12	6.8988E+12
	$\Pi^*(H \quad p)$	8.9246E+12	1.6415E+13	2.0693E+13
0.5	w^*	914.9928	1239.7955	1391.6310
	p^*	1.2795	1.7283	1.9375
	H^*	0.2758	0.5999	0.7993
	$\Pi^*_g(H \quad w)$	5.9497E+12	1.0943E+13	1.3795E+13
	$\Pi^*_z(H \quad p)$	2.9750E+12	5.4724E+12	6.8992E+12
	$\Pi^*(H \quad p)$	8.9248E+12	1.6415E+13	2.0694E+13
0.9	w^*	914.9738	1239.7765	1391.6168
	p^*	1.2794	1.7283	1.9375
	H^*	0.2847	0.6193	0.8250
	$\Pi^*_g(H \quad w)$	5.9498E+12	1.0943E+13	1.3796E+13
	$\Pi^*_z(H \quad p)$	2.9751E+12	5.4726E+12	6.8996E+12
	$\Pi^*(H \quad p)$	8.9249E+12	1.6416E+13	2.0695E+13

Comparing the results of Table 3 and Table 4, it can be found that when considering carbon quota sharing contracts for collaborative innovation in the photovoltaic industry chain, the degree of technological innovation, individual benefits, and overall benefits of the industry chain will all be improved.

Under the carbon quota sharing contract, photovoltaic power station enterprises can significantly enhance the technological innovation enthusiasm of photovoltaic system suppliers by sharing a portion of carbon quotas with them, thereby improving the level of technological innovation, and achieving the effect of carbon reduction and emission reduction. Secondly, through sensitivity analysis of the carbon quota sharing coefficient, it can also be found that the higher the proportion of carbon quotas shared by photovoltaic power station enterprises, the higher the level of technological innovation of photovoltaic system suppliers.

Under the carbon quota sharing contract, the wholesale prices of the photovoltaic system supply chain and the electricity prices of photovoltaic power stations have decreased, indicating that the carbon sharing mechanism can effectively reduce the electricity price level by promoting technological innovation of photovoltaic system suppliers, enabling global photovoltaic power generation to achieve parity online.

The profits of photovoltaic system suppliers and photovoltaic power plant enterprises under carbon quota sharing contracts are significantly higher than those under decentralized decision-making. It can be found that the profits of photovoltaic system suppliers and photovoltaic power plant enterprises both increase with the increase of carbon quota sharing coefficient, indicating that achieving carbon alliances and carbon clusters in the photovoltaic industry can better achieve industrial value.

5. Conclusion

This article has studied the impact of carbon quota sharing contracts on collaborative decision-making in the photovoltaic industry chain based on carbon quota trading policies. By establishing a profit model between photovoltaic system suppliers and photovoltaic power stations under decentralized and carbon quota sharing contracts, the optimal parameter solution and profit function in the model were obtained using differential game method, and empirical analysis was conducted. Research findings:

(1) The carbon quota sharing contract can effectively promote green innovation of the photovoltaic industry chain entities. Considering the tendency of carbon quota sharing contracts, the willingness of photovoltaic system suppliers to green innovation is more obvious, and the degree of technological innovation is higher. Moreover, the degree of technological innovation of photovoltaic system suppliers increases with the increase of carbon quota sharing coefficient.

(2) In the case of carbon quota sharing contracts, the pricing between photovoltaic system suppliers and photovoltaic power plant enterprises is lower. Under carbon quota sharing, photovoltaic power station enterprises actually transfer some of their carbon trading profits to photovoltaic system suppliers to balance their carbon emission costs and tilt the innovation costs of photovoltaic system suppliers. The progress of technological innovation gradually reduces the cost of photovoltaic power, reducing the grid electricity price of photovoltaic power, which is conducive to promoting the fair grid access of photovoltaic power.

(3) Under the carbon quota sharing contract, the profits and overall profits of each entity in the photovoltaic industry chain are better than the optimal profits under decentralized conditions. Under the consideration of carbon quota sharing contracts, the profits of photovoltaic system suppliers and photovoltaic power plant enterprises are gradually increasing, and the optimal profits are influenced by the carbon quota sharing coefficient, which increases with the increase of the sharing coefficient.

Therefore, based on the three findings of this article, the photovoltaic industry chain or other carbon emitting industries can consider establishing carbon alliances and carbon cluster mechanisms when making decisions, which may better solve the balance problem between carbon emission costs and innovation costs for carbon emitting large enterprises, enabling them to have sufficient funds for green innovation and achieve technological progress in the industry chain. Secondly, governments around the world should actively establish carbon quota trading policies, attempt to promote the implementation and reform of carbon sharing policies, and implement carbon sharing guarantee systems.

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