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Research Article

Hybrid Power Generation Supply Chain Financing and Purchasing Strategies with Option Hedging against Disruption

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Environmental pollution has stimulated cleaner and sustainable energy (CSE) resource consumption which fuels low-carbon electric-power growth. This consumption is particularly affected by two factors. One of them is the power grid's capital size in the electricity supply chain (ESC) and the other is the carbon emission reduction level elasticity of electricity consumption. Further, the financial strategy directly exerts quantifiable influence on one of the factors of capital size, while the procurement strategy plays a role in another factor. However, the impact of strategic behavior on all participants in the ESC remains unexplored. Thus, we construct a game model for the ESC consisting of two heterogeneous power plants and a strategic power grid with financial constraints, in order to analyze the purchasing and financing strategies for low-carbon electric-power consumption and examine the profit scenario from the credit and option hedging. We find that for the power grid, high self-owned funds level or affluent credit line encourages procurement. And when considering the power grid funds are uniformly distributed on or are constant, this funds property variation surely imposes influence on the wind electricity purchases. We find price elasticity of demand shows monotonic on the purchase when the power grid funds are constant but not necessarily when funds are uniformly distributed. The two power plants pursue the most favorable scenario for profit-maximizing by means of credit interest rate. Whether the power plants increase the financial credit interest is contingent upon option portfolios, the grid's fund property, and wind yield conditions. We also find whether the relations between the two power plants are competitive or complementary depending on the wind yield rate. Numerical study shows that when the power grid funds are uniformly distributed, executing the double option seems to be the most profitable choice for the power grid and the traditional energy power plant, whereas with the uniform distribution of the grid's funds, executing the call option but abandoning put is the most profitable to the traditional energy power plant. Moreover, under the grid's fund of uniform distribution, it can both motivate power user consumption for clean energy generation and expand the power grid's capital size.

1. Introduction

Clean and sustainable energy power generation has greatly reduced carbon emission pollution. In recent years, wind power generation presents a large-scale development trend: the installed capacity of wind electric power has increased by about 100% in recent three years: in terms of single unit capacity, 2~3 MW wind turbines have been put into commercial operation, 5~6 MW wind turbines have completed technical development, and above10 MW wind turbines are under research and development. However, when the wind is insufficient, the electric-power plant cannot generate electricity conventionally, which will lead the electricity industry to partially out of action, hence following with huge losses to the power grid and power users downstream. Although CSE power generation helps reduce carbon emissions, intermittence restricts the large-scale use of CSE for the power generation industry. Traditional energy provides a sustainable supply, nonetheless accelerating carbon emissions and deteriorating environmental pollution [1]. The power grid adopts the dual source procurement from two types of power plants. When CSE power generation achieves sustainable supply [2], CSE power generation from the wind power plant is preferred. When CSE supply is cut off, the power grid exercises the option contract to purchase power from the traditional power plant who works as the backup supplier [3] and [4].

In addition, financial behavior between upstream and downstream enterprises in the supply chain is one of the hotspots in the research field of supply chain finance. In the electric-power supply chain, the downstream power grid executes dual purchases from two power plants, and the dual-source procurement strategy may give rise to CSE supply disruption risk. The self-owned fund's deficiency in the power grid inspires financing requirements. So, the grid's capital budget and distribution property, combined with the risk hedging strategies in different scenarios Kaufmann et al. [5], have a practical impact on the power grid's procurement decision. Further, since the two types of electric-power plants optimize decision-making on the premise of observing the follower's optimal strategy, the fund property and option hedging will also affect the plants' financing decision by the power grid procurement decision.

Based on the ESC enterprise development in China, the following research questions are proposed: Motivated by the emergence of green electricity financing, a new business model is enabled by financial derivatives options. In this paper, we aim to study the operational mechanism behind the disruption risk hedged against by options under supplier financing, explore the impact of risk hedging and financing schemes on green electricity supply chain operations, and provide management suggestions that could guide the decision-making in practice. Therefore, we focus on the following questions: (1) For the power grid, is it always motivated to hedge against risk arising from CSE intermittence by double option? (2) For the power plant *with traditional energy*, does the power plant always benefit from providing supplier financing under different options strategies? (3) For the generating plant *with* CSE, does the power plant always benefit from providing supplier financing under different option portfolios? (4) How does the introduction of the power grid's working capital property affect the three participants' operational or financial decisions in the supply chain? To answer these questions, we develop a game-theoretic model, and focus on the cases where the power grid's working capital is constant or uniformly distributed, respectively; we specifically examine participants' operational and financial strategies and the corresponding equilibrium profit in the face of the gird's financial constraint.

The main contributions of the study are as follows:

(i) Jointly considering the capital property and option hedging impacts on participants' strategies.

(ii) Introducing that the capital is uniform distribution into the ESC supply chain.

(iii) Considering double option to hedge against energy supply intermittence when the power plants provide supplier financing.

On this basis, we further investigate CSE intermittence and disruption risk with options hedging, in which case the traditional energy electricity plant acts as both the creditor and the option seller. We then examine the changes in the power grid's working capital, as well as the interest rate of each power plant. The rest of this paper is organized as follows. We first review the related literature in Section 2. In Section 3, we introduce our model and picture of the problem statement, assumption notation (sets (indices), parameters, decision variables), and all formulation solution approach. Section 4 investigates the results for the model under respective scenarios. Section 5 investigates the managerial insights and practical implications. In Section 6, we make managerial insights and practical implications. Finally, we draw conclusions and outlook in Section 7.

2. Literature Review

Our work is primarily connected with three streams of research: the literature on option hedging, the literature on supply chain finance, and the ESC operational strategy.

2.1. Option Hedging. Such literature mainly studies the retailers' optimal procurement decision, establishes models, and designs contracts under different conditions. Schummer and Vohra [4] analyzed a set of options contracts, built a model, and formulated the optimal procurement strategy, but the defect of the model is ignoring the spot market. Ritchken and Tapiero [3] established the purchase model with an option contract and considered the derivative market intersection with the spot market. This paper extends its option model to discuss the coexistence of the derivative market and spot market under supply disruption risk. Wu [6] used the method of the Nash game to analyze the optimal purchase quantity of retailers, the option premium, and the striking price of suppliers. But it assumed that supply in the spot market was infinite, which was different from this paper. For the reason of CSE intermittence, this article assumed that supply disruption was in the power spot market when using CSE for power generation. Similarly, Spinler et al. [7] and Golovachkina and Bradley [8] also analyzed this game based on the purchase model. Moreover, Martinez et al. [9]and Wu et al. [6, 10] extended the traditional purchase model to the coexistence of option and spot based on the Nash game. From the view of the power grid, this paper maximizes the expected profit of enterprises in the ESC by establishing a purchase model based on an option contract and spot market with constraint supply. Further, Fu et al. [11] studied and solved the risk management model in a purchase based on an options portfolio contract and spot market with unconstraint supply, but did not study the possible shortage in the spot market. This paper focuses on the analysis of how the power grid should optimize the purchase strategy under the options portfolio hedging contract when there is a supply disruption in the power spot market. It also analyzes factors such as the impact of power grid financial constraints, different power plants' credit loan interest rates, and power users' preference for CSE on the optimal purchase, providing guidance for power grid decision-making. Tomlin [12] studied the emergency effect of dual source procurement strategy, emergency inventory strategy, and multi-product flexible ordering strategy when suppliers have supply disruption. Cachon and Zhang. [13]studied the optimal option contract design under the condition that the supplier's production cost is used as public information, while that for the demand is as private. Li and Liu [14] specifically gave solution for the optimal dynamic trading strategy between a riskless asset and a risky asset with momentum. The dynamics models reflect the long-term projections variability and are well-suited for financial applications where long-term demographic uncertainty is relevant [15].

Most of these studies take an empirical approach to examine the option design and its impact on the supply chain, nevertheless, they merely land on disruption risk in the supply chain rather than on credit, or low-carbon requirements. In contrast, we adopt a modeling approach to explore the heterogeneous power plants' motivations to provide credit with strategic interest rates and the intentions of power gird to option design. Furthermore, given strategic interest rates and various option portfolios, our model deeply investigates the grid's reflection on the credit strategy considering the grid's funds property. And because of the assumption that the grid's fund is uniform distribution and also option hedging selection assumption, which will influence the leading factors to electricity consumption, we will proclaim the transmission mechanism of participants' decision effects on electricity consumption in ESC. And thus, our paper could be more conducive to providing suggestions for the sustainable development of ESC with supplier credit and option hedging against disruption risk.

2.2. Supplier Finance. Our study is also closely related to the literature on SCF. For example, Srinivasa Raghavan and Mishra [16] discussed the lender's decision on the number of loans to enterprises. In Gong and Chao's (2014) [17] study, retailers with capital constraints could obtain short-term financing. Kouvelis and Zhao (2016) [18] studied the coordination of the supply chain with bank loan (BL) participation. Only BL is available in the above models. In addition, trade credit (TC) is also a common financing method [19]. Chen and Wang [20], Yu , as well as Yang et al. [21]studied the impact of TC on enterprises' operational decisions. In comparison, Yang et al. [22] and Hosseini-Motlagh et al. (2018) [23] introduced competition into the retail market in which retailers solve financial distress through TC. Kouvelis and Zhao (2012) [24] focused on the optimal TC structure, but the supplier in their model allows the retailer to delay partial payment until demand is realized. Researches of Tunca and Zhu (2018) [25] and Deng et al. (2018) [26]were different from many previous studies on TC, which mainly focused on retailer capital constraints. They highlighted the role of buyer finance to address the supplier's financial needs. Kouvelis and Zhao (2018) [27]. (2019). Nguyen et al. (2019) [28] analyze the energy efficiency (EE) investment decisions with the manufacturer as the debtor who competes with an alternative supplier in order for business from a large industrial buyer and find some interesting results that assessment assistance helps reduce the EE gap but procurement commitment eliminates it.

All these papers discuss wholesale price contracts with supplier financing without considering the buyer's capital property. In contrast, we consider supplier financing under two scenarios, in one of which the buyer's working capital is constant and the other is the buyer's capital is uniformly distributed. A key feature of the buyer's working capital is that it derives different impacts on purchases. The traditionally related researches only involve the impact of the capital budget on purchasing decision but does not refer to the option hedging and the option selection influence on carbon emission reduction level, which is the leading factor in electricity consumption. Till so far, our model firstly discusses how options strategies determine the carbon emission reduction level embedded in the demand function. Even if some funds property expands the budget and inspires the electricity demand, it cannot encourage the power grid to purchase wind power radically. As a debtor, the power grid should also evaluate the disruption risk arising from wind intermittence, and then determine the optimal wind power procurement strategy under different option hedging. Compared to the existing literature ignoring the fund property and option strategy impacts on decision-making, this paper analyzes the influence of the two factors in detail, establishes decision-making models in four different scenarios, and discusses the influence of key parameters on each participant. Overall, our study provides certain guidelines for the power grid, the power plant with traditional energy, and the power plant with CSE. Crane et al. [29] Funds employ a wide range of strategies for acquiring public filings. Those that systematically scrape large volumes of information, specialize in certain filing types, acquire filings with more content changes, or access information immediately outperform other funds. C. C. Blanco [30] This study classifies 16,525 implemented carbon abatement projects using text analysis, and results show that latent classes exist and statistically differ in the sense of metrics they examine.

The research contribution is as follows:

(i) Using a Stackelberg game to evaluate optimal strategies of ESC participants.

(ii) Applying option portfolio to hedge against CSE supply disruption and discuss the impact of the options on carbon emission reduction level, which is one of the leading factors in electricity consumption.

(iii) Considering the power grid's funds may conform to a uniform distribution, combined with financing strategy and options portfolio, we investigate funds' property impact on electricity consumption under different scenarios.

2.3. Research Gap. The pieces of supply chain research literature considering SCF and options strategies are listed in Table 1, and the research aspects involved in the literature are summarized.

Table 1: Literature review.

	Option policy						SCF				
	Option contracts	Option hedge against disruption	Extended procurement model	Capital constraints	Dual source procurement	With information asymmetry	SCF strategy	BL&TC	Retailer financing	Clean energy supply intermittence	Fund property
[14, 15]	√	√	√								
[4]	√										
[3]	√	√									
[6–8]	√	√									
[6, 10]		√	√								
[11]	√	√		√							
[12]		√			√						
[13]	√					√					
[16, 17]							√				
[9, 18–22]				√			√	√			
[22, 27]									√		
[23–28]				√			√		√		
[31–34]				√			√			√	
[29, 30, 35–37]				√			√				√
This study	√	√	√	√	√		√	√		√	√

3. Problem Statement

3.1. Model Description. Take wind as the representative clean energy input to generate electricity, taking the wind power plant as the strategic supplier and the traditional energy power plant as the backup supplier, respectively. Both plants generate electric power to the power grid, who transmits electricity to its downstream users. If the power grid has financial constraints, both plants are willing to provide supplier financing.

The decision model introduces a power option contract to deal with wind supply disruption risk. For one thing, when the power grid start-up the backup supplier-that is the traditional power plant performs the consignment obligations under a low wind yield level, and the carbon emission reduction level for the whole supply chain reduces to L_2, which is lower than the carbon emission reduction level L in the previous purchase plan. So, the electric-power purchase quantity is adapted correspondingly. For another, when the wind yield rate is high, the power grid procurement strategy can be set divided into two scenarios: dual-source electric-power procurement or executing the put option to withdraw the traditional energy power order in exchange for electric-power all from the wind power plant. However, when executing the put option, the carbon emission reduction level L_1 that can be achieved by wind power generation is higher than L anticipated in the original procurement plan. Because L directly impacts demand, the power purchase quantity varies correspondingly compared with the quantity in the original procurement plan.

The decision of participants in the power supply chain can be made under four scenarios: The self-owned capital k of the power grid is constant only when executing call options; The self-owned capital k of the power grid is constant when executing both call and put; The self-owned funds of the power grid and power users are uniform distribution when the power grid only executes the call option; The self-owned funds of the power grid and the funds of power users are uniform distribution when the power grid executes both call and put. The model structure is shown in Figure 1.

3.2. Problem Assumptions

(i) Wind supply is intermittent. The actual wind yield is a certain probability distribution of $\begin{cases} 1, & v, \\ 0, & 1-v. \end{cases}$ $v \in (0,1)$ and is a random variable for the uncertainty of wind energy. The power output is available with probability v and is unavailable with probability $1-v$. Sam and Serguei (2017) [31], Tomlin and Wang (2005) [32], Ambec and Crampes (2012) [33];

(ii) Considering the power grid funds property can be divided into two scenarios: One is that the self-owned capital is constant for k, and the other is that the capital is uniformly distributed on $U \sim (0, (1/\alpha))$.

(iii) The electricity demand function adopts a linear form $q = A - \alpha p + \beta L$. When the wind yield rate is low, the carbon emission reduction level is L_2. When the wind yield rate is high, the level turns to be L_1, and $L_1 > L > L_2$.

In this section, we have described the problem indices. We will examine the problem decision variables, parameters, and problem primitives, all of which are shown in Tables 2–5:

We will provide the mathematical model of the research as follows:

The wind power plant decides the commercial credit interest rate r_w. As the leader of the Stackelberg game, he can observe the optimal wind power ordering decision Q_w^* and the optimal credit strategy r_G^*. Here, both commercial credit rate r_w and r_G are the dependent variable of Q_w. Considering such influential factors as the probability of wind, and wind intermittent, the power grid adopts different options and strategies to hedge the supply disruption risk.

(i) The power grid's purchasing strategy

The power grid executes the call option under dual purchase.

(ii) When wind is insufficient

The power grid purchases electricity from two heterogeneous energy power plants. The power grid plans to purchase electricity Q_w from the wind power plant. The total power purchase quantity can be written as the multiple forms of Q_w, which is δQ_w. Then it is planned to purchase electricity from traditional power plants $Q_{G2} = (\delta - 1)Q_w$.

If the wind power supply is cut off due to the wind being insufficient, that is $Q_w = 0$, the power grid must execute the call option. The power grid purchases power from the traditional energy power plant. In this case, the working capital of the power grid is expressed as its own capital with a constant k, not related to the funds of the downstream users. If the power grid purchases a double option, the sum of total expenditure for the power grid includes the total electric-power purchase cost and option premium. Considering that the self-owned funds of the power grid are not enough to pay for all the purchases, financial behavior is required in the power purchase process. The financing limit is provided by the upstream power plant (the creditor) is B_{G2}. The power grid (the debtor) as the follower in the Stackelberg game cannot observe the decisions of the leader and subleader by the reverse induction method, and the financing interest rate r_G is regarded as a given constant. Then the profit function of the power grid is

$$\pi_{R1}(Q_{G2}) = -k + pq - (1 + r_G) \cdot B_{G2}. \tag{1}$$

Call option executing under low wind yield will increase the procurement from traditional energy power generation. This causes more traditional energy consumption with high levels of carbon emission. Therefore, the carbon emission reduction level reduces from L to L_2. The carbon emission reduction level will affect the power market demand. The

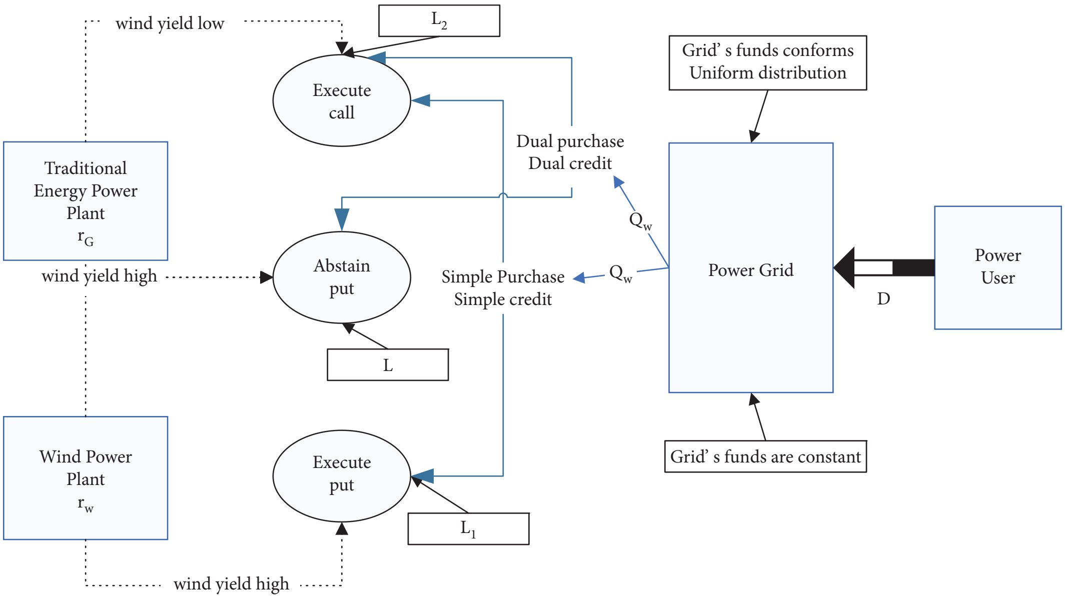


Figure 1: Supply chain participants' decisions under different option hedging with varied funds property of the grid.

Table 2: Subscripts and superscripts.

Subscripts and superscripts	Description
w, G, R	The renewable type of plant, the traditional type of plant, the gird
w, g	Direct financing from renewable tydslupe plants, direct financing from a traditional type plant

Table 3: Decision variables.

Decision variables	Description
r_w	Supplier financing interest from the renewable energy type of plant
r_G	Supplier financing interest from the traditional energy type of plant
Q_w	Induced order quantity under the renewable type generation

total amount of power procurement decreases to $Q_{G2} + Q_w - \beta(L - L_2)$. Therefore, the power grid profit function is

$$\pi_R(Q_w) = p[q - \beta(L - L_2)] - k - (1 + r_G) \cdot B_{G2}. \tag{2}$$

The power grid credit line is $B_{G2} = w_2[q - \beta(L - L_2)] + w_7(R_1 + R_2) - k$, $B_{G2} > 0$ is the constraint condition. Among them, $q = Q_w + Q_{G2} = \delta Q_w, \delta > 1$. Therefore, when the power grid finds Q_w through the optimization process, the total purchase amount δQ_w can be obtained accordingly. Then q is obtained.

(i) When wind is sufficient

The power grid abstains from the put option and sticks to the dual source purchasing, which leads to an additional loss of the option premium. Otherwise, the power grid plans to purchase power Q_w from the wind power plant, and $\dot{Q}_{G1}$ from traditional power plants. On-grid price of new energy power plants is represented by wind power generation w_1. In this case, the self-owned capital of the power grid is a constant presented by k. Since p and L in the demand are exogenous variables, given p and L, the power market demand can be determined following this equation: $q = A - \alpha p + \beta L = \vartheta Q_w$, and the retail price of electricity is $p = (A - q + \beta L/\alpha)$. Therefore, the electricity purchased from traditional energy power plants time is $\dot{Q}_{G1} = (\vartheta - 1)Q_w, \vartheta > 1$. Since the power grid has not adjusted the proportion of wind power, the carbon emission reduction level is still L, and the market electricity demand remains unchanged in this scenario.

Here, considering that the self-owned funds of the power grid are insufficient, the power grid can borrow from the two types of power plants respectively. The two power plants will formulate their financing interest rate strategies which amount to the power grid's financing cost. The credit line from the traditional energy power plant is $\dot{B}_{G1} = w_2\dot{Q}_{G1} - k_G = w_2(\vartheta - 1)Q_w + w_7(R_1 + R_2) - k_G$. The power grid will pay for part of the purchase funds k_G to power plants in advance, $k_G = gk$, whereas the balance payment will delay to pay. In addition, the credit line from wind power plants is $\dot{B}_w = w_1 Q_w - k_w$. It pays part of the purchase funds k_w to the wind power plant in advance, and $k_w = (1 - g)k$. We use inequality $\dot{B}_{G1} + \dot{B}_w > 0$ to show the power grid's financial constraints. Therefore, when the power grid finds the

Table 4: Problem primitives.

Problem primitives	Description
w_1	The wholesale price offered by the renewable energy type of electricity plant, which also is the strike price of the put option
w_2	The wholesale price offered by the traditional energy type of electricity plant, which also is the strike price of a call option
w_7	The option premium
p	Electricity retail price
δ	The coefficient of total order quantity with respect to wind power generation whose capital is constant when the wind is unavailable and the call option is exercised
ϑ	The coefficient of total order quantity with respect to wind power generation whose capital is constant when the wind is available and only the call option is exercised
τ	The coefficient of total order quantity with respect to wind power generation whose capital is constant when the wind is available and call and put options are both exercised
δ_1	The coefficient of total order quantity with respect to wind power generation whose capital is uniform when the wind is unavailable and the call option is exercised
ϑ_1	The coefficient of total order quantity with respect to wind power generation whose capital is uniform when the wind is available and only the call option is exercised
τ_1	The coefficient of total order quantity with respect to wind power generation whose capital is uniform when the wind is available and call and put options are both exercised
w_7	Option premium
$\alpha\beta A$	Price elasticity of electric user demand/who's reciprocal cap on electricity users' funds carbon emission reduction level elasticity of electricity user demand electricity users spontaneous demand
c_1	Climbing and start-up costs
c_2	Power generation operation and energy procurement costs
c_3	Service cost for normal operation and maintenance of wind turbines
L	The carbon emissions reduction level
L_1	The carbon emissions reduction level when exercising the put option and replenishment wind energy electricity
L_2	The carbon emissions reduction level when exercising the call option and replenishment of traditional energy electricity
k	The grid's working capital
g	The payment proportion for the traditional type of plant when the grid makes electricity procurement ordering
k_G	A part of the grid's working capital paid for the procurement from the traditional type of plant
k_w	A part of the grid's working capital paid for the procurement of renewable types of plant
R_1	The call option's quantities
R_2	The put option's quantities
D	Demand
w_1	The wholesale price offered by the renewable energy type of electricity plant, which also is the strike price of the put option
w_2	The wholesale price offered by the traditional energy type of electricity plant, which also is the strike price of a call option

Table 5: Variables introduced during analysis.

Variables introduced during analysis	Description
q	The total order quantity before the actual wind availability is observed
B_w	Direct financing amount from the wind generation plant
B_G	Direct financing amount from the traditional generation plant
Q_G	Induced order quantity under traditional type generation

optimal solution for Q_w, the total purchase amount ϑQ_w can be obtained accordingly. Then $\dot{Q}_{G1}$ is further obtained from $\dot{B}_{G1}$. Therefore, the power grid profit function is

$$\pi_{R1}\left(Q_w, \dot{Q}_{G1}\right) = -k + pq - \left(1 + r_G\right) \cdot \dot{B}_{G1} - \left(1 + r_w\right) \cdot \dot{B}_w. \tag{3}$$

(i) Under the dual source power procurement where the power grid only executes the call option, the profit for the power grid is

$$\pi_{R-1} = (1 - \nu)\pi_R\left(Q_{G2}, Q_w\right) + \nu\pi_R\left(\ddot{Q}_{G1}, Q_w\right), \tag{4}$$

$$\text{s.t. } B_{G2} \geq 0, \tag{4a}$$

$$\text{s.t. } \dot{B}_w \geq 0, \tag{4b}$$

$$\text{s.t. } \dot{B}_{G1} \geq 0, \tag{4c}$$

$$\text{s.t. } \pi_w\left(r_w\right) > 0. \tag{4d}$$

The power grid performs the option seller's obligations under the double option exerted.

(ii) When the wind power is insufficient

The power grid profit function is

$$\pi_R(Q_w) = p[q - \beta(L - L_2)] - k - (1 + r_G)\cdot B_{G2}. \tag{5}$$

Here, wind energy is abundant and the wind power generation exceeds the order quantity. In this situation, the power grid chooses to execute the put option, withdrawing the preceding order and changing to repurchasing more wind electric power. This can not only make better use of abundant CSE but also improve the carbon emission reduction level, which can better meet the power market demand for a strong preference for CSE generation.

In this case, the demand $q = A - \alpha p + \beta L = \tau Q_w$. Therefore, the retail price of electricity can be rewritten as $p = (A - q + \beta L/\alpha)$. The self-owned funds of the power grid are not enough to pay all the orders, so the grid as debtor applies for the credit line from the upstream traditional energy power plant, which is $\ddot{B}_{G1}$. Since additional wind power plant orders will substitute for the traditional energy order, it will promote the carbon emission reduction level to L_1. Then the total power procurement increases by $\beta(L_1 - L)$. Because exercising the put option causes us to buy back the preceding traditional energy power, then we have $\ddot{Q}_{G1} = 0$, and $\ddot{B}_{G1} = 0$. Here, the profit function of the power grid is

$$\pi_{R1}\left(Q_w, \ddot{Q}_{G1}\right) = -k + p[\tau Q_w + \beta(L_1 - L)] - (1 + r_w)\cdot \ddot{B}_w. \tag{6}$$

When executing a double option portfolio, the weighted average profit of the power grid is

$$\begin{aligned}\pi_{R-1} &= (1 - \nu)\pi_R(Q_{G2}, Q_w)\\ &\quad + \nu\pi_R\left(\ddot{Q}_{G1}, Q_w\right),\end{aligned} \tag{7}$$

$$\text{s.t. } B_{G2} > 0, \tag{7a}$$

$$\text{s.t. } \ddot{B}_w \geq 0. \tag{7b}$$

(i) The traditional energy power plant's financing strategy

Traditional energy power plants need to pay equipment operation and maintenance costs and power generation energy procurement costs. Considering different option contract execution strategies from the power grid, the profit function of traditional energy power plants should also be weighted average in the light of wind yield rate.

The power plant performs the call option seller's obligations under dual purchase.

When the wind is insufficient, the profit function of the traditional energy power plant is as follows:

$$\pi_{G-C}(r_G) = k_G + (1 + r_G)\cdot B_{G2} - (c_1 + c_2)Q_{G2}. \tag{8}$$

Among them, the prepaid part $k_G = gk$ and the credit line here is $B_{G2} = w_2[q - \beta(L - L_2)] + w_7(R_1 + R_2) - k$.

(i) When the wind is sufficient

When the power grid abandons the put option while the wind yield rate is high, the profit function of the traditional energy power plant is as follows

$$\begin{aligned}\pi_{G-N}(r_G) &= k_G + (1 + r_G)\cdot \dot{B}_{G1}\\ &\quad - (c_2 + c_1)\cdot \dot{Q}_{G1}.\end{aligned} \tag{9}$$

From them, we have. $\dot{Q}_{G1} = (\vartheta - 1)Q_w$

The weighted average profit of the traditional energy power plant is

$$\begin{aligned}\pi_{G-1} &= (1 - \nu)\pi_{G-C}(Q_{G2}, Q_w)\\ &\quad + \nu\pi_{G-N}\left(\dot{Q}_{G1}, Q_w\right),\end{aligned} \tag{10}$$

$$\text{s.t.} B_{G2} > 0, \tag{10a}$$

$$\text{s.t.} \dot{B}_{G1} > 0. \tag{10b}$$

The power plant performs as the call option seller under the double option exerted.

(i) When the wind is insufficient

n this part, the traditional energy power plant profit function is the same as the function (8).

(ii) When the wind is sufficient.

Here, when the power grid executes the put option, the power plant repurchases all power orders. The traditional energy power plant shall stock energy to fulfill the original power order $\ddot{Q}_{G1} = (\tau - 1)Q_w$, but there still has c_2 cost even if the grid buys backorders. However, there are no start-up and climbing costs. Therefore, the profit of the energy power plant is the sum of the income of the option fee minus some costs and fees such as the expenditure of raw materials, operational costs, and maintenance costs. The profit function is

$$\begin{aligned}\pi_{\text{put}}(r_G) &= w_7(R_1 + R_2) - c_2\ddot{Q}_{G1}\\ &= w_7(R_1 + R_2) - c_2(\tau - 1)Q_w.\end{aligned} \tag{11}$$

The weighted average profit of the power plant is $\pi_{G-2} = (1 - \nu)(\pi_{\text{cal}}) + \nu(\pi_{\text{put}})$.

(iii) The wind power plant's financing strategy

The setting of r_w will also be affected by the option strategy. According to the decision-making process of the Stackelberg game, the decision sequence of each participant is as follows: wind power plant takes the lead in determining commercial credit interest rate r_w through observation r_G^* and Q_w^*, then given r_w the traditional energy power plant determines credit interest rate r_G by observing the power grid procurement strategy Q_w^*. Finally, the credit interest rate strategy r_w and r_G, the power grid determines the wind power procurement strategy Q_w.

(iv) Only call option transaction is exerted under dual purchase

(v) When the wind is insufficient

With low wind yield, the wind power supply is disrupted, $Q_w = 0$, and the wind power plant has no yield or profit.

(vi) When the wind is sufficient

The wind power plant generates electric power according to the previous procurement plan. The plant profit is

$$\pi_w(r_w) = k_w + (1 + r_w)\dot{B}_w - c_3 Q_w, \tag{12}$$

$$\text{s.t. } \pi_w(r_w) > 0, \tag{12a}$$

$$\text{s.t. } \dot{B}_w > 0. \tag{12b}$$

Here, $\dot{B}_w = w_1 \cdot Q_w - k_w$, $k_w = (1 - g)k$.

(vii) When the power supply chain enterprise executes the put option transaction, the profit of the wind power plant is

$$\pi_{w-1}(r_w) = v\big(k_w + (1 + r_w) \cdot (w_1 \cdot Q_w - k_w) - c_3 Q_w\big). \tag{13}$$

The wind power plant performs as put option transaction seller under double option exerted

(viii) When the wind is insufficient

With low wind yield, the wind power supply is disrupted. The wind power plant has no yield or profit.

(ix) When the wind is sufficient

The wind power plant generates electric power according to the original procurement plan. Due to the wind energy particularity, the acquisition cost of wind energy is almost zero. However, wind power generation will produce the service cost of maintaining the normal operation and maintenance of wind turbines c_3. The wind power plant profit is

$$\pi_w(r_w) = k_w + (1 + r_w)\dot{B}_w - c_3 Q_w, \tag{14}$$

$$\text{s.t. } \pi_w(r_w) \rangle 0, \tag{14a}$$

$$\text{s.t.} \dot{B}_w > 0, \tag{14b}$$

here, $\dot{B}_w = w_1 \cdot Q_w - k_w$, $k_w = (1 - g)k$.

When the power supply chain participant executes the put option transaction, the weighted average profit of the wind power plant is

$$\pi_{w-1}(r_w) = v\big(k_w + (1 + r_w) \cdot (w_1 \cdot Q_w - k_w) - c_3 Q_w\big). \tag{15}$$

It can provide more electricity than the original order. The traditional energy power plant sells the put option and purchases additional power from the wind power plant when the put option is executed. The wind power plant undertakes all power generation, and the number of wind power orders is updated to $\tau Q_w + \beta(L_1 - L)$, and $\ddot{B}_w = w_1 \cdot (\tau Q_w + \beta(L_1 - L)) - k$.

$$\pi_w(r_w) = k + (1 + r_w)\ddot{B}_w - c_3\left[Q_w + \beta(L_1 - L)\right], \tag{16}$$

$$\text{s.t.} \ddot{B}_w > 0. \tag{16a}$$

When executing the put option, the weighted average profit of the power grid is

$$\pi_{w-2} = v\big(k + (1 + r_w)B_w - c_3\left(\tau Q_w + \beta(L_1 - L)\right)\big). \tag{17}$$

(i) The Power Grid's Purchasing Strategy

the power user is downstream against the power grid. It is assumed that the user's funds y is of the uniform distribution.

$$f(y) = \begin{cases} (1/(1/\alpha)) = \alpha, & 0 < y < (1/\alpha), \\ 0, & \text{else}, \end{cases}$$

$$F(y) = \begin{cases} \alpha y, & 0 \le y \le (1/\alpha), \\ 1, & y > (1/\alpha). \end{cases}$$

The power grid funds come from the power users with regular payments for electricity bills. It is assumed that the number of users with power demand in the market is standardized as 1(Tian et al., 2018 [34]; Abhishek, 2016 [35]; Gao et al., 2015 [36]; Xie et al., 2021 [37]). Then the self-owned funds x for the power grid are related to the funds of its downstream users and also conform to a uniform distribution, $f(x) = \begin{cases} \alpha, & 0 < x < (1/\alpha), \\ 0, & \text{else}, \end{cases}$ $F(x) = \begin{cases} \alpha x, & 0 \le x \le (1/\alpha), \\ 1, & x > (1/\alpha). \end{cases}$

Therefore, the self-owned funds of the power grid are $\int_0^{(1/\alpha)} x(\alpha)\mathrm{d}x = (1/2\alpha)$, Market demand is affected by electricity price p, carbon emission reduction level L and consumer capital level y.

(ii) Only Executes the Call Option

(iii) When the wind is insufficient

The capital of the power grid is related to the capital of downstream power users. So, the profit of the power grid is

$$\pi_R(Q_w) = p[q - \beta(L - L_2)] - k - (1 + r_G) \cdot \overline{B}_{G2}, \tag{18}$$

$$\text{s.t. } \overline{B}_{G2} > 0, \tag{18a}$$

where $\overline{B}_{G2} = w_2[q - \beta(L - L_2)] + w_7(R_1 + R_2) - (1/2\alpha)$, $\delta_1 Q_w = Q_w + \overline{Q}_{G2}$, $(\delta_1 > 1)$. So, $\overline{Q}_{G2} = (\delta_1 - 1)Q_w$.

(iv) When the wind is sufficient

$$\pi_{R1}(Q_w, \overline{Q}_{G1}) = -k + pq - (1 + r_G) \cdot \overline{B}_{G1} - (1 + r_w) \cdot \overline{B}_w, \tag{19}$$

$$\text{s.t. } \overline{B}_{G1} > 0, \tag{19a}$$

$$\text{s.t. } \overline{B}_w > 0, \tag{19b}$$

where $\overline{B}_{G1} = w_2\overline{Q}_{G1} - k_G = w_2(\vartheta_1 - 1)Q_w + w_7(R_1 + R_2) - k_G$, $k_G = g\int_0^{(1/\alpha)} x(\alpha)\mathrm{d}x, g < 1$, credit line supplied by the wind power plant is $\overline{B}_w = w_1 \cdot Q_w - k_w$, where $k_w = (1 - g)\int_0^{(1/\alpha)} x(\alpha)\mathrm{d}x$ and $\overline{Q}_{G1} = (\vartheta_1 - 1)Q_w$. The total amount of procurement plan formulated by the power grid is $q = A - \alpha p + \beta L = \vartheta_1 Q_w, \vartheta_1 > 1$. The weighted average profit of the power grid is

$$\pi_{R-\mathrm{U1}} = (1 - \nu)\pi_R(\overline{Q}_{G2}, Q_w) + \nu\pi_R(\overline{Q}_{G1}, Q_w), \tag{20}$$

$$s.t.\overline{B}_{G2} > 0, \tag{20a}$$

$$s.t.\overline{B}_w > 0, \tag{20b}$$

$$s.t.\overline{B}_{G1} > 0. \tag{20c}$$

(v) The Power Grid Executes Double Option

When the wind power is insufficient, the power grid profit is the same as that in equation (18).

When wind energy is abundant

If the power generation exceeds the order quantity. The power grid purchases and exercises put options from the traditional power plant. All funds can be used to purchase CSE power, to remission carbon emissions under the current budget. The total procurement quantities are still set in multiple forms of Q_w. $\tau_1 Q_w = Q_w + \overline{\overline{Q}}_{G2}, \tau_1 > 1$, then the power grid's profit is

$$\pi_{R1}\left(Q_w, \overline{\overline{Q}}_{G1}\right) = -k + p\left(\overline{\overline{Q}}_{G1} + Q_w\right), - (1 + r_w) \cdot \overline{\overline{B}}_w \tag{21}$$

$$\text{s.t. } \overline{\overline{B}}_w > 0, \tag{21a}$$

where $\overline{\overline{B}}_w = w_1 \cdot [Q_w + \overline{\overline{Q}}_{G1} + \beta(L_1 - L)] - k = w_1(\tau_1 Q_w + \beta(L_1 - L)) - (1/2\alpha)$

The weighted average profit of the grid is

$$\pi_{R-\mathrm{U2}} = (1 - \nu)\pi_R\left(\overline{\overline{Q}}_{G2}, Q_w\right) + \nu\pi_R\left(\overline{\overline{Q}}_{G1}, Q_w\right), \tag{22}$$

$$\text{s.t. } \overline{B}_{G2} > 0, \tag{23}$$

$$\text{s.t. } \overline{\overline{B}}_w > 0. \tag{24}$$

(i) The Traditional Energy Power Plant's Financing Strategy

The power plant performs the seller's obligations under dual purchase.

When the wind power is insufficient, the profit function for the traditional energy power plant is

$$\pi_{G-\mathrm{UC}}(r_G) = x + (1 + r_G) \cdot \overline{B}_{G2} - (c_1 + c_2)\overline{Q}_{G2}, \tag{25}$$

$$\text{s.t. } \overline{B}_{G2} > 0, \tag{25a}$$

where the credit line is $\overline{B}_{G2} = w_2(\delta_1 Q_w - \beta(L - L_2)) + w_7(R_1 + R_2) - (1/2\alpha)$, the total electric power is $\delta_1 Q_w = Q_w + \overline{Q}_{G2}$, $\overline{Q}_{G2} = (\delta_1 - 1)Q_w$.

When wind energy is abundant, the profit function for the traditional energy power plant is

$$\pi_{G-\mathrm{UN}}(r_G) = k_G + (1 + r_G) \cdot \overline{B}_{G1} - (c_2 + c_1) \cdot \overline{Q}_{G1}, \tag{26}$$

$$\text{s.t. } \overline{B}_{G1} > 0, \tag{26a}$$

where the credit line is $\overline{B}_{G1} = w_2(\vartheta_1 - 1)Q_w + w_7(R_1 + R_2) - k_G$, the part of the payment in advance is $k_G = g\int_0^{(1/\alpha)} x(\alpha)\mathrm{d}x, g < 1$, $\overline{Q}_{G1} = (\vartheta_1 - 1)Q_w$.

The weighted average profit of the traditional energy power plant is

$$\pi_{G-\mathrm{U1}} = \int_0^{(1/\alpha)} ((1 - \nu)\pi_{G-\mathrm{UC}} \cdot + \nu(\pi_{G-\mathrm{UN}}))\alpha\mathrm{d}x, \tag{27}$$

$$\text{s.t. } \overline{B}_{G2} > 0. \tag{27a}$$

When the power grid executes the put option, the traditional energy power plant performs the obligations of the call option seller

(ii) The wind is insufficient

In this part, the traditional energy power plant profit function is the same as the function (20)

(iii) The wind is sufficient

$$\pi_{G-\mathrm{UCP}}(r_G) = x + (1 + r_G) \cdot \overline{B}_{G2} - (c_1 + c_2)\overline{Q}_{G2}, \tag{28}$$

$$\text{s.t. } \overline{B}_{G2} > 0. \tag{28a}$$

Here, when the power grid executes the put option, the power plant buybacks all power orders. The traditional energy power plant shall prepare power generation energy to fulfill the original power order $\overline{\overline{Q}}_{G1} = (\tau_1 - 1)Q_w$. The profit function is

$$\pi_G(r_G) = w_7(R_1 + R_2) - c_2(\tau_1 - 1)Q_w, \tag{29}$$

$$\text{s.t. } \pi_G(r_G) > 0. \tag{29a}$$

According to the above analysis, the weighted average profit of the power plant is

$$\pi_{G-\mathrm{U2}} = \int_0^{(1/\alpha)} ((1 - v)(\pi_{G-\mathrm{UCP}}) \cdot + v(\pi_{G-\mathrm{UP}}))\alpha \mathrm{d}x, \tag{30}$$

$$\text{s.t. } \overline{B}_{G2} > 0. \tag{30a}$$

3.2.1. The Wind Power Plant's Financing Strategy.

When the power grid abandons the put option, the wind power plant will supply power according to the original plan.

(i) When the wind is insufficient

With low wind yield, the wind power supply is disrupted. The wind power plant has no yield and no profit.

(ii) When the wind is sufficient

The profit of the power plant is

$$\max \pi_w(r_w) = \int_0^{(1/\alpha)} \{k_w + (1 + r_w)\overline{B}_w - c_3Q_w\}\alpha \mathrm{d}x, \tag{31}$$

$$\text{s.t. } \overline{B}_w > 0, \tag{31a}$$

where $\overline{B}_w = w_1 \cdot Q_w - k_w$, and $k_w = (1 - g)\int_0^{(1/\alpha)} x(\alpha)\mathrm{d}x$.

When the power grid abandons the put option transaction, the weighted average profit of the wind power plant is

$$\pi_{w-\mathrm{U1}} = v\left\{\int_0^{(1/\alpha)} [(1 - g)x + (1 + r_w) \cdot (w_1 \cdot Q_w - (1 - g)x) - c_3Q_w]\alpha \mathrm{d}x\right\}. \tag{32}$$

3.2.2. The Power Grid Executes the Put Option So That the Wind Power Plant Provides Additional Power beyond the Primitive Plan

(i) When the wind is insufficient

With low wind yield, the wind power supply is disrupted. The wind power plant has no yield and no profit.

When the wind is sufficient, the profit of the power plant is

$$\pi_w(r_w) = \int_0^{(1/\alpha)} \{x + (1 + r_w) \cdot (w_1 \cdot [\tau_1 Q_w + \beta(L_1 - L)] - x) - c_3(\tau_1 Q_w + \beta(L_1 - L))\}\alpha \mathrm{d}x, \tag{33}$$

$$\text{s.t. } \overline{B}_w > 0, \tag{33a}$$

where $\overline{B}_w = w_1 \cdot [\tau_1 Q_w + \beta(L_1 - L)] - \int_0^{(1/\alpha)} x(\alpha)\mathrm{d}x$.

3.3. Solution Method. According to the risk-aversion methods of different option portfolios adopted by the power grid, the optimal wind power procurement strategy can be solved in two situations: one is a single options strategy: executing call option to buy the wind electric power when the wind yield is low whereas abstaining the call option when the wind yield is high; the other is the dual option procurement strategy: executing call option when the wind yield is high and switching on a put option when the wind yield is high. The power grid establishes the weighted average profit function by different wind yield rates and then finds the optimal solution Q_w^* in each situation by optimization processing.

4. Results

Proposition 1. *There is an optimal purchasing strategy Q_w^* which can maximize the power grid's profit without considering the constraints. We have Q_{w1} when $B_{G2} = 0$ and we have Q_{w2} when $\dot{B}_w = 0$, then we have Q_{w3} when $\dot{B}_{G1} = 0$. Then we have the following conclusions:*

(i) *When $Q_w^* > Q_{w1}$, given all the other parameters, the optimal wind power purchase strategy of the power grid with financing is Q_w^*, that is $Q_w = Q_w^*$.*

(ii) *When $Q_w^* < Q_{w1}$, the grid purchases the electricity of quantity Q_{w1}, that is $Q_w = Q_{w1}$. However, at this time, the two types of power plants cannot relate their own decision to the optimal strategy of the power grid, so they cannot make decisions with Q_{w1}.*

(iii) *When $\dot{B}_w \geq \dot{B}_{G1} \geq B_{G2}$, then $Q_w^* = Q_{w2} = (gk - w_7(R_1 + R_2)/w_2(\vartheta - 1))$. However, the two types of power plants cannot make decisions with Q_{w2};*

(iv) *When $\dot{B}_w \geq B_{G2} \geq 0$, then $Q_w^* = Q_{w3} = ((1 - g)k/w_1)$. However, the two types of power plants cannot make decisions related to Q_{w3}.*

Proposition 2. *There is the optimal purchasing strategy Q_w^*, which can maximize the power grid's profit without financial constraints. We have Q_{w1} when $B_{G2} = 0$ and we have Q_{w2} when $\ddot{B}_w = 0$. Whereas considering the constraints*

$B_{G2} \geq \ddot{B}_w \geq 0$, when wind yield is low the grid executes the call option to hedge against wind electric-power disruption, and when wind yield is high the grid executes the put option. If the parameters δ and τ satisfy inequality conditions $(k - w_7(R_1 + R_2) + w_2\beta(L - L_2)/w_2\delta) > (k/\tau w_1) - (\beta/\tau)(L_1 - L)$, then we have the following conclusions:

- *(i) When $Q_w^* > Q_{w1}$, given all the other parameters, the optimal wind power purchase strategy of the power grid with financing is Q_w^*, that is $Q_w = Q_w^*$;*
- *(ii) When $Q_w^* < Q_{w1}$, the grid purchases the electricity with quantity Q_{w1}, that is $Q_w = Q_{w1}$. However, at this time, the two types of power plants cannot associate their decision to the optimal strategy of the power grid, so they cannot make decisions as reflection functions of Q_{w1}.*

  Considering the constraints $\ddot{B}_w \geq B_{G2} \geq 0$, and δ and τ satisfy inequality condition: $(k/\tau w_1) - (\beta/\tau)(L_1 - L) > (k - w_7(R_1 + R_2) + w_2\beta(L - L_2)/w_2\delta)$, then we have conclusions.
- *(iii) When $Q_w^* > Q_{w2}$, given all the other parameters, the optimal wind power purchase strategy of the power grid with financing is Q_w^*, that is $Q_w = Q_w^*$;*
- *(iv) When $Q_w^* < Q_{w2}$, the grid purchases the electricity with quantity Q_{w2}, that is $Q_w = Q_{w2}$. However, at this time, the two types of power plants cannot make decisions associated with the optimal strategy of the power grid.*

Corollary 1. *Given other parameters, Q_w is a decreasing function of α, and is an increasing function of β.*

Proposition 3. *Without considering financial constraints, the optimal credit strategy of the traditional energy power plant is r_G^*. Nonetheless, considering financing constraints and with low wind yield, the grid executes the call option; with high wind yield, the grid abstains from executing the put option. If the parameters δ and ϑ satisfy the inequality conditions: $w_2(\vartheta - 1)Q_w^* - gk \geq w_2[\delta Q_w^* - \beta(L - L_2)] - k$, we will have conclusions.*

- *(1) if $B_{G2} \geq \dot{B}_{G1} \geq 0$, by financial constraints $B_{G2} \geq 0$ and when the constraint is tight, the corresponding interest rate r_{G2} can be obtained, but if $r_G^* \leq r_{G2}$, the optimal interest rate is r_G^*;*
- *(2) if $\dot{B}_{G1} \geq B_{G2} \geq 0$, by financial constraints $\dot{B}_{G1} \geq 0$ and, when the constraint is tight, the corresponding interest rate r_{G1} can be obtained, but if $r_G^* \leq r_{G1}$, the optimal interest rate is r_G^*.*

Corollary 2. *Given other parameters, there is a threshold for $L_2 = L_{20}$, when $L_2 > L_{20}$, r_G is a decreasing function of β, when $L_2 < L_{20}$, r_G is an increasing function of β.*

Proposition 4. *Without considering financial constraints, the optimal corresponding interest rate is r_G^*; Considering financing constraints $B_{G2} \geq \dot{B}_{G1} \geq 0$, and by $B_{G2} \geq 0$, the corresponding interest rate r_{G2} can be obtained under tight constraints. Then if $r_G^* \leq r_{G2}$, the optima interest rate is r_G^*.*

Corollary 3. *Given other parameters, there is a threshold for $v = v_{00}$, when $v < v_{00}$, r_G is a decreasing function of β; when $v > v_{00}$, r_G is an increasing function of β.*

Proposition 5. *The optimal financial strategy without considering financial constraints is r_w^*. When considering financing constraints, by financial constraints $\dot{B}_w \geq 0$ and when this constraint is tight, r_{w1} can be obtained and the optimal interest rate is r_w^*, and $r_w^* \leq r_{w1}$.*

Corollary 4. *Given other parameters, there is a threshold for $L_2 = L_{22}$, when $L_2 > L_{22}$, r_w is a decreasing function of β; when $L_2 < L_{22}$, r_w is an increasing function of β.*

Proposition 6. *Without considering financial constraints, the optimal financial strategy is r_w^*. When considering financing constraints, by financial constraints $\ddot{B}_w \geq 0$ and when the constraint is tight, r_{w2} can be obtained and the optimal interest rate is r_w^* when $r_w^* \leq r_{w2}$.*

Corollary 5. *Given other parameters, there is a threshold for $v = v_{01}$, when $v < v_{01}$, r_w is a decreasing function of β; when $v > v_{01}$, r_w is an increasing function of β.*

Proposition 7. *There is an optimal purchasing strategy Q_w^* who can maximize the power grid's profit without considering the constraints. We have Q_{w1} when $\overline{B}_{G2} = 0$ and we have Q_{w2} when $\overline{B}_w = 0$, then we have Q_{w3} when $\overline{B}_{G1} = 0$.*

- *(i) considering the constraints, when $\overline{B}_{G2} > max(\overline{B}_w, \overline{B}_{G1})$, $Q_w^* > Q_{w1}$. If $Q_w^* > Q_{w1}$, $Q_w = Q_w^*$; while if $Q_w^* < Q_{w1}$, $Q_w = Q_{w1}$;*
- *(ii) considering the constraints $\overline{B}_w \geq \overline{B}_{G1} \geq \overline{B}_{G2}$, $Q_w^* = Q_{w2}$. However, the two types of power plants cannot make decisions associated with the grid's strategy;*
- *(iii) when $\overline{B}_w \geq \overline{B}_{G2} \geq 0$, then $Q_w^* = Q_{w3}$. However, the two types of power plants cannot make decisions associated with the grid's strategy;*

Corollary 6. *Given other parameters, there is a critical value for $g = g_0$, when $g > g_0$, Q_w is convex with α and $Q_w(\alpha_{00})$ is the minimal value; when $g < g_0$, Q_w is concave with α and $Q_w(\alpha_{00})$ is the maximal value. Q_w is an increasing function of β.*

Proposition 8. *There is an optimal purchasing strategy Q_w^* without considering the constraints. We have Q_{w1} when $\overline{B}_{G2} = 0$ and we have Q_{w2} when $\overline{B}_w = 0$.*

- *(i) considering the constraints, when $\overline{B}_{G2} \geq \overline{\overline{B}}_w \geq 0$. If $Q_w^* > Q_{w1}$, $Q_w = Q_w^*$; while if $Q_w^* < Q_{w1}$, $Q_w = Q_{w1}$;*
- *(ii) considering the constraints $\overline{\overline{B}}_w \geq \overline{B}_{G2} \geq 0$, $Q_w^* = Q_{w2}$. However, the two types of power plants cannot make decisions in this condition;*

Corollary 7. *Given other parameters,* Q_w *is convex with* α *and* α_{01} *is the minimal value;* Q_w *is an increasing function of* β*.*

Proposition 10. *Without financial constraints, the optimal financial strategy is* r_G^**. When considering financial constraints, if the financial constraint* $\overline{B}_{G2} \geq 0$ *is tight, we have* r_{G2}*. The optimal interest rate solution is* r_G^* *and satisfy* $r_G^* \leq r_{G2}$*.*

Corollary 9. *Given other parameters, there is a threshold* $\alpha = \alpha_{030}$ *for* $(d^2 r_G / d\alpha^2) = 0$*, and there is another threshold* $\alpha = \alpha_{03}$ *for* $(dr_G / d\alpha) = 0$*,*

- *(i) If* $\alpha_{03} > \alpha_{030}$*, then we have,*

  when $\alpha > \alpha_{030}$*,* r_G *is convex with* α*, when* α *is assigned with interior solution,* r_G *reach the minimal value* $r_G(\alpha_{03})$*,*

  when $\alpha < \alpha_{030}$*,* r_G *is concave with* α*, when* α *is assigned with corner solution,* r_G *reach the maximum value* $r_G(\alpha_{030})$*;*

- *(ii) If* $\alpha_{03} < \alpha_{030}$*, then we have,*

  when $\alpha > \alpha_{030}$*,* r_G *is convex with* α*, when* α *is assigned with corner solution,* r_G *reach the minimal value* $r_G(\alpha_{030})$*,*

  when $\alpha < \alpha_{030}$*,* r_G *is concave with* α*, when* α *is assigned with interior solution,* r_G *reach the maximum value* $r_G(\alpha_{03})$*;*

- *(iii) There is a threshold for* $v = v_{01}$*, when* $v > v_{01}$*,* r_G *is a decreasing function of* β*; when* $v < v_{01}$*,* r_G *is an increasing function of* β*.*

Proposition 11. *Without financial constraints, the optimal financial strategy is* r_w^**. When considering financing constraints, by financial constraints* $\overline{B}_w = w_1 \cdot Q_w - (k/2\alpha) \geq 0 \dot{B}_w \geq 0$ *and when the constraint is tight, the corresponding interest rate is* r_{w2} *and the optimal interest rate is* r_w^**, and* $r_w^* \leq r_{w2}$*.*

Corollary 10. *Given other parameters, there is a threshold* $\alpha = \alpha_{040}$ *for* $(d^2 r_w / d\alpha^2) = 0$*, and there is another threshold* $\alpha = \alpha_{04}$ *for* $(dr_w / d\alpha) = 0$*,*

- *(i) If* $\alpha_{04} > \alpha_{040}$*, then we have,*

  when $\alpha > \alpha_{040}$*,* r_w *is convex with* α*, when* α *is assigned with interior solution,* r_w *reach the minimal value* $r_w(\alpha_{04})$*.*

  when $\alpha < \alpha_{040}$*,* r_w *is concave with* α*, when* α *is assigned with corner solution,* r_w *reach the maximum value* $r_w(\alpha_{040})$*;*

- *(ii) If* $\alpha_{04} < \alpha_{040}$*, then we have,*

  when $\alpha > \alpha_{040}$*,* r_w *is convex with* α*, when* α *is assigned with corner solution,* r_w *reach the minimal value* $r_w(\alpha_{040})$*.*

  when $\alpha < \alpha_{040}$*,* r_w *is concave with* α*, when* α *is assigned with interior solution,* r_w *reach the maximum value* $r_w(\alpha_{04})$*;*

- *(iii) There is a critical value for* $v = v_{02}$*, when* $v < v_{02}$*,* r_w *is a decreasing function of* β*; when* $v > v_{02}$*,* r_w *is an increasing function of* β*.*

Proposition 12. *Without constraints, the optimal financial strategy is* r_w^**. When considering financial constraints, by financial constraints* $\overline{\overline{B}}_w$ *and when the constraint is tight, the corresponding interest rate is* r_{w2} *and the optimal interest rate is* r_w^**, and* $r_w^* \leq r_{w1}$*.*

Corollary 11. *Given other parameters, there is a threshold* $\alpha = \alpha_{050}$ *for* $(d^2 r_w / d\alpha^2) = 0$*, and there is another threshold* $\alpha = \alpha_{05}$ *for* $(dr_w / d\alpha) = 0$*,*

- *(i) If* $\alpha_{05} > \alpha_{050}$*, then we have,*

  when $\alpha > \alpha_{050}$*,* r_w *is convex with* α*, when* α *is assigned with interior solution,* r_w *reach the minimal value* $r_w(\alpha_{05})$*.*

  when $\alpha < \alpha_{050}$*,* r_w *is concave with* α*, when* α *is assigned with corner solution,* r_w *reach the maximum value* $r_w(\alpha_{050})$*;*

- *(ii) If* $\alpha_{05} < \alpha_{050}$*, then we have,*

  when $\alpha > \alpha_{050}$*,* r_w *is convex with* α*, when* α *is assigned with corner solution,* r_w *reach the minimal value* $r_w(\alpha_{050})$*.*

  when $\alpha < \alpha_{050}$*,* r_w *is concave with* α*, when* α *is assigned with interior solution,* r_w *reach the maximum value* $r_w(\alpha_{05})$*;*

- *(iii) There is a threshold for* $v = v_{03}$*, when* $v < v_{03}$*,* r_w *is a decreasing function of* β*; when* $v > v_{03}$*,* r_w *is an increasing function of* β*.*

5. Discussion

To investigate the validation of the model conclusions, we conduct numerical simulation experiments to further analyze the impact of key parameters on supply chain decision-making and participants' profits. Meanwhile, based on the data of Hunan Chenzhou thermal power plants, the values of each parameter are as follows: $A = 1kw, \alpha = (0.01kw/\$), L = 6ERU, L_1 = 7ERU, L_2 = 2ERU, \beta \in ((1, 30)kw/ERU)$, $v = 0.01, g = 0.12, \delta = 7kw, \delta_1 = 7kw, \vartheta = kw, \vartheta_1 = 2kw, \tau = 10kw, \tau_1 = 10kw, c_1 = (2\$/kw), c_2 = (2\$/kw), c_3 = (2\$/kw)$, $k = (0.1\$/kw), w_7 = (1\$/kw), R_1 = 1\,kw, R_2 = 1kw, w_2 = (20\$/kw), w_1 = (20\$/kw)$.

In Figure 2, blue, purple, yellow, and green are respectively used to denote the four scenarios: the power grid capital line is confirmed and only call is executed; the power grid capital line is confirmed and double options are executed; the power grid fund is of uniform distribution and only call option is executed, and the power grid fund is of uniform distribution and double option are executed. Figure 2 shows the changing of the power grid profit curve under the four scenarios. Given other parameters, with the increase of users' demand sensitivity to carbon emission reduction levels in the second scenario, the profit of the power grid π_{R-2} exceeds the profits in other scenarios so far

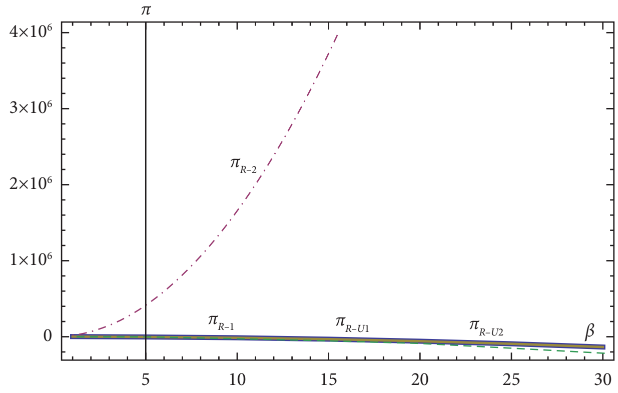


FIGURE 2: Impact of β on the grid profits under four situations.

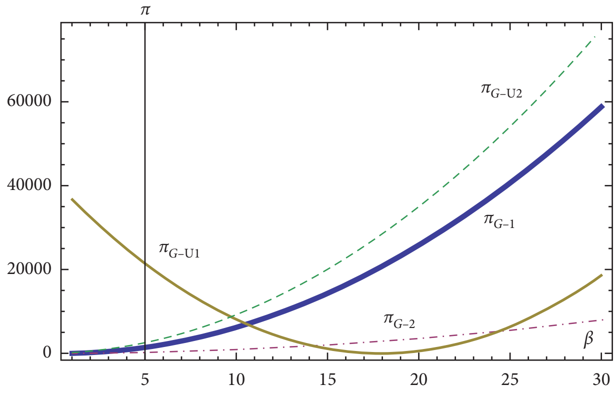


FIGURE 3: Impact of β on the traditional energy power plant profits under four situations.

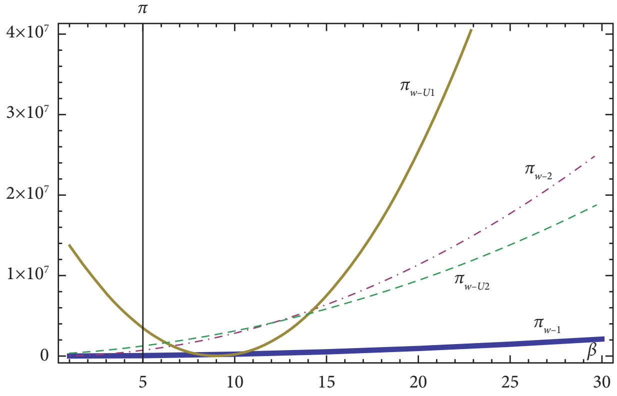
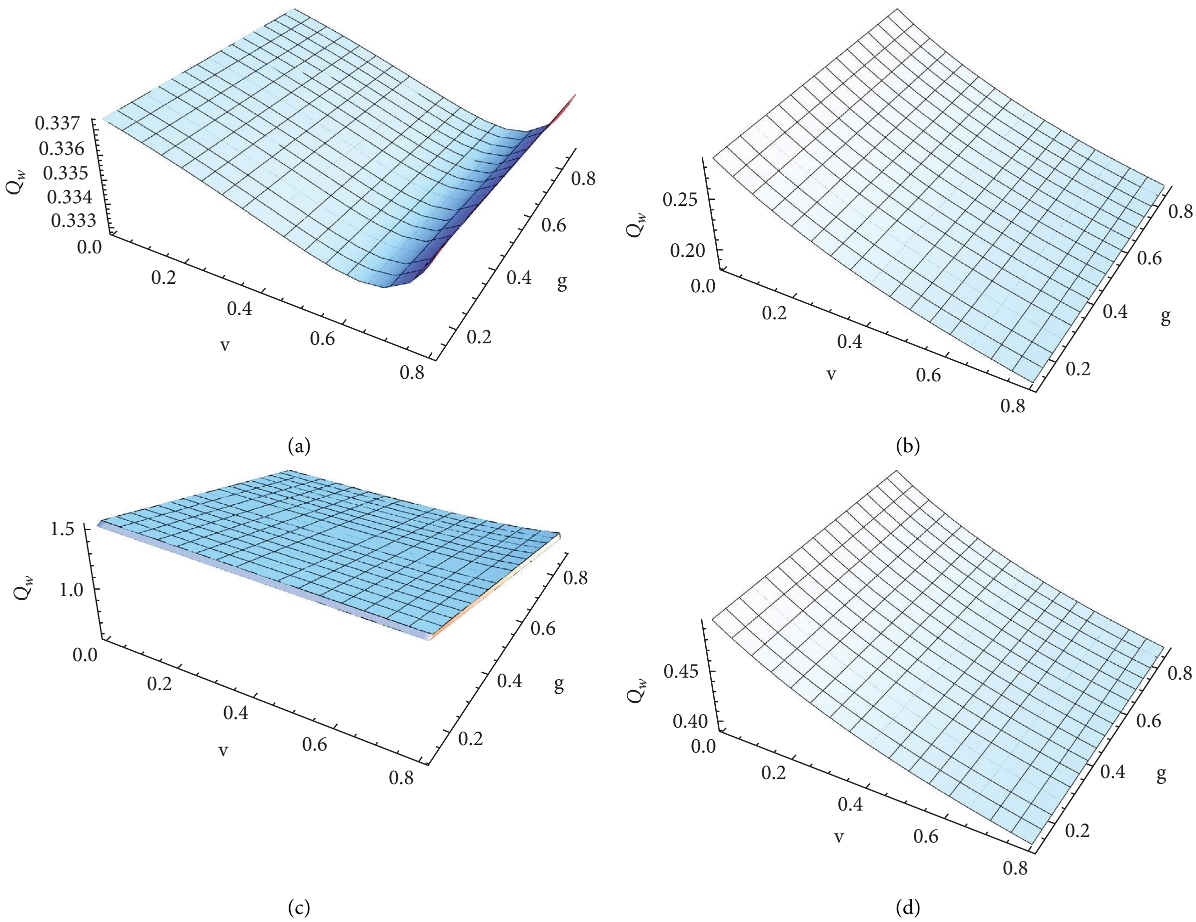


FIGURE 4: Impact of β on the wind power plant profits under four situations.

away as a new force emerges. The power grid profit curves under the other three scenarios tend to be bonded. It shows that when the power grid capital line is confirmed, the hedging strategy of executing a double option against disruption will be the most profitable choice for the power grid.

In Figure 3 shows that given other parameters, with the increasing carbon emission reduction level elasticity of demand, the profit of the traditional energy power plant is a convex function of β under the four scenarios. In β‘s value range for the curve π_{G-U1}, there is an intersection with π_{G-U2} and π_{G-1}, respectively. On the right range of the intersection of π_{G-U1} and π_{G-U2}, π_{G-U2} is at the top within this range. The put options execution is most beneficial to the traditional energy power plant as put option sellers. Moreover, due to the uniform distribution of the grid's funds, both of the CSE generation consumption and the power grid's capital budget can be promoted. That grid fund's dual impact will eventually act on revitalizing the traditional energy power plant profits. In contrast, when the grid's fund is confirmed instead of uniform distribution and has no impact on power users' consumption, the profit π_{G-2} is obviously at a lower level, which explains the important impact of power grid fund property on the traditional energy power plant. On the left range of the intersection of π_{G-U1} and π_{G-U2}, π_{G-U1} is at the top within this range. It illustrates that with the uniform distribution of the grid's fund, the options portfolio of executing a call and abandoning put is the most profitable scenario for the traditional energy power plant. There are two intersections with π_{G-U1} and π_{G-2}, respectively. π_{G-2} is at the top within this range between the two intersections. It illustrates that with the grid's confirmed capital line, executing the double option is most profitable for the traditional energy power plant. Whereas outside the range between the two intersections, when the power grid's fund follows the uniform distribution, executing the call but abandoning the put is most beneficial to the traditional energy power plant.

In Figure 4 shows that given other parameters, with the increasing sensitivity of users to carbon emission reduction level, the profit of the traditional energy power plant is a convex function of β under the four scenarios. In β‘s value range for the curve π_{w-U1}, it has two intersections with the other three curves, respectively. Between the range of all the two intersections for π_{w-U1} and the other three, π_{w-U1} is at the bottom. The execution of call options but abstaining from the put is most beneficial for the wind power plant when the grid's fund is of uniform distribution. On the outside space of the range between the two intersections, option impact (executing call but abstaining put) on the wind power plant is just on the opposite, and the wind power plant produces the most profit in this range. Between π_{w-U2} and π_{w-2}, there is an intersection point. The positions of these two curves show the power grid funds' impact on the profits of wind power plants under the same option strategy. When the power grid funds are uniformly distributed on the left side of the intersection point, it is more favorable for the wind power plant. On the right range of the intersection, it is more beneficial to the wind power plant when the grid capital is confirmed. The location of π_{w-1} has always been low, indicating that the first scenario is usually unfavorable to the wind power plant. Within the range between the two intersections of π_{w-1} and π_{w-U1}, π_{w-1}, it shows a weak advantage relative to π_{w-U1}. From the perspective of the wind power plant, with option portfolio (executing call but abstaining put), it is in the range of being outside of the two intersections for π_{w-1} and π_{w-U1} that emerges favorable condition to the wind power plant when the gird's fund is uniformly distributed.



(a)

(b)

(c)

(d)

Figure 5: (a): Purchasing decision when power grid capital is confirmed and the call is executed. (b): Purchasing decision when power grid capital is confirmed and the double option is executed. (c): Purchasing decision, when power grid capital is of uniform distribution and only call, is executed. (d): Purchasing decision when power grid capital is of uniform distribution and the double option is executed.

In Figure 5 shows the impact of two key parameters impact on the procurement decision of the power grid under four scenarios, such as the wind yield rate and prepayment proportion to the traditional energy power plant. Figure 5(a) shows that when the grid's fund is confirmed, the wind power purchase initially decreases and then increases with the increase of wind yield rate when executing the call abandoning the put strategy. And it is not sensitive to the change in the payment proportion to the traditional energy power plant. Figure 5(b) shows that when executing the double option, the wind power procurement of the power grid with confirmed funds shows an obvious downward trend with the wind yield rate increasing, and is not sensitive to the change of the advance payment proportion to the traditional energy power plant. It shows that the higher the wind yield rate is, the greater the probability of executing the put. Executing the put option makes the power grid bear a higher risk of a wind power outage. Therefore, the power grid should adopt a more cautious procurement strategy when the wind yield rate is increasing. Figure 5(c) shows that when the grid's funds are uniformly distributed, the wind power procurement is not sensitive to the wind yield rate changing under call executing but abandoning put. With the increase in the proportion of advance payment to the traditional energy power plant, wind power procurement is reduced. This shows that with g increasing the amount of advance payment to the wind power plant is becoming less. So even if there is financing, it cannot stop the trend of reducing wind power procurement. Figure 5(d) shows that for the power grid with uniform distribution of funds, under double option executing, the wind power procurement volume shows an obvious downward trend with the increase of wind yield rate and is not sensitive to the change of advance payment proportion to the traditional energy power plant. Although the changing trend of procurement is similar to that in 5(b), the maximum procurement of wind power in this scenario is more than that in 5(b).

6. Managerial Insights and Practical Implications

There are differences in the wind power procurement decision-making with different option combinations, and the level of risk-reducing with wind power disruption is also different with option hedging strategies. If option hedging can reduce the disruption risk of electric-power supply to a greater extent, it will motivate supply chain firm managers to purchase aggressively. By comparing the benefits of procurement decisions with different option combinations, managers decide which option combination is more beneficial for them to hedge against the wind power supply disruption risk.

The debtor's (the power grid) funds property variation will enlarge the manager's purchase only on the budget side or on both manager's budget and user demand. However, the debtor should decide on the purchase while the creditors set credit interest rates considering the debtor's options strategy because different option combinations mean that the debtor bears energy supply disruption risks at a different level.

The two creditors have their strengths. One creditor can provide sustainable power generation energy (the traditional energy power plant) but will emit a large amount of carbon dioxide with power generation, resulting in environmental pollution. Under exerting a double option strategy, when facing sufficient wind, the creditor should compete for more orders by reducing credit interest rate with carbon emission reduction elasticity of demand. Inappropriate interest rates involve creditors in the predicament of coping with potential order loss; Or else, when facing the insufficient wind, this creditor should increase the credit interest rate with carbon emission reduction elasticity of demand to gain more benefit. In addition, the distinction of the grid funds property has an impact on the threshold of defining the wind yield rate. Under the option strategy of exerting call but abstaining put, instead of considering the wind yield rate, when in the higher range of carbon emission reduction level, the creditor should be fully prepared to compete for more orders through reducing credit interest rate with carbon emission reduction elasticity of demand; Or else, in the lower range of carbon emission reduction level, this creditor should increase the credit interest rate with carbon emission reduction elasticity of demand to gain more benefit. Here the grid funds property distinction also has an impact on defining the threshold of carbon emission reduction level.

Although the other creditor (the wind power plant) can provide CSE to ensure the prevention of carbon dioxide being released during power generation, CSE shows intermittence during electricity generation, which may cause electricity supply disruption. In this sense, when the power grid employs dual purchase, the two types of creditors are both complementary and competitive. The creditor with CSE should increase the credit interest rate with wind yield rate when facing sufficient wind while decreasing the credit interest rate with wind yield rate when facing insufficient wind. The two factors of the grid funds property and options strategy illustrate the impact on the threshold of defining the wind yield rate.

The two types of creditors acting as managers determine their credit interest rate by observing the decisions of other participants and find the most favorable situation by comparing the changes in profits in several situations.

7. Conclusions and Outlook

Over the past few years, supplier financing boosts economic growth taking the stand of purchasers. CSE has gained popularity among electric users and enhances low-carbon emission preference. The above two factors encourage economic growth from the perspective of environmental protection. But whether the introduction of CSE generation can help achieve the same operational and financial strategy remains unexplored in the literature. In this paper, we establish a Stackelberg game model consisting of two heterogeneous energy power plants, and a strategic power grid with capital constraints, in order to study the impact of different option hedging on the purchase of the power grid under supplier financing, and further investigate the power grid funds property's influence on participant strategies. From the model analysis, we obtain the following management conclusions to guide the development of the CSE generation business and supply chain financing improvement hoping to facilitate the electricity industry growth rapidly and healthily.

The results are as follows:

When the funds of the power grid are of uniform distribution, funds affect not only the power users' demand but also the power grid budget. High self-owned funds level or affluent credit line simulate the purchase volume. That is, the fund influence on power procurement decisions is illustrated by the above two aspects.

(i) When the power grid funds are to be confirmed, the price elasticity of demand shows monotonic on wind power purchase strategy; while when the power grid fund is of the uniform distribution, there is a threshold for payment to the traditional power plant. In the range of the payment lower than the threshold, wind power purchase has minimal value on the price elasticity of demand; whereas this payment is higher than the threshold, and wind power purchase has maximal value.

(ii) when the power grid funds are to be confirmed, under executing the call while abstaining the put, when carbon emission reduction level is high, the traditional energy power plant credit interest rate increases with a sensitivity of the power user to the carbon emission reduction level; under executing double option when wind yield is high, the traditional energy power plant's credit interest rate increases with a sensitivity of power user to the carbon emission reduction.

(iii) when the power grid funds are to be confirmed, under executing the call while abstaining the put when carbon emission reduction is at a high level, the wind power plant credit interest rate increases with a sensitivity of the power user to the carbon emission reduction level; under executing double option when wind yield is high, the wind power plant credit interest rate increases with a sensitivity of power user to the carbon emission reduction; when the power grid fund is of the uniform distribution, whatever option hedging, the wind power plant credit interest rate illustrates ambiguous relations with a sensitivity of user demand to the carbon emission reduction than that in funds are confirmed.

In addition, we find that the optimal wind power purchasing under supplier financing must surmount the purchasing amount without financing no matter whether the wind is sufficient or not. This implies supplier financing advantage over no financing scenario. The more sensitivity of the power user to carbon emission reduction, the higher of power user demand.

There are still some limitations in our paper, which could provide directions for future research. First, we examined solely supplier credit, which would be interesting when combined with the use of bank loans. To be specific, it is necessary to study if there is a third financial party such as a bank can provide credit together with power plants, and how can supply chain participants make decisions. Second, this paper assumes linear electric-power demand, but when demand is uncertain, the problem in this story will present another interesting scene. And we can also consider cost minimization as a novel bi-objective mixed-integer linear programming (MILP) model EB. Tirkolaee al et. (2020) [38], which is proposed FSS with an outsourcing option.

Data Availability

All data are given in the article file.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Guoshu Dong conceived the article. Both authors have contributed to writing, editing, proofing, and revising the manuscript. Conceptualization, Q.X. and B.X.; methodology, Q.X.; software, G.D. and B.X.; validation, Z.G.; formal analysis, G.D.; investigation, Z.G.; resources, G.D. and B.X.; data curation, G.D.; visualization, B.X. All authors have read and agreed to the published version of the manuscript.

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