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Research on collaborative decision making of China's photovoltaic supply chain based on competition policy

Jun Hu[a,b,c]* and Jie Wu[b]

[a]*Business School of Huaiyin Normal University, 223000 Huai'an, Jiangsu, China*
[b]*School of Economics and Management, Jiangsu University of Science and Technology, Zhenjiang, Jiangsu 212001, China*
[c]*Zhenjiang Jinzhou Software Co., Ltd., Zhenjiang 212001, Jiangsu, China*

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A B S T R A C T

Introduce government competition policies and technological innovation efforts into the profit game model of the photovoltaic industry supply chain, establish two different supply chain profit models, and study the impact of government competition policies and manufacturers' technological innovation efforts on the profits of each manufacturer and the overall profit of the supply chain. Construct profit models in both competitive and cooperative situations, and empirically analyze the impact of government competition policies and manufacturers' technological innovation efforts on the optimal supply chain profits in both competitive and cooperative situations. Research has shown that: (1) government competition policies are conducive to promoting an increase in manufacturers' profits; (2) The increase in technological innovation efforts can quickly increase manufacturers' profits; (3) Compared to the cooperation situation, the profit of each manufacturer and the total profit of the entire supply chain are higher in the competitive situation.

1. Introduction

With the convening of the 28th Conference of the Parties to the United Nations Framework Convention on Climate Change, international attention has become increasingly focused on carbon emissions. How to achieve carbon reduction and zero emissions is an issue that every country in the world should pay attention to. From an energy perspective, reducing the application of fossil fuels and gradually transitioning to clean energy is the core of achieving the International Carbon Convention. Photovoltaic energy, as one of the cleanest energy sources, has received significant attention from various countries. With the development of the photovoltaic industry, countries have basically completed the protection transition of the photovoltaic industry, that is, they have moved from industrial protection policies to industrial competition policies. Under the guidance of competition policy, how the photovoltaic industry entities make decisions to achieve optimal profits is a practical problem that the photovoltaic industry faces. Therefore, under the dual constraints of upstream silicon manufacturers and the photovoltaic competitive market in the photovoltaic industry, it is of practical significance to study how the photovoltaic industry entities (photovoltaic silicon wafer manufacturers, photovoltaic system manufacturers) make collaborative decisions to achieve optimal profits for each entity or the overall profit.

Numerous international scholars have conducted research on collaborative innovation decision-making in the industrial chain from multiple industries and perspectives. From the perspective of supply chain competition, some scholars have studied the equipment manufacturing industry (Tan et al., 2023; Khompatraporn & Somboonwiwat, 2017) and environmental industry (Arshed, 2022; Bányai & Kaczmar, 2021; Aćimović et al., 2020). The competition models of supply chains have been studied in industries such as the healthcare industry (Singh & Parida, 2022), e-commerce industry (Febransyah & Camelia Goni, 2022), agriculture industry (Yan et al., 2019), and information technology industry (Nowicka, 2019). From the perspective of supply chain cooperation, some scholars have studied supply chain cooperation models from industries such as e-commerce

* Corresponding author
E-mail: 1434120126@qq.com (J. Hu)
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(Wang et al., 2023; Su et al., 2022; Wang et al., 2021) and environmental industry (Jiang et al., 2021). Secondly, some scholars have studied model reconstruction from the perspective of supply chain competition coordination methods (Narayanan et al., 2005; Iyer, 1998; Verma & Singhal, 2018; Verma et al., 2018), and resource return rate from the perspective of supply chain cooperation performance (Woo & Suresh, 2022; Momeni & Bagheri, 2022; Chen & Su, 2021; Zhou & Zhu, 2021).

Few scholars have conducted research on supply chain competition and cooperation in the photovoltaic industry from the perspective of the photovoltaic industry. Only some scholars have studied competition and cooperation in the photovoltaic industry from the perspectives of competition and cooperation in the photovoltaic industry (Chen et al., 2011; Hu & Wu, 2023; Hu et al., 2020), carbon contract, etc. (Zhou & Lund, 2023; He et al., 2020; Hu., 2023). Subsidy strategies of a two-level industrial chain composed of suppliers and manufacturers. Considering the limited rationality of the supply chain entities in the photovoltaic industry, many experts and scholars use differential game models to study the competition and cooperation issues in the supply chain. Others performed studies on cooperation in the supply chain by constructing differential game models in the forms of performance, incentives, and contracts (Xu et al., 2022; Liu et al., 2022; Zhu, G., 2021). The differential game model can be used to study the competition and cooperation problems in the supply chain.

Previous studies by scholars and experts have provided useful references for this article to study the competition and cooperation relationship of the photovoltaic industry chain under the promotion of government competition policies. In the past, scholars only studied the competition and cooperation relationships between various industrial chains from a theoretical perspective, and there was little research on the industrial chain issues of the photovoltaic industry. They also ignored the impact of government competition policies on the relationships between manufacturers in the industrial chain, and there was little research on whether manufacturers' technological innovation can drive the optimal profits of manufacturers at all levels. Therefore, based on relevant research, this article introduces government competition policy and technological innovation effort level factors into the competition and cooperation model, introduces government competition rewards as an interpretation of government competition policy, and introduces technological innovation effort level as the effort made by manufacturers to achieve technological innovation; By linking government competition rewards to the level of technological innovation efforts, we focus on the optimal profit situation of manufacturers at all levels under different government competition rewards and different levels of technological innovation efforts of manufacturers year by year. This article establishes a game model on the wholesale price of silicon wafers and the sales volume of photovoltaic systems, analyzes the dynamic impact of competition policy and technological innovation on two level manufacturers in different situations, obtains the optimal profit function of each level of manufacturer, and empirically analyzes the impact of competition policy and technological innovation factors on the optimal and overall industry chain total profit of each level of manufacturer in both competition and cooperation situations.

2. Model Construction

2.1 Assumptions

This article establishes a two-level photovoltaic silicon industry chain consisting of silicon manufacturer G and n photovoltaic system manufacturers F. It is known that photovoltaic system manufacturers need to consume k silicon wafers to produce a photovoltaic system. Based on the actual situation of manufacturers in the industrial chain, the following assumptions are made:

Assumption 1: Level of technological innovation efforts. This article introduces the level of technological innovation efforts to measure the degree of technological innovation among manufacturers at all levels under the promotion of government competition policies. Use R_g to represent the level of technological innovation efforts of silicon manufacturers under competition policies; Use R_{fi} to represent the level of technological innovation efforts of the i photovoltaic system manufacturer under competition policies. Among them, $0 \le R_g \le 1$ and $0 \le R_{fi} \le 1$.

Assumption 2: Cost of technological innovation. The study uses C_{Rg} to represent the cost of technological innovation by silicon manufacturers; the study also uses C_{Rfi} to represent the cost of technological innovation by the i photovoltaic system manufacturer. This article introduces the cost model proposed (Zhang et al., 2015), and constructs an innovation cost function for each manufacturer as follows: $C_{Rg} = \frac{1}{2} hR_g$, $C_{Rfi} = \frac{1}{2} hR_{fi}$, where h is the innovation cost coefficient.

Assumption 3: Production cost. Manufacturers at all levels need to pay a certain cost when producing products, where C_g represents the cost of silicon wafers produced by silicon manufacturers; the study uses C_{fi} to represent the non-raw material costs (such as processing costs, etc.) incurred by the i photovoltaic system manufacturer when producing the photovoltaic system.

Assumption 4: Product Price. Use W to represent the wholesale price of silicon wafers sold by silicon manufacturers; the study uses P to represent the price at which a photovoltaic system manufacturer sells a photovoltaic system. Regulations

$W \geq C_g + R_g$, $P \geq kW + C_{fi} + R_{fi}$.

Assumption 5: Market size and sales volume. There is a maximum capacity in the market, where α represents the market size of photovoltaic systems. Due to the instability of the market, β represents the elasticity coefficient of demand price. Use S_i to represent the number of i photovoltaic system manufacturers before selling technological innovation, and use q_i to represent the number of i photovoltaic system manufacturers after selling technological innovation. Due to the influence of technology on the quantity of products sold by photovoltaic system manufacturers, the higher the level of technological innovation, the greater the sales volume. Therefore, $q_i = \left(1 + R_{fi}\right) S_i$ represents the actual sales volume after technological innovation. Use Q to represent the total sales volume of all photovoltaic systems in the market, $Q = \sum_{i=1}^{n} q_i$.

Assumption 6: Government competition rewards. According to competition policies, the government will provide competition rewards to relevant manufacturers. The higher the level of innovation efforts and sales of manufacturers, the greater the government's reward intensity. We use J_g to represent the competitive rewards given by the government to silicon manufacturers and use J_f to represent the competitive rewards given by the government to photovoltaic system manufacturers. This article assumes that the government invests technological innovation rewards B_g in the technological innovation behavior of silicon manufacturers. For all photovoltaic system manufacturers planning to invest competitive rewards B_f , the competitive reward that silicon manufacturers can receive is $J_g = \mathrm{R}_g B_g$, and the competitive reward that the i photovoltaic system manufacturer can receive is $J_{fi} = \frac{q_i}{\alpha} \mathrm{B}_f$.

Based on the above assumptions, the market sales volume is influenced by the elasticity of demand and price. The total sales volume of all photovoltaic system manufacturers in the market is $Q = \alpha - \beta P$, then $P = \frac{1}{\beta}\alpha - \frac{1}{\beta}\mathrm{Q}$. If $Q = \sum_{i=1}^{n} q_i$ is known, then $P = \frac{1}{\beta}\alpha - \frac{1}{\beta}\sum_{i=1}^{n} q_i$; The total sales volume of the silicon manufacturer is $kQ = k\sum_{i=1}^{n} q_i$, therefore, the expected profit between the silicon manufacturer and the i photovoltaic system manufacturer can be calculated as:

$$\prod{}_G\left(W \quad q_i\right) = (W - C_g)kQ - C_{Rg} + J_g = (W - C_g)k\sum_{i=1}^{n} q_i - \frac{1}{2}hR_g + \mathrm{R}_g B_g$$

$$\prod{}_{Fi}\left(W \quad q_i\right) = (P - kW - C_{fi})(q_i) - C_{Rfi} + J_{fi} = (\frac{1}{\beta}\alpha - \frac{1}{\beta}\sum_{i=1}^{n} q_i - kW - C_{fi})q_i - \frac{1}{2}hR_{fi} + \frac{q_i}{\alpha}B_f$$

2.2 Model Solution and Analysis

2.2.1 Competition Analysis in the Industrial Chain

For the competition situation in the industrial chain, driven by government competition policies, there will be sales and profit competition among photovoltaic system manufacturers. By solving the optimal profit of each manufacturer, the competition situation among photovoltaic system manufacturers is analyzed, and the impact of various factors on the optimal profit of manufacturers in the competition situation is analyzed. The first and second derivative functions of the expected profit of the i photovoltaic system manufacturer regarding q_i are:

$$\frac{\partial \prod{}_{Fi}\left(W \quad q_i\right)}{\partial q_i} = (\frac{1}{\beta}\alpha - \frac{1}{\beta}\sum_{i=1}^{n} q_i - kW - C_{fi}) - \frac{1}{\beta}q_i + \frac{1}{\alpha}B_f$$

$$\frac{\partial^2 \prod{}_{Fi}\left(W \quad q_i\right)}{\partial q_i^{\,2}} = -\frac{2}{\beta} \prec 0$$

Order $\frac{\partial \prod{}_{Fi}\left(W \quad q_i\right)}{\partial q_i} = 0$; The reaction function can be obtained: $q_i = \dfrac{(\frac{1}{\beta}\alpha - \frac{1}{\beta}\sum_{l \neq i} q_l - kW - C_{fi}) + \frac{1}{\alpha}B_f}{\frac{2}{\beta}}$.

Similarly, it can be obtained that: $q_j = \dfrac{(\frac{1}{\beta}\alpha - \frac{1}{\beta}\sum_{l \neq j} q_l - kW - C_{fj}) + \frac{1}{\alpha}B_f}{\frac{2}{\beta}}$.

Order $q_i - q_j$, it can be obtained that:

$$\sum_{l \neq i} q_l = q_1 + q_2 + \cdots + q_{i-1} + q_{i+1} + \cdots + q_n = (n-1) q_i - \frac{\sum_{j \neq i} C_{fj} - (n-1) C_{fi}}{\frac{1}{\beta}}$$

From the above equation, it can be obtained: $q^*_i(W) = \dfrac{\frac{1}{\beta}\alpha + \sum_{j \neq i} C_{fj} - nC_{fi} - kW + \frac{1}{\alpha} B_f}{\frac{1}{\beta}(n+1)}$, then

$$\sum_{i=1}^{n} q^*_i(W) = \frac{\sum_{i=1}^{n} \left(\frac{1}{\beta}\alpha - nC_{fi} - kW + \frac{1}{\alpha} B_f + \sum_{j \neq i} C_{fj} \right)}{\frac{1}{\beta}(n+1)} = \frac{n\left(\frac{1}{\beta}\alpha - kW + \frac{1}{\alpha} B_f \right) - \sum_{i=1}^{n} C_{fi}}{\frac{1}{\beta}(n+1)}$$

Substituting $\sum_{i=1}^{n} q^*_i(W)$ into the expected profit function of silicon manufacturers yields:

$$\prod_G \left(W \quad q^*_i(W) \right) = (W - C_g)kQ - C_{Rg} + J_g = (W - C_g)k \left(\frac{n\left(\frac{1}{\beta}\alpha - kW + \frac{1}{\alpha} B_f \right) - \sum_{i=1}^{n} C_{fi}}{\frac{1}{\beta}(n+1)} \right) - \frac{1}{2} hR_g + \mathrm{R}_g B_g$$

The first and second derivative functions for solving the expected profit of silicon manufacturers are:

$$\frac{\partial \prod_G \left(W \quad q^*_i(W) \right)}{\partial W} = \frac{k}{\frac{1}{\beta}(n+1)} \left(n\left(\frac{1}{\beta}\alpha - kW + \frac{1}{\alpha} B_f \right) - \sum_{i=1}^{n} C_{fi} - nk(W - C_g) \right)$$

$$\frac{\partial^2 \prod_G \left(W \quad q^*_i(W) \right)}{\partial W^2} = \frac{-2nk^2}{\frac{1}{\beta}(n+1)} \prec 0$$

By using the first-order derivative function $\dfrac{\partial \prod_G \left(W \quad q^*_i(W) \right)}{\partial W} = 0$ of silicon manufacturers, the optimal wholesale price of silicon wafers can be obtained as:

$$W^* = \frac{n\left(\frac{1}{\beta}\alpha + \frac{1}{\alpha} B_f + kC_g \right) - \sum_{i=1}^{n} C_{fi}}{2nk}$$

By substituting W^* into $q^*_i(W)$, the optimal sales volume for the i photovoltaic system manufacturer can be obtained as:

$$q^*_i(W) = \beta \left(\frac{\frac{1}{\beta}\alpha + \frac{1}{\alpha} B_f - kC_g}{2(n+1)} + \frac{2n+1}{2n(n+1)} \sum_{i=1}^{n} C_{fi} - C_{fi} \right)$$

Therefore, the optimal profit between the silicon manufacturer and the i photovoltaic system manufacturer is:

$$\prod_G \left(W^* \quad q^*_i \right) = \frac{1}{\frac{4}{\beta} n(n+1)} \left(n\left(\frac{1}{\beta}\alpha + \frac{1}{\alpha} B_f - kC_g \right) - \sum_{i=1}^{n} C_{fi} \right)^2 - \frac{1}{2} hR_g + \mathrm{R}_g B_g$$

$$\prod_{Fi} \left(W^* \quad q^*_i \right) = \beta \left(\frac{\frac{1}{\beta}\alpha + \frac{1}{\alpha} B_f - kC_g}{2(n+1)} + \frac{2n+1}{2n(n+1)} \sum_{i=1}^{n} C_{fi} - C_{fi} \right)^2 - \frac{1}{2} hR_{fi}$$

Property 1: It can be seen from W^* and $q^*_i(W)$ that under the government's competition policy, the optimal wholesale price of silicon manufacturers increases with the increase of silicon chip cost, decreases with the increase of marginal cost of photovoltaic system manufacturers, and increases with the increase of competition incentives given by the government to photovoltaic system manufacturers.

Property 2: shows from W^*, $q^*_i(W)$, and $q_i=(1+R_{fi})S_i$ that the optimal retail volume and optimal silicon wafer procurement volume of photovoltaic system manufacturers decrease with the increase of silicon wafer costs, increase with the increase of price elasticity coefficient, increase with the increase of competition rewards given by the government, and increase with the improvement of technological innovation efforts of photovoltaic system manufacturers.

Property 3: From the optimal profits of silicon manufacturers and the i photovoltaic system manufacturer, we can see that the higher the level of technological innovation efforts, the greater the manufacturer's optimal retail volume, the richer the government's competitive incentives, and the greater the optimal profits of silicon manufacturers and photovoltaic system manufacturers.

2.2.2 Analysis of Cooperation in the Industrial Chain

Industry chain cooperation refers to the cooperation between photovoltaic system manufacturers, which may lead to vicious competition due to the existence of certain competitive relationships among photovoltaic system manufacturers. This section establishes a cooperation model for various photovoltaic system manufacturers under a cooperative relationship, analyzes the optimal profits of all photovoltaic system manufacturers under the cooperative situation, and establishes the expected profits of silicon manufacturers and all photovoltaic system manufacturers as follows:

$$\prod{}_G(W \quad q_i) =(W-C_g)kQ-C_{Rg}+J_g=(W-C_g)k\sum_{i=1}^{n}q_i-\frac{1}{2}hR_g+\mathrm{R}_gB_g$$

$$\sum\prod{}_{Fi}(W \quad q_i) =\sum_{i=1}^{n}((P-kW-C_{fi})q_i-C_{Rfi}+J_{fi})=\sum_{i=1}^{n}((\frac{1}{\beta}\alpha-\frac{1}{\beta}\sum_{i=1}^{n}q_i-kW-C_{fi})q_i-\frac{1}{2}hR_{fi}+\frac{q_i}{\alpha}B_f)$$

The first derivative and second derivative of total revenue of all PV manufacturers are respectively:

$$\frac{\partial\sum\prod(W \quad q_i)}{\partial q_i}=\left(\frac{1}{\beta}\alpha-kW-C_{fi}+\frac{B_f}{\alpha}\right)-\frac{2}{\beta}\sum_{i=1}^{n}q_i$$

$$\frac{\partial^2\sum\prod(W \quad q_i)}{\partial {q_i}^2}=-\frac{2}{\beta}\prec 0$$

Let the first-order derivative function $\frac{\partial\sum\prod(W \quad q_i)}{\partial q_i}=0$, it can be obtained: $q_i=\dfrac{\frac{1}{\beta}\alpha-kW-C_{fi}+\frac{B_f}{\alpha}-\frac{2}{\beta}\sum_{l\neq i}q_l}{\frac{2}{\beta}}$.

Similarly, it can be obtained that: $q_j=\dfrac{\frac{1}{\beta}\alpha-kW-C_{fj}+\frac{B_f}{\alpha}-\frac{2}{\beta}\sum_{l\neq j}q_l}{\frac{2}{\beta}}$, $j\neq i$;

Order q_i-q_j, it can be obtained that: $C_{fj}=C_{fi}$, The optimal silicon wafer order quantity for the i photovoltaic system manufacturer is:

$$q_i^*=\frac{\frac{1}{\beta}\alpha-kW-C_{fi}+\frac{B_f}{\alpha}}{\frac{2}{\beta}n}, \quad \sum_{i=1}^{n}q_i^*=\frac{1}{\frac{2}{\beta}}\left(\frac{1}{\beta}\alpha-kW+\frac{B_f}{\alpha}-C_{fi}\right)$$

By incorporating the obtained silicon wafer orders from all photovoltaic system manufacturers into the profit function of the silicon manufacturer, the optimal expected profit for the silicon manufacturer can be obtained as:

$$\prod{}_G(W \quad q_i) =(W-C_g)k(\frac{1}{\frac{2}{\beta}}\left(\frac{1}{\beta}\alpha-kW+\frac{B_f}{\alpha}-C_{fi}\right))-\frac{1}{2}hR_g+\mathrm{R}_gB_g$$

The first derivative and second derivative of the total profit of silicon manufacturers are:

$$\frac{\partial\prod_G\left(W \quad q^*_i(W)\right)}{\partial W}=\frac{\partial((W-C_g)k(\frac{1}{\frac{2}{\beta}}\left(\frac{1}{\beta}\alpha-kW+\frac{B_f}{\alpha}-C_{fi}\right))-\frac{1}{2}hR_g+\mathrm{R}_gB_g)}{\partial W}=\frac{k}{\frac{2}{\beta}}\left(\left(\frac{1}{\beta}\alpha-kW+\frac{B_f}{\alpha}-C_{fi}\right)-k(W-C_g)\right)$$

$$\frac{\partial^2\prod_G\left(W \quad q^*_i(W)\right)}{\partial W^2}=\frac{-2k^2}{\frac{2}{\beta}}\prec 0$$

By using the first-order derivative function $\frac{\partial\prod_G\left(W \quad q^*_i(W)\right)}{\partial W}=0$ of silicon manufacturers, the optimal wholesale price of silicon wafers can be obtained as:

$$W^*=\frac{\frac{1}{\beta}\alpha+\frac{1}{\alpha}B_f+kC_g-C_{fi}}{2k}$$

By substituting W^* into $q^*_i(W)$, the optimal sales volume for the i photovoltaic system manufacturer can be obtained as:

$$q_i^*=\frac{\frac{1}{\beta}\alpha-kW-C_{fi}+\frac{B_f}{\alpha}}{\frac{2}{\beta}n}$$

$$q^*_i(W)=\beta\left(\frac{\frac{1}{\beta}\alpha+\frac{1}{\alpha}B_f-C_{fi}-kC_g}{4n}\right)$$

Then there are $\sum_{i=1}^{n}q^*_i\left(W^*\right)=\beta\left(\frac{\frac{1}{\beta}\alpha+\frac{1}{\alpha}B_f-C_{fi}-kC_g}{4}\right)$.

Therefore, the optimal profit for silicon manufacturers, the i photovoltaic system manufacturer, and the entire industry chain is:

$$\prod_G\left(W^* \quad q_i^*\right)=\frac{\beta}{8}\left(\frac{1}{\beta}\alpha+\frac{1}{\alpha}B_f-kC_g-C_{fi}\right)^2-\frac{1}{2}hR_g+\mathrm{R}_gB_g$$

$$\prod_{Fi}\left(W^* \quad q_i^*\right)=\frac{\beta}{16n}\left(\frac{1}{\beta}\alpha+\frac{1}{\alpha}B_f-kC_g-C_{fi}\right)^2-\frac{1}{2}hR_{fi}$$

$$\prod(W \quad q_i)=\prod_G(W \quad q_i)+\sum_{i=1}^{n}\prod_{Fi}(W \quad q_i)=\frac{3\beta}{16}\left(\frac{1}{\beta}\alpha+\frac{1}{\alpha}B_f-kC_g-C_{fi}\right)^2-\frac{1}{2}h\sum_{i=1}^{n}R_{fi}-\frac{1}{2}hR_g+\mathrm{R}_gB_g$$

Property 4: It can be seen from q_i^* that under the government's competition policy, the optimal sales volume and optimal silicon wafer purchase volume of the photovoltaic system will decrease with the increase of the wholesale price of silicon wafers, with the increase of the marginal cost of the photovoltaic system, with the increase of government competition incentives, and with the increase of the number of photovoltaic system suppliers.

Property 5: It can be seen from $\prod_G(W \quad q_i)$, $\prod_{Fi}(W \quad q_i)$ and $\prod(W \quad q_i)$ that the government competitive incentives increase with the increase of the cost of silicon chips and the marginal cost of photovoltaic systems decrease; At the same time, the profits of photovoltaic system manufacturers decrease as the number of manufacturers increases. The total profit of the entire industry chain increases with the increase of demand elasticity coefficient.

3. Empirical Analysis

Integrate relevant data from research reports on the development of China's photovoltaic industry, analysis reports on the photovoltaic and solar energy industry, and other internal reports. Through analysis and organization, the cost and scale data of China's photovoltaic industry from 2017 to 2023 were obtained, with some of the data being predicted. The data is shown in Table 1.

Table 1
Cost and Scale Data of China’s Photovoltaic Industry from 2017 to 2023

Project parameters	2017	2018	2019	2020	2021	2022	2023
Cost of polycrystalline silicon (yuan/W)	0.16	0.13	0.08	0.06	0.04	0.02	0.01
Non polycrystalline silicon cost (yuan/W)	0.85	0.77	0.69	0.52	0.43	0.32	0.22
Market size (GW)	75	85.7	93	141.2	196.08	265.28	346.88

This paper studies the photovoltaic system industry chain based on the construction of power stations. According to the research report on the development of China's photovoltaic industry, each photovoltaic system used for the construction of power stations needs 72 silicon wafers. The power of each photovoltaic system is about 24W, and the conversion rate is 19.2%, so each photovoltaic system produces about 4.608W of power. According to this, calculate the marginal cost and silicon wafer cost of each photovoltaic system; And this article stipulates that there is one silicon manufacturer and five photovoltaic system manufacturers. Based on the relative static analysis, assume that the marginal cost of the five photovoltaic system manufacturers is the average value and the average value+2,+4, - 2, - 4; Meanwhile, due to the significant demand in the photovoltaic system market, this article stipulates a price demand elasticity coefficient of 100; Silicon manufacturers and each photovoltaic system manufacturer have different levels of effort in technological innovation in the photovoltaic industry. The assumption in this article is that the enterprise's technological effort level is between 0-1, and the intermediate effort level is set to 0.5. As silicon manufacturers are in a non competitive state as a primary industry chain, the effort level of silicon manufacturers is set to 0.5, while photovoltaic system manufacturers are in competition in the same level industry chain, To reflect the impact of different levels of technological innovation efforts on the optimal profits of photovoltaic system manufacturers, it is set that the levels of technological innovation efforts of each photovoltaic system manufacturer are different, and fluctuate around the level of intermediate technological innovation efforts. The technological innovation efforts of other photovoltaic system manufacturers are 0.3, 0.4, 0.5, 0.6, 0.7, and the cost coefficient of technological innovation is set at 500; This article introduces government competition rewards as recognition of manufacturers' technological innovation efforts, and sets the maximum competition reward given by the government to silicon manufacturers to be 2 million yuan; The highest competitive reward given to photovoltaic system manufacturers has been increasing year by year, starting from 2017 with a reward of 10 million yuan and increasing by 500000 yuan year by year. Five photovoltaic system manufacturers account for 1% of the national photovoltaic system market. Based on this data, the relevant data required for this article is calculated as shown in Table 2 (both with two decimal places).

Table 2
Parameters of China's Photovoltaic Silicon Industry Chain from 2017 to 2023 (yuan, W)

Project parameters	2017	2018	2019	2020	2021	2022	2023
C_g	0.16	0.13	0.08	0.26	0.23	0.2	0.18
C_{f1}	278.01	251.47	224.93	168.53	138.67	102.17	68.99
C_{f2}	280.01	253.47	226.93	170.53	140.67	104.17	70.99
C_{f3}	282.01	255.47	228.93	172.53	142.67	106.17	72.99
C_{f4}	284.01	257.47	230.93	174.53	144.67	108.17	74.99
C_{f5}	286.01	259.47	232.93	176.53	146.67	110.17	76.99
α	2260561	2583068	2803096	4255883	5910012	7995756	10455247.
B_f	10000000	10500000	11000000	11500000	12000000	12500000	13000000

β=100 ; n=5 ; k=72 ; h=5000000 ; R_g=0.5 ; B_g=2000000 ; R_{f1}=0.3 ; R_{f2}=0.4 ; R_{f3}=0.5 ; R_{f4}=0.6 ; R_{f5}=0.7 .

3.1 Optimal Analysis of Industrial Chain in Competitive Situations

Based on the data in Table 2, the optimal parameter table for the polycrystalline silicon industry chain under competitive conditions can be calculated, as shown in Table 3. From the data in Table 3, from 2017 to 2023, the optimal silicon wafer procurement volume and optimal photovoltaic system sales volume of each manufacturer increased year by year. This is because the cost of photovoltaic system silicon wafers is gradually decreasing, and as the number of competitive awards awarded by the government increases year by year, the profits that manufacturers can earn are also increasing. The optimal wholesale price of silicon chips is negatively correlated with the marginal cost of photovoltaic systems.

The wholesale prices of silicon wafers have been increasing year by year. The profit of PV system manufacturers has increased year by year, mainly because the sales volume of PV system has increased year by year, but it has nothing to do with the competitive incentives given by the government and the marginal cost of PV system. The increase of government competitive incentives and the reduction of marginal cost of PV system assembly have increased the profits of manufacturers. At the same time, the profits of silicon manufacturers are also increasing year by year, and the cost of silicon is also decreasing year by year. The increase in wholesale prices is the main reason for the profit growth of silicon manufacturers.

Table 3

Optimal Parameters of Polycrystalline Silicon Industry Chain in Competitive Situations

Project parameters	2017	2018	2019	2020	2021	2022	2023
q_1^*	186370.86	213482.62	232068.29	353485.72	491591.04	665721.28	870964.68
q_2^*	186170.86	213282.62	231868.29	353285.72	491391.04	665521.28	870764.68
q_3^*	185970.86	213082.62	231668.29	353085.72	491191.04	665321.28	870564.68
q_4^*	185770.86	212882.62	231468.29	352885.72	490991.04	665121.28	870364.68
q_5^*	185570.86	212682.62	231268.29	352685.72	490791.04	664921.28	870164.68
W^*	155.14	177.70	193.14	294.50	409.56	554.63	725.65
$\prod_{F1}$	346590989.50	454998309.41	537806890.28	1248771550.80	2415867526.79	4431098240.80	7585044766.36
$\prod_{F2}$	345595906.05	453894778.91	536629017.14	1247108007.92	2413651562.62	4428185755.68	7581311307.63
$\prod_{F3}$	344601622.59	452792048.41	535451944.00	1245445265.03	2411436398.45	4425274070.55	7577578648.90
$\prod_{F4}$	343608139.13	451690117.91	534275670.86	1243783322.15	2409222034.28	4422363185.43	7573846790.18
$\prod_{F5}$	342615455.68	450588987.42	533100197.72	1242122179.26	2407008470.12	4419453100.30	7570115731.45
$\prod_{G}$	10375298677.70	13621011452.36	16100808319.92	37400607950.98	72380341953.58	132795472116.54	227364609467.08
$\prod$	12098310790.64	15884975694.42	18778072039.91	43627838276.15	84437527945.84	154921846469.29	265252506711.60

3.2 Optimal analysis of the industrial chain under cooperative situations

According to the data in Table 2, the optimal parameters of the polycrystalline silicon industry chain under cooperation can be calculated, as shown in Table 4 below.

Table 4

Optimal Parameters of Polycrystalline Silicon Industry Chain under Cooperation Situation

Project parameters	2017	2018	2019	2020	2021	2022	2023
q_1^*	111602.52	127869.57	139020.97	211871.43	294734.63	399212.77	522358.81
q_2^*	111592.52	127859.57	139010.97	211861.43	294724.63	399202.77	522348.81
q_3^*	111582.52	127849.57	139000.97	211851.43	294714.63	399192.77	522338.81
q_4^*	111572.52	127839.57	138990.97	211841.43	294704.63	399182.77	522328.81
q_5^*	111562.52	127829.57	138980.97	211831.43	294694.63	399172.77	522318.81
$\prod_{F1}$	622006105.70	816781406.29	965591521.14	2243725199.92	4342674966.47	7967791732.53	13642186265.64
$\prod_{F2}$	621644508.18	816403541.72	965202505.17	2243263333.49	4342130236.84	7967142524.76	13641413911.83
$\prod_{F3}$	621282920.66	816025687.14	964813499.20	2242801477.06	4341585517.21	7966493326.99	13640641568.03
$\prod_{F4}$	620921343.14	815647842.57	964424503.22	2242339630.63	4341040807.59	7965844139.22	13639869234.22
$\prod_{F5}$	620559775.62	815270007.99	964035517.25	2241877794.19	4340496107.96	7965194961.45	13639096910.41
$\prod_{G}$	6227311056.99	8175064062.91	9663165211.38	22444501999.24	43433999664.65	79685167325.29	136429112656.43
$\prod$	9333725710.29	12255192548.62	14487232757.35	33658509434.54	65141927300.73	119517634010.26	204632320546.56

From Table 4, the optimal wholesale volume of silicon wafers and sales volume of photovoltaic system manufacturers under cooperative situations are like those under competitive situations, both of which increase with the decreasing cost of silicon wafers and increasing government competition rewards year by year; The profits of silicon manufacturers and photovoltaic system manufacturers have also increased. However, comparing the competition and cooperation situation, it can be seen that the wholesale volume of silicon wafers and sales volume of photovoltaic systems by photovoltaic system manufacturers have significantly increased under the competition situation; The profits and cooperation between silicon manufacturers and photovoltaic system manufacturers have significantly improved compared to the situation; Compared to the cooperation situation, competition policy effectively enhances the profits of the entire industrial chain system, and the total profits of the entire industrial chain have significantly increased. However, in cooperative situations, although an increase in the level of technological innovation efforts can still enable manufacturers to obtain high profits faster, the impact of technological innovation efforts on manufacturers' profits is less significant than in competitive situations.

4. Discussion of Results

According to the empirical analysis of competition and cooperation among photovoltaic supply chain entities under the guidance of competition policy in section 2.1 and 2.2, it can be found that under the guidance of competition policy, the optimal profits of photovoltaic silicon wafer manufacturers and photovoltaic system manufacturers vary with changes in policies, technological innovation, and other factors. However, the optimal profit results of each entity still show some patterns, as shown in Fig. 1.

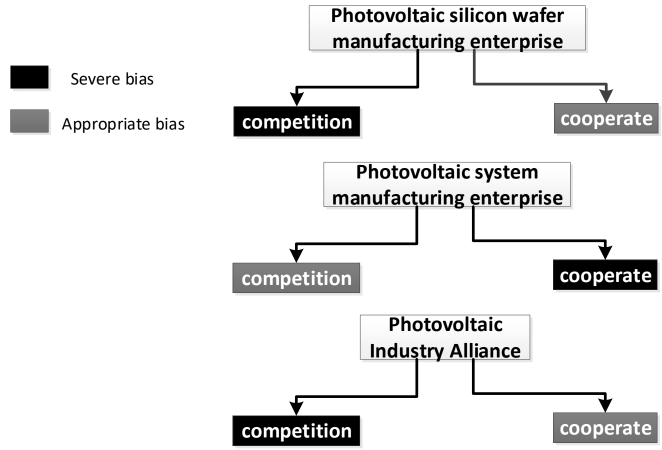

Fig. 1. Coordination strategy of photovoltaic industry alliance under the guidance of competition policy

The collaborative strategy of the photovoltaic industry collaborative innovation alliance enterprise entities under the guidance of competition policy is shown in Fig. 1. The collaborative strategy chosen by photovoltaic silicon wafer manufacturing enterprises is more inclined towards competitive strategies; Although photovoltaic system manufacturing enterprises are more inclined to choose cooperation strategies; The photovoltaic industry alliance leans more towards competitive strategies.

5. Conclusion

This article studies the sustainable relationship between silicon manufacturers and photovoltaic system manufacturers in the two-stage photovoltaic silicon industry chain under the guidance of competition policy, to achieve optimal profits for each manufacturer and the overall optimal situation of the industry chain. Through theoretical and empirical analysis of the impact of competition and cooperation on the profits of the industrial chain, the following conclusions are drawn:

(1) The government's competition policy is conducive to increasing manufacturers' profits. The government's competition policy promotes technological innovation in the manufacturing industry. The competition awards awarded by the government are related to the technological innovation efforts of various manufacturers and the sales volume of photovoltaic systems. The greater the degree of technological innovation efforts, the more competitive awards the government will receive; Meanwhile, with the increasing number of government competition awards year by year, the better the competition environment among manufacturers, the higher their final profits. Therefore, the government not only needs to strive to create a competitive atmosphere, but also needs to formulate appropriate competition policies for related manufacturing industries, such as using small funds for direct support, tax incentives, etc., but should try to avoid large funds for direct investment.

(2) The increase in technological innovation can quickly increase manufacturers' profits. Technological innovation not only refers to the technological innovation of the product itself, but also includes energy conservation and environmental protection. Technological innovation can effectively improve product performance, reduce product costs, and enhance competitiveness. For the photovoltaic system manufacturing industry, although technological innovation requires a certain cost of innovation, the resulting profits are significantly increased, and high profits can be obtained faster. Therefore, the manufacturing industry should carry out technological innovation within its capabilities, improve product utilization while reducing product costs, but cannot blindly carry out technological innovation, otherwise the gains and losses will be outweighed by the high cost of innovation.

(3) Compared to the cooperation situation, the profit of each manufacturer and the total profit of the entire industry chain are higher in the competitive situation. In competitive situations, the level of technological innovation efforts can effectively increase the profits of various manufacturers, significantly higher than in cooperative situations, and the total profit of the entire industry chain is significantly increased. Therefore, in the entire industrial chain system, the government can establish appropriate competition policies to promote the development of enterprises, promote healthy competition among manufacturers, and introduce third-party governments as supervisory parties to regulate the behavior of manufacturers at all levels, thereby effectively improving the overall profit of the industrial chain.

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