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ARTICLE

Optimal Trading Decision-Making of Power Supply Chain under Renewable Portfolio Standards

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ABSTRACT

Under the background of implementing renewable portfolio standards and the ever-improving tradable green certificate scheme, the increasingly environmentally-friendly preference of power users is leading to changes in electricity demand, which, in turn, is driving changes in the decision-making behaviors of various actors in the power supply chain. Based on this, with the goal of pursuing maximum profit, consumer-power-demand functions have been introduced with some consideration of the factors of consumer preference to establish an optimal profit model for each trading subject in non-cooperative states of the power supply chain, under the constraints of meeting renewable energy portfolio standards. Here, the optimal strategy of each trading subject is presented by adopting the reverse induction method. Furthermore, examples are used to analyze factors such as the influence of environmental protection preferences, quota ratios, price substitutions, and market demand as well as the optimal profit of each trading subject in view of providing a reference for the decision-making in the power supply chain trading subjects.

KEYWORDS

Renewable portfolio standards; electricity sales company; renewable energy generators; power supply chain

1 Introduction

In the context of fossil fuel shortage and increasingly serious environmental pollution, the implementation of renewable portfolio standards (RPS) and the improvement of the green certificate system has resulted in the decision-making for all subjects in the power supply chain becoming increasingly diversified [1]. Because of its environmentally-friendly nature, renewable energy has attracted increasing attention worldwide. Simultaneously, the growing awareness of environmental protection on the demand-side has increased some consumers' demand for renewable energy power consumption. Some consumers, with strong environmental awareness, are willing to pay for pricier products. In fact, more consumers are now willing to accept higher prices [2]. The change in consumer demand for electricity is undoubtedly affecting the trading decisions of the main bodies in the power market, which is, in turn, profoundly affecting the supply and demand pattern of the power supply chain.

1.1 Development Background of China's Renewable Portfolio Standards

The feed-in tariff (FIT) scheme was first established in China in 2006 and subsequently spurred the rapid development of China's renewable energy system, with the nation's current installed capacity for wind power and photovoltaic power ranking first in the world [3]. However, the gap in subsidies for renewable energy is widening, with the subsidies unable to cover the rapidly growing installed capacity of renewable energy systems. In view of this, the energy authorities have successively lowered the benchmark tariffs for wind power and photovoltaic subsidies in an effort to address the growing subsidy gap. In May 2018, China Energy Administration [4] issued the "Notice on Matters Related to Photovoltaic Power Generation in 2018," which directly led to a sharp decline in the domestic photovoltaic installed capacity. Additionally, China's renewable energy power generation distribution is geographically strong, and because of the insufficient grid transmission capacity, the problem of renewable energy transmission and consumption remains a serious one. Therefore, it is crucial to establish a long-term mechanism to promote the development and consumption of renewable energy power [5]. China's multiple policy adjustments for wind power and photovoltaics, and the "Renewable Energy Power Quotas and Assessment Measures (Draft for Comment)" issued in 2018 [6], mean that China's renewable energy support policy will shift from the FIT scheme to one mandatory institutional renewable energy system that combines the RPS and the renewable energy certificate (REC) systems. Under the RPS system, the government imposes mandatory controls over the market share of renewable energy through various laws and regulations [7] while using the REC system to assist in assessing the completion of the RPS indicators [8].

1.2 Progress of China's Renewable Portfolio Standards

China is currently in the transition stage from FIT to RPS [9]. The early research on RPS, which includes the trading model, the RPS implementation scheme, and market power, is focused on the power generation side [10–12], while several studies on system dynamics have provided an in-depth analysis of the development prospects of a RPS/renewable energy sources (RES)-based power generation industry [13–16]. Meanwhile, related models have been used to empirically analyze the efficacy and feasibility of regional power generation industry planning under the RPS system [17,18]. To improve the market competitiveness, power companies must meet the needs of both the RPS and the power users, thus holding the qualifications of basic power sales and value-added services and showing a preference for signing long-term contracts with RES power generators [19]. In fact, this followed by an evolutionary equilibrium process involving the RPS and the behavioral strategies of power generation companies. Here, targeted research suggested that the key to the success of the RPS lay in whether the fairness of the quota indicators could be guaranteed [20]. Based on literature [20], the area of quota allocation was researched in terms of entropy weight and cost minimization methods [21,22]. Given the attention paid to the RES-related trading decisions in the power market, a dynamic game model of the supply chain was constructed to study the optimal decision for high-load absorption blocked wind power during the period of peak reduction [23]. With some consideration of RES and a distributed power supply, various power packages for power sales companies were proposed [24]. However, these power packages lacked universality because of the assumption that RES purchase costs could be ignored. An optimal decision model for each trading subject was then constructed under the conditions of supply chain non-cooperation and cooperation [25].

The development of RES in China has resulted in high requirements for the power supply chain. In face of the pressure induced by the renewable energy quotas and the change in consumer demand, it is of great practical significance for the main bodies of the power supply chain to make optimal trading decisions. However, there is a lack of research in this area.

1.3 Impact of the Renewable Portfolio Standards Mechanism on the Electricity Market

The RPS mechanism affects the decision-making behavior of market entities, such as electricity sales companies, power generators, and users. The electricity markets in the US [26], Australia, the UK, Italy, the Netherlands, and other countries [27] have all implemented renewable energy quota systems. The impact of the US RPS system on the electricity market has been studied, with its implementation found to have had a positive impact on all related entities [28]. A dominant enterprise–competitive edge model based on the RPS system was built to analyze the mid- and long-term investment strategies and the market power of renewable energy in the electricity market [29]. Meanwhile, several models were built to simulate market trading under the RPS mechanism, which was found to have the potential to enhance the competitiveness of the renewable energy power generation entities [30]. Elsewhere, a profit model of cooperation among electricity sales companies and microgrid group agents was proposed [31], which helped reduce the evaluation pressure faced by electricity sales companies under the RPS and deviation power evaluation mechanisms, with great importance attached to the environmental benefits of microgrid groups. A Bayesian hybrid logic model was also used to analyze the users' preference for the RPS mechanism, while their marginal willingness to pay more was analyzed through the scenario method [32].

1.4 Design Concept of the Renewable Portfolio Standards Mechanism Framework

An ideal design of the RPS framework involves some consideration of balance among environmental governance, renewable energy development goals, and implementation costs and must align with top-level energy policies [33,34]. The design should also relate to the interactions among the quota indicators, market structure, and market entities in view of not distorting the attendant goals and causing unnecessary loss of social benefits [35]. Finally, a perfect RPS mechanism must also take into account certain parallel mechanisms and supporting measures. An electricity market trading mechanism was proposed with some consideration of absorbing responsibility and constructing a market framework under the coordination of multiple energy policies [36]. Additionally, it is important to consider the REC trading system, carbon emission trading system, attendant additional taxes, corresponding penalty mechanisms, etc. As an emerging market participant after the power sales market is liberalized, electricity sales companies primarily rely on participating in market purchases and sales of electricity to obtain profits [37]. Diversified market transaction paths, electricity price forecasts, and risk assessment are key links that affect electricity purchase decisions of retail companies [38–40]. Zhang et al. [41] has proposed building a renewable energy market trading plan with electricity sales companies as the main body and renewable energy trading volume as an evaluation indicator. Wang et al. [25] has also put forward planning and construction suggestions for establishing a multi-level renewable energy trading market on a time scale. Further, Huang et al. [35] has formulated two different renewable energy retail schemes according to user needs and analyzed the purchasing and selling decision behavior of electricity companies from the implementation of the quota system and environmental benefits. Moreover, Zhao et al. [42] has placed the electricity market transaction mechanism under the responsibility of consumption and built a market framework under the coordination of multiple energy policies.

1.5 Current Research Status of RPS and Its Power Market Linkage

At present, domestic and foreign scholars' researches on RPS and its linkage with the electricity market mainly focuses on two aspects. The first is the RPS framework system and its effectiveness. Liu et al. [43] has used system dynamics to study the mechanism and effect of RPS on China's power supply structure, and results show that it can effectively promote power supply structure adjustment and achieve government policy goals. Feng et al. [40] has proposed compensating ancillary services for green power certificates under RPS and quantifying them into a certain amount of green certificates to encourage ancillary service providers to offer services for RE. Jiang et al. [44] has designed an RPS framework with power users as the main body of obligation and demonstrated its feasibility. Further, the literatures [45–47] has analyzed and compared various foreign RE support policies and made recommendations on the Chinese RPS framework. The second aspect is the study of multi-agent trading strategies under the background of RPS. Additionally, literatures [48–51] have established a power market equilibrium model for green certificate trading and analyzed the role of RPS in promoting RE power consumption and market characteristics but set the obligation subject to the power generation. Literatures [52–56] have established the mathematical planning problem with equilibrium constraints for maximizing the revenue of RE generators, transforming it into a mixed-integer linear through linearization methods, such as strong duality theorem and binary expansion method. Thus, the mixed-integer linear programming model is solved.

Given the influence of the changes in the RPS system and in consumer demand on the trading decisions of the main bodies within the power supply chain, this paper constructs a model based on power-user demand, renewable energy generation, conventional energy generation, and power sales optimal profit and uses the reverse induction method to propose optimal decisions for the non-cooperative game among the subjects in the power market. To verify the validity of the model, concrete examples are used to analyze the influence of renewable energy quota ratios, environmentally-friendly preferences, and user demand on the purchase and sales strategy of each trading subject within the power supply chain.

2 Trading Market Structure of the Power Supply Chain under the Renewable Portfolio Standards Mechanism

The notice on establishing and perfecting the guarantee mechanism of renewable energy power consumption issued in 2019 marked the entry of renewable energy consumption into the era of compulsory examination [57]. The implementation of the RPS system led to the formation of a new trading structure in the power supply chain market. As shown in Fig. 1, conventional energy generators sell conventional electricity to the wholesale power market compared with renewable energy generators that bundle their green certificates to sell renewable electricity to the wholesale power market. The two types of electricity supply interact with each other. The electricity selling company, as a middleman, purchases the corresponding conventional and renewable electricity from the wholesale market according to the demands of its consumers (such as traditional electricity consumers, traditional and green electricity consumers, and pure green electricity users). And because of quotas, companies must annually consume a certain amount of renewable electricity. The subject of quota obligation first purchases conventional and RES power through the electricity wholesale market and then sells it to all kinds of electricity consumers in the retail market.

RES electricity prices were determined by the market competition in the new power market environment, with the aim of restoring the commodity attribute of electric power. In the power supply chain, each trading subject presented a pairwise game relationship. Here, each trading body had its own game goal, while the power users needed to satisfy their own electricity preference and demand, which determined the retail sales of conventional and RES electricity for power-selling companies. Meanwhile, for the intermediary companies, retail electricity remains consistent with buying electricity from two types of upstream generator. Overall, the electricity sales companies and the power generation companies hoped to achieve their own specific goals.

3 The Profit Function of Each Trading Subject in the Power Supply Chain under the Renewable Portfolio Standards Mechanism

3.1 The Function of Power-User Demand

The environmental awareness of power users has become an important factor affecting their willingness to pay. In fact, the actual purchase behavior of power users in terms of renewable energy power products is not entirely consistent with their preference for renewable energy power products, which is also affected by the market price of the products and the price competition between these products and conventional energy power products. Meanwhile, electricity sales enterprises have both conventional electricity consumption channels and renewable power consumption channels.

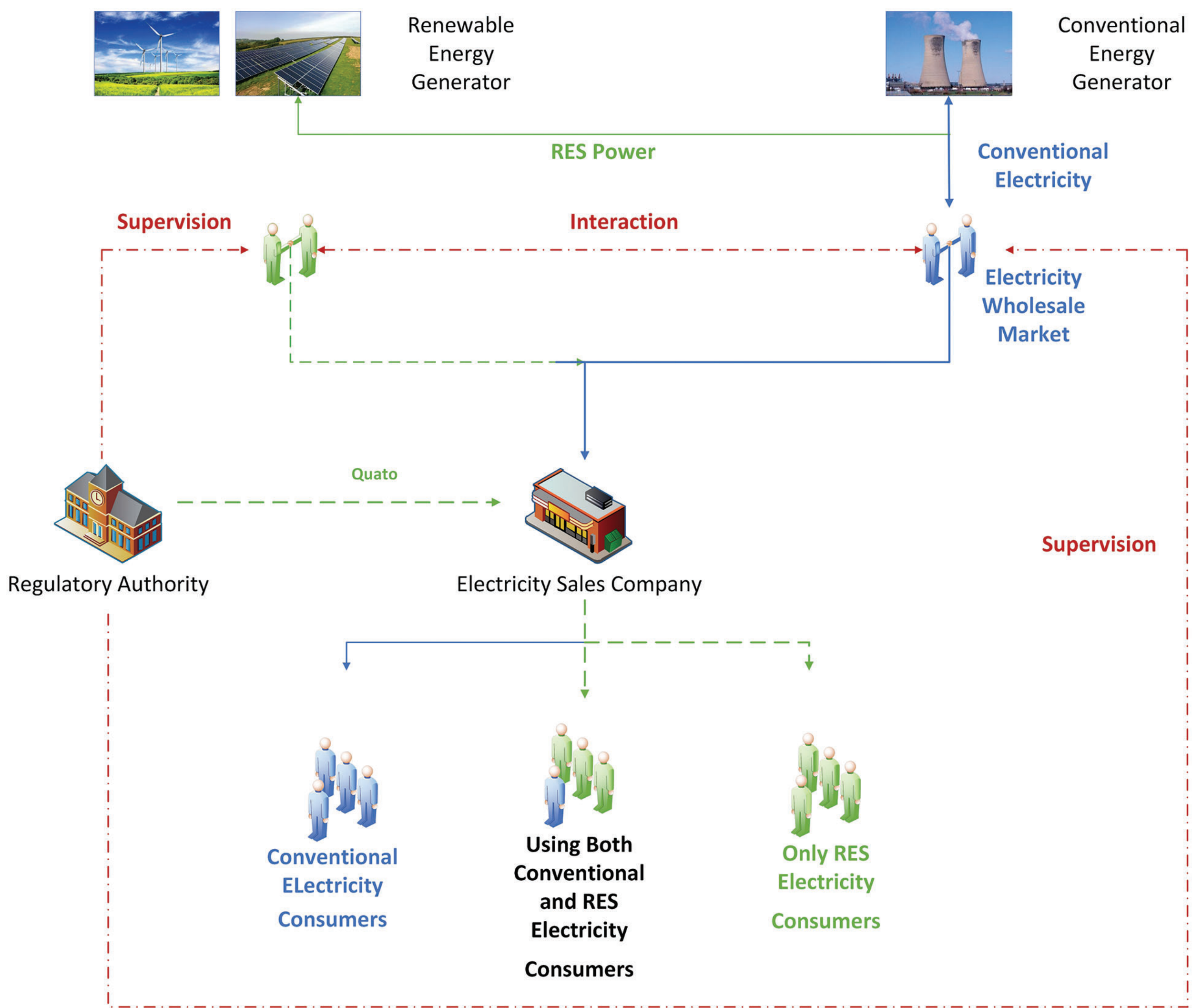

Figure 1: Market structure of electricity supply chain trading under RPS

User demand comprehensively reflects the interaction among users' electricity consumption behavior and preference and different energy and electricity prices. Among them, energy and electricity prices are the most intuitive for consumers' demand feedback. Consuming renewable energy can improve user utility; however, its demand decreases with price growth. This paper uses a demand function similar to the literature [58] to describe the power user's demand function for renewable and conventional energy.

$$\begin{cases} q_k = \mu q - p_k + \theta p_c \\ q_c = (1-\mu)q - p_c + \theta p_k \end{cases} \tag{1}$$

with the following constraints:

1) tariff constraints:

$$\begin{cases} p_k \le p_{kg} \\ p_c \le p_{cg} \end{cases} \tag{2}$$

2) quota constraints:

$$\frac{q_k}{q_k + q_c} \ge \delta \tag{3}$$

where q_k and q_c are renewable electricity and conventional electricity demand, respectively, p_{kg} and p_{cg} are FITs, q is the total potential market demand for renewable and conventional power, $\mu(0 < \mu < 1)$ is the preference of electricity users for renewable energy power (i.e., customers' environmental preference), δ is the quota tasks that the power sale company must perform in terms of RES power consumption every year, and p_k and p_c are the retail prices of renewable and conventional energy electricity, respectively. There is also a certain price competition between renewable power and conventional power, and $\theta(0 < \theta < 1)$ is the price substitution factor. From the supply chain demand function, the price substitution factor θ between renewable energy power and conventional energy power creates the price competition between the two commodities.

3.2 Profit Function of Conventional Energy Generators

We can assume that conventional energy generators (i) have the following profit function [37]:

$$\Pi_{c,i} = \omega_{c,i} q_{c,i} - C_{c,i}\left(q_{c,i}\right) \tag{4}$$

where $C_{c,i}\left(q_{c,i}\right) = 0.5 c_{c,i} {q_{c,i}}^2 + b_{c,i} q_{c,i} + a_{c,i}$ is the cost function of conventional energy generators, $q_{c,i}$ is the cost function of conventional energy generators, $c_{c,i}$ and $b_{f,i}$ are cost factors greater than 0, and $a_{c,i}$ is the fixed cost.

The constraints to be met are as follows [59]:

$$q_{c,i}^{min} \le q_{c,i} \le q_{c,i}^{max} \tag{5}$$

where $q_{c,i}^{min}$ and $q_{c,i}^{max}$ are the minimum and maximum power generation of conventional energy generators.

3.3 Profit Function for Renewable Energy Generators

We can assume that renewable energy generators (j) have the following profit functions:

$$\Pi_{k,\,i} = \omega_{k,\,i} q_{k,\,i} - C_{k,i}\left(q_{k,\,i}\right) \tag{6}$$

where $C_{k,\,j}\left(q_{k,\,j}\right)$ is given by:

$$C_{k,j}\left(q_{k,\,j}\right) = 0.5 c_{k,\,j} {q_{k,\,j}}^2 + b_{k,\,j} q_{k,\,j} + a_{k,\,j} \tag{7}$$

The above formula presents the cost function of renewable energy generators where $q_{k,j}$ is renewable energy generator electricity generation, $c_{k,j}$ and $b_{k,j}$ are cost factors greater than 0, and $a_{k,j}$ is the fixed costs.

The constraints to be met are as follows: $q_{k,i}^{min} \le q_{k,i} \le q_{k,i}^{max}$
where $q_{c,i}^{min}$ and $q_{c,i}^{max}$ are the minimum and maximum generation of renewable energy generators.

3.4 Profit Function of Electricity Selling Companies

Electricity sales companies act as the bridge between the generator and the power users, which is determined according to the type of electricity market trading and their own needs. In this paper, the power resources are divided into two types: renewable energy power and conventional energy power.

The profit function of the power sale company can be written as follows:

$$\pi_s = \pi_k + \pi_c = (p_k - \omega_k) \times q_k + (p_c - \omega_c) \times q_c \tag{8}$$

With the following constraints:

$$q_k \geq \delta q \tag{9}$$

where π_s,π_k and π_c are total profit of the power sales company, renewable energy power profit, and conventional energy power profit, respectively, q_k and q_c are sales of renewable energy and conventional electricity, respectively, ω_k and ω_c are renewable energy and conventional electricity wholesale prices, respectively, and δq is the lowest renewable energy power quota for power companies sold under the renewable energy quota system.

4 Optimal Decision-Making Model of Each Trading Subject in the Non-Cooperative Game

In the structure of the power supply chain constructed in this paper, the game relationship of each market subject can be summarized as follows. In the first layer, two types of power generators determine their respective wholesale electricity prices based on profit maximization, while the electricity sales companies determine the retail price of electricity and the amount of electricity purchased according to cost and maximum profit. Meanwhile, in the second layer, consumers maximize their demand for electricity on the basis of the retail prices of the power-selling companies.

$$\left(q_k^*, q_c^*\right) = argmax\begin{cases} q_k = \mu q - p_k + \theta p_c \\ q_c = (1-\mu)q - p_c + \theta p_k \end{cases} \tag{10}$$

$$\begin{aligned}\left(p_k^*, p_c^*\right) = argmax(((p_k - \omega_k) \times (\mu q - p_k + \theta p_c) + (p_c - \omega_c) \\ \times [(1-\mu)q + \theta p_c) + (p_c - \omega_c) \times [(1-\mu)q - p_c + \theta p_k])\end{aligned} \tag{11}$$

$$\omega_i^* = argmax(\omega_i q_i^* - C_i(q_i^*)) \tag{12}$$

$$(p_k^*, p_c^*) \in \arg\max \Pi(p_k, p_c) \tag{13}$$

$(q_k^*$,$q_c^*)\in \arg\max \Pi(q_k, q_c)$

where $\Pi(p_k, p_c), \Pi(q_k, q_c)$, and $\Pi(\omega_k, \omega_c)$are strictly differentiable concave functions for (p_k, p_c), (q_k, q_c), and (ω_k, ω_c), respectively.

The constraints are as follows:

1) Total constraint:

$$q = q_k + q_c \tag{14}$$

2) Power constraints:

$$0 \leq q_k \leq q_f \tag{15}$$

3) Quota constraints:

$$\frac{q_k}{q_k + q_c} \geq \delta \tag{16}$$

The essence of the supply chain non-cooperative game is a pairwise game. As the profit π_s is a strictly concave function about the retail price (p_k, p_c), assuming that the electricity purchase price of the retailer is known as ω_i, and find $(p_k^*, p_c^*) = argmax\pi_s$. The two sides in Eq. (4) are respectively derived for p_k and p_c and set to zero, and the optimal retail price in a stable state is solved as:

$$p_k^* = \frac{\omega_k}{2} + \frac{q(\mu\theta - \mu - \theta)}{2(\theta^2 - 1)} \tag{17}$$

$$p_c^* = \frac{\omega_c}{2} + \frac{q(\mu - \mu\theta - 1)}{2(\theta^2 - 1)} \tag{18}$$

According to the calculated p_k^*, p_c^* in the stationary state introduced into formula (1), the optimal balance between conventional and renewable power can be obtained. According to formulas (5)–(8), the retail prices of the two types of power and the purchased power of the selling company are determined by the second tier of the power-selling company based on its purchase cost and the goal of profit maximization.

$$q_k^* = \frac{1}{2}\mu q + \frac{1}{2}(\theta\omega_c - \omega_k) \tag{19}$$

$$q_c^* = \frac{1}{2}(1 - \mu)q + \frac{1}{2}(\theta\omega_k - \omega_c) \tag{20}$$

Based on formulas (19) and (20), formulas (9) and (10) can solve the first layer problem of the two types of wholesale prices for electricity generators and the optimal wholesale price of conventional and renewable energy generators can be obtained via reverse induction:

$$\omega_c^* = \frac{\theta\omega_k(2 + c_c) + (1 - \mu)(2q + 1) + 2b_c}{c_c + 4} \tag{21}$$

$$\omega_k^* = \frac{(2 + c_k)(\theta\omega_c + \mu q) + 2b_k}{c_k + 4} \tag{22}$$

As the power supplier and the power company sell the same electricity after the game—and because the users satisfy their own electricity preference and the demand for electricity is the same as the balance in the stable state of the power company, namely, formulas (7) and (8) solve the problem of third-tier consumers maximizing their power demand based on the retail price of the electricity selling company—the following models of the supply chain subjects apply.

4.1 Profits of Conventional Energy Generators

$$\Pi_C^* = \omega_c^* \times q_c^* - C_c(q_c^*) \tag{23}$$

Here, the optimal profit of conventional power generators can be obtained by substituting formula (4) into the conventional power generator model, formula (20), the optimal electricity purchase price of conventional power generators, and formula (21), the optimal wholesale price of conventional power generators:

$$\Pi_C^* = \frac{\mu qA + qB + \theta^2\omega_k C + \theta D - c_c^2 E - c_c F + G}{2(c_c + 4)} \tag{24}$$

where

$$A = -4\theta\omega_k - c_c\theta\omega_k - 4q + 3\mu - b_c + 2\omega_c - 2 \tag{25}$$

$$B = 4\theta\omega_k + c_c\theta\omega_k + 2q + b_c - 2\omega_c + 1 \tag{26}$$

$$C = 2\omega_k + c_c \tag{27}$$

$$D = -2\omega_k\omega_c - c_c\omega_k\omega_c + \omega_k - \mu\omega_k + 4b_c\omega_k \tag{28}$$

$$\begin{aligned} E = &\frac{1}{4}q^2 - \frac{1}{2}\mu q^2 + \frac{1}{4}\mu^2 q^2 + \frac{1}{2}q\theta\omega_k - \frac{1}{2}q\theta\omega_c - \frac{1}{2}q\mu\theta\omega_k + \frac{1}{2}q\mu\omega_k + \frac{1}{2}q\mu\omega_c \\ &+ \frac{1}{4}\theta^2{\omega_k}^2 - \frac{1}{2}\theta\omega_k\omega_c + \frac{1}{4}{\omega_c}^2 \end{aligned} \tag{29}$$

$$\begin{aligned} F = &q^2 - 2q^2\mu c_c + q^2\mu^2 + 2q\theta\omega_k - 4q\mu\theta\omega_k + 2q\mu\omega_c + \theta^2{\omega_k}^2 - 2\theta\omega_k\omega_c + {\omega_c}^2 \\ &+ b_c q - 2\mu b_c + b_c\theta\omega_k - \omega_c b_c + 2a_c \end{aligned} \tag{30}$$

$$G = 4b_c q - 8\mu b_c q + 4\theta b_c\omega_k - 4b_c\omega_c + 8a_c - \omega_c + 2a_c \tag{31}$$

4.2 Profits of Renewable Energy Generators

$$\Pi_k^* = \omega_k^* \times q_k^* - C_k\left(q_k^*\right) \tag{32}$$

Here, substituting formula (6) for the renewable energy power generator model, formula (19) for the optimal purchase power of conventional energy, and formula (22) for the optimal wholesale price of conventional energy power generator into the optimal profit of conventional energy power generator, the following is obtained:

$$\Pi_k^* = \frac{\mu qA' + qB' + \theta^2\omega_c C' + \theta D' - c_k^2 E' - c_k F' + G'}{2(c_k + 4)} \tag{33}$$

where

$$A' = -4\theta\omega_c - c_k\theta\omega_c - 4q + 3\mu - b_k + 2\omega_k - 2 \tag{34}$$

$$B' = 4\theta\omega_c + c_k\theta\omega_c + 2q + b_k - 2\omega_k + 1 \tag{35}$$

$$C' = 2\omega_c + c_k \tag{36}$$

$$D' = -2\omega_k\omega_c - c_c\omega_k\omega_c + \omega_c - \mu\omega_c + 4b_c\omega_c \tag{37}$$

$$\begin{aligned} E' = &\frac{1}{4}q^2 - \frac{1}{2}\mu q^2 + \frac{1}{4}\mu^2 q^2 + \frac{1}{2}q\theta\omega_c - \frac{1}{2}q\theta\omega_k - \frac{1}{2}q\mu\theta\omega_c + \frac{1}{2}q\mu\omega_c + \frac{1}{2}q\mu\omega_k + \frac{1}{4}\theta^2{\omega_c}^2 \\ &- \frac{1}{2}\theta\omega_k\omega_c + \frac{1}{4}{\omega_k}^2 \end{aligned} \tag{38}$$

$$\begin{aligned} F' = &q^2 - 2q^2\mu c_k + q^2\mu^2 + 2q\theta\omega_c - 4q\mu\theta\omega_c + 2q\mu\omega_k + \theta^2{\omega_c}^2 - 2\theta\omega_k\omega_c + {\omega_k}^2 \\ &+ b_k q - 2\mu b_k q + b_k\theta\omega_c - \omega_k b_k + 2a_k \end{aligned} \tag{39}$$

$$G' = 4b_kq - 8\mu b_kq + 4\theta b_k\omega_c - 4b_k\omega_k + 8a_k - \omega_k + 2a_k \quad (40)$$

4.3 Optimal Profit of Electricity Sales Companies

$$\Pi_s^* = \left(p_k^* - \omega_k^*\right) \times q_k^* + \left(p_c^* - \omega_c^*\right) \times q_k^* \quad (41)$$

$$\Pi_s^* = \frac{2quw_kA1 + 2quw_cB1 + 2q^2C1 - D1 + 2E1 + 2F1}{4A1} \quad (42)$$

where

$$A1 = (c_k + 4)(c_c + 4)(\theta - 1)(\theta + 1)^2 \quad (43)$$

$$B1 = (1 - u)(c_k + 4)(c_c + 4)(\theta - 1)(\theta + 1)^2 \quad (44)$$

$$C1 = (c_k + 4)(c_c + 4)(\theta + 1)\left[2u^2(\theta - 1) - 2u(\theta - 1) - 1\right] \quad (45)$$

$$D1 = (c_k + 4)(c_c + 4)(\theta - 1)*[(w_k - w_c)(\theta + 1) + 2u - 1]^2 \quad (46)$$

$$E1 = (\theta - 1)(\theta + 1)^2(c_c + 4)*(w_k - \theta w_c - qu)*[(2 + c_k)(\theta w_c + uq) + 2b_k] \quad (47)$$

$$F1 = (c_k + 4)(\theta - 1)(\theta + 1)^2*[w_c - \theta w_k - q(1 - u)]*[\theta w_k(2 + c_c) + (1 - u)(2q + 1) + 2b_c] \quad (48)$$

5 Example Analysis

The following assumptions are made based on the on-grid price of conventional power and wind power price in China and the parameters of major power producers; let us suppose that the total potential demand q for renewable power and conventional power is 500 MW for both and reference [12] data source hypothesis that the market's initial price is 0.308/kwh for renewable energy power ω_k and 0.18/kwh for conventional energy power ω_c. And according to reference [20], the generator data in Tab. 1 below are introduced.

Table 1: Generator parameters

Generators	c/(yuan$((\mathbf{MW})^2 \cdot \mathbf{h})^{-1}$)	b/(yuan$(\mathbf{MW} \cdot \mathbf{h})^{-1}$)	a/(yuan)
$G_{c,1}$	0.0726	166.749	0
$G_{k,1}$	0.0951	250.0674	0

5.1 The Influence of User Preference and the Quota Ratio on the Optimal Profit of the Supply Chain

The preference coefficient for renewable energy power μ varies from 0 to 0.9, as does the quota ratio δ. User preference affects the proportion of the two forms of electricity purchasing, which satisfies the constraints greater than the quota ratio, while the other parameters remain unchanged. Put μ, δ into formulas (5)–(10) to get the electricity selling company's optimal retail price p_k^*, p_c^* and its quantity of electricity purchased q_k^*, q_c^* and the wholesale price of the two types of electricity producers ω_k^*, ω_c^*. Uniformly put $p_k^*, p_c^*, q_k^*, q_c^*, \omega_k^*, \omega_c^*$ into formula (15) to obtain the company's optimal profit; into formula (13) to obtain the optimal profit of renewable energy power generators; into formula (14) to obtain the optimal profit of the conventional power generator and record the optimal profit values of different μ and δ, corresponding to the main body of the supply chain with Excel, and plot the results with Origin to obtain Figs. 3 and 5.

Fig. 2 shows the optimal profit of power sales companies in relation to the changes in the users' environmental preference μ and the quota ratio δ. This reflects that the users' environmental preference μ is negatively correlated with the optimal profit of the power sale company before it gradually presents a positive correlation, while, with the increase in the quota ratio δ, the optimal profit of the power sale company decreases continuously. When $\mu = \delta = 0.4$, the optimal profit of the power sale company reaches the lowest value. As the users' environmental preference is positively correlated in the long run, and the power purchase cost of RES for the power company is on the high side in the short term, the profit drops or the small range halts the surplus, and so on. With the long-term development of renewable energy, the users' preference for environmental protection is increasing, and the whole of social environmental protection electricity consumption trend is gradually being formed. The RES power output of the power sale company will also become more stable, and a profit model based on RES power and conventional power could be obtained such that the power sales companies' profits will steadily increase accordingly. Meanwhile, before the situation of social environmental protection power consumption is fully formed, the increase in the quota ratio δ means that the RES power that power sales companies must absorb every year must increase, while the companies must compress their profits and may even lose money.

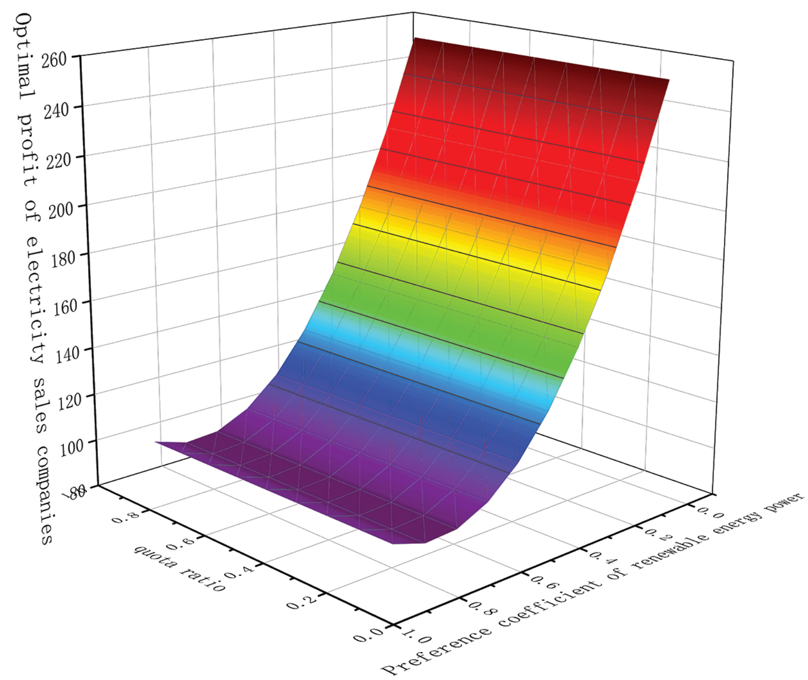

Figure 2: Optimal profit of power sales companies under different μ and δ

Fig. 3 shows the optimal profit of conventional energy generators in relation to the changes in the users' environmental preference μ and the quota ratio δ. As the users' preference for environmental protection increases, the proportion of renewable energy purchasing and selling increases, while those of conventional energy decrease and the attendant optimal profits present a downward trend. Therefore, the change in environmental preference and the quota ratio increase have a negative impact on conventional energy generators.

Fig. 4 shows the optimal profit of renewable energy generators in relation to the changes in user preference μ and the quota ratio δ. The optimal profit of renewable energy generators is positively related to both μ and δ as, with the gradual improvement in both, society will be encouraged to create a greener environment in terms of electricity consumption. This will, in turn, encourage sales companies to purchase more RES electricity and increase the consumption of it, thus increasing the profits of renewable energy generators. Overall, the improvement in μ and δ will have a positive impact on the profits of renewable energy generators.

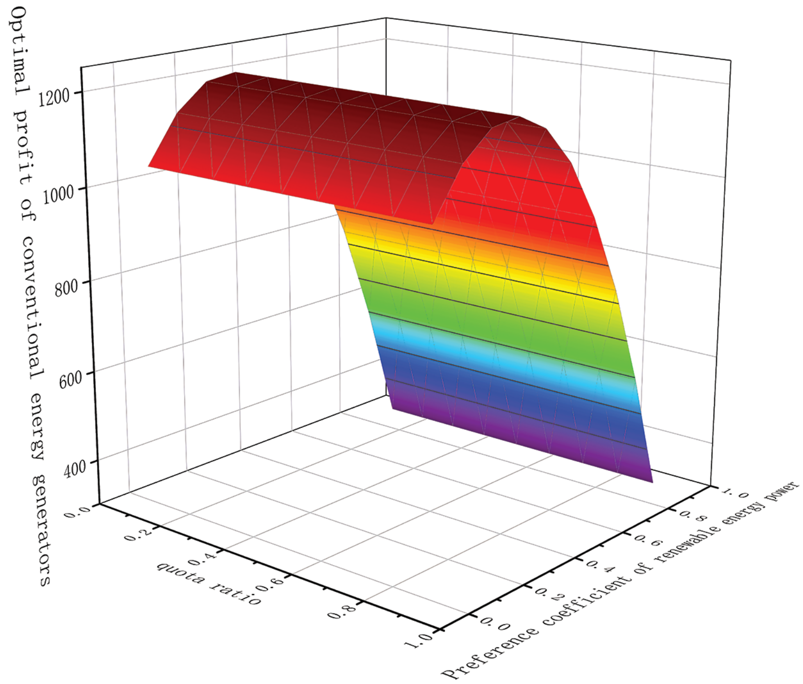

Figure 3: Optimal profit of conventional energy generators under different μ and δ

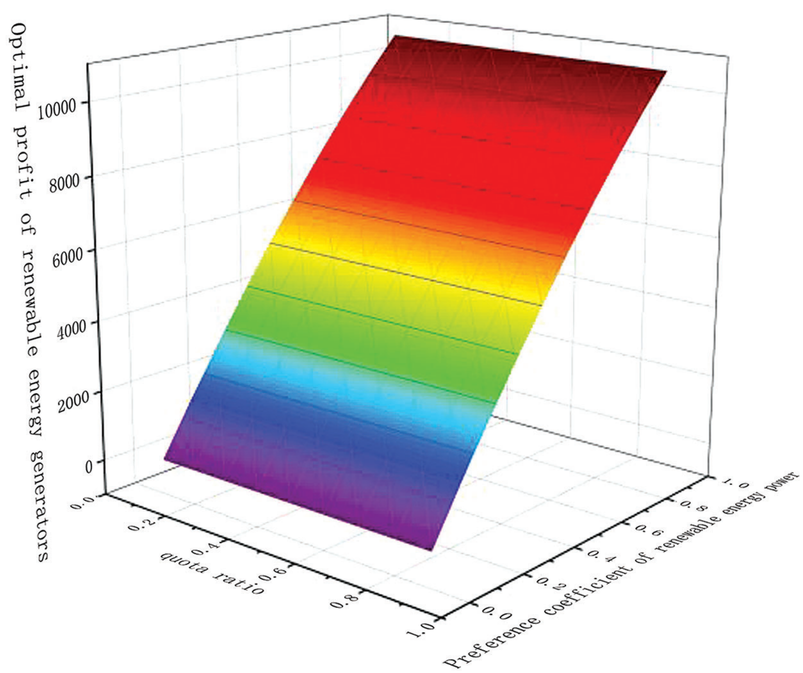

Figure 4: Optimal profit of renewable energy generators under different μ and δ

Fig. 5 shows the change of optimal profit of power supply chain under the change of environmental preference and quota ratio of different users. The optimal profit of power supply chain is positively correlated with environmental preference of users, while negatively correlated with quota ratio. The analysis shows that when users' environmental preference keeps increasing, the consumption of renewable energy gradually occupies the main part of profit in the power supply chain. Compared with the profit of conventional energy, the profit space of renewable power is greater; thus, the optimal profit of the overall supply chain has been increasing positively. However, when the quota ratio of electricity selling companies keeps increasing the optimal profit will reduce and lead to negative situations, such as slow sales. The profit proportion of each main body in the supply chain is dominated by the electricity selling companies; therefore, the optimal profit of the whole supply chain will decrease.

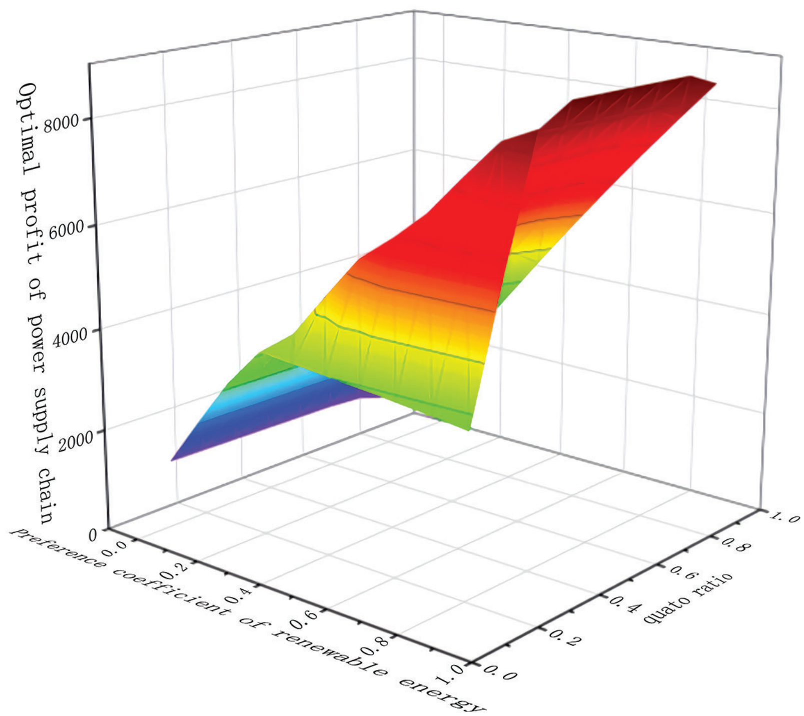

Figure 5: Optimal profit of power supply chain under different μ and δ

5.2 Volatility of Market Demand and the Quota Ratio

Let us suppose that the price substitution coefficient of renewable power energy and conventional energy $\theta = 0.4$ and that the preference coefficient of users in terms of purchasing renewable electricity $\mu = 0.65$. The optimal wholesale price of conventional and renewable energy generators can be obtained according to Eqs. (11) and (12) as follows: $\omega_c{}^* = 0.27$, $\omega_k{}^* = 0.33$.

Let us also suppose that the change in total potential demand q for renewable and conventional electricity presents a shift from 400 to 800. The output of the conventional power generator is $0.6(1 - \delta)$ and 0.4δ for the renewable energy generator output, while the remainder of the parameters remain unchanged. Moreover, the optimal profit of each main body of the supply chain is calculated according to formulas (13)–(15). Origin was used to illustrate the data.

Fig. 6 shows the influence of market demand q and quota ratio δ fluctuations on the optimal profit of power sales companies. It is clear that, with the increase in q, the electricity sales volume of power sales companies increases as does the optimal profits of power sales companies. Meanwhile, with the increase in δ, when the q value is small and the preference for RES power is not high, the profit of the power sale company will exhibit negative growth as the RES power cost quota increases. When the q increases gradually, the quota of RES electricity produced by the power sales company is lower than the consumption level, while with the improvement in δ, the optimal profit of the power sales company increases rapidly because the profit related to RES power is larger than that related to conventional electricity.

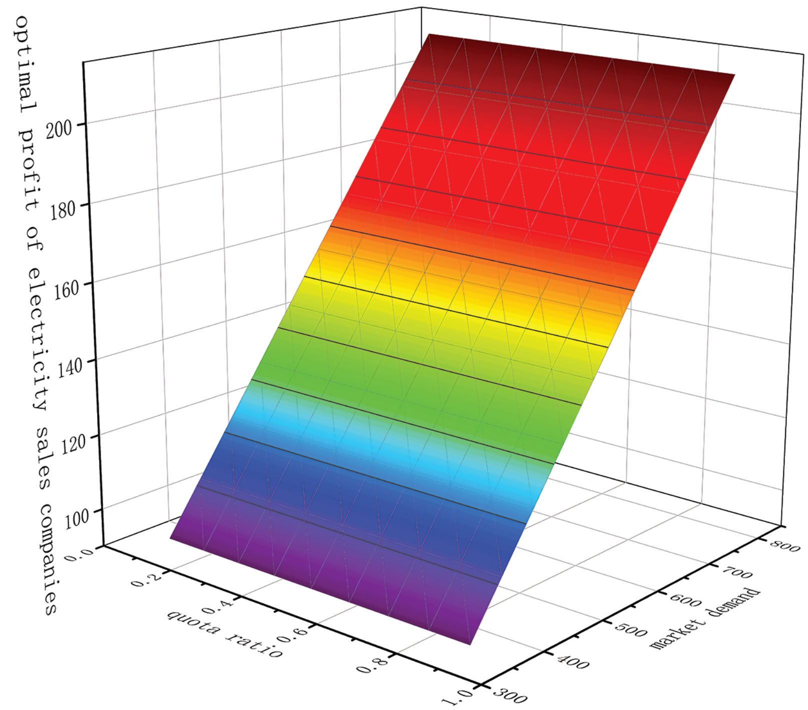

Figure 6: The impact of market demand and quota ratio fluctuations on the optimal profit of electricity sales companies

Fig. 7 shows the influence of market demand q and quota ratio δ fluctuations on the optimal profit of conventional energy generators. The curve indicates that the optimal profit for these generators is positively correlated with the growth in q before it becomes negatively correlated because of the increase in market demand, where the preference for RES power increases gradually. Here, more power users opt for RES power, while the conventional electricity sales undergo only a slight change, fading slightly on occasion. With the improvement in δ, the optimal profit of conventional energy generators is decreasing, which means the power sales company must purchase more RES electricity to meet the power consumption quota. Overall, the purchase of conventional electricity will decrease as will the profits of the generators.

Fig. 8 shows the influence of market demand p and quota ratio δ fluctuations on the optimal profit of renewable energy generators. The curve indicates that with the increase in market demand and the quota ratio, the sales companies have to purchase more RES electricity from the power generators, with the users' environmental preference resulting in an increased consumption of RES electricity. As such, the optimal profit of renewable energy generators is increasing.

5.3 Sensitivity Analysis of Price Substitution Coefficient

The preference coefficient for purchasing renewable power $\mu = 0.4$, and the total potential demand for renewable power and conventional power q = 500. Let us assume that the quota ratio δ = 0.4, the conventional power source generator output is 300, and the renewable energy generator output is 200. Then, the price substitution coefficient of renewable power energy and conventional energy θ varies from 0 to 0.9. The optimal profit of each main body of the supply chain can be obtained by using Eqs. (13)–(15). Origin was used to illustrate the analysis.

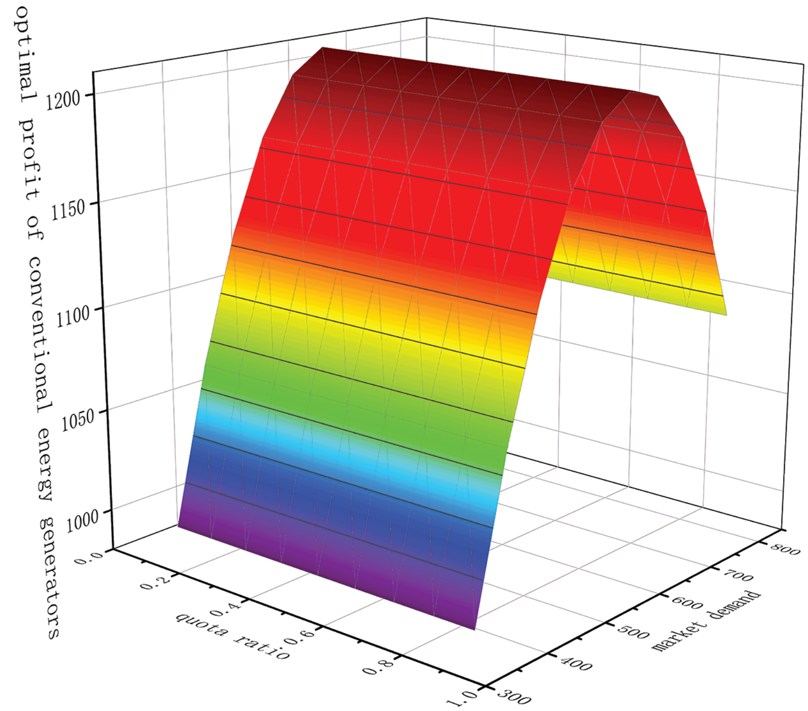

Figure 7: The impact of the fluctuations in market demand and quota ratio on the optimal profit of conventional energy generators

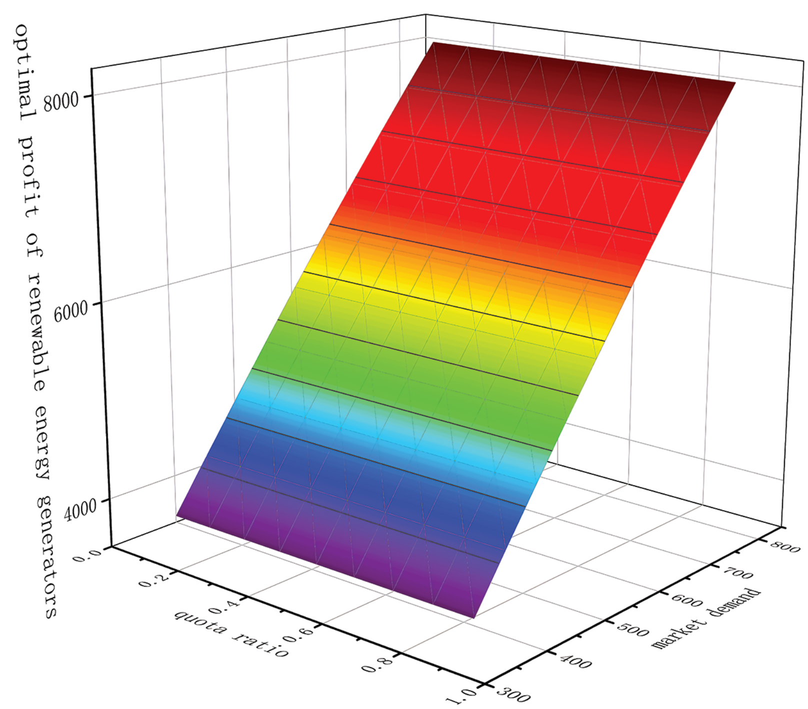

Figure 8: Impact of fluctuations in market demand and quota ratio on the optimal profit of renewable energy generators

Fig. 9 shows the optimal profit curve in relation to the fluctuations in the price substitution coefficient θ and the attendant effect on the power sales companies as well as the conventional energy and renewable energy generators. Clearly, with the increase in price substitution coefficient, renewable energy is gradually affected by the price competition of conventional energy, and the optimal profit of renewable energy generators will exhibit a slightly accelerated downward trend. Because conventional energy occupies a dominant position in the market, as the price substitution coefficient increases, the profits of RES power sales companies will be compressed, while those of conventional energy companies will be magnified, which means the optimal profits will not be affected. Overall, the conventional energy generators will not be greatly affected by this factor.

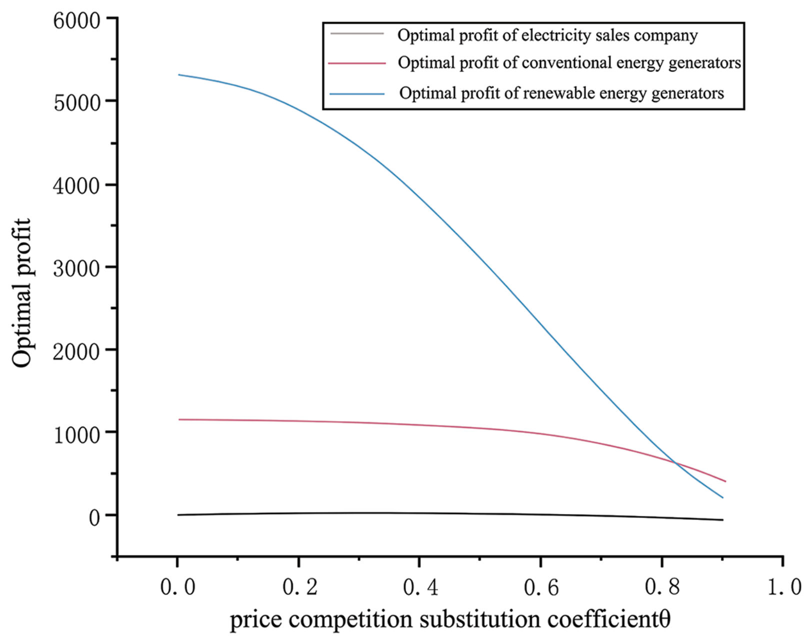

Figure 9: Impact of price competition substitution coefficient θ on the optimal profit of electricity sales companies and conventional and renewable energy generators

6 Conclusions

Given the influence of consumer environmental awareness, RPS quotas, and the price competition between renewable energy and conventional power energy, this paper outlined the relationship between the main bodies of the power supply chain and established an optimal profit model of the supply chain. Through empirical analysis of the model, the following conclusions can be drawn:

1. Enhancing user awareness of environmental protection will promote the progress of the RPS system, which could effectively increase the profits of integrated energy sales companies, while the appropriate quota ratio could enhance the efficiency of the power sales companies. However, because of the presently low understanding of environmental protection among Chinese users, the profitability of renewable power generators lies at the weak end of the power supply chain.
2. During the fluctuations in market demand and the quota ratio, the renewable energy generators in the supply chain are strongly affected as the proportion of RES electricity in the current power market is small. As the market demand rises and the quota ratio increases, the positive response of the RES power generator is the clearest. When the quota ratio increases, the optimal profit of the power sale company decreases slightly in the short term because the absorption task cannot be

effectively undertaken by the user, while the optimal profit of RES from a long-term perspective is still increasing. Because conventional electricity dominates the market, the change in market demand has had little effect on the profits of conventional energy generators. Meanwhile, the increase in the quota ratio reduces the consumption of RES electricity as the attendant policy requires the power companies to buy more electricity. Therefore, the optimal profit will be negatively affected.

3. The price substitution coefficient has a significant influence for renewable energy generators, and the field of RES power is clearly affected by the price competition with the field of conventional power. As such, RES power producers must set RES power prices at reasonable levels to ensure that the field can survive and develop within the context of market competition.

Considering the implementation of RPS, the change in users' environmental awareness leads to the change in power demand. Each main body in the power supply chain should make the optimal power trade decision according to the differentiated power demand of power consumers. All the transaction participants in the electric power market should finish the corresponding quota, and at the same time pay attention to the potential profit margin of renewable energy power and build the operation pattern from the developmental perspective, so as to promote the implementation of RPS and the optimal configuration of renewable energy.

The following are shortcomings in this paper: The function model used to build users' two types of power demand is quite simple. In the future, we will introduce green certificate price and unbundled green power transaction to draw a more comprehensive conclusion, and provide a reference for practical power supply chain transaction.

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