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Renewable Energy Investment Decisions of Power Supply Chain under Dual Environmental Policies and Intermittency Constraints

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SUMMARY: *Under the condition of parallel promotion of "double carbon" target, new power system construction and high proportion of renewable energy access, dual environmental policies and intermittent constraints jointly change the investment boundary and price transmission mechanism of the power supply chain. This paper builds a two-level power supply chain model composed of a single power producer and a single electricity seller. Under the combined effect of carbon cap-and-trade mechanism, renewable energy quota system and intermittent shocks, four scenarios are set up: power producer leading non-cooperation, electricity seller investing non-cooperation, technology cooperation and full cooperation. Stackelberg game, backward induction and symbolic computation methods are used to solve the equilibrium results, and the sensitivity of key parameters is analyzed by numerical experiments. The results show that complete cooperation can increase the investment level by 37.98% and the total profit of the system by 43.18% compared with the non-cooperation led by power producers. When the price of green certificate rises, the investment in scenario 3 increases by 34.1%. After the increase of carbon trading price, the profit of power generators in scenario 3 will increase by about 26.1%. When the probability of intermittency increases, the profit of the generator in scenario 2 still rises from 4.82 to 7.48, reflecting the intensification of bargaining under the guaranteed supply advantage. This study can provide theoretical and decision-making significance for power enterprises to optimize green investment and cooperation contract design, and to improve policy portfolio.*

KEYWORDS: *Power supply chain; Renewable energy investment; Dual environmental policy; Intermittent constraints*

1 Introduction

Under the background of the continuous promotion of the "double carbon" goal and the accelerated construction of new power systems, the power industry is transforming from the traditional fossil energy dominated supply system to the direction of low carbon and green. With the continuous expansion of the grid-connected scale of wind power, photovoltaic and other renewable energy, the problems of resource fluctuation and output uncertainty become increasingly prominent, and extreme weather and environmental disturbance will further amplify the system operation risk [1, 2]. In this process, the carbon cap-and-trade mechanism and the renewable energy quota system have gradually become important policy tools affecting the operation of the electricity market. On the one hand, they raise the constraints of traditional thermal power through the internalization of carbon costs, and on the other hand, they promote the investment and consumption of green power through the compliance

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requirements of green certificates [3, 4]. Previous studies have shown that carbon trading policy can promote enterprises' low-carbon technology investment and change their investment boundary, and carbon price and initial quota will further affect enterprises' investment timing and investment intensity [5, 6].

Around the renewable energy quota system, scholars have carried out a systematic discussion from the aspects of regional quota allocation, green license price mechanism and incentive path optimization. It is pointed out that the quota proportion and green license price can significantly affect the renewable energy investment level and the performance cost of enterprises, and the policy incentive does not always show a monotonic enhancement relationship [7, 8]. On this basis, some studies further focus on the superposition effect of carbon trading and quota system, and find that the dual environmental policy is more conducive to increasing the proportion of renewable energy and accelerating the low-carbon transition than the single policy [9, 10]. However, as the proportion of renewable energy continues to increase, its intermittency and volatility will weaken the effective supply of green power, and then trigger a chain reaction of increasing thermal power compensation, rising carbon compliance costs and widening green certificate gap [11]. This means that power enterprises are no longer faced with a single policy cost, but with a composite decision-making environment interwoven by policy constraints and physical fluctuations [12].

Although the existing studies have discussed the single environmental policy, renewable energy investment and supply chain cooperative decision-making, the systematic analysis of the composite scenario of "dual environmental policy - renewable energy intermittency - power supply chain cooperative decision-making" is still insufficient, especially the lack of a unified comparison of investment levels, electricity price decisions and profit distribution changes under different cooperation depths. Based on this, this paper builds a two-level power supply chain model composed of a single power producer and a single electricity seller under the Stackelberg game framework, and sets up four scenarios: power producer leading non-cooperation, e-commerce seller investment non-cooperation, technical cooperation and full cooperation, and analyzes the renewable energy investment and pricing decision-making problem under the joint effect of dual environmental policies and intermittent constraints. Through equilibrium solution and numerical experiments, the influence of key parameters change on the profit of each party and the stability of cooperation is revealed.

2 Related work

Focusing on the problem of renewable energy volatility risk and electricity market coordination, existing studies have explored intermittent management, the role of environmental policies, and supply chain collaborative decision-making. Johnathon et al. proposed an energy market model based on hedging mechanism and pointed out that diversifying the volatility risk of renewable energy through contract design can help alleviate the impact of intermittency on system revenue and reserve cost [13]. Lu et al. evaluated the impact of climate policies such as carbon trading, energy saving subsidies and carbon tariffs on risk exposure from the perspective of sustainable insurance, and showed that the superposition of multiple policy tools would change the revenue expectation and investment boundary of enterprises [14]. Zheng et al. constructed a two-layer coordination mechanism under hybrid carbon regulation and found that cooperative contracts could improve the overall performance of low-carbon supply chains and profit distribution among members [15]. Subsequently, Zheng et al. further studied the multi-agent competition-cooperation strategy under the hybrid carbon trading mechanism, indicating that policy pressure and competitive relationship jointly affect the optimal decision-making of supply chain members [16].

In terms of green license market and power investment behavior, Zhang et al. used the system dynamics method to analyze the decision-making behavior of power suppliers in the green license market, and pointed out that quota pressure and certificate price would have a significant impact on the degree of market participation [17]. Ji et al. compared the decision-making differences of retail supply chain under different carbon quota allocation rules, and showed that the initial quota allocation method would significantly affect the emission reduction incentive and profit level of enterprises [18]. Kok et al. revealed the dual transmission effect of price mechanism on renewable energy investment and carbon emissions from the perspective of electricity price policy, indicating that pricing rules would directly affect green investment intensity [19]. Song et al. further discussed the interval optimization problem of flexible collaboration between wind power and carbon capture power plants from the perspective of low-carbon scheduling, indicating that cross-agent collaboration is helpful to improve system environmental performance and scheduling flexibility [20].

From the perspective of green supply chain in a broader sense, Gawusu et al. systematically sorted out the evolution logic of green supply chain management under the framework of renewable energy, and pointed out that supply chain governance under the background of energy transition is changing from single-point optimization to multi-link collaboration [21]. Ji et al. focused on energy storage investment decisions in the power supply chain and found that environmental policies would jointly affect energy storage configuration behavior through cost compensation, risk sharing and profit expectation [22]. Jiang et al. studied the problem of green investment and operation under the background of dual market and generation right trading, and revealed the linkage characteristics of enterprise investment decisions after the complexity of power market mechanism [23]. Starting from different quota allocation schemes, Xie et al. analyzed the dynamic decision-making process of carbon emission reduction in the power supply chain, indicating that the system design would continuously affect the behavior adjustment path among members [24].

In general, existing studies have fully discussed intermittent risk, environmental policy and supply chain synergy respectively, but there are still two shortcomings: first, multi-focus single policy, single market or single investment object, and the research on the investment decision under the joint effect of "dual environmental policy and renewable energy intermittency" is still insufficient. Second, there is a lack of unified comparison of investment division of labor, pricing transmission and profit redistribution between power producers and electricity sellers under different cooperation depths. Based on this, this paper defines the research object as the two-level power supply chain composed of a single power producer and a single electricity seller. Under the joint action of carbon cap-and-trade mechanism, renewable energy quota system and intermittent constraints, four scenarios are set up: power producer leading non-cooperation, electricity seller investing non-cooperation, technology cooperation and full cooperation. The evolution law of renewable energy investment, wholesale zero electricity price and member profit with the change of policy parameters and intermittent parameters was investigated, so as to lay a foundation for subsequent model construction and numerical analysis.

3 Methodology and model construction

3.1 Modeling the coupling of benefits and costs under dual environmental policies and intermittency constraints

This paper considers a two-level power supply chain composed of a single generator and a single electricity seller. The generator is equipped with both traditional thermal power and renewable energy supply capacity, and supplies power to the seller at the wholesale price w. The seller then sells electricity to the end market at the retail electricity price p. The carbon cap-and-trade mechanism acts on the generation side, and the renewable energy quota production is used on the electricity sales side. When intermittent shocks of renewable energy occur, the effective supply of green electricity decreases, and the gap compensation is borne by the traditional thermal power. In order to characterize the joint impact of policy constraints and physical fluctuations on investment and pricing decisions, the market demand, investment cost, thermal power compensation, carbon performance cost, green license performance cost and member profit are integrated into the unified analysis framework.

Let the potential market size be a, the renewable energy investment size be q, the consumer green preference coefficient be θ, the renewable energy intermittency occurrence probability be μ, and the loss rate be δ. Under these conditions, renewable energy investment will enhance the green attributes of power products and expand terminal demand, while intermittency will weaken this demand-pull effect. Therefore, the system expected demand function can be written as follows:

$$D=a-p+\theta(1-\mu\delta)q \tag{1}$$

Equation (1) shows that retail electricity price has a restraining effect on demand, renewable energy investment has a promoting effect on demand, and intermittent reduction of effective green electricity supply weakens the positive market effect of investment, which provides a unified demand basis for subsequent income measurement.

Considering that renewable energy construction usually presents increasing marginal cost characteristics, setting the investment cost coefficient as k, the renewable energy investment cost function is as follows:

$$C_I(q)=\frac{k}{2}q^2 \tag{2}$$

On the supply side, the traditional thermal power undertakes the compensation task when the green power is insufficient. Since the expected effective green power supply of the system is (1−μδ)q, the expected thermal power compensation can be expressed as follows:

$$T=D-(1-\mu\delta)q \tag{3}$$

Equation (2) and Equation (3) together show that although expanding renewable energy investment can enhance green supply capacity, it will also bring higher construction investment. However, the stronger the intermittency, the larger the thermal power compensation scale, and the more obvious the dependence of the supply chain on traditional power sources.

Suppose that the unit production cost of conventional thermal power is c and the unit carbon emission intensity is e, then the expected carbon emission in the system operation cycle is as follows:

$$E = eT \tag{4}$$

If the initial carbon quota allocated by the government to the power generator is E¯ and the unit carbon trading price is pc, the carbon performance cost borne by the power generator is as follows:

$$C_c = p_c \max(E - \bar{E}, 0) \tag{5}$$

Equations (4) and (5) directly link the compensation demand of thermal power and the cost of carbon regulation, which means that intermittent-induced thermal power substitution not only increases conventional production expenditures, but also may widen the emission gap and drive up the cost of carbon market compliance. The coupling relationship makes the impact of carbon policy no longer limited to the emission management at the generation side, but further transmitted to the overall profit distribution of the supply chain.

Under the renewable energy quota system, e-commerce sellers need to meet the green electricity consumption responsibility with a proportion of λ. If the system expects the effective green electricity supply to be insufficient to cover the quota requirements, it needs to purchase green certificates to make up the gap. Let the price of unit green license be pg, then the performance cost of green license is written as follows:

$$C_g = p_g \max\{\lambda D - (1 - \mu\delta)q, 0\} \tag{6}$$

Equation (6) shows that quota proportion, market demand, green license price and effective green electricity supply jointly determine the performance pressure of the electricity selling side. When the quota proportion increases or the price of green certificate rises, e-commerce sellers will face stronger cost constraints. And when intermittence leads to the decline of effective green electricity supply, the green certificate gap will be further expanded. Therefore, the dual environmental policy forms the carbon cost constraint and the green certificate cost constraint on the generation side and the electricity sales side respectively, and is linked through the intermediary variable of effective green electricity supply.

In order to describe the revenue structure under different decision scenarios, the investment cost sharing parameter α is introduced. When the power producer bears the investment cost with a proportion of α and the electricity seller bears the proportion of 1−α, the expected profit function of both parties can be expressed as follows:

$$\Pi_g = wD - cT - C_c - \alpha \frac{k}{2} q^2 \tag{7}$$

$$\Pi_r = (p - w)D - C_g - (1 - \alpha)\frac{k}{2} q^2 \tag{8}$$

Among them, α=1 corresponds to the separate investment of power producers, α=0 corresponds to the separate investment of electricity sellers, and 0<α<1 corresponds to the technical cooperation scenario. Equations (7) and (8) integrate market revenue, thermal power compensation cost, carbon performance cost, green certificate performance cost and investment sharing mechanism into a unified expression, which can provide a consistent analysis starting point for game modeling, reverse induction solution and equilibrium comparison under subsequent non-cooperative and cooperative scenarios.

3.2 Game model of renewable energy investment decision under non-cooperative and cooperative scenarios

Under the joint effect of dual environmental policies and intermittent constraints, power generators and e-commerce sellers form differentiated decision-making relationships around renewable energy investment scale, wholesale electricity price and retail electricity price. According to the different investment subjects, cost bearing methods and decision-making order, four scenarios are constructed: power generation provider leading non-cooperation, electricity sales provider investment non-cooperation, technology cooperation and full cooperation. Figure 1 shows the decision-making framework for renewable energy investment in the power supply chain under the four decision scenarios.

Figure 1: Framework diagram of renewable energy investment decision in power supply chain under four decision scenarios

In the non-cooperative scenario dominated by the power provider, the power provider as the leader first determines the renewable energy investment scale q and the wholesale electricity price w, and the e-commerce seller as the follower determines the retail electricity price p. In this case, the generator independently bears all the investment costs, and the expected profit functions of both parties can be expressed as follows:

$$\Pi_g^{(1)} = wD - cT - C_c - \frac{k}{2}q^2 \tag{9}$$

$$\Pi_r^{(1)} = (p - w)D - C_g \tag{10}$$

In this scenario, power producers bear the pressure of investment and carbon performance at the same time, e-commerce sellers mainly face the terminal market pricing and green license compliance constraints, and profit distribution has obvious characteristics of upstream and downstream separation.

In the non-cooperative investment scenario of e-commerce sellers, the generator still holds the wholesale pricing power, and decides w first. On this basis, the e-commerce sellers jointly determine the investment scale q and the retail electricity price p. Since the investment responsibility is transferred to the electricity selling side, the expected profit function of both parties can be expressed as follows:

$$\Pi_g^{(2)} = wD - cT - C_c \tag{11}$$

$$\Pi_r^{(2)} = (p - w)D - C_g - \frac{k}{2}q^2 \tag{12}$$

In this scenario, the renewable energy investment and green license performance responsibility are concentrated on the side of the e-commerce seller, which can strengthen its incentive to expand green electricity supply, but also amplify the pressure of downstream participants in price setting and risk taking.

In the technical cooperation scenario, the generation provider and the e-commerce seller form a cost-sharing relationship around the investment, and the generation provider bears the investment cost with a proportion of α, and the e-commerce seller bears the proportion of $1-\alpha$. Considering that the investment scale will affect the carbon performance cost of the generation side and the green certificate performance cost of the electricity selling side at the same time, the two sides usually determine q jointly, then the power generator decides w, and finally the electricity seller decides p. The expected profit function of both parties can be expressed as follows:

$$\Pi_g^{(3)} = wD - cT - C_c - \alpha\frac{k}{2}q^2 \tag{13}$$

$$\Pi_r^{(3)} = (p - w)D - C_g - (1 - \alpha)\frac{k}{2}q^2 \tag{14}$$

Accordingly, the total profit function of the system is:

$$\Pi_s^{(3)} = \Pi_g^{(3)} + \Pi_r^{(3)} \tag{15}$$

In this scenario, the investment responsibility is redistributed within the supply chain, members improve the common tolerance to intermittent risks and dual policy pressures through cost sharing, and the characteristics of system coordination are more obvious than the previous two non-cooperative scenarios.

In the full cooperation scenario, the power generator and the electricity seller act as a unified decision-making body to maximize the total profit of the system, and simultaneously determine the renewable energy investment scale q and the retail electricity price p. Since the wholesale electricity price is only an internal transfer payment, it no longer has a substantial impact on the total profit of the system, so the total profit function can be expressed as follows:

$$\Pi_s^{(4)} = pD - cT - C_c - C_g - \frac{k}{2}q^2 \tag{16}$$

The full cooperation scenario eliminates the repeated mark-up and local optimum constraints between upstream and downstream, and makes the investment decision, terminal pricing and compliance cost control coordinately carried out under a unified objective, which is more conducive to characterizing the optimal investment boundary from the perspective of the power supply chain as a whole.

Taken together, the core differences of the four scenarios are reflected in three aspects: investment subject, decision sequence and cost sharing structure. Non-cooperation led by power producers emphasizes upstream investment and wholesale pricing ability, while non-cooperation of e-commerce sellers emphasizes downstream performance and market response mechanism. Technical cooperation reflects the risk sharing characteristics under partial coordination, and complete cooperation corresponds to the overall optimum of the system. Based on the above game structure, the next section will use the backward induction method to derive the optimal reaction functions and equilibrium outcomes under each scenario, so as to compare the differences in renewable energy investment decisions under different cooperation depths.

3.3 Equilibrium solving and symbolic computation process based on backward induction

Under the four decision scenarios, the decision variables of the power generator and the electricity seller are the renewable energy investment scale, the wholesale electricity price and the retail electricity price, respectively. Due to the differences in investment subjects, cost bearing methods and decision-making sequence in each scenario, this paper uses the backward induction method to solve the equilibrium results, and uses symbolic computation to complete the first-order condition derivation, second-order condition test and equilibrium expression simplification. The equilibrium solving process based on backward induction is shown in Figure 2.

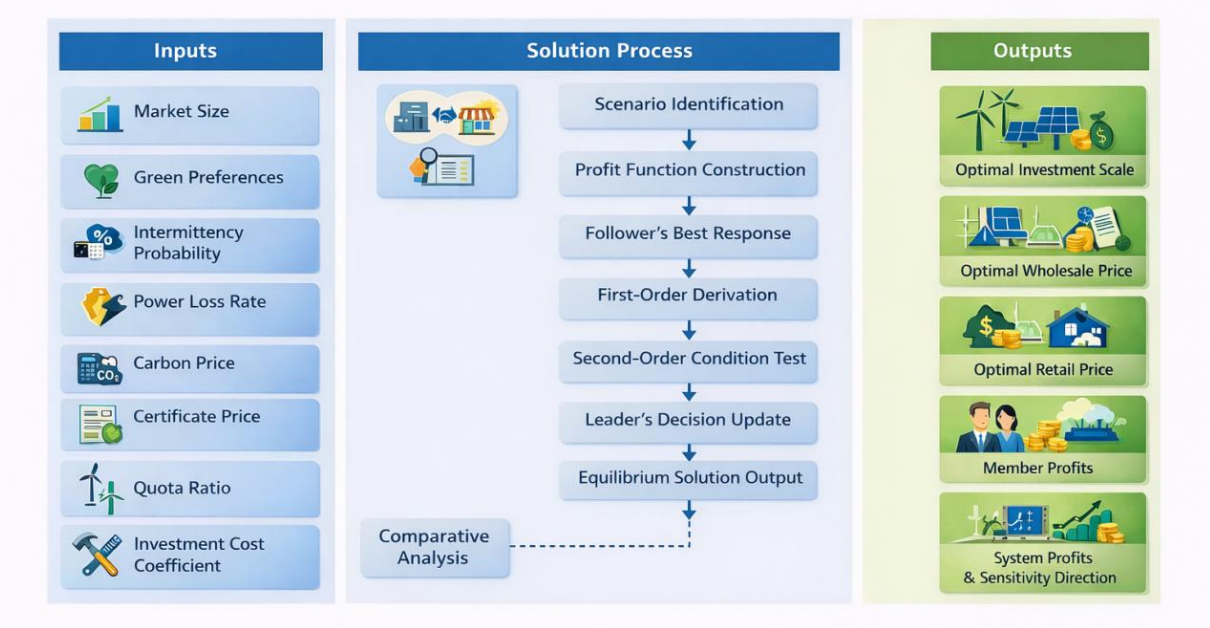

Figure 2: Flowchart of equilibrium solution based on backward induction

The core idea of backward induction is to solve the optimal response of the second-acting party first, and then substitute it back to the objective function of the first-acting party, so as to push back layer by layer to the equilibrium point. Taking the non-cooperative scenario dominated by the generator as an example, the e-commerce seller as the follower chooses the retail electricity price p to maximize its own profit given the investment scale q and the wholesale electricity price w. The optimization problem of e-commerce can be expressed as follows:

$$\max_{p} \Pi_r^{(1)} = (p - w)D - C_g \tag{17}$$

Taking the first derivative of Equation (17) with respect to p and setting it equal to zero, the optimal reaction function of the e-commerce seller can be obtained as follows:

$$\frac{\partial \Pi_r^{(1)}}{\partial p} = 0 \tag{18}$$

If the second derivative satisfies:

$$\frac{\partial^2 \Pi_r^{(1)}}{\partial p^2} < 0 \tag{19}$$

It shows that the profit function of the e-commerce seller is strictly concave function with respect to the retail electricity price, and the optimal response is unique. The obtained reaction function p*(w,q) will be used as the input of the upper decision, which provides a closed expression for the subsequent solution. This step endogenizes the downstream pricing behavior into the upstream investment and wholesale pricing decisions, so that the equilibrium solution has a clear hierarchical structure.

After substituting p*(w,q) into the profit function of the generator, the generator faces a joint optimization problem about w and q. Its solution condition can be expressed as follows:

$$\frac{\partial \Pi_g^{(1)}}{\partial w} = 0, \frac{\partial \Pi_g^{(1)}}{\partial q} = 0 \tag{20}$$

Further construct the Hessian matrix as follows:

$$H_g = \begin{bmatrix} \frac{\partial^2 \Pi_g^{(1)}}{\partial w_g^2} & \frac{\partial^2 \Pi_g^{(1)}}{\partial w \partial q} \\ \frac{\partial^2 \Pi_g^{(1)}}{\partial q \partial w} & \frac{\partial^2 \Pi_g^{(1)}}{\partial q^2} \end{bmatrix} \tag{21}$$

When H_g is a negative definite matrix, there is a unique equilibrium solution for the optimal wholesale electricity price and the optimal investment size of the generator. The solution sequence of the non-cooperative investment scenario is similar, but the upper variable is reduced to the wholesale electricity price, and the lower variable is expanded to the joint optimization of investment scale and retail electricity price. Therefore, the optimal reaction of the e-commerce supplier about p and q should be solved first, and then the optimal wholesale pricing of the generator should be deduced.

The solution structure of the technical cooperation scenario is different from that of non-cooperation. Because the investment cost sharing makes the two sides form part coordination in the investment stage, the system first makes joint decision around the investment scale, and then enters the sequential game between wholesale and retail electricity price. At this time, the optimization problem of the system with respect to the investment variable can be expressed as follows:

$$\max_{q} \Pi_s^{(3)} = \Pi_g^{(3)} + \Pi_r^{(3)} \tag{22}$$

After obtaining the optimal investment scale q*, the price decisions of the power generator and the electricity seller are solved respectively. In the full cooperation scenario, the constraint of internal transfer price is further eliminated, and the investment scale and retail electricity price are uniformly determined by the system. The first-order condition can be written as follows:

$$\frac{\partial \Pi_s^{(4)}}{\partial p} = 0, \frac{\partial \Pi_s^{(4)}}{\partial q} = 0 \tag{23}$$

This scenario corresponds to the centralized decision result under the maximization of the total profit of the system and can be used as an important benchmark to compare the collaborative efficiency of the other three scenarios.

In order to improve the efficiency of the solution and ensure the consistency of the expression, the first derivative, the second derivative and the equilibrium result are automatically deduced and simplified by symbolic calculation. The specific steps include: first, input the demand function, cost function and profit function; Then, the reaction function and Hessian matrix are automatically calculated by setting the decision order according to different scenarios. Finally, the analytical expressions of the optimal investment scale, the optimal wholesale electricity price, the optimal retail electricity price, the member profit and the system profit are output. This process not only reduces the complexity of manual derivation in the multi-parameter scenario, but also enables the subsequent sensitivity analysis to be directly carried out based on the analytical results. Through the above reverse induction and symbolic calculation process, the equilibrium solutions under the four decision-making scenarios can be compared in a unified framework, which provides a clear basis for the model comparison dimension and analysis index setting in the next section.

3.4 Model comparison dimensions and analysis index setting

In order to ensure the comparability of the model results under the four decision-making scenarios, it is necessary to specify the comparison dimensions and analysis indicators under a unified parameter system. The four scenarios discussed in this paper are non-cooperation dominated by power generation providers, non-cooperation invested by e-commerce sellers, technical cooperation and full cooperation. The differences among the scenarios are mainly reflected in the investment subject, cost bearing mode, decision-making sequence and objective function setting, but their external environmental parameters are consistent, that is, they are all in the decision-making environment with dual environmental policies and intermittent constraints. The purpose of this treatment is to focus on the impact of the depth of cooperation and the difference in the distribution of rights and responsibilities on the investment decision of renewable energy, rather than the result deviation caused by the inconsistent parameters. Therefore, on this basis, this section uniformly merges the model output into five dimensions of investment, price, profit, synergy and stability.

From the perspective of investment dimension, renewable energy investment scale is the most core comparison object. This index directly reflects the incentive strength of supply chain to green capacity expansion under different decision-making structures, and also determines the change direction of subsequent effective green power supply, thermal power compensation scale, and carbon and green certificate performance costs. The optimal investment scale under the four scenarios is q_1^*, q_2^*, q_3^* and q_4^*, respectively. Then the investment increase can be defined as follows:

$$\mathrm{R}_{\mathrm{q}}^{(\mathrm{i,j})} = \frac{\mathrm{q}_{\mathrm{i}}^* - \mathrm{q}_{\mathrm{j}}^*}{\mathrm{q}_{\mathrm{j}}^*} \tag{24}$$

Equation (24) is used to compare the increase or decrease in investment scale of one scenario relative to another. When $\mathrm{R}_{\mathrm{q}}^{(\mathrm{i,j})}>0$, it indicates that the green investment incentive of scenario i is stronger than that of scenario j. This indicator can intuitively reveal whether technical cooperation or complete cooperation positively promotes renewable energy investment.

From the perspective of price dimension, wholesale electricity price and retail electricity price constitute important transmission variables within the supply chain and in the end market. Under different decision-making scenarios, the wholesale electricity price reflects the bargaining power of the generator, and the retail electricity price reflects the degree to which the seller transfers the policy cost and supply fluctuation to the market. To observe the degree of price coordination, the price mark-up rate index can be further defined as follows:

$$\mathrm{M}_{\mathrm{p}} = \frac{\mathrm{p}^* - \mathrm{w}^*}{\mathrm{w}^*} \tag{25}$$

Equation (25) reflects the expansion degree of the wholesale price spread relative to the wholesale price. A high value indicates that the downstream price mark-up is stronger and terminal demand is more likely to be suppressed. A low value indicates a relatively higher degree of price coordination within the supply chain. This indicator is particularly important for comparing the difference in price transmission between the non-cooperative and cooperative scenarios.

From the perspective of profit dimension, it is necessary to investigate the profit of power generators, the profit of electricity sellers and the total profit of the system at the same time. Suppose that the optimal profits of the generator and the seller under scenario i are $\Pi_{\mathrm{g}}^{\mathrm{i}*}$ and $\Pi_{\mathrm{r}}^{\mathrm{i}*}$, respectively, and the total system profit is $\Pi_{\mathrm{s}}^{\mathrm{i}*}$, then:

$$\Pi_{\mathrm{s}}^{\mathrm{i}*} = \Pi_{\mathrm{g}}^{\mathrm{i}*} + \Pi_{\mathrm{r}}^{\mathrm{i}*} \tag{26}$$

On this basis, in order to describe the system gain brought by the cooperation mechanism, the cooperative return rate can be defined as follows:

$$R_s^{(i,j)} = \frac{\Pi_s^{i*} - \Pi_s^{j*}}{\Pi_s^{j*}} \tag{27}$$

Equation (27) is used to measure the degree of system profit improvement of technical cooperation or full cooperation relative to the non-cooperation scenario. If the value is significantly positive, it indicates that the cooperative mechanism can form better resource coordination and cost hedging effects under the dual environmental policy and intermittent constraints.

In addition to the system profit, it is necessary to investigate the equilibrium of profit distribution. If the cooperation scenario improves the total profit of the system, but the profit mainly focuses on one party, the stability of cooperation may be insufficient. To this end, the deviation index of profit distribution is introduced:

$$B_i = \frac{\left|\Pi_g^{i*} - \Pi_r^{i*}\right|}{\Pi_s^{i*}} \tag{28}$$

Equation (28) describes the relative degree of the difference between the two parties in the total profit of the system. The smaller the value, the more balanced the profit distribution; The larger the value is, the more obvious advantage a member has in revenue acquisition. For the technical cooperation scenario, this index can be analyzed together with the cost sharing ratio to determine whether the cooperation contract has a stable and sustainable realistic basis.

From the perspective of stability dimension, this paper mainly investigates the fluctuation degree of optimal investment and system profit under the change of key parameters, especially the impact of intermittent probability, loss rate, carbon trading price, green certificate price and quota proportion. In order to uniformly measure the sensitivity of output results to external parameter perturbations, the elastic response index is defined as follows:

$$S_x = \frac{\Delta Y/Y}{\Delta x/x} \tag{29}$$

Here, x represents the policy parameter or intermittent parameter, and Y represents the target output such as investment size, price or profit. Equation (29) can be used to identify which type of parameters have the strongest influence on the equilibrium results under different scenarios, thus providing a unified aperture for the sensitivity analysis in Chapter 4 A larger absolute value of a parameter indicates that the model output is more sensitive to this parameter and the system stability is weaker.

In summary, the comparison of the four decision-making scenarios is uniformly based on the five indicators of investment scale, price transmission, profit level, synergy income and stability response, so that the optimal solutions under different scenarios have stronger interpretability and readability. For ease of presentation, Table 1 presents an inductive explanation of the model setting and comparison dimensions under different decision-making scenarios.

Table 1: Model settings and comparison dimensions under different decision scenarios

Decision Scenario	Investment Entity	Cost-Bearing Mode	Key Comparison Dimensions
Generator-led Non-cooperation	Generator	Generator bears all investment cost	Investment incentive; upstream bargaining power; carbon cost pressure
Retailer-investment Non-cooperation	Retailer	Retailer bears all investment cost	Downstream compliance pressure; investment transfer effect; price transmission
Technical Cooperation	Generator and retailer	Both share investment cost	Investment improvement; profit balance; cooperation stability
Full Cooperation	Generator and retailer	System-wide unified cost bearing	System optimality; collaborative gain; overall stability

4 Numerical experiments and result analysis

4.1 Parameter setting and experimental scenario design

In order to ensure the comparability of equilibrium results under different decision-making scenarios, the numerical experiments adopted a uniform parameter aperture, and investigated the influence of key parameters on the model output under the condition of controlling the other variables unchanged. The baseline parameters are set as follows. Potential market size $a=10$, traditional thermal power unit production cost $c=0.4$, renewable energy investment cost coefficient $k=2$, market demand elasticity parameter $\beta=0.8$, consumer green preference coefficient $\theta=0.3$, unit carbon emission intensity $e=0.6$, initial carbon quota $e_0=4$, green certificate transaction price $p_g=1$, The carbon trading price $p_e=0.6$, the proportion of renewable energy quota $\lambda=0.75$, and the intermittency probability $\mu=0.25$. The above parameters jointly determine the level of market demand, the scale of thermal power compensation, and the changing direction of carbon performance and green certificate performance costs.

On this basis, the perturbation analysis of green certificate transaction price, carbon transaction price, intermittency probability and cost sharing proportion under technical cooperation are carried out respectively, in order to describe the impact of dual environmental policy, physical fluctuation risk and cooperation mechanism changes on renewable energy investment decisions. In order to avoid the simultaneous fluctuation of multiple parameters interfering with the conclusion interpretation, the control variable method was used in each group of experiments, that is, only one target parameter was changed each time, and the other parameters were kept unchanged in the benchmark setting. In this way, the marginal effects of different parameters on investment scale, wholesale electricity price, retail electricity price and member profits can be more accurately identified. At the same time, it is also convenient to compare the differences of equilibrium results under the four scenarios of non-cooperation dominated by power producers, non-cooperation by electricity sellers, technical cooperation and full cooperation.

4.2 Comparison of equilibrium results under different decision modes

To compare the equilibrium differences under the four decision scenarios, the renewable energy investment level, wholesale electricity price, retail electricity price and total system profit are selected as the core indicators, and the solution results are normalized. The comparison of equilibrium results for different decision scenarios is shown in Figure 3.

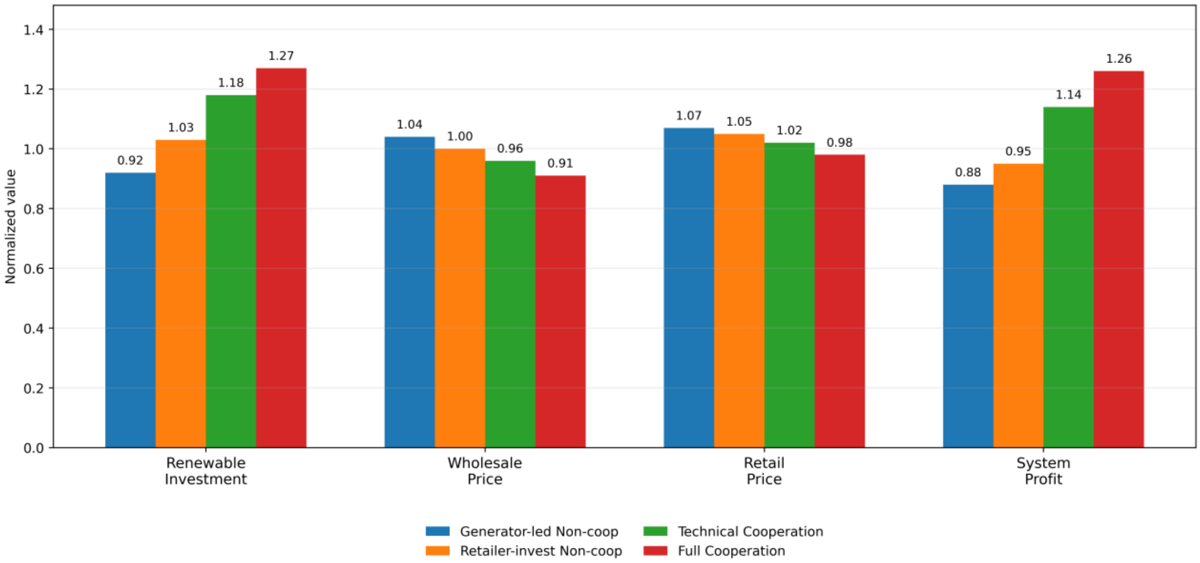

Figure 3: Bar charts for comparison of equilibrium results in different decision scenarios

As shown in Figure 3, with the deepening of cooperation, the overall investment level and system income show an upward trend, while the price level shows a certain downward feature. In the non-cooperative scenario, the investment level and the total profit of the system are only 0.92 and 0.88, respectively. The non-cooperation scenario of e-commerce investment has improved, and the corresponding indicators have increased to 1.03 and 0.95. In the technical cooperation scenario, the investment level is further increased to 1.18, and the total profit of the system reaches 1.14, indicating that cost sharing can effectively alleviate the pressure caused by dual environmental policies and intermittent constraints. The full cooperation scenario has the best performance, and its investment level and total system profit reach 1.27 and 1.26 respectively, while the wholesale price and retail price drop to 0.91 and 0.98 respectively. In general, compared with the non-cooperation led by power producers, the full cooperation increases the investment level by 37.98% and the total profit of the system by 43.18%, indicating that the cooperation mechanism can significantly enhance green investment incentives and improve the overall performance of the supply chain.

4.3 Sensitivity analysis of dual environmental policy parameters

Under the condition that $a=10$, $c=0.4$, $k=2$, $\beta=0.8$, $\theta=0.3$, $e=0.6$, $e0=4$, $\lambda=0.75$, $\mu=0.25$ remain unchanged, the influence of the change of green license trading price and carbon trading price on the equilibrium result is investigated respectively, where the green license trading price ranges from $p_g \in [0.5,2.0]$. The value range of carbon trading price is $p_e \in [0.2,1.0]$. Figure 4 shows the effect of changes in the transaction price of green certificates on the equilibrium results.

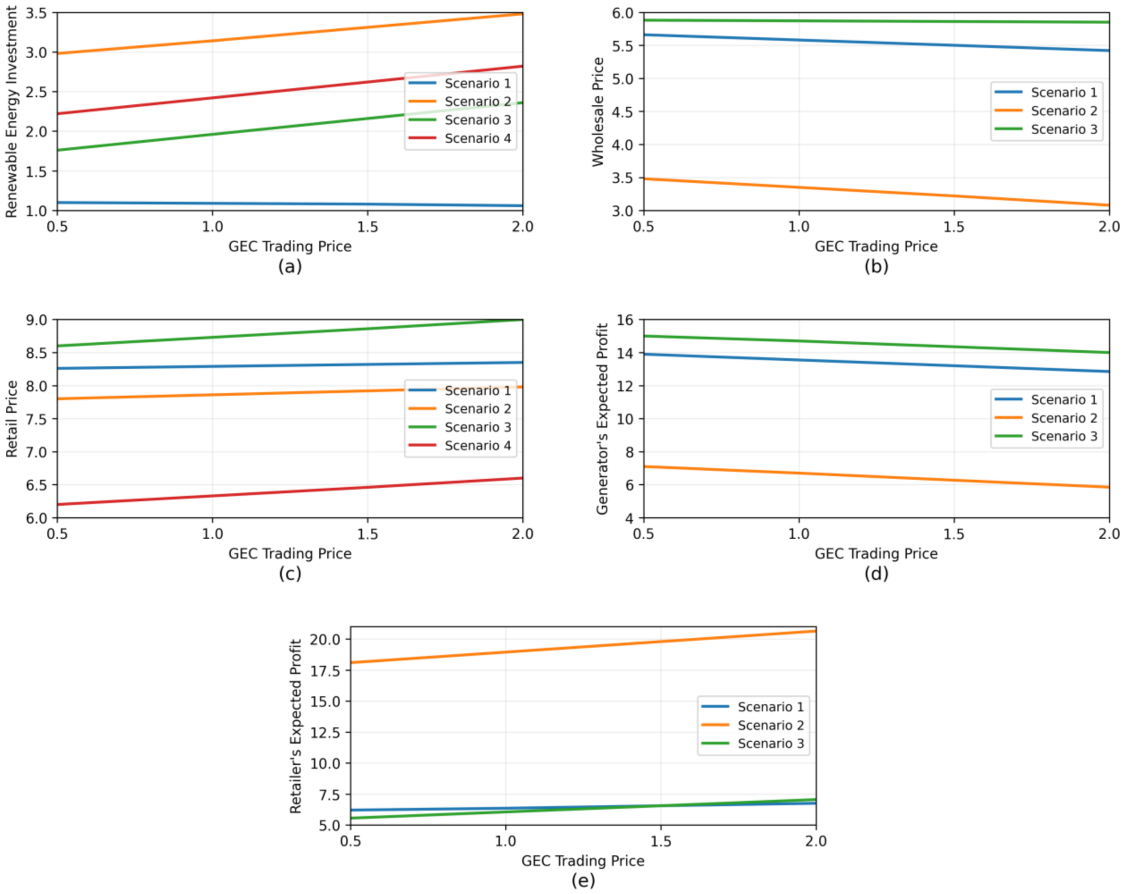

Figure 4: Graph of the effect of changes in the transaction price of green certificates on the equilibrium results

As shown in Figure 4, as the transaction price of green certificates increases, the investment in renewable energy under scenarios 2, 3 and 4 increases significantly, while scenario 1 only shows a small decrease. Compared with the endpoints of the interval, the investment level in scenario 2 increases from about 2.98 to 3.48, scenario 3 from about 1.76 to 2.36, and scenario 4 from about 2.22 to 2.82, with increases of about 16.8%, 34.1% and 27.0%, respectively. Scenario 1 is reduced from about 1.10 to 1.06. At the same time, the wholesale electricity price decreased as a whole, and the retail electricity price showed an upward trend under the four scenarios, indicating that the compliance pressure on the electricity sales side would be transmitted to the terminal market after the green license price increased, but the cooperation scenario could transform the green license benefits into stronger green investment incentives. In terms of profit, the revenue of power generators decreased in general, while the revenue of e-commerce sellers increased significantly. In scenario 2, the profit of e-commerce sellers increased from about 18.10 to 20.65, with an increase of about 14.1%. This shows that the green certificate mechanism is more conducive to strengthening the revenue acquisition of the electricity sales side and promoting the green expansion under the cooperation mode.Figure 5 shows the effect of carbon trading price changes on equilibrium outcomes.

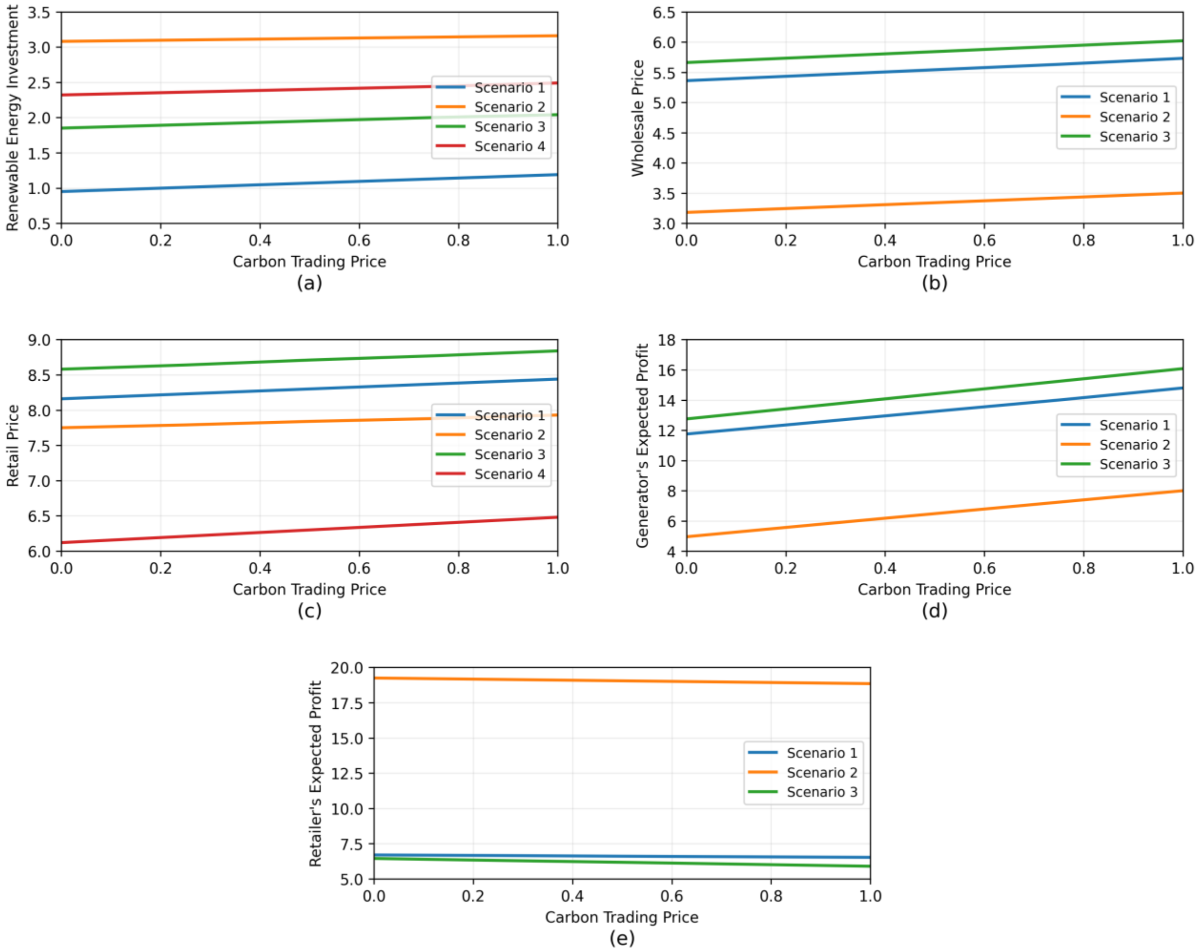

Figure 5: Diagram of the impact of carbon trading price changes on equilibrium outcomes

As shown in Figure 5, after the increase of carbon trading price, renewable energy investment in the four scenarios shows an increasing trend, and scenario 2 always maintains the highest investment level. Wholesale and retail electricity prices have also risen in tandem. Compared by the endpoints of the interval, the investment level in scenario 1 increases from about 0.95 to 1.19, scenario 3 increases from about 1.85 to 2.04, and scenario 4 increases from about 2.32 to 2.49, showing a more obvious positive response. Unlike the green license mechanism, the rising carbon price will compress the profit of e-commerce sellers, but increase the profit of power generators. For example, under scenario 3, the profit of the generator increases from about 12.75 to 16.08, an increase of about 26.1%, while the profit of the e-commerce seller decreases from about 6.45 to 5.90. This shows that after the increase of carbon trading price, power generators obtain stronger carbon asset returns by means of initial carbon quota and higher green electricity investment level, while the electricity sales side bears more profit squeeze brought by cost transmission.

In conclusion, both the dual environmental policies can promote the investment in renewable energy, but there are obvious differences in the direction of income distribution: the increase of green certificate trading price is more conducive to the increase of electricity sales side revenue, and the increase of carbon trading price is more conducive to the generation side to obtain policy dividends. Compared with the non-cooperative scenario, the cooperation mode, especially technical cooperation and full cooperation, performs better in terms of investment promotion and revenue coordination, indicating that the incentive effect of dual environmental policies can only be more fully released under the supply chain collaboration framework.

4.4 Analysis of the impact effect of intermittent constraint parameters

The effect of intermittent probability changes on the equilibrium results is shown in Figure 6.

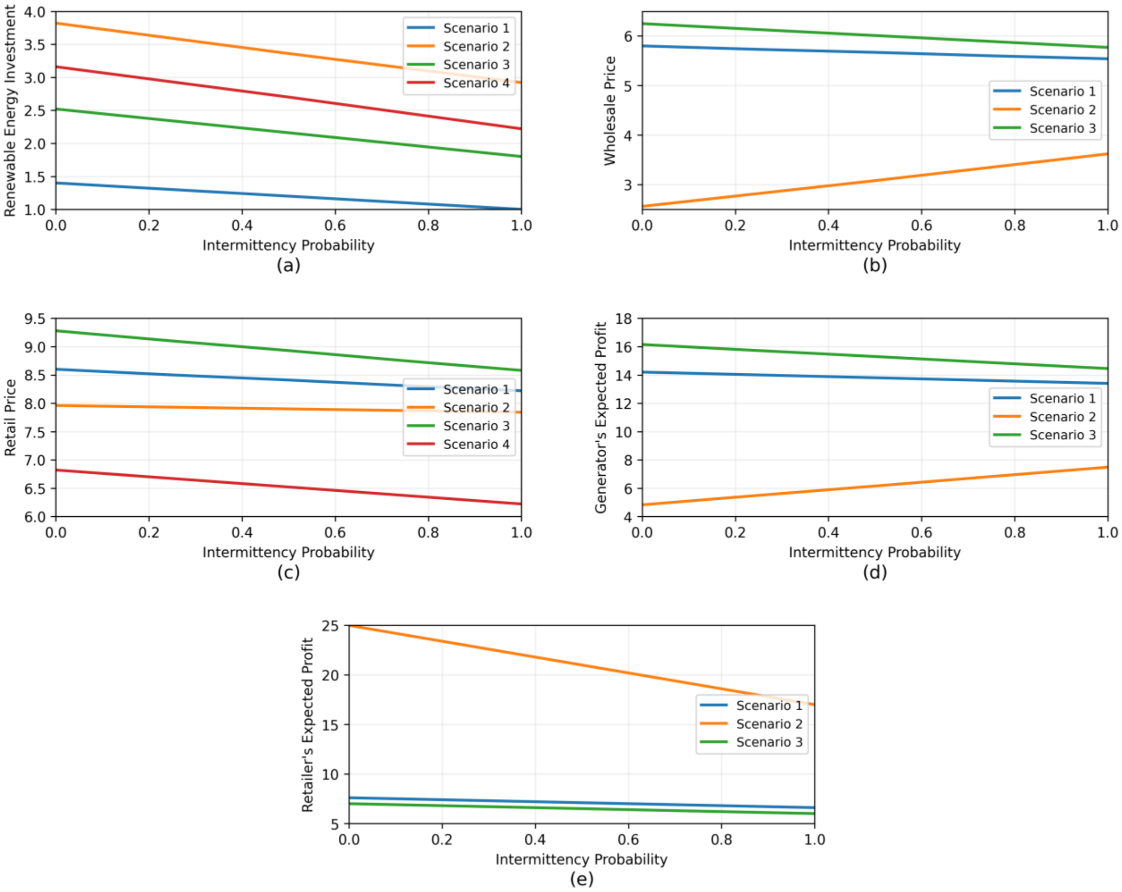

Figure 6: Diagram of the effect of intermittent probability changes on the equalization results

As the intermittency probability increases from 0 to 1, the level of renewable energy investment decreases in all the four scenarios, indicating that the marginal return of green investment is significantly weakened after the increase of supply instability. Among them, the investment level of scenario 2 is reduced from about 3.82 to 2.92, scenario 3 from about 2.52 to 1.80, scenario 4 from about 3.16 to 2.22, with a decrease of about 23.6%, 28.6% and 29.7%, respectively. The investment level of scenario 1 is also reduced from about 1.40 to 1.00. The overall synchronous decline in retail electricity prices indicates that intermittent shocks weaken consumers' willingness to pay for green electricity, and the electricity selling side can only maintain demand by letting prices. In contrast, the wholesale electricity price and the profit of the generator show significant heterogeneity: except for scenario 2, the wholesale electricity price and the profit of the generator all decline in the other scenarios, while in scenario 2, the wholesale electricity price rises from about 2.56 to 3.62, and the profit of the generator rises from about 4.82 to 7.48, showing the characteristics of rising against the trend. The reason is that when green power is frequently out of supply, e-commerce sellers are more dependent on traditional thermal power compensation, and power producers gain stronger bargaining space by relying on supply guarantee ability. In general, the intermittent probability rise will reduce the system green investment and weaken the retail side income, but the technical cooperation scenario is still better than the independent decision-making mode in terms of investment maintenance and profit stability, indicating that the cooperation mechanism has a stronger buffer effect on physical volatility risk.

4.5 Analysis of synergistic effect and stability of cooperation mechanism

In the technical cooperation scenario, the cost sharing proportion directly affects the revenue distribution between the power generation provider and the electricity seller, and also determines whether the cooperation mechanism can operate stably for a long time. Figure 7 shows the changes of the total profit of the system and the profit of the members under different cost sharing ratios.

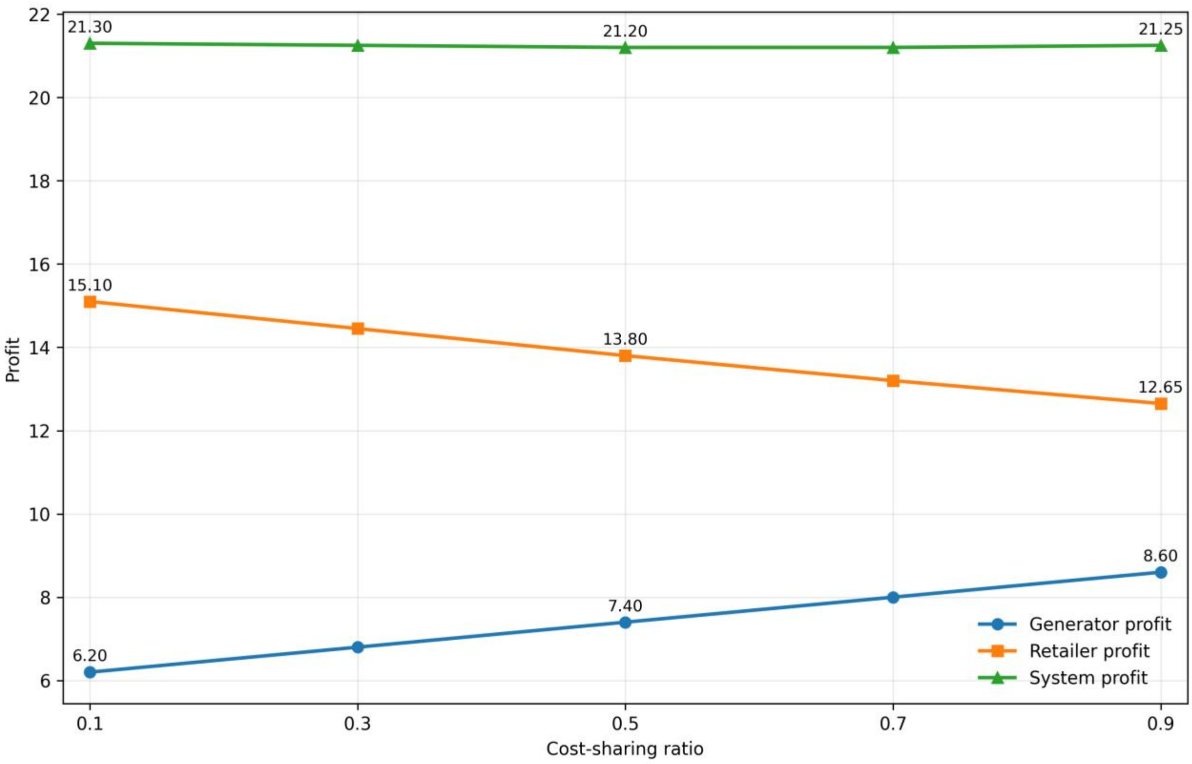

Figure 7: Changes of total system profit and member profit under different cost sharing ratios

It can be seen that as the burden ratio of the generator increases from 0.1 to 0.9, the profit of the generator continues to rise, while the profit of the electricity seller decreases synchronously, and the overall fluctuation of the total profit of the system is small. This indicates that the adjustment of cost sharing ratio is more reflected in the redistribution of cooperation benefits among members, and will not significantly change the overall synergy level under the technical cooperation mode. Specifically, the profit of power generators increased from 6.20 to 8.60, an increase of 38.71%; The profit of e-commerce sales decreased from 15.10 to 12.65, a decrease of 16.23%; The total profit of the system is always maintained between 21.20 and 21.30, and the maximum fluctuation is less than 0.5%. This indicates that technical cooperation can maintain the stability of system benefits in a large range, but there are obvious differences in the sense of gain of members under different sharing ratios.

Further comparison shows that when the cost sharing ratio is around 0.5, the profit of the power generator is 7.40, the profit of the electricity seller is 13.80, and the total profit of the system is 21.20. The profit gap between the two sides is relatively controllable, and the cooperation relationship is easier to maintain. If the share ratio is too low, the power generators will not bear enough responsibility, which may weaken their enthusiasm to participate in green investment. If the share ratio is too high, the profit of e-commerce is significantly compressed, which is not conducive to the continuous participation of downstream cooperation. In general, the key to technical cooperation is not to simply increase the profit of one party, but to seek a middle sharing interval that takes into account the interests of both parties on the premise of maintaining the stability of the total profit of the system. It can be seen that the cost sharing ratio is the core adjustment variable that affects the stability of cooperation, and setting the ratio reasonably is helpful to realize the dynamic balance between the supply chain collaboration benefits and the incentive of members.

5 Discussion

The numerical results show that, under the joint action of dual environmental policies and intermittent constraints, the investment decision of the power supply chain is no longer a cost-benefit calculation problem of a single enterprise, but a systematic allocation problem after the interweaving of three factors: policy incentives, physical fluctuations and cooperation structure. The increase of green certificate trading price and carbon trading price can improve the investment level of renewable energy, but the two types of policies have different impact paths on income distribution. The former is easier to enhance the revenue acquisition ability of the electricity sales side, and is transformed into a stronger green investment impetus through the cooperation mechanism. The latter will strengthen the advantages of carbon assets on the generation side, so that it can obtain higher marginal revenue under high carbon constraints. This shows that although the dual environmental policies both have the function of promoting green transformation, there are differences in the incentive centers formed within the supply chain. If there is no appropriate coordination mechanism, the policy effect may concentrate on a certain link, and then weaken the overall synergy efficiency.

The impact of intermittent constraints is more realistic. With the increase of the probability of intermittency, the return on renewable energy investment is weakened, the retail electricity price and the profit of the electricity sales side fall synchronously, and the green expansion ability of the system is significantly suppressed. It is worth noting that in the non-cooperative scenario of e-commerce investment, power producers obtain stronger bargaining space by relying on the traditional thermal power supply protection ability, and the wholesale electricity price and their own profits rise against the trend, indicating that physical risks will reshape the power distribution in the supply chain. It can be seen that after a high proportion of new energy access, supply stability is not only a technical issue, but also affects the game relationship between enterprises through price transmission and profit redistribution.

From the perspective of cooperation mechanism, technical cooperation shows better comprehensiveness in terms of investment promotion, profit maintenance and volatility buffer. Although full cooperation can maximize the total profit of the system, it often faces the constraints of high organizational integration cost and difficult contract execution in the real market. In contrast, technical cooperation realizes risk sharing through cost sharing, which is more feasible. The further cost sharing analysis shows that the total profit of the system is not very sensitive to the sharing proportion, but the profit of members will be significantly redistributed. Therefore, the key to the stability of cooperation is not the total profit scale, but whether the incentives of both sides are taken into account in the distribution interval. The subsequent research can further introduce dynamic demand, energy storage configuration and multi-agent competition factors to expand the analysis of cooperative stability boundary in more complex market environments.

6 Conclusion

Focusing on the renewable energy investment decision problem of power supply chain under dual environmental policy and intermittency constraints, this paper constructed a two-level supply chain game model including four scenarios: power supplier leading non-cooperation, e-commerce seller investment non-cooperation, technology cooperation and full cooperation. The market demand, thermal power compensation, carbon performance cost, green certificate performance cost and investment sharing mechanism are integrated into the unified analysis framework, and the equilibrium solution is obtained by using reverse induction and symbolic calculation method. Numerical experiments show that different cooperation depth will significantly change the investment level, price structure and profit distribution pattern. Full cooperation performs best at the system level. Compared with the non-cooperation led by power producers, the investment level is increased from 0.92 to 1.27, and the total profit of the system is increased from 0.88 to 1.26, indicating that centralized decision-making can more effectively coordinate the interests of upstream and downstream and release the potential of green investment. Although technical cooperation does not reach the system optimum of complete cooperation, it shows stronger practicability and robustness under realistic constraints.

The dual environmental policies both have the effect of promoting green investment, but the effect paths are obviously different. When the transaction price of green certificate increases, the investment level of scenario 2, scenario 3 and scenario 4 increases by about 16.8%, 34.1% and 27.0%, respectively, while scenario 1 decreases slightly, indicating that when the benefit of green certificate cannot be shared by investors, the investment incentive will be inhibited. In the cooperative scenario, the benefit of green certificate can be transformed into a stronger green expansion impetus through the internal conduction of the system. After the carbon trading price increases, the investment in the four scenarios shows an increasing trend, while the wholesale and retail electricity prices rise synchronously. In scenario 3, the profit of power generators increases from 12.75 to 16.08, with an increase of about 26.1%, and the profit of electricity sellers decreases from 6.45 to 5.90, indicating that the carbon market is more likely to strengthen the profit of carbon assets on the generation side, while the electricity sellers are under more obvious cost transmission pressure. It can be seen that the incentive effect of policy tools has link differences, and the higher the degree of supply chain coordination is, the easier the policy dividend is transformed into investment income at the system level.

The impact of intermittent constraints on the system is more complex. As the intermittency probability increases from 0 to 1, the renewable energy investment in the four scenarios generally declines, and the decline in scenario 2, scenario 3 and scenario 4 is about 23.6%, 28.6% and 29.7%, respectively. The retail electricity price also decreases simultaneously, indicating that the supply stability reduces the green investment return and the terminal willingness to pay. At the same time, the profit of the generator in the non-cooperative scenario of the e-commerce seller investment increased from 4.82 to 7.48, and the wholesale electricity price increased from 2.56 to 3.62, reflecting the bargaining strengthening effect of the traditional thermal power supply protection ability after the loss of green power supply. The cost sharing analysis under technical cooperation further shows that the total profit of the system is always maintained between 21.20 and 21.30, with a fluctuation range of less than 0.5%, but the profit of the power generator increases from 6.20 to 8.60, and the profit of the electricity seller decreases from 15.10 to 12.65, indicating that the key to the stability of cooperation is not the total profit of the system. It lies in setting the cost sharing ratio reasonably to keep the incentives of both sides in an acceptable range. In general, technical cooperation is a better choice to balance investment promotion, risk buffering and contract enforceability. In the future, the research can be further expanded in the environment of energy storage configuration, dynamic demand response and multi-agent competition.

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