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Construction and Application of the Double Game Model for Direct Purchase of Electricity by Large Consumers under Consideration of Risk Factors

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Abstract: With the development of global clean energy and the implementation of carbon emission reduction policies, the direct purchase of electricity by large consumers has been increasingly promoted as a special form of electricity trading. Therefore, on the basis of the completion of low-carbon emission reduction targets in each country, how to rationalize the electricity purchase by large consumers in the electricity market so as to reduce their electricity purchase costs has become the main target of attention in each country. Currently, there are fewer studies in existing research on the direct electricity purchase strategy of large consumers under the consideration of the weight of consumption responsibility and risk. Based on this, this paper constructs a dual-game model for direct electricity purchase by large consumers based on the Stackelberg game and non-cooperative game theory. The concept of value at risk is further introduced, and the optimal strategy of direct electricity purchase by large consumers is proposed. The results of this study show that when market players make decisions on the purchase and sale of electricity, power suppliers will increase their biddings to obtain the highest returns, and large consumers can reduce the transaction costs by combining the medium- and long-term market with the spot market to purchase electricity. In the choice of electricity purchase market, with the increasing risk factor, large consumers shift from the risky spot market to the less risky medium- and long-term market and option market. This paper provides a reference for the issues of power suppliers' contract bidding and large consumers' electricity purchase strategy in the medium- and long-term contract transactions.

Keywords: stackelberg game; expected utility–entropy; direct purchase of electricity by large consumers

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1. Introduction

With the development of the world economy and the continuous improvement of power generation, transmission, and distribution technology, the monopoly of power trading has become a stumbling block to economic development, and large power users for the highest proportion of electricity consumption and voltage level. From the United States, the United Kingdom, and other developed countries in the direct purchase of electricity situation, the direction of development of different countries is basically "open the grid, increase the user's right to choose". That is, the ultimate goal is to open up the power purchase options for end users.

The domestic power system reform process is slow compared to foreign countries. At the end of 2016, all provinces and cities across the country started the electricity reform, and the development of China's direct power purchase transactions entered a peak [1]. Large consumers can make direct transactions with power suppliers to purchase electricity at lower prices to reduce the impact of unstable power prices, fierce market competition, and other factors on the cost of power purchases by large consumers. At the end of 2023, many places in China released the implementation plan for renewable energy power consumption [2], requiring all types of market players to complete the corresponding amount of renewable energy and non-water renewable energy consumption, and substantively promoting the implementation of the quota system on the ground.

There are various ways of direct purchase of electricity by large consumers, among which, the bilateral transaction is the main transaction mode of large consumers, which has the advantages of fully reflecting the wishes of buyers and sellers, a flexible transaction mode, and simplicity and ease of implementation [3]. In the process of bilateral transactions, each power supplier pursues the highest profit, which triggers the non-cooperative competition between the power suppliers to sell electricity, while the goal of large consumers in the formulation of the power purchase strategy is generally to seek the minimum of the weighted sum of the cost and risk of electricity purchase.

In the game between different market players under the bilateral trading model, large consumers face the situation of purchasing electricity in multiple markets while taking risks. Existing research focuses more on the multilateral bargaining model of the electricity market to minimize the cost of electricity purchase as the goal, and, at the same time, consider the avoidance of market risk.

In response to the game between electricity sellers [4,5], Peng Liao [6] established a quantitative model of clean energy limiting power from the perspective of supply and demand balance in the power system. Meanwhile, in the medium- and long-term power market and the day-ahead market, the electricity purchase cost, electricity sale revenue, deviation assessment cost, and electricity purchase and sale risk of the electricity sales company are considered. Chao ping Zhu [7] considered the energy regulator and two types of electricity sales companies with heterogeneous strengths, established a system dynamics model of the three-party evolutionary game, analyzed the strategic interactions among the stakeholders, and simulated the corresponding evolution. Cheng feng Wu [8] proposed a two-layer stochastic optimization model for generating optimal joint demand and virtual bidding strategies for a strategic retailer in a short-term electricity market and investigated the effects of various model parameters on the strategic retailer′s joint demand and virtual bidding strategies.

For the game between electricity sellers and other consumers [9–12], Bao Jie [13] proposed a Markowitz portfolio improvement method based on value at risk, which explored the optimal procurement strategies for distribution system operators and energy retailers under deregulated electricity markets. Li Fe [3] established a two-layer game optimization model for RPS-driven green and thermal power suppliers' bidding and large consumer direct electricity purchase, and solved the coupled optimization decision problem of multi-power suppliers bidding and multi-large consumer direct electricity purchase transactions. Lu Qing [14] constructed a non-cooperative Stackelberg model based on game theory to study the demand response characteristics of multiple types of consumers according to the principles of consumer psychology. The impacts of grid load fluctuations on the benefits of electric companies and the satisfaction of consumers with electricity consumption were quantified, the Nash equilibrium solution of the model was obtained by the NSGA-II algorithm, and the sensitivity analysis of the correlation coefficients was carried out. Sun Bo [15] proposed an incentive mechanism considering three different participants, namely, the government, the retailers, and the residents, and set up a two-level Stackelberg game to operate the proposed incentive mechanism, and proved that the Stackelberg game is a two-stage game. A two-level Stackelberg game is established to operate the proposed incentive mechanism, the existence and uniqueness of the Stackelberg equilibrium are proved, and the optimal strategies of each participant are given.

In summary, most of the current research considers the different electricity markets and the renewable electricity consumption quota conditions of power suppliers and large consumers' bidding game, but does not analyze the excess consumption market trading mechanism under the large consumers' direct electricity purchase strategy. The introduction of excess consumption trading mechanisms renewable energy tariffs, tradable green certificates prices, and consumption constraints will have an impact on the large consumers' cost and risk, so the development of a reasonable strategy for the purchase and sale of electricity is key to the large consumers' electricity purchase. In this paper, we study the bidding game between power suppliers and large consumers to realize the responsibility of consumption under the weight of renewable energy power consumption responsibility, as well as the electricity purchase strategy of large consumers under risk avoidance, so as to provide the optimal decision of electricity purchase from the perspective of the lowest cost and the lowest risk for large consumers.

As shown in Figure 1, the research content of this paper is as follows. First of all, based on the data of large consumers' electricity load and power suppliers' base tariffs, we established a double game model for direct electricity purchases by large consumers. The outer layer of the model is a non-cooperative game between different power suppliers, and the inner layer is a primary–secondary game between power suppliers and large consumers. Since the optimization of the returns of each participant in the dual-game model is nonlinear, the KKT condition is used to simplify the dual-game model into a single-layer linear model, so that the electricity purchase strategy of large consumers is formulated according to the results of the equilibrium of the game between the power suppliers' biddings and the electricity price in the spot market. The goal of maximizing the revenue of the power supplier is achieved on this basis.

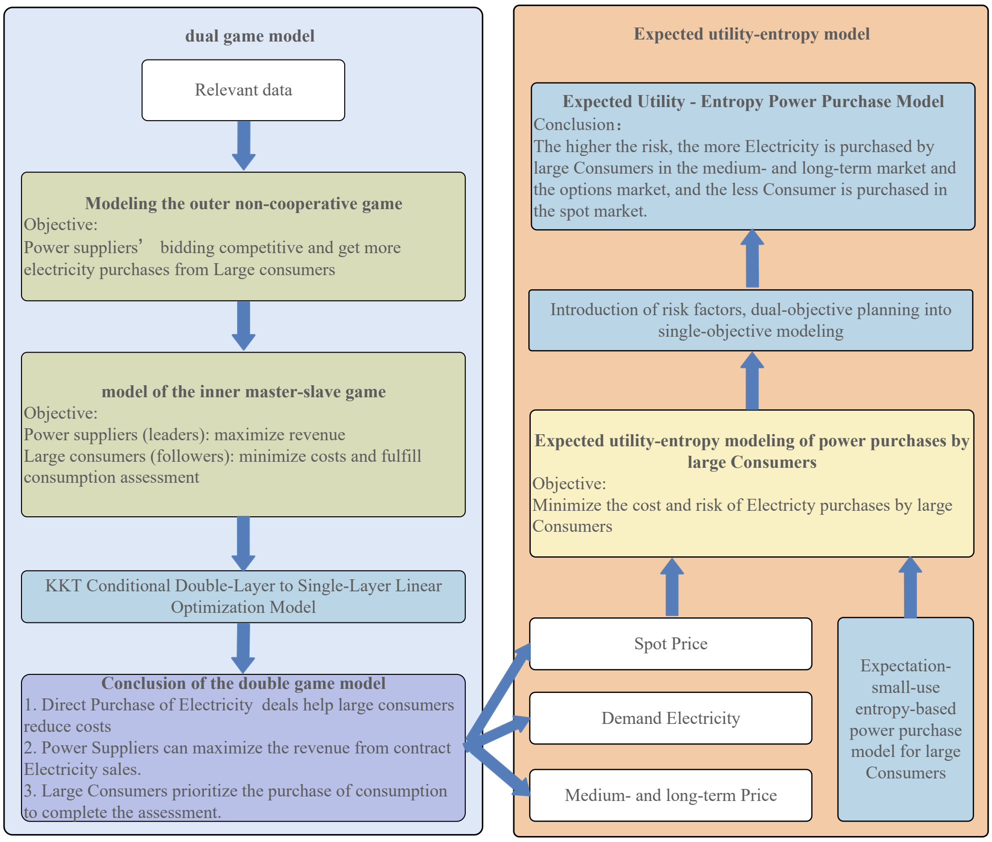

Figure 1. Research roadmap.

In addition, this paper takes into account the fact that large consumers have to control the risk of purchasing electricity while reducing the cost of purchasing electricity; therefore, the concept of value at risk is introduced, and the expected utility–entropy model is constructed to derive the electricity purchasing strategy of large consumers under the consideration of different risk factors. Combined with the conclusions drawn from the above double game model, further analysis can make it clear that this study provides important theoretical support and decision-making reference for the electricity purchase strategy of large consumers in direct electricity purchase transactions.

The innovation points of this paper are as follows:

First, it considers the bidding game of each power supplier and large consumer that realizes the responsibility of consumption under the weight of renewable energy power consumption responsibility, and comprehensively considers the allocation ratio of green electricity in the purchase of tradable green certificates, excess consumption, and green electricity sales by the three parties, so as to provide sufficient reference for the decision making of large consumers when purchasing green electricity.

Second, this paper for the first time applies the expectation–information entropy theory to the primary–secondary game model of large consumers and power suppliers under the weight of renewable energy power consumption responsibility. In this study, the objective functions of the game participants are optimized based on the dual objectives of maximizing the profits of thermal and green power suppliers, and minimizing the costs of large consumers in meeting the requirements of the weight of renewable energy power consumption responsibility.

Third, this study refers to the actual demand for electricity and trading price of large consumers in the Beijing–Tianjin–Hebei region, to fill the gap of the study with enterprises as examples, and then enrich the proposal of electricity purchase strategy for large consumers, and put forward the optimal strategy choice for large consumers of direct electricity purchase, which is conducive to the formation of a win–win situation for multiple subjects.

2. A Double Game Model for Direct Electricity Purchase by Large Consumers

This paper constructs a dual-game model for direct electricity purchases by large consumers. Firstly, it establishes a competitive non-cooperative game model between multiple power suppliers, in which each power supplier formulates a bidding strategy and strives to stand out among multiple power suppliers in order to win more electricity purchases from large consumers and maximize the benefits of electricity sales; secondly, it constructs a primary–secondary game model of multiple power suppliers and multiple large consumers, in which each power supplier aims to increase the profit of electricity sales and adjusts its biddings in order to promote electricity purchases from large consumers; and large consumers formulate electricity purchase strategies based on the biddings of power suppliers to minimize electricity purchase costs and meet the renewable electricity consumption quota assessment requirements.

2.1. Construction of Double Game Model for Direct Purchase of Electricity by Large Consumers under the Weight of Renewable Energy Power Consumption Responsibility

Figure 2 shows the architecture of the dual-game relationship between various market participants in the large consumer direct electricity purchase transaction under the weight of renewable energy power consumption responsibility, which mainly includes the following:

(1) Inner game: Multiple power suppliers and multiple large consumers constitute a multi-primary–multi-secondary game relationship: power suppliers incentivize large consumers to purchase electricity by changing the biddings to maximize the profit of electricity sales [16]; large consumers respond to the biddings of the power suppliers to formulate the electricity purchase strategies, and trade with the tradable green certificates market and the market of excess consumption, to balance green electricity under the renewable electricity consumption quota assessment requirements, in order to achieve the minimum electricity purchase cost, tradable green certificates transaction cost, and excess consumption transaction cost [17].

(2) Outer game: each power supplier constitutes a competitive non-cooperative game among themselves, and reaches bilateral transactions with large consumers through bidding strategies [18]; each power supplier strives to make its own bidding competitive among

the biddings of multiple power suppliers in order to obtain more electricity purchases from large consumers and maximize its profit from the sale of electricity [19].

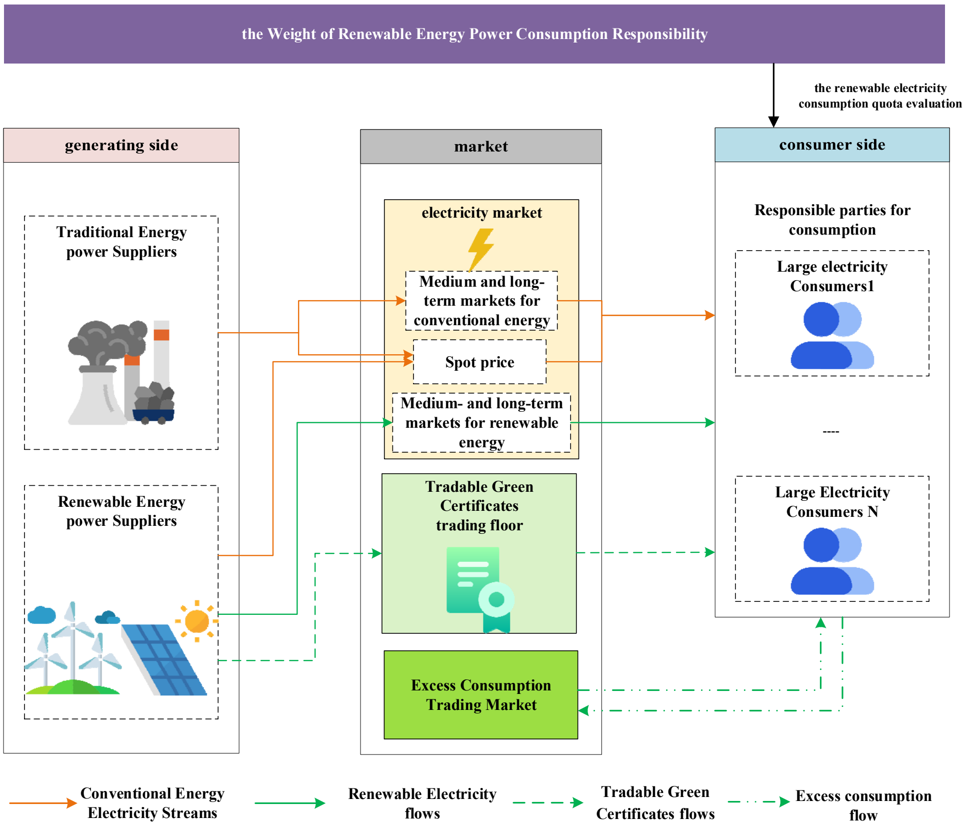

Figure 2. Transactional relationships between market participants.

The double game flow is shown in Figure 3.

(1) Each major consumer constructs an electricity purchase strategy based on the cost function, and the power supplier constructs a bidding strategy based on the revenue model;
(2) The outer game round is $l = 1$;
(3) Iterate through each power supplier n so that the current power supplier is $n = 1$;
(4) Enter the inner game round $m = 1$;
(5) Each outer leader plays the game with L large consumers, and each leader changes the bidding strategy in turn, and the large consumer changes the corresponding electricity purchase strategy;
(6) If the difference between two neighboring biddings of the power supplier is less than ε ($\varepsilon = 0.001$), the inner layer game ends; otherwise, the number of inner layer iterations is $m = m + 1$;
(7) Whether the power supplier $n \geq M$; otherwise, update the outer layer iteration number $n = n + 1$;
(8) In the outer layer game, each power supplier plays the game to find the optimal bidding and update the bidding strategies of all power suppliers;
(9) In the outer layer game, if the difference between two neighboring rounds of bidding is less than ε, a Nash equilibrium is reached; otherwise, the number of iteration rounds is updated $l = l + 1$;
(10) Output the solutions at the equilibrium of the game for power suppliers and large consumers, respectively.

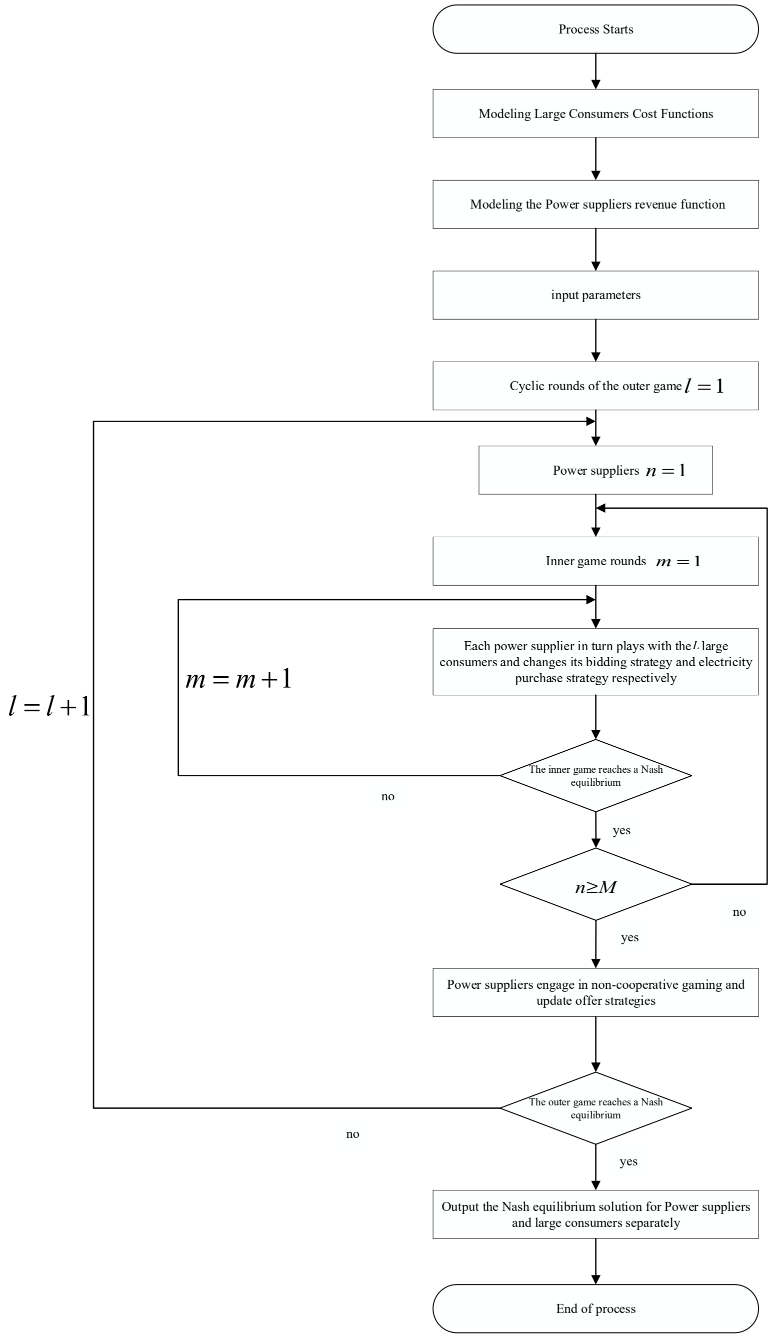

Figure 3. Multi-power suppliers and multi-large consumers direct the power purchase gaming process.

2.1.1. Objective Function for Each Participant

(1) Profit function of power suppliers

Power suppliers are divided into green power suppliers i and thermal power suppliers j, according to the type of electricity generation, and their profits are divided into two parts, and the algorithm is the revenue from selling electricity to large consumers through bilateral contracts minus the cost of power suppliers, as shown in Equation (1).

$$\begin{cases} J_{R,i} = R_{R,i} - C_{R,i}, & i = 1,2,\ldots,m_g \\ J_{C,j} = R_{C,j} - C_{C,j}, & j = 1,2,\ldots,m_f \end{cases} \tag{1}$$

where the profits of the green power suppliers and the profits of the thermal power suppliers in selling electricity are $J_{R,i}$ and $J_{C,j}$; the number of large consumers is K, the number of green power suppliers is m_g and the number of thermal power suppliers is m_f; revenues from electricity sales of green power supplier i and thermal power supplier j are $R_{R,i}$ and $R_{C,j}$; and the generating costs of the green power supplier i and the thermal power supplier j are $C_{R,i}$ and $C_{C,j}$, respectively; the generating cost of the green power suppliers and the thermal power suppliers can be fit with the following quadratic functions [20]:

$$\begin{cases} C_{R,i} = A_i((\sum_{k=1}^{K} q_{i,k}^t)^T)^2 + B_i(\sum_{k=1}^{K} q_{i,k})^T + C_i \\ C_{C,j} = X_j((\sum_{k=1}^{K} q_{j,k}^t)^T)^2 + Y_j(\sum_{k=1}^{K} q_{j,k})^T + Z_j \end{cases} \tag{2}$$

where the cost factors of the green power supplier i are A_i, B_i, C_i, the cost factors of the thermal power supplier j are X_j, Y_j, Z_j, and $q_{i,k}^t$ denotes the amount of electricity purchased by a large consumer k from a green power supplier i during the t time period, $q_{j,k}^t$ denotes the amount of electricity purchased by a large consumer k from a thermal power supplier j during the t time period.

$$\begin{cases} R_{R,i} = \sum_{t=1}^{T} B_i^t Q_i^t i = 1, 2, \ldots, m_g \\ R_{C,j} = \sum_{t=1}^{T} B_j^t Q_j^t j = 1, 2, \ldots, m_f \end{cases} \tag{3}$$

$$\begin{cases} B_i^t = P_i^t + n^T Q_i^t i = 1, 2, \ldots, m_g \\ B_j^t = P_j^t + n^T Q_j^t j = 1, 2, \ldots, m_f \end{cases} \tag{4}$$

where the power supplier's revenue from the sale of electricity is the product of the contract bidding and the contract electricity signed in time period t, the contract biddings of green power supplier i and thermal power supplier j in time period t are B_i^t and B_j^t, and the contract electricity in time period t signed by all large consumers with green power supplier i and thermal power supplier j are $Q_i^t = \left[q_{i.1}^t, q_{i.2}^t \cdots q_{i.K}^t\right]$ and $Q_j^t = \left[q_{j.1}^t, q_{j.2}^t \cdots q_{j.K}^t\right]$, respectively, the power supplier's contract bidding to the large consumers is the product of the power supplier's base bidding plus the marginal bidding growth parameter and contract electricity. The base bidding combinations of green power supplier i and thermal power supplier j for all green power suppliers and all thermal power suppliers are $P_i^t = \left[p_{i.1}^t, p_{i.2}^t \cdots p_{i.m_g}^t\right]$ and $P_j^t = \left[p_{j.1}^t, p_{j.2}^t \cdots p_{j.m_f}^t\right]$, respectively; n^T is the marginal bidding growth coefficient of the green power supplier, and m^T is the marginal bidding growth coefficient of the thermal power supplier.

(2) Cost function for large consumers

The transaction costs J_k of large consumer k include the cost of purchasing electricity C_k^B, the cost of tradable green certificates transactions I_k^T, and the cost of excess consumption transactions E_k^T, as shown in Equation (5).

$$J_k = C_k^B + I_k^T + E_k^T \tag{5}$$

There should be positive, general, and negative attitudes for large consumers to fulfill the renewable electricity consumption quota assessment, but this paper considers the situation of large consumers with negative attitudes and proposes the worst-case electricity purchase strategy for large consumers [21]. If the actual amount of new energy consumed by a large consumer is less than the amount specified in the renewable electricity consumption quota K, the large consumer needs to purchase excess consumption from the excess consumption market, of which $q_{E,k,t}$ is a positive value in this case. In addition, if the purchase of excess consumption is not enough, it is necessary to purchase tradable green certificates from the market to fulfill the renewable electricity consumption quota K. Where the transaction cost of tradable green certificates is I_k^T, the expansion is as follows [22]:

$$\begin{cases} C_k^B = \sum_{t=1}^{T} (M_k^t + n^T Q_{k,m_g}^t) Q_{k,m_g}^t + \sum_{t=1}^{T} (N_k^t + m^T Q_{k,m_f}^t) Q_{k,m_f}^t + \sum_{t=1}^{T} p_t q_{k,t} \\ I_k^T = (K \sum_{t=1}^{T} d_{k,t} - \sum_{t=1}^{T} Q_{k,m_g}^t - \sum_{t=1}^{T} q_{E,k,t}) p_R \\ \sum_{t=1}^{T} q_{R,k,t} = K \sum_{t=1}^{T} d_{k,t} - \sum_{t=1}^{T} Q_{k,m_g}^t - \sum_{t=1}^{T} q_{E,k,t} \\ p_R = x - d \sum_{t}^{T} Q_{k,m_g}^t \\ p_E = 0.5 p_R \\ E_k^T = \sum_{t=1}^{T} q_{E,k,t} p_E \end{cases} \tag{6}$$

where $M_k^t = [m_{1,k}^t, m_{2,k}^t, \cdots m_{m_g,k}^t]$ is the portfolio of biddings from all green power suppliers to large consumer k in the market, $N_k^t = [m_{1,k}^t, m_{2,k}^t, \cdots m_{m_f,k}^t]$ is the portfolio of biddings from all thermal power suppliers to large consumer k in the market, $Q_{k,m_g}^t = [q_{1,k}^t, q_{2,k}^t, \cdots q_{m_g,k}^t]$ is the portfolio of contract electricity from all green power suppliers to large consumer k, $Q_{k,m_f}^t = [q_{1,k}^t, q_{2,k}^t, \cdots q_{m_f,k}^t]$ is the portfolio of contract electricity from all thermal power suppliers to large consumer k, the spot price at time t is p_t, the quantity of electricity purchased from the spot market in time period t by large consumer k is $q_{k,t}$, the trading cycle is T, the responsibility weighting of the government-mandated renewable electricity consumption quota is K, the electricity demand of large consumer k in time period t is $d_{k,t}$, the amount of consumption purchased by large consumer k from the excess consumption market in time period t is $q_{E,k,t}$; the amount of tradable green certificates purchased by the large consumer k from the tradable green certificates market in time period t is $q_{R,k,t}$, the price in the tradable green certificates market is p_R; and the price in the excess consumption market is p_E. The coefficients of the supply function of the price of tradable green certificates in the tradable green certificates market as a function of the change in green electricity load are x and d, respectively. In order to fulfill the renewable electricity consumption quota assessment requirement, large consumers preferred to purchase electricity from green power suppliers [23], and the balance of green electricity after fulfilling the renewable electricity consumption quota assessment requirement was balanced through the tradable green certificates market and the excess consumption market.

2.1.2. Game Modeling for Each Participant

According to the game relationship and objective function of each participant, the model of the upper-level leader (green and thermal power suppliers) and the lower-level follower (large consumers) are constructed, respectively.

(1) Leader model construction

Power suppliers' objective function:

The optimization objective of the power suppliers is profit maximization, corresponding to Equation (1).

Bidding constraint: the power suppliers' biddings do not exceed the upper and lower limits of the contract biddings [24]:

$$\begin{cases} P_i^{\min} \le p_{i,k}^t \le P_i^{\max} \\ P_j^{\min} \le p_{j,k}^t \le P_j^{\max} \end{cases} \tag{7}$$

where the upper and lower bounds of the green power supplier i biddings are $P_i^{\max}$ and $P_i^{\min}$, and the upper and lower bounds of the thermal power supplier j biddings are $P_j^{\max}$ and $P_j^{\min}$. The lower limit of the bidding is the maximum of the supplier's marginal cost and the minimum spot price, the upper limit of the thermal power supplier's bidding can be the maximum spot price, and the upper limit of the green power supplier's bidding can be the maximum spot price superimposed on the price of the tradable green certificates or the maximum of the price of the excess consumption [25].

The proof of existence and uniqueness of the equilibrium solution of the non-cooperative game between power suppliers is detailed in Appendix A.

(2) Follower model construction

Large consumer objective function:

The large consumer optimization objective is the minimum transaction cost, which corresponds to Equation (6).

Constraints

(1) Load balancing constraints

The sum of electricity purchased by the large consumer from the m_g green power suppliers, plus the sum of electricity purchased from the m_f thermal power suppliers, plus the sum of electricity purchased by the large consumer from the spot market in cycle T is equal to the electricity demanded by the large consumer in cycle T.

$$\sum_{i=1}^{m_g} q_{i,k}^t + \sum_{j=1}^{m_f} q_{j,k}^t + q_{k,t} = d_{k,t} \quad t = 1, 2 \cdots T \tag{8}$$

(2) The renewable electricity consumption quota assessment requirement constraints

Large consumers who fulfill the renewable electricity consumption quota assessment requirement can purchase in three ways, signing a contract electricity from green power suppliers, purchasing tradable green certificates, and purchasing excess consumptions, and the sum of the above three kinds of electricity is equal to the renewable electricity consumption quota assessment requirement [26].

$$K \sum_{t=1}^{T} d_{k,t} = \sum_{t=1}^{T} q_{R,k,t} + \sum_{t=1}^{T} Q_{k,m_g}^t + \sum_{t=1}^{T} q_{E,k,t} \tag{9}$$

(3) Restrictions on the amount of electricity purchased

The contract electricity signed between large consumers and each power supplier is not allowed to exceed the upper limit of its stipulated contract electricity, and the purchased electricity from the spot market cannot exceed the load demand electricity at time t.

$$\begin{cases} 0 \le q_{i,k}^t \le \overline{q}_i^t \\ 0 \le q_{j,k}^t \le \overline{q}_j^t \quad t = 1, 2 \cdots T \\ q_{k,t} \ge 0 \end{cases} \tag{10}$$

where $\overline{q}_i^t$ is the maximum amount of contract electricity by the green power supplier i with the large consumers, $\overline{q}_j^t$ is the maximum amount of contract electricity by the thermal power supplier j with the large consumers.

(4) Purchased excess consumption constraints

When $q_{E,k,t}$ is positive, there is a purchased excess consumption:

$$0 \le q_{E,k,t} \le \overline{q}_{E,b}^t \quad t = 1, 2 \cdots T \tag{11}$$

$\overline{q}_{E,b}^t$ is the upper limit of the amount of excess consumption that can be purchased by large consumers. The upper limit of $\overline{q}_{E,b}^t$ is not higher than the minimum requirement for the large consumer to complete the weight of renewable energy power consumption responsibility [27].

(5) The large consumer is also required to purchase tradable green certificates to fulfill the renewable electricity consumption quota assessment requirement, and the constraint on purchasing tradable green certificates is as follows:

$$0 \leq q_{R,k,t} \leq \overline{q}_R^t \quad t = 1, 2 \cdots T \tag{12}$$

$\overline{q}_R^t$ is the upper limit of tradable green certificates that can be purchased by the large consumer. The upper limit of $\overline{q}_R^t$ is not higher than the minimum requirement for the large consumer to complete the weight of renewable energy power consumption responsibility.

2.2. Measurement of the Double Game Model

In the primary–secondary game problem, the payoff optimization problem of the game participants at each level is a nonlinear optimization problem, and it is known from the nonlinear programming theory that the necessary condition for the solution of a nonlinear optimization problem is the Karush–Kuhn–Tucker (KKT) condition; therefore, the solution of a nonlinear optimization problem can be obtained by solving the KKT condition of that nonlinear optimization problem [28]. The KKT condition consists of the constraints of the original lower-level problem, the constraints of the dual problem, the complementary relaxation condition, and the gradient of the Lagrangian function [29]. Thus, optimization can be achieved using KKT conditions. The derivation of the KKT condition formula is detailed in Appendix B.

2.3. Dual-Game Modeling Arithmetic Example Analysis

This study examines the analysis of the results when the primary–secondary game played between power suppliers and large consumers reaches equilibrium, while the non-cooperative game played between power suppliers achieves Nash equilibrium.

2.3.1. Parameters of the Example

In the model developed in this paper, this arithmetic example investigates the optimal strategies for different power suppliers to enter into bilateral contracts with large consumers in one year. It is assumed that there are two green power suppliers (S1, S2), two thermal power suppliers (C1, C2), and four large consumers (L1, L2, L3, L4) included in this market transaction.

The spot trading cycle is 12 h and the load profile of the large consumers is shown in Figure 4.

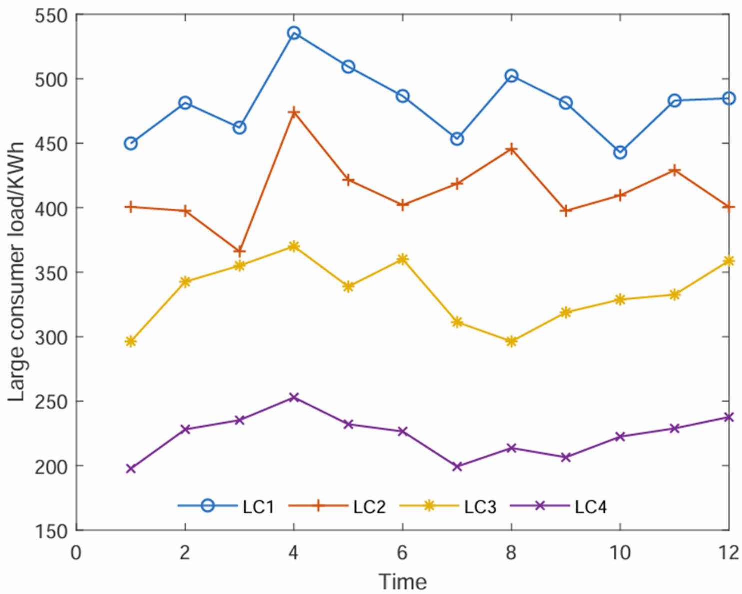

Figure 4. Load of large consumers by time period.

The parameters of green and thermal power suppliers are shown in Table 1.

Table 1. Parameters of green and thermal power suppliers.

Parameters	GPS1	GPS2	Parameters	TPS1	TPS2
a_i	0.6375	0.6	x_j	0.4575	0.615
b_i	240	284	y_j	189	199
c_i	0	0	z_j	0	0
$\overline{q}_{R,i}$	200	250	$\overline{q}_{C,j}$	400	250
$b_{R,i}$	0.25	0.15	$b_{C,j}$	0.43	0.26

Parameters source: National Development and Reform Commission, Tianjin Development and Reform Commission.

2.3.2. Analysis of Results

Analysis of Power Suppliers' Bidding Behaviors

(1) From the data in Figure 5, it can be observed that there is a decreasing trend in the electricity load of large consumers. Due to the weight of renewable energy power consumption responsibility of large consumers' consumption, as well as the reality that the price of electricity in the spot market is generally higher than that in the medium- and long-term market, large consumers need to purchase the electricity they need from green and thermal power suppliers through multiple channels and in multiple ways at the same time. Under this premise, the green and thermal power suppliers will try to maximize their biddings in order to obtain the highest revenues, as they are sure that large consumers will buy a certain amount of electricity from them [30]. Since the marginal biddings of the green and thermal power suppliers will increase with the increase in contract electricity, the green and thermal power suppliers will make decisions based on this situation, i.e., the biddings to the large consumer 1 (LC1) will be higher than the biddings to the large consumer 2 (LC2), which are higher than the biddings to the large consumer 3 (LC3), and the biddings to the large consumer 3 (LC3) are higher than the biddings to the large consumer 4 (LC4). In particular, when the contract electricity purchased by large consumers increases, the green and thermal power suppliers increase their contract bidding prices to maximize their profits. However, when the spot price is low, the power suppliers, in order to avoid large consumers switching to purchasing electricity from the spot market, will lower their biddings accordingly to ensure that the contract electricity is not lost to large consumers as a result of excessively high biddings.

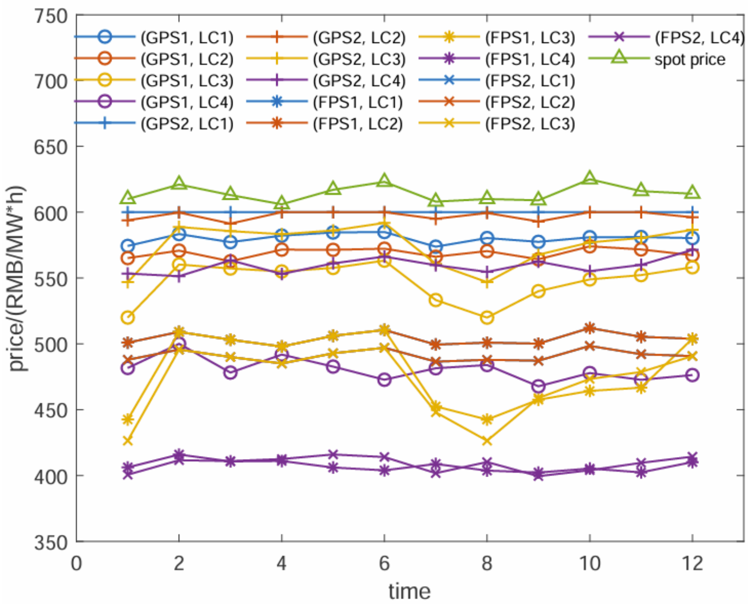

Figure 5. Power suppliers' biddings at Game Equilibrium.

(2) For large consumers 1, 2, 3, and 4, the analysis based on the comparison of the biddings of green power supplier 1 (GPS1) and thermal power supplier 1 (TPS1) shows that the contract biddings of green power supplier 1 (GPS1) are higher than the thermal power supplier 1 (TPS1). This is due to the fact that green power supplier 1 (GPS1) has a lower marginal bidding growth rate compared to thermal power supplier 1 (TPS1). Even if the biddings of green power supplier 1 (GPS1) are higher, the lower marginal bidding growth parameter when green power suppliers sign more contract electricity ensures that it obtains a reasonable share of contract electricity in the market. This conclusion applies equally to other green power suppliers and thermal power suppliers.

(3) In addition, it can be found that the contract bidding prices of green and thermal power suppliers are lower than the spot price. In the actual electricity market, for large consumers, the medium- and long-term contract bidding prices are lower than the spot market, so the strategy of direct purchase of electricity by large consumers is an important step for large consumers to reduce the cost of electricity. For green and thermal power suppliers, the direct sale of electricity to the spot market will be more profitable, but in reality, green and thermal power suppliers cannot accurately predict the spot price, and a variety of trading methods can help green and thermal power suppliers to avoid market risks and reduce the dependence of green and thermal power suppliers on spot market transactions.

Analysis of Electricity Purchase Strategies for Large Consumers

(1) From the Nash equilibrium power purchase strategy of large consumers, it can be seen that, thanks to the lower marginal cost increase rate (i.e., the quadratic term coefficient of the generation cost function), according to the trend of the biddings of the suppliers to large consumers in Figure 5 and combined with the total sales of electricity by each supplier to different large consumers in Figure 2, we can determine that thermal power supplier 1 (TPS1) has the lowest final contract bidding among the three suppliers, and the sum of the contract electricity sold is the highest. Because of the dual attributes of tradable green certificates and electricity, green power supplier 2 (GPS2) has a higher competitive contract bidding price, while the final sum of contract electricity sold is the lowest due to the higher rate of marginal cost increase (i.e., the quadratic term coefficient of the generation cost function).

(2) From Figure 6, it can be seen that large consumers 1, 2, and 3 will generally choose to purchase part of their electricity in the green, thermal, and spot markets according to the biddings of the green and thermal power suppliers. Large consumer 4 (LC4) will choose to purchase electricity from green and thermal power suppliers. For the strategic allocation of purchased electricity, for large consumers 1, 2, and 3 of the electricity load in decreasing order, the spot price is generally higher than the bidding of the thermal power suppliers, and large consumers give priority to the purchase of electricity from the thermal power suppliers, but the amount of electricity purchased by large consumers is also subject to the weight of renewable energy power consumption responsibility assessment [31]; thus, when the price of the spot market is lower, even if the green power suppliers' biddings are higher, the large consumers will still be purchased from the green power suppliers of a small amount of green electricity to meet the assessment requirements. There is an upper limit on the amount of electricity contracted between large consumers and power suppliers, so large consumers will choose to purchase electricity from the spot market for the part of their load demand that exceeds the contracted amount of electricity. Therefore, from Figure 6, according to the difference in the amount of electricity purchased in the spot market by large consumers with different load demands, it can be seen that the amount of electricity purchased in the spot market is directly proportional to the load demand of large consumers.

As shown in Figure 7, in the primary–secondary game process, the green power supplier and thermal power supplier are in the upper layer of the game, although the large consumers are in the lower layer of the game, and can only passively accept the bidding of the green power supplier and thermal power supplier. However, it can be found that all large consumers through bilateral trading direct electricity purchase and the spot market electricity purchase strategy are lower than only the spot market electricity purchase cost [32]; at the same time, the combination of electricity purchase strategy can help large consumers to reduce the cost of electricity purchase and reduce the risk of electricity purchase. Therefore, bilateral contract trading has positive significance and is indispensable for green power suppliers, thermal power suppliers, the electricity market, and large consumers.

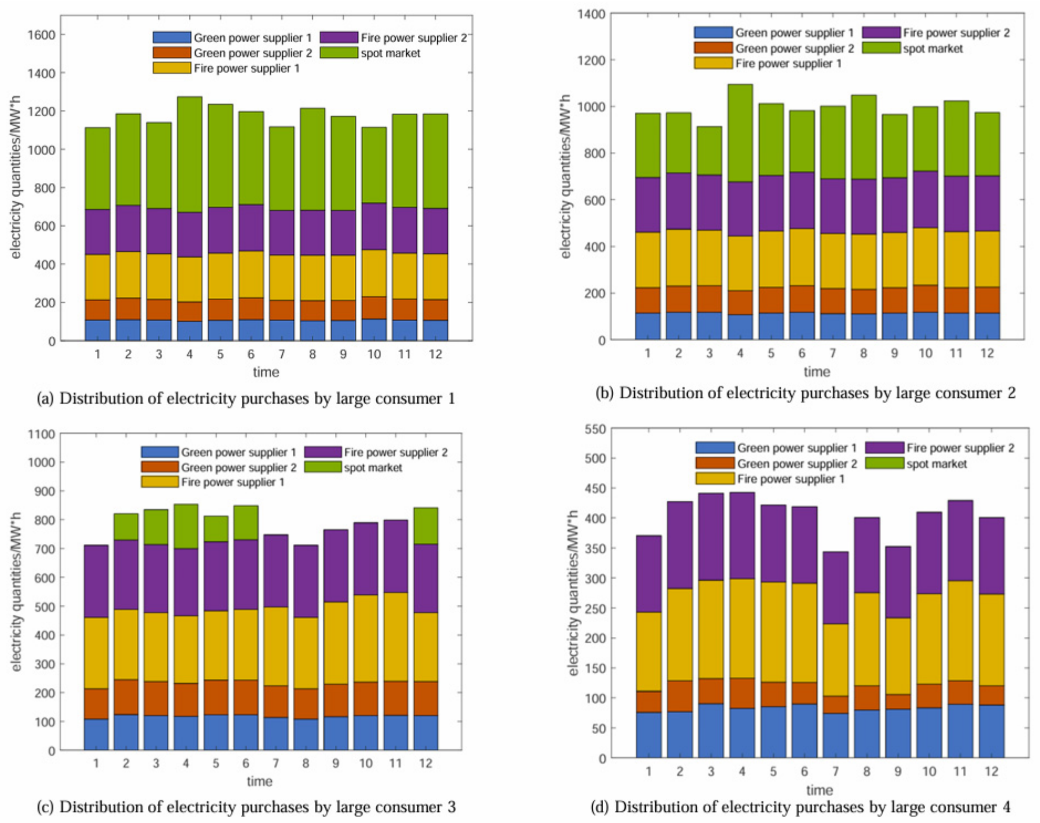

Figure 6. Distribution of electricity purchases by large consumers in Nash equilibrium.

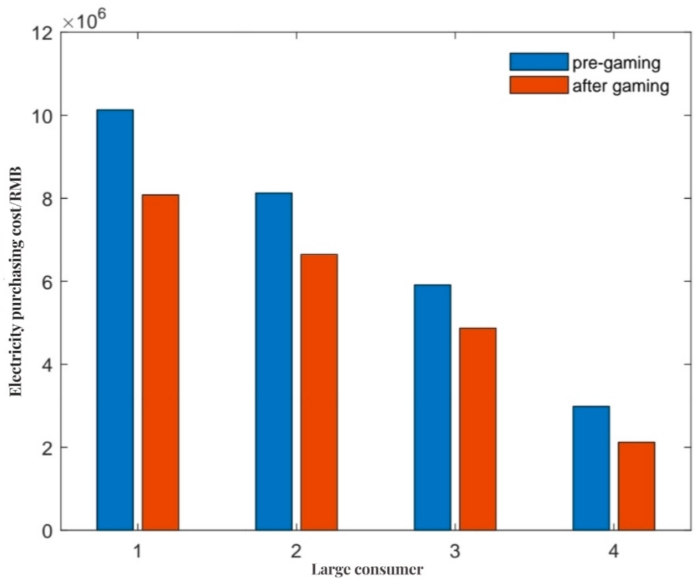

Figure 7. Changes in the cost of purchasing electricity before and after gaming by large consumers.

3. Expected Utility–Entropy-Based Power Purchase Model for Large Consumers

Section 2 analyzes how multiple large consumers sign bilateral contracts with multiple power suppliers. In this section, based on the study in Section 2, assuming that the medium- and long-term contract biddings of the suppliers do not change with the change in the large consumers' willingness to purchase electricity and that the large consumers can only sign a medium- and a long-term contract with one supplier, and then find out how the large consumers can reasonably formulate their own power purchasing strategies taking into account the risk when they face multiple ways of purchasing electricity (spot market, medium and long term, and options market).

3.1. Expected Utility–Entropy and Analysis of Electricity Purchase Costs for Large Consumers

3.1.1. Expected Utility–Entropy Modeling

The information entropy (differential entropy) of continuous information source is then defined as follows [33]:

$$H_n(X) = -k\int_{-\infty}^{+\infty} p(x)\log p(x)dx \tag{13}$$

where $p(x)$ is the probability density function corresponding to X.

Bringing the probability density function of normal distribution into Equation (13), the information entropy under normal distribution is obtained as follows [34]:

$$H_n(X) = -k\int_{-\infty}^{+\infty} p(x)\log p(x)dx = \ln\sqrt{2\pi\sigma} + \frac{1}{2} \tag{14}$$

For the decision behavior, assume that the action party $a \in A$ is the decision behavior taken by this decision maker, and the corresponding states under different decision behaviors are $\theta \in \Theta$. Assume that the utility function $u(x) \geq 0$ is the benefit gained by the decision maker after taking the action and that the expectation $E[u(X(a,\theta))]$ of the utility function $u(x)$ satisfies $\max\limits_{a\in A}\{E[u(X(a,\theta))]\} > 0$. u is the utility function of $\Theta \times A$ for the benefit gained by the decision maker after taking the decision action, and is denoted by $u(X(a,\theta))$. Then, the expected utility–entropy risk of this decision action under action option a can be defined as follows [35]:

$$R(a) = \lambda\frac{H_a(\theta)}{\min\limits_{a\in A}H_a(\theta)} + (1-\lambda)\frac{E[u(X(a,\theta))]}{\min\limits_{a\in A}E[u(X(a,\theta))]} \tag{15}$$

where $R(a)$ is the composite risk measure corresponding to action plan a; $H_a(\theta)$ is the entropy of the state θ corresponding to action plan a. $\lambda \in [0,1]$ denotes the type of risk preference of the decision maker, $\lambda \in [0,0.5]$ stands for risk preferring, $\lambda \in [0.5,1]$ stands for risk averse, and when $\lambda = 0.5$, it is risk neutral. In particular, when $\max\limits_{a\in A}\{E[u(X(a,\theta))]\} = 0$, for any $a \in A$ course of action, there is $E[u(X(a,\theta))] = 0$, at which point, $R(a) = H_a(\theta)$ is defined [36].

3.1.2. Analysis of Electricity Purchase Costs for Large Consumers in Mature Electricity Markets

Next, the electricity purchase costs of large consumers in each market are analyzed separately:

Spot price fluctuation being larger is the main reason for the risk of large consumers of electricity purchase costs. The variables are defined as follows: the amount of electricity purchased in the spot market is q_t, the spot market price is p_t, and the cost of electricity purchased by large consumers in the spot market is C_t.

$$C_t = p_t q_t \tag{16}$$

The price of electricity in the medium- and long-term market is jointly finalized by large consumers and power suppliers, and when the contract price is linked to the spot price, i.e., the real transaction price of the contract price will change along with the changes in the spot price, thus reducing to a certain extent the risks brought about by price fluctuations [37]. Large consumers obtaining electricity through medium- and long-term contract transactions is one of the most effective measures to reduce the risk of large consumers purchasing electricity. Here, assume that large consumers and power suppliers contract prices for p_F, the amount of power purchased for q_F, respectively, at this time, large consumers in the medium- and long-term market electricity purchase cost C_F is as follows:

$$C_F = p_F q_F \tag{17}$$

In the options market, when the spot price p_t is greater than the contract price V, the large consumer uses the option, i.e., purchases electricity at the price V in the contract; when p_t is less than the contract price V, the large consumer gives up the option and purchases electricity from the spot market after paying for the option P_o. C_o denotes the cost of purchasing through the power option. Assuming that the large consumer purchases electricity q_o through the power option, the cost of purchasing power is as follows [38]:

$$C_o = (\min(p_t, K) + P_o) \cdot q_o \tag{18}$$

Thus, the total cost of power purchase for large consumers is as follows:

$$C = p_t q_t + p_F q_F + (\min(p_t, K) + P_o) \cdot q_o \tag{19}$$

3.2. Expected Utility–Entropy-Based Power Purchase Transaction Model for Large Consumers

Let the electricity purchased by large consumers in the medium- and long-term market, spot market, and power option market be q_t, q_F, and q_o, respectively; the total purchased power demand of large consumers be D; the medium- and long-term and spot electricity prices be p_F and p_t, respectively; the option price be V; and the option fee be P_o. Since the medium- and long-term contract prices are less volatile in terms of price fluctuations and the spot prices are subject to many influencing factors and fluctuate drastically, it is assumed in this paper that the spot market and the medium- and long-term markets' prices obey the joint normal distribution, i.e., p_F and p_t obey the normal distribution of $N\left(\mu_t, \sigma_t^2, \mu_F, \sigma_F^2, \rho\right)$ [39]. Where the mean values of the contracted tariffs and spot trading tariffs for bilateral transactions are μ_F and μ_t, and the mean squared deviations are σ_F and $\sigma_t.\rho$ is the correlation coefficient of the two. q_F, q_t are the decision variables representing the amount of electricity purchased in the medium- and long-term market and the spot market, then the expectations of large consumers of electricity purchase can be expressed as follows:

$$E(C) = q_F \cdot \mu_F + q_t \cdot \mu_t + q_o \cdot p_o + \left(K - \int_{-\infty}^{K} \Phi(p_t) dp_t\right) \cdot q_o \tag{20}$$

where Φ represents the standard normal distribution function. For example, q_F, q_t are the decision variables representing the amount of electricity purchased in the medium- and long-term market and the spot market. Generally, there is $\mu_F < \mu_t$. Notation $p = [p_t, p_F]$, $q = [q_F, q_t, q_o]$, q, for example, are decision variables representing the amount of electricity purchased in the medium- and long-term market and the spot market.

In using the expected utility–entropy model to analyze the risk problem of largecon-sumer portfolios, it is necessary to first analyze the probability distribution of the large consumer electricity purchase cost function represented by $E(C)$. The expectation and variance of the electricity purchase costs are calculated based on $D(C) = E\left(C^2\right) - E^2(C)$. In order to find the variance $D(C)$, this paper starts with $E\left(C^2\right)$. Since C^2 can be expressed as

$$C^2 = (p_t q_t + p_F q_F + p_o q_o)^2 + q_o^2 \min^2(p_t, K) + 2q_o(p_t q_t + p_F q_F + p_o q_o)\min(p_t, K) \tag{21}$$

$C_1 = (p_t q_t + p_F q_F + p_o q_o)^2, C_2 = q_o^2 \min^2(p_t, K), C_3 = 2q_o(p_t q_t + p_F q_F + p_o q_o)\min(p_t, K)$, then solving for $E(C^2)$ can be divided into the following three parts:

$$\begin{aligned} E(C_1) = & \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}(p_t q_t + p_F q_F + p_o q_o)^2 dp_t dp_F = q_t^2(\sigma_t^2 + \mu_t^2) \\ & + q_F^2(\sigma_F^2 + \mu_F^2) + p_o^2 q_o^2 + 2p_o\mu_t q_t q_o + 2p_o\mu_F q_F q_o + \\ & 2q_t q_F\left[\frac{\rho\sigma_F}{\sigma_t}(\sigma_t^2 + \mu_t^2) + \frac{\mu_F\sigma_t - \rho\mu_t\sigma_F}{\sigma_t}\mu_t\right] \end{aligned} \tag{22}$$

$$E(C_2) = q_o^2\left[K^2 - 2\int_{-\infty}^{K} p_t \Phi\left(\frac{p_t - \mu_t}{\sigma_t}\right)dp_t\right] \tag{23}$$

$$\begin{aligned} E(C_3) = & 2p_o q_o^2 \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\min(p_t, K) f(p_t, p_F) dp_F dp_t + \\ & 2q_o\int_{-\infty}^{\infty}\min(p_t, K)\left[\int_{-\infty}^{\infty}(p_t q_t + p_F q_F) f(p_t, p_F) dp_F\right]dp_t = \\ & 2p_o q_o^2\left[K - \int_{-\infty}^{K}\Phi\left(\frac{p_t - \mu_t}{\sigma_t}\right)dp_t\right] + \\ & 2q_o\frac{\mu_F\sigma_t q_F - \mu_t q_F\rho\sigma_F}{\sigma_t}\left[K - \int_{-\infty}^{K}\Phi\left(\frac{p_t - \mu_t}{\sigma_t}\right)dp_t\right] + \\ & 2q_o\frac{\sigma_t q_t + q_F\rho\sigma_F}{\sigma_t}\left[K\mu_t + \int_{-\infty}^{K}(K - 2p_t)\Phi\left(\frac{p_t - \mu_t}{\sigma_t}\right)dp_t\right] \end{aligned} \tag{24}$$

The variance of the total profit of direct electricity purchase by large consumers according to statistical theory is as follows:

$$D(C) = E(C_1) + E(C_2) + E(C_3) - E^2(C) \tag{25}$$

The resulting information entropy is as follows:

$$H_a(\theta) = \ln\sqrt{2\pi}\sigma + \frac{1}{2} = \ln\sqrt{2\pi[E(C_1) + E(C_2) + E(C_3) - E^2(C)]} + \frac{1}{2} \tag{26}$$

The analysis method is based on the assumption that the electricity purchase costs of large consumers obey a normal distribution, and the expectation and variance of the electricity purchase costs are calculated based on $D(C) = E(C^2) - E^2(C)$. The entropy value is calculated using Equation (14), and the entropy value and the average value of the electricity purchase cost of large consumers can be substituted into Equation (14) to obtain the large consumer portfolio optimization model based on expected utility–entropy:

$$\min R(a) = \lambda\frac{H_a(\theta)}{\min\limits_{a\in A} H_a(\theta)} + (1-\lambda)\frac{E[u(X(a,\theta))]}{\min\limits_{a\in A} E[u(X(a,\theta))]} \tag{27}$$

where $H_a(\theta)$ and $E[u(X(a,\theta))]$ are the entropy value and the expected value of the utility function corresponding to the large consumer electricity allocation strategy, respectively. The constraints of Equation (27) are Equation (28).

$$s.t.\left\{\begin{array}{l} D = q_F + q_t + q_o \\ \min q_F \le q_F \le \overline{q_F} \\ \min q_t \le q_t \le \overline{q_t} \\ q_t \ge 0 \end{array}\right\} \tag{28}$$

3.3. Example Analysis

Assume that a large consumer is developing a 12 h electricity purchase strategy and that it can obtain electricity through the medium- and long-term markets, the spot market, and the options market. Let the mean value of the spot market price μ_t be CNY 340/MWh, and its mean variance σ_t 120; the mean value of the medium- and long-term contract price μ_F is CNY 380/MWh, and its mean variance σ_F is 30; the correlation coefficient ρ between the spot market and the medium- and long-term contract market is 0.2; the option price P_o is CNY 40/MWh, and the finalized price K is CNY 335/MWh; and the amount of electricity purchased Q is 8500 MWh.

As can be seen from Figure 8, when $\lambda \in [0, 0.5]$ indicates that the decision maker is a risk-preferring type, at this time, if the spot price is less than the option price and the medium- and long-term contract price, large consumers will choose to purchase electricity from the spot market to reduce their own cost of purchasing electricity. With the increase of λ, the large consumers of the importance of the risk of purchasing electricity has gradually become greater in order to avoid the risk of fluctuating spot price, embodied in the development of the strategy for the purchase of electricity; that is, to reduce the purchase of electricity in the spot market, the medium- and long-term contract transactions gradually become more and more and increase the purchase of electricity in the options market.

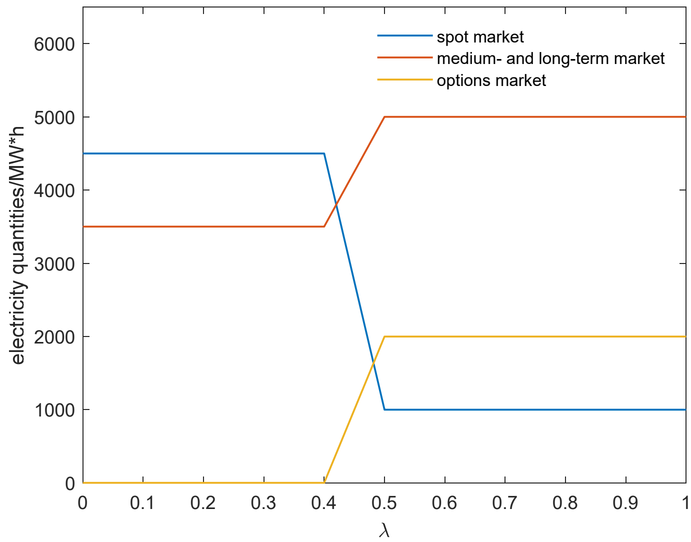

Figure 8. Optimization results of electricity purchase portfolio for large consumers.

Of course, it is important to note here that although the electricity purchased by large consumers in the options market gradually increases as λ increases, this does not mean that all option electricity purchased by large consumers will be delivered; when the spot price is lower than the option price, large consumers can choose to give up the execution of the current time period of the option electricity, and turn to obtain electricity from the spot market. Large consumers purchase a large number of option contracts just to lock in a cap on the future price of electricity on a single day, thus minimizing the risk of their electricity purchases.

In addition, when large consumers formulate medium- and long-term electricity purchase strategies, their main concern is the electricity purchase strategy in the options market and medium- and long-term contract market, because the contract electricity in these two markets will be decided at the moment of contract signing, while the purchased electricity in the spot market can be changed according to the demand of large consumers and the spot price in real time. The simulation results show that the expected utility–entropy-based decision-making model for large consumers established in this paper can reflect their own attitude towards risk changes, and give the corresponding electricity allocation decisions.

In the primary–secondary game process, the green power suppliers and thermal power suppliers are in the upper layer of the game, although the large consumers are in the lower layer of the game, and can only passively accept the biddings of the green power suppliers and thermal power suppliers. However, it can be found that the combination of electricity purchase strategy can help large consumers to reduce the cost of electricity purchase and reduce the risk of electricity purchase. Therefore, bilateral contract trading has positive significance and is indispensable for green power suppliers, thermal power suppliers, the electricity market, and large consumers.

4. Discussion and Conclusions

In this paper, for the multifaceted coupled optimization problem of direct electricity purchase by large consumers and multi-power suppliers bidding decision making in the context of the weight of renewable energy power consumption responsibility, a dual-game optimization model of green and thermal power suppliers bidding for electricity and direct electricity purchase by large consumers is established, and, according to the simulation analysis, the concept of value at risk is introduced, and expected utility–entropy method is used to optimize the addressed problem is optimized, and the following conclusions are obtained:

(1) When conducting bilateral transactions of direct purchase of electricity by large consumers, power suppliers increase their revenue through independent biddings, large consumers can reduce the cost of purchasing electricity, reduce the dependence on the spot market, and the competition in the electricity market is more adequate. In the existing studies, Guo Lin [40], Tian Yuyang [41], and other scholars reached the same conclusion in their studies. They proved that power suppliers can improve their revenue through autonomous bidding when conducting bilateral transactions of direct electricity purchases by large consumers.

(2) With the advancement of the game in many rounds, the bidding of power suppliers is mainly affected by the spot price of electricity and the electricity demanded by large consumers, and in order to ensure their share of contract power, choosing reasonable bidding is the key to profit maximization. This conclusion is likewise confirmed by other scholars [3,42].

(3) Under the effect of the consumption assessment requirement and the double game bidding mechanism designed in this paper, large consumers can only make electricity purchase decisions passively according to the power suppliers' biddings. At the same time, considering the reality that the price of electricity in the spot market is generally higher than that in the medium- and long-term market, the power suppliers, in order to attract large consumers to purchase electricity, optimize their own decision making to enhance competitiveness to obtain the highest return.

(4) In consideration of the spot market, medium- and long-term contracts and options market can be purchased, based on risk factors to establish the optimization model of the electricity purchase strategy of large consumers, the results of this study concluded that the combination of the electricity purchase strategy of large consumers under different risk preferences. The pattern of change is the conclusion that diversified electricity purchases can reduce the risk of large consumers, and with the continuous reduction of risk preference, electricity purchases in the spot market with the highest risk will continue to decrease. And the amount of electricity purchased in the less risky option market and the medium- and long-term market will keep increasing. The study by Wu Cheng [8] and other authors verifies this conclusion and suggests that diversified electricity purchase methods can reduce the risk of electricity purchases by large consumers.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Proof of Existence and Uniqueness of Solutions to Noncooperative Games

According to the Nash equilibrium point existence theorem: in a game problem with finite participants, if the set of strategies of the participants is a closed, bounded convex set, and every objective function on the strategy space is a continuous convex function (by the definition of a convex–concave function), a Nash equilibrium point exists for the game problem.

In the multi-power supplier non-cooperative game, the players are each power supplier and the bidding is the optimization-seeking strategy of each power supplier. Taking green power supplier i as an example, according to Equation (1), its profit function is obtained as follows:

$$J_{R,i} = \sum_{t=1}^{T} (P_i^t + n^T Q_i^t) Q_i^t - (A_i((\sum_{k=1}^{K} q_{i,k}^t)^T)^2 + B_i(\sum_{k=1}^{K} q_{i,k})^T + C_i) i = 1, 2, \ldots, m_g \quad \text{(A1)}$$

where the number of green power suppliers is m_g, i.e., the participants of the game are finite. And each green power supplier bidding satisfies the following constraints:

$$P_i^{\min} \le p_{i,k}^t \le P_i^{\max} \quad \text{(A2)}$$

The contract bidding price B_i^t of a green power supplier is a primary function on its base bidding P_i^t. Therefore, the set of base price strategies of the m_g green power suppliers is a closed, bounded convex set, and there must be a corresponding price strategy P_i^t that exists when the green power supplier i participates in a transaction, and thus the set of its strategies is non-empty.

In the multi-power supplier non-cooperative game process, when seeking to optimize the bidding of a green power supplier i, the biddings of other power suppliers should remain unchanged and can be considered constants. Therefore, the transaction cost function of the lower large consumer k can be rewritten as follows:

$$J_k = \begin{cases} \sum\limits_{t=1}^{T} (M_k^t + n^T Q_{k,m_g}^t) Q_{k,m_g}^t + \sum\limits_{t=1}^{T} (M_k^t + n^T Q_{k,m_g,m_g}^t) Q_{k,m_g,m_g}^t + \\ \sum\limits_{t=1}^{T} (N_k^t + m^T Q_{k,m_f}^t) Q_{k,m_f}^t + \sum\limits_{t=1}^{T} p_t q_{k,t} + \\ (K \sum\limits_{t=1}^{T} d_{k,t} - \sum\limits_{t=1}^{T} Q_{k,m_g,m_g}^t - \sum\limits_{t=1}^{T} q_{E,k,t}) p_R + \sum\limits_{t=1}^{T} q_{E,k,t} p_E \end{cases} \quad \text{(A3)}$$

If the constant term is replaced by C, Equation (A3) can be rewritten as

$$J_k = (M_k^t + n^T Q_{k,m_g}^t) Q_{k,m_g}^t - p_R Q_{k,m_g,m_g}^t + C \quad \text{(A4)}$$

Solving the first-order partial derivative of Equation (A4) with respect to Q_{k,m_g}^t, the optimal amount of electricity purchased by the large consumer k from the green power supplier i can be found to be

$$M_k^t + 2n^T Q_{k,m_g}^t = p_R \quad \text{(A5)}$$

$$Q_{k,m_g}^t{}^* = \frac{p_R - M_k^t}{2n^T} \quad \text{(A6)}$$

Through Equation (A6), it can be determined that for a given power supplier's bidding strategy, the large consumer has a unique electricity purchase strategy corresponding to it, which can be obtained by substituting Equation (A6) into Equation (A1) and replacing the constant term with *C*:

$$J_{R,i} = \sum_{t=1}^{T} (P_i^t + n^T(\frac{p_R - M_k^t}{2n^T}))(\frac{p_R - M_k^t}{2n^T}) - (A_i(\frac{p_R - M_k^t}{2n^T})^2 + B_i(\frac{p_R - M_k^t}{2n^T})) + C \quad \text{(A7)}$$

The second-order partial derivative with respect to M_k^t for Equation (A7) is obtained:

$$\frac{\partial^2 J_{R,i}}{\partial (M_k^t)^2} = -\frac{(A_i - n^T)}{2(n^T)^2} < 0 \quad \text{(A8)}$$

From Equation (A8), it can be seen that the Hessian matrix of the objective function of the green power supplier is a negative definite matrix, and the profit function of each green power supplier is a continuous convex function with respect to its bidding strategy. Similarly, the profit function of each thermal power supplier also satisfies the continuous convex function characteristics. Based on the above analysis, there exists a unique Nash equilibrium solution for the non-cooperative game between multiple power suppliers.

Appendix B. Derivation of KKT Conditional Equations

Appendix B.1. Construction of KKT Conditions

(1) Construction of the follower model Lagrangian function

The dual variable of Equation (8) is λ_k, the dual variable of Equation (9) is λ_E, and the dual variable of Equations (10)–(12) is $\left\{\eta_k^{i+}, \eta_k^{i-}, \eta_k^{j+}, \eta_k^{j-}, \eta_{k,t}^{m+}, \eta_{k,t}^{m-}, \eta_{k,t}^{Eb-}, \eta_{k,t}^{Eb+}, \eta_{k,t}^{R-}, \eta_{k,t}^{R+}\right\}$. In this case, the large consumer purchases both the excess consumption and the tradable green certificates, and the follower model Lagrangian function is shown below.

$$L = \left\{ \begin{array}{l} \sum\limits_{t=1}^{T} (M_k^t + n^T Q_{k.m_g}^t) Q_{k.m_g}^t + \sum\limits_{t=1}^{T} (N_k^t + m^T Q_{k,m_f}^t) Q_{k,m_f}^t + \sum\limits_{t=1}^{T} p_t q_{k,t} + \sum\limits_{t=1}^{T} q_{E,k,t} p_E + \\ (K \sum\limits_{t=1}^{T} d_{k,t} - \sum\limits_{t=1}^{T} Q_{k.m_g}^t - \sum\limits_{t=1}^{T} q_{E,k,t}) p_R + \lambda_k (\sum\limits_{i=1}^{m_g} q_{i,k}^t + \sum\limits_{j=1}^{m_f} q_{j,k}^t + q_{k,t} - d_{k,t}) + \\ \lambda_E (\sum\limits_{t=1}^{T} q_{R,k,t} + \sum\limits_{t=1}^{T} Q_{k,m_g}^t + \sum\limits_{t=1}^{T} q_{E,k,t} - d_{k,t}) + \eta_k^{i+} (q_{i,k}^t - \overline{q}_i^t) + \eta_k^{i-} (-q_{i,k}^t) + \\ \eta_k^{j+} (q_{j,k}^t - \overline{q}_j^t) + \eta_k^{j-} (-q_{j,k}^t) + \sum\limits_{t=1}^{T} \eta_{k,t}^{m+} (q_{k,t} - d_{k,t}) + \sum\limits_{t=1}^{T} \eta_{k,t}^{m-} (-q_{k,t}) + \\ \eta_{k,t}^{Eb+} (q_{E,k,t} - \overline{q}_{E,b}^t) + \eta_{k,t}^{Eb-} (-q_{E,k,t}) + \eta_{k,t}^{R+} (q_{R,k,t} - \overline{q}_R^t) + \eta_{k,t}^{R-} (-q_{R,k,t}) \end{array} \right. \quad \text{(A9)}$$

(2) Constraints on dual variables

$$\eta_k^{i+}, \eta_k^{i-}, \eta_k^{j+}, \eta_k^{j-}, \eta_{k,t}^{m+}, \eta_{k,t}^{m-}, \eta_{k,t}^{Eb-}, \eta_{k,t}^{Eb+}, \eta_{k,t}^{R-}, \eta_{k,t}^{R+} \geq 0 \; \forall k, \forall t \quad \text{(A10)}$$

(3) Construction of complementary relaxation conditions

By constructing the lower follower model Lagrangian function (A9) and the lower follower model KKT complementary relaxation condition, the lower follower model can be transformed into an additional constraint of the upper leader model, so the complementary relaxation condition is as follows:

$$
\begin{aligned}
&0 \le \eta_k^{i+} \perp \overline{q}_i^t - q_{i,k}^t \ge 0\\
&0 \le \eta_k^{i-} \perp q_{i,k}^t - 0 \ge 0\\
&0 \le \eta_k^{j+} \perp \overline{q}_j^t - q_{j,k}^t \ge 0\\
&0 \le \eta_k^{j-} \perp q_{j,k}^t - 0 \ge 0\\
&0 \le \eta_{k,t}^{m+} \perp d_{k,t} - q_{k,t} \ge 0\\
&0 \le \eta_{k,t}^{m-} \perp q_{k,t} - 0 \ge 0\\
&0 \le \eta_{k,t}^{Eb+} \perp \overline{q}_{E,b}^t - q_{E,k,t} \ge 0\\
&0 \le \eta_{k,t}^{Eb-} \perp q_{E,k,t} - 0 \ge 0\\
&0 \le \eta_{k,t}^{R+} \perp \overline{q}_R^t - q_{R,k,t} \ge 0\\
&0 \le \eta_{k,t}^{R-} \perp q_{R,k,t} - 0 \ge 0
\end{aligned}
\tag{A11}
$$

(4) Linearization of complementary relaxation variables

After converting to a single-layer model, the complementary relaxation condition (A11) is a nonlinear constraint, and the Big-M method is used to equivalently transform the original nonlinear constraint into a mixed-integer linear constraint by introducing a number of Boolean variables, where $\theta_{R,i,k}^+, \theta_{R,i,k}^-$ Boolean variables for the amount of electricity contracted with the green power suppliers, $\theta_{C,j,k}^+, \theta_{C,j,k}^-$ Boolean variables for the amount of electricity contracted with the thermal power suppliers, and $\theta_{k,t}^+, \theta_{k,t}^-$ Boolean variables for the amount of electricity purchased from the spot market. And of the $\theta_{R,k,t}^+, \theta_{R,k,t}^-$ Boolean variables for the amount of tradable green certificates purchased from the tradable green certificates market, and the $\theta_{Eb,k,t}^+, \theta_{Eb,k,t}^-$ Boolean variables for the amount of excess consumptions purchased by large consumers, M is a sufficiently large number.

$$
\begin{aligned}
&0 \le \eta_k^{i+} \le M\theta_{R,i,k}^+\\
&0 \le \overline{q}_i^t - q_{i,k}^t \le M(1-\theta_{R,i,k}^+)\\
&0 \le \eta_k^{i-} \le M\theta_{R,i,k}^-\\
&0 \le q_{i,k}^t - 0 \le M(1-\theta_{R,i,k}^-)\\
&0 \le \eta_k^{j+} \le M\theta_{C,j,k}^+\\
&0 \le \overline{q}_j^t - q_{j,k}^t \le M(1-\theta_{C,j,k}^+)\\
&0 \le \eta_k^{j-} \le M\theta_{C,j,k}^-\\
&0 \le q_{j,k}^t - 0 \le M(1-\theta_{C,j,k}^-)\\
&0 \le \eta_{k,t}^{m+} \le M\theta_{k,t}^+\\
&0 \le d_{k,t} - q_{k,t} \le M(1-\theta_{k,t}^+)\\
&0 \le \eta_{k,t}^{m-} \le M\theta_{k,t}^-\\
&0 \le q_{k,t} - 0 \le M(1-\theta_{k,t}^-)\\
&0 \le \eta_{k,t}^{Eb+} \le M\theta_{Eb,k,t}^+\\
&0 \le \overline{q}_{E,b}^t - q_{E,k,t} \le M(1-\theta_{Eb,k,t}^+)\\
&0 \le \eta_{k,t}^{Eb-} \le M\theta_{Eb,k,t}^-\\
&0 \le q_{E,k,t} - 0 \le M(1-\theta_{Eb,k,t}^-)\\
&0 \le \eta_{k,t}^{R+} \le M\theta_{R,k,t}^+\\
&0 \le \overline{q}_R^t - q_{R,k,t} \le M(1-\theta_{R,k,t}^+)\\
&0 \le \eta_{k,t}^{R-} \le M\theta_{R,k,t}^-\\
&0 \le q_{R,k,t} - 0 \le M(1-\theta_{R,k,t}^-)
\end{aligned}
\tag{A12}
$$

(5) The gradient of the follower model Lagrangian function is 0

The follower model Lagrangian function obtains a minimum value at the optimal solution of the lower problem, i.e., the gradient is 0.

$$\begin{cases} M_k^t + 2(n^T + d)Q_{k.m_g}^t + 0.5dq_{E,k,t} - x + \lambda_k \eta_k^{i-} + \eta_k^{i+} = 0 \\ N_k^t + 2m^T Q_{k,m_f}^t + \lambda_k - \eta_k^{j-} + \eta_k^{j+} = 0 \\ p_t + \lambda_k - \eta_{k,t}^{m-} + \eta_{k,t}^{m+} = 0 \end{cases} \tag{A13}$$

Appendix B.2. Linearization of the Objective Function

Since the optimization of the objective function is a nonlinear optimization problem, it can be replaced by using the strong dual property, i.e., the optimal solution of the lower problem is equal to the optimal solution of the lower problem dual problem.

(1) Linear optimization treatment of the objective function of the green power suppliers

For the green power supplier i to say, the objective function $J_{R,i}$ has the product of two decision variables $\sum_{t=1}^{T} (P_i^t + n^T Q_i^t)Q_i^t$. Let the dual problem of the lower problem be $g_k(\lambda, n)$ [24], denoted as follows:

$$g_k(\lambda, n) = \lambda_k \sum_{t=1}^{T} d_{k,t} - \sum_{t=1}^{T} \eta_k^{i+} \cdot \overline{q}_i^t - \sum_{t=1}^{T} \eta_k^{j+} \cdot \overline{q}_j^t - \sum_{t=1}^{T} \eta_k^{j+} \cdot \overline{q}_{C,i} - \sum_{t=1}^{T} \eta_{k,t}^{m+} \cdot d_{k,t} \tag{A14}$$

By the equivalence of the optimal solution of the lower problem and the optimal solution of the lower dual problem, viz:

$$\min(C_k^B + I_k^T + E_k^T) = \max g(\lambda, n) \tag{A15}$$

$$p_{R,i,k} q_{R,i,k} = \begin{Bmatrix} g_k(\lambda, \eta) - \sum_{t=1}^{T} (M_k^t + n^T Q_{k,m_g}^t) Q_{k,m_g}^t - \sum_{t=1}^{T} (N_k^t + m^T Q_{k,m_f}^t) Q_{k,m_f}^t - \sum_{t=1}^{T} p_t q_{k,t} \\ -(K \sum_{t=1}^{T} d_{k,t} - \sum_{t=1}^{T} Q_{k,m_g}^t - \sum_{t=1}^{T} q_{E,k,t}) p_R - \sum_{t=1}^{T} q_{E,k,t} p_E \end{Bmatrix} \tag{A16}$$

Substituting (17) into (1), the primary–secondary game two-layer nonlinear game optimization model can be transformed into a single-layer linear optimization model.

$$J_{R,i} = \left\{ -C_{R,i} + \sum_{k=1}^{K} \begin{Bmatrix} g_k(\lambda, \eta) - \sum_{t=1}^{T} (M_k^t + n^T Q_{k,m_g}^t) Q_{k,m_g}^t - \sum_{t=1}^{T} (N_k^t + m^T Q_{k,m_f}^t) Q_{k,m_f}^t - \sum_{t=1}^{T} p_t q_{k,t} \\ -(K \sum_{t=1}^{T} d_{k,t} - \sum_{t=1}^{T} Q_{k,m_g}^t - \sum_{t=1}^{T} q_{E,k,t}) p_R - \sum_{t=1}^{T} q_{E,k,t} p_E \end{Bmatrix} \right\} \tag{A17}$$

The constraints are (7)–(12), (A10)–(A12).

(2) Linear optimization treatment of the objective function of the thermal power suppliers

For the thermal power supplier j to say, the objective function $J_{C,j}$ has the product of two decision variables $\sum_{t=1}^{T} (P_j^t + m^T Q_j^t)Q_j^t$. Let the dual problem of the lower problem be $g_k(\lambda, n)$ [25], i.e., Form (A14).

By the equivalence of the optimal solution of the lower problem and the optimal solution of the lower dual problem, i.e., Equation (A18) viz:

$$p_{C,j,k} q_{C,j,k} = \begin{Bmatrix} g_k(\lambda, \eta) - \sum_{t=1}^{T} (M_k^t + n^T Q_{k,m_g}^t) Q_{k,m_g}^t - \sum_{t=1}^{T} (N_k^t + m^T Q_{k,m_f}^t) Q_{k,m_f}^t - \sum_{t=1}^{T} p_t q_{k,t} \\ -(K \sum_{t=1}^{T} d_{k,t} - \sum_{t=1}^{T} Q_{k,m_g}^t - \sum_{t=1}^{T} q_{E,k,t}) p_R - \sum_{t=1}^{T} q_{E,k,t} p_E \end{Bmatrix} \tag{A18}$$

Substituting (A18) into (1), the primary–secondary game two-layer nonlinear game optimization model can be transformed into a single-layer linear optimization model.

$$J_{C,j}=\left\{-C_{C,j}+\sum_{k=1}^{K}\left\{\begin{array}{l} g_k(\lambda,\eta)-\sum\limits_{t=1}^{T}(M_k^t+n^T Q_{k,m_g}^t)Q_{k,m_g}^t-\sum\limits_{t=1}^{T}(N_k^t+m^T Q_{k,m_f}^t)Q_{k,m_f}^t-\sum\limits_{t=1}^{T}p_t q_{k,t} \\ -(K\sum\limits_{t=1}^{T}d_{k,t}-\sum\limits_{t=1}^{T}Q_{k,m_g}^t-\sum\limits_{t=1}^{T}q_{E,k,t})p_R-\sum\limits_{t=1}^{T}q_{E,k,t}p_E \end{array}\right\}\right\} \quad \text{(A19)}$$

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