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A game-theoretic model for renewable and conventional energy generators under tradable green certificate mechanism

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A B S T R A C T

This paper explores the strategic behavior of power generators under green certificate trading policies, considering both renewable and conventional energy generators. Using game theory, we construct a Nash equilibrium model that incorporates the unit price of green certificates, the required quantity of certificates, and the cap on the quantity. By applying the Karush-Kuhn-Tucker conditions, we reform this Nash equilibrium problem as a mixed complementarity system, which can be solved by MATLAB software. Furthermore, we conduct sensitivity analysis and numerical tests on a number of important parameters. The results reveal that, under certain conditions, the unit price of green certificates does not affect the number obtained by renewable energy generators or purchased by conventional energy generators. However, as the required number of certificates for conventional energy generators increases, both the quantity of certificates that renewable generators obtained and conventional generators purchased increase proportionally. Additionally, the outcomes of limiting the quantity of green certificates awarded to renewable energy generators align with government regulations on the purchase requirements for conventional energy generators. This research provides new insights for power generators in ensuring financial viability and optimizing operations under green certificate trading policies. By enhancing carbon emission reduction capacity, these findings may contribute to the effective management of the electrical supply chain.

1. Introduction

In recent years, environmental and resource issues have been widely recognized as key factors limiting the comprehensive development of human society. Renewable energy, with its renewable nature and excellent environmental properties, has become an important means for both domestic and international efforts to address energy shortages and achieve sustainable development (Hassan et al., 2024). By taking part in green certificate trading markets, nations are aggressively encouraging the growing proportion of renewable energy in the energy grid and setting renewable energy quota targets, striving for a greener future. A more sustainable electricity market and the incorporation of clean energy is strongly supported by the exchange of green certificates. This market-based mechanism offers multiple benefits, enhancing economic efficiency, regulatory compliance, and environmental sustainability. For example, by providing an additional revenue stream for renewable energy producers, green certificate trading makes clean energy projects more financially viable. This propels the shift to a low-carbon energy system by incentivizing increased investment in solar, wind, and other renewable energy sources. Besides, the flexibility of certificate trading allows market participants to meet their renewable energy obligations at the lowest possible cost. Instead of forcing every entity to generate green electricity directly, the system enables those with higher production capabilities to supply certificates to others, optimizing resource allocation.

Green power certificates, also known as renewable energy green power certificates, are official vouchers issued by the government. They function not only as the definitive verification of the ecological advantages of renewable energy electricity but also as the critical framework for validating the creation and use of renewable energy. In basic terms, green certificate

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trading entails the exchange of these certificates. In the green certificate marketplace, sellers are enterprises that own renewable energy generation projects, and they sell these certificates to earn additional economic benefits. Buyers include industrial and commercial users, electricity trading companies, grid enterprises, government agencies, public institutions, non-governmental organizations, and others. They purchase green certificates to meet their green electricity needs or to fulfill policy requirements. There are two main types of green certificate trading: bilateral trading and listing trading. Bilateral negotiation involves the seller and buyer independently agreeing on the amount, pricing, and further stipulations of the agreement, which are then confirmed through the green certificate trading platform. This method is highly flexible, suitable for long-term cooperation or customized trading needs. Listing trading, on the other hand, involves buyers or sellers posting their intended quantity and price of green certificates on the trading platform. The other party can then choose to accept the offer and make payment. This method is more open and transparent, fostering a market price discovery mechanism (Song et al., 2022; Nan et al., 2024).

As a creative way to encourage the growth of renewable energy, green power certificate trading is steadily taking center stage in the energy market (Li et al., 2024). Green certificate trading provides a mechanism to drive the implementation and usage of renewable energy, and inspire a greater number of firms and individuals to participate in the production and consumption of clean energy, working together to accelerate the global transformation toward sustainable energy and environmental development. Competitive behavior of power generators under the green certificate trading policy, including both conventional and renewable generators, with the purpose of increasing their revenues and lowering carbon emissions, is the focus of this paper. Based on the information available to us, there has been a lot of research on green certificate trading, but not much of it has examined the competitive behavior of power producers in the electricity supply chain. This work is largely dedicated to examining the following matters:

1) What mathematical model can be used to describe the competitive behavior among generators under the green trade certificate mechanism?
2) How can a Nash equilibrium model be solved when each generator's objective function is influenced by the decisions of its competitors?
3) How does the unit price for green certificates, the required quantity of certificates, and the cap on the quantity affect power generators' decision-making?

We use game theory to develop a Nash equilibrium model for power generators within a power supply chain network, which incorporates multiple power generators and is shown to be convex, enabling the derivation of Nash equilibria through the Karush-Kuhn-Tucker conditions. We introduce several key parameters, such as unit price of green certificates, required quantity of certificates, and cap on the quantity, to capture the complexities of real-world scenarios. Additionally, sensitivity analysis is conducted to explore the model's implications further. Our objective is to establish a solid theoretical foundation for the competition among power generators within the electricity market. This paper aims to offer new approaches for addressing the difficulties power generators encounter in green certificate transactions and provides insightful information for policymakers.

The following sections of this research are organized in this way. Section 2 conducts a comprehensive literature analysis. Section 3 articulates the problem and establishes the model's core assumptions. In Section 4, we introduce the mathematical model for competitive power generators. Section 5 explores the convexity of the model and reformulates it into a mixed complementarity system, which by using the Fischer-Burmeister function can be reformed as nonlinear equations. Section 6 presents numerical experiments and sensitivity analyses. Finally, Section 7 concludes our findings and suggestions for future research.

2. Literature review

We do a literature analysis that concentrates on a number of crucial topics, such as power supply chains, modeling for energy markets, and green certificate trading, aiming to establish a robust research framework and showcase the pivotal insights of this exploration.

2.1 Green certificate trading

The environmentally friendly qualities of renewable energy production are embodied by green certifications. Currently, many countries around the world have implemented voluntary purchases of green certificates. Li et al. (2019) examined the history and salient features of China's green certificate program, proposed a green certificate trading model for China. For America, Wang et al. (2019) study the U.S. green certificate trading mechanism, compare the situation in China and describe the multiple categories of environmental certificate markets and their operations, the regulatory architecture, and the policy's favorable outcomes. Additionally, the paper summarized the experiences and challenges faced by the U.S. in building a green certificate trading market. Yu et al. (2021) formulated a simulation approach by embedding tradable environmental certificates and carbon pricing mechanisms, illustrating a robust connection between the renewable energy regulation and the advancement of the energy infrastructure.

In a bid to enhance the efficiency of clean energy usage, Zhang et al. (2023) delved into the intricacies of virtual power plants under the auspices of carbon and green certificate trading systems. They crafted and compared three unique scenarios, weaving these methods into a refined dispatch model for VPPs. This model encompasses wind energy, solar power generation, energy storage systems, and gas turbines. The research revealed that the proposed VPP optimization model, coupled with its innovative solving algorithm, possesses the potential to boost the adoption of renewable energy, slash carbon emissions, and uphold economic viability. Yan et al. (2023) unveiled a cutting-edge stochastic optimization model, synthesizing the Stackelberg game, inter-regional carbon pricing, and green credit mechanisms. This multifaceted framework is crafted to drive the large-scale adoption of renewables and amplify their influence in energy trading.

In addition, Chrysikopoulos et al. (2024) applied bibliometric approaches to map the historical trajectory and present status of research on sustainable energy certifications, covering 940 documents from 2000 to 2022. The analysis revealed four key themes in the research, pinpointing crucial issues at the core of discussions on renewable energy support and policy, sustainable renewable tech and market trends, tech breakthroughs in green certificate exchange, and strategies for renewable energy investments.

2.2 Power supply chains

Nagurney and Matsypura (2007) developed a grid-based energy logistics model from the perspective of electricity production, supply, transmission, and consumption, and derived the optimality conditions and characterized the equilibrium state. By solving the variational inequality related to the equilibrium state, the model determines the equilibrium electricity flows and nodal prices. Electric energy is unique in that it is crucial to constantly maintain a balance between its production and consumption. In the field of pertinent thermal power generation, Eguchi et al. (2021) examined the fluctuations in the efficiency of coal-fired power plants across China between 2009 and 2011, and shed light on how variations in plant size and regional diversity affect efficiency. It was found that, on the whole, large-scale power plants boast an efficiency that is 13% superior to their smaller counterparts. Lee and Lee (2021) kicked off their work with fundamental combustion research on ammonia as a fuel. Later on, they delved into the practical uses of the technology in gas turbines and coal-burning power stations. In the end, the research paper detailed the findings from the investigation into ammonia-air combustion flames and the co-firing of coal with ammonia and air, which was all done at the research facility. Attari et al. (2022) relied on the grounded theory method to dissect the scholarly landscape. Their findings are goldmine, effectively steering the way forward for further inquiry in the complex realm of the electricity supply chain. Given its fragile nature, the electricity sector is ripe for all sorts of threats, whether Mother Nature's wrath, the whims of climate change, or cyber-attacks. Stepping into the breach, Vafadarnikjoo et al. (2022) introduced a robust risk assessment model designed to pinpoint and evaluate the risks associated with the UK's power grid. They applied the nuanced neutrosophic decision-making framework to delve into the root causes of these risks. Their analysis revealed that natural calamities and shifting weather patterns pose the greatest risks to our power infrastructure.

In the realm of renewable energy generation, Yang et al. (2022) introduced an advanced fuzzy time series model for renewable energy forecasting. Combining hesitant fuzzy sets and an optimized algorithm, the system excels in small-sample power output prediction, as validated by experiments. Furthermore, Zheng et al. (2023) introduced a novel mixed model. This system melds a convolutional neural network, which is adept at pinpointing the local connections among various energy sources. To get a grip on the complex, non-linear patterns of weather patterns and individual energy sources, they have employed an attention-driven long short-term memory network. To unearth the linear aspects of each energy source, they have also integrated an auto-regressive model. The empirical findings reveal that this framework trumps alternatives like artificial neural networks and decision trees in terms of precision. It provides a sharper, more reliable forecast for renewable energy generation, a crucial factor in fine-tuning energy distribution and bolstering the reliability of the power grid. Given the significance of augmenting the adaptability of multiple stations and maximizing the storage resource, Pei et al. (2024) presented three unique ways to divide up the costs: the one-size-fits-all approach, the guesswork-heavy weighted technique, and the ever-changing weighted system. They used these strategies to craft a fusion model that integrates both operational processes and cost distribution. The ultimate aim is to beef up the productivity of the power production setup through the addition of a shared battery storage solution and the equitable distribution of expenses related to the usage of numerous renewable energy sites.

2.3 Modeling for electricity markets

Against the backdrop of carbon reduction strategies for coal-fired power enterprises, Tan et al. (2019) considered corporate investment budget funds as a fuzzy variable and integrates the costs and benefits of energy-saving and emission reduction technologies. A carbon reduction strategy selection model is constructed with the reducing carbon reduction costs, providing a reference for coal-fired power enterprises in formulating their carbon reduction strategies. In light of the intricate design challenges, Tsao et al. (2021) demonstrated that the elaborate model they constructed could effectively adapt to either a centralized or decentralized supply chain structure. To tackle these issues, they employed a continuous approximation technique. The crux of these models lies in determining the optimal service zones for power plants, electricity tariffs, and maintenance budgets, all while maximizing the network's profitability or the entity's benefits. Sun et al. (2022) introduced a novel stochastic optimization approach aimed at enhancing the efficiency of electricity supply chains. Utilizing a scenario-based decision tree, the researchers meticulously accounted for the unpredictability of renewable energy sources. They then developed and tackled a multifaceted stochastic supply equilibrium model to ensure that demand is met across all time periods. Furthermore, they demonstrated the model's practicality through a real-world case study and delved into its potential for bolstering electricity supply chain management tactics. Moreover, Vafadarnikjoo et al. (2022) proposed a vulnerability assessment model designed to pinpoint and assess the perils associated with the UK's power grid. They leveraged a neutrosophic modified decision-making and evaluation lab technique to scrutinize the root causes of these risks. Moreover, they came up with an innovative model for selecting and weighting expert opinions, a tool that aids policy makers in making expert choices. Moreover, in an effort to meticulously consider the entire electricity supply chain and its related components, Tian et al. (2023) crafted a novel, expanded bilateral contract model. Leveraging the Stackelberg game theory, the research investigates the changing dynamics and strategies among power plants, suppliers, and consumers in the electricity trade process, taking into account the inherent unpredictability of demand. This framework was then tested using real-world electricity trade data from Guangdong, China, where penalties are imposed for misjudging the shifts in demand. The simulation outcomes reveal that our model's solution is notably more dependable and significantly reduces penalty expenditures. The electric power sector is uniquely prone to a range of risks, both natural and man-made, including natural calamities, climate shifts, and cybersecurity attacks. In addition, utilizing a Stackelberg game approach, Wang and Guan (2023) considered an electricity supply chain comprising coal-fired power generators, electricity retailers, and consumers. Four supply chain models are developed to examine two scenarios: generators independently developing carbon reduction technologies or collaborating with energy service providers for carbon reduction. Both scenarios are analyzed under two structural settings: an integrated generation-retail model and a separated generation-retail model. The study showed that when the cost paid by generators to energy service providers is relatively low, generators tend to collaborate on carbon reduction under the integrated generation-retail model.

2.4 Research motivation and contribution

Here, Table 1 is used to highlight the contributions of our study and further clarify the gaps compared to existing literature. Current studies mainly focus on the power supply chain, with some scholars considering the issue of green certificate trading. However, there are few studies that consider all the green certificate trading, power supply chain and game theory, while addressing both renewable and conventional energy generation. To fill this gap, this paper focuses on the competitive behavior among renewable and conventional energy generators. A Nash equilibrium model is employed to examine the optimal decision-making behavior of power generators. Unlike existing studies, our research combines green certificate trading with power generation based on the game theory, providing more practical insights to enhance the performance of power generators.

Table 1
Synthesis of the literature review most related to this study

Reference	Green certificate trading	Power supply chains	Game theory
Li et al. (2019)	✓		
Attari et al. (2022)		✓	
Vafadarnikjoo et al. (2022)		✓	✓
Nagurney and Matsypura (2007)		✓	
Wang et al. (2019)	✓		
Tan et al. (2019)		✓	✓
Eguchi. (2021)		✓	
Yan et al. (2023)	✓		
Otsuka. (2023)		✓	
Sun et al. (2022)		✓	✓
Chrysikopoulos et al. (2024)	✓		
Lee et al. (2021)		✓	
Yan et al. (2023)		✓	
This paper	✓	✓	✓

The central achievements of this study are described below:

- Under tradable green certificate mechanism, we examine the competitive behavior among renewable and conventional energy generators. Moreover, we come up with a Nash equilibrium model with the unit price of green certificates, the quantity required, and the cap on the quantity when power generators are making decisions.
- To crack the Nash equilibrium conundrum, we implement the Karush-Kuhn-Tucker constraints to reform it as a mixed complementary system, all while maintaining convexity. This new system is then restructured into a collection of non-linear equations. By tackling these equations head-on, we can pinpoint the Nash equilibria.

3. Problem description

The electricity sector is a multifaceted chain, involving players like power plant operators, wholesalers, transmission firms, and the end-consumers. Our analysis delves into two primary categories of generators on the production front: those harnessing renewable resources and those using traditional methods. The layout of the power supply chain can be visualized in Figure 1. Specifically, the top nodes consist of I renewable energy generators, denoted by $1,\cdots,i,\cdots I$, each renewable energy generator owns and operates M power plants. There are M power plants of generator i, as shown in the second level nodes in Fig. 1, are denoted as $i1, \cdots, im, \cdots iM$. Renewable energy generators produce electricity using clean energy sources, and these plants are powered by clean energy sources such as hydroelectric, photovoltaic, and tidal energy. In addition, the top nodes include J conventional energy generators, denoted by $1, \cdots j, \cdots J$. Each conventional energy generator owns and operates N power plants. The N power plants of the conventional energy generator j are denoted as $j1, \cdots jn, \cdots jN$. Conventional energy generators use disposable energy sources to produce electricity, and these plants are powered by conventional energy sources such as coal.

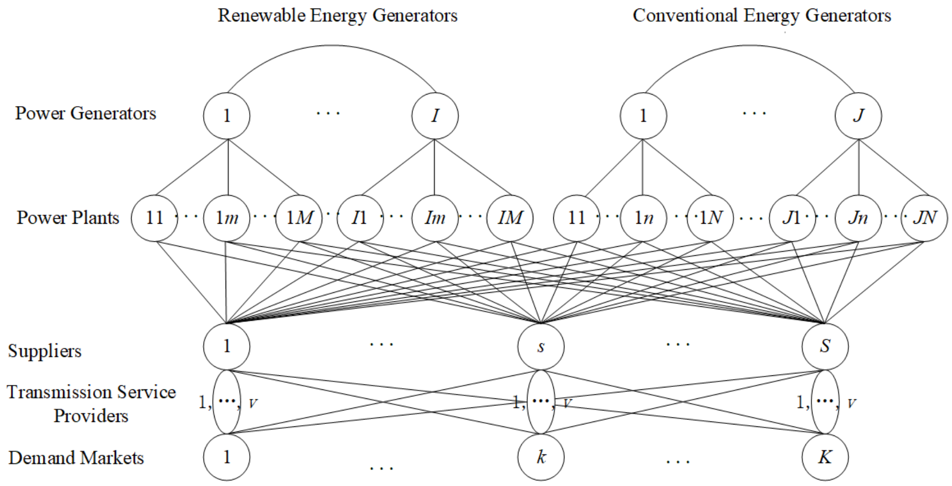

Fig. 1 The network of power supply chain

In the visual representation of Fig. 1, notice that power stations supply their generated electricity to the suppliers. These suppliers, situated at the third tier within the supply chain, are essentially the go-between players. They do not manage the electricity directly; rather, they act as brokers, wielding the authority to trade the electricity. The supplier nodes are denoted as $1, \cdots s, \cdots S$. As the entity that owns and operates the electricity transmission and distribution system, the transmission service provider, which sells electricity to consumers in different demand markets, is denoted here by v to denote the transmission service provider. Network structures do not typically include transmission service providers as nodes. The core nodes in Figure 1 stand for a variety of demand markets, and these can vary based on where they are situated or the type of consumer they cater to. Say, for instance, commercial entities and residential households have distinct power needs. The nodes associated with these demand markets are labeled $1, \cdots, k, \cdots K$. You can find the necessary notation for our model outlined in Table 2.

Table 2
Notations

Parameter	Explanation
α	Unit price for green certificates
$\bar{g}_{ims}$	Cap on the quantity of electricity traded by renewable energy generator i with supplier s using power plant m
$\underline{g}_{ims}$	Lower bound on the quantity of electricity traded by renewable energy generator i with supplier s using power plant m
$\bar{g}_{jns}$	Cap on the quantity of electricity traded by renewable energy generator j with supplier s using power plant n
$\underline{g}_{jns}$	Lower bound on the quantity of electricity traded by renewable energy generator j with supplier s using power plant n
$\bar{r}_{im}$	Cap on the number of green certificates in the green certificate market for power plant m of renewable energy generators i
$\bar{t}_{jn}$	Number of green certificates required to be purchased by the government for power plant n of conventional energy generators j
π	Unit penalty cost
Variable	**Explanation**
g_{ims}	Amount of electricity traded by renewable energy generator i with supplier s using power plant m
g_{im}	Quantity of electricity generated by renewable energy generator i using power plant m
r_{im}	Number of green certificates awarded to renewable energy generator i using power plant m
g_{jns}	Quantity of electricity traded by renewable energy generator j with supplier s using power plant n
g_{jn}	Quantity of electricity generated by renewable energy generator j using power plant n
t_{jn}	Number of green certificates purchased by conventional energy generator j using power plant n

Drawing from the trials and tribulations of introducing the renewable energy quota system abroad, it is clear that when the green certificate market is glutted with supply, renewable energy producers often find themselves in a pickle. They are left with the unenviable task of generating electricity at a higher cost, since they cannot recoup their expenses by selling their green certificates. This situation can really deflate their motivation to keep churning out power. However, if there is not enough supply to satiate the demand, energy companies that hold a bigger chunk of the market may decide to hold onto their green certificates. They do this to boost the market prices and make a bigger profit. This kind of action is harmful to the well-being of the entire green certificate trade system. For example, the Norwegian market for Hauge certificates has a quantitative limit. In 2019, the Norwegian government announced the issuance of 1.5 million Hauge certificates per year to support renewable energy projects. These certificates are purchased by electric utilities to certify the percentage of renewable energy they use.

However, the price of the certificates has soared as demand has outstripped supply. This has prompted the government to review the issuance policy to ensure adequate supply of renewable energy and market equilibrium. Therefore, we make the following assumptions throughout this paper:

1) The market for green certificates is balanced between supply and demand, and companies sell as many green certificates as they have, with no retention;
2) Market sales of green certificates by renewable energy producers match the market purchases of green certificates by conventional energy producers.

4. Mathematical model

In this section, under the tradable green certificate mechanism, we construct the equilibrium models for renewable energy generators and conventional energy generators, respectively.

4.1 Equilibrium model of renewable energy generators

The electricity price renewable energy generator i trades with supplier s depends on the amount of electricity supplied by all generators, and the price of electricity that the generator charges supplier s is denoted as P_s. Let $\sum_{s=1}^{S}\sum_{m=1}^{M} P_s(w_s)g_{ims}$ be denoted as the revenue from the sale of electricity by renewable energy generator i, where $w_s = \sum_{i=1}^{I}\sum_{m=1}^{M} g_{ims} + \sum_{j=1}^{J}\sum_{n=1}^{N} g_{jns}$. Renewable energy generator i operates power plants utilizing multiple generation technologies, which involves multiple stages and generation cost, let $\sum_{m=1}^{M} f_{im}(g_{im})$ denote the generation cost of renewable energy generator i. Transaction cost is incurred when a power generator trades with power suppliers, and it is related to the amount of electricity traded between the two parties, let $\sum_{s=1}^{S}\sum_{m=1}^{M} C_{ims}(g_{ims})$ denote the renewable energy generator i transaction cost. Renewable energy generators enter the green trading certificate market, where the price of green certificates is based on market pricing, but not higher than the subsidized price. For the sake of convenience, we set the price of green certificate to a fixed value α that is smaller than the current subsidized price. The certificate trading revenue is determined based on the number of green certificates, then $\alpha\sum_{m=1}^{M} r_{im}$ is the green certificate trading revenue of renewable energy generator.

Now the model for renewable energy generator i can be expressed as

$$(\mathrm{P}_i) \quad \max_{g_{ims},\, g_{im}, r_{im}} \sum_{s=1}^{S}\sum_{m=1}^{M} P_s(w_s)g_{ims} - \sum_{m=1}^{M} f_{im}(g_{im}) - \sum_{s=1}^{S}\sum_{m=1}^{M} c_{ims}(g_{ims}) + \alpha\sum_{m=1}^{M} r_{im} \tag{1}$$

$$\text{s.t.} \quad \sum_{s=1}^{S} g_{ims} = g_{im}, \qquad m = 1, \cdots, M \tag{2}$$

$$\underline{g}_{ims} \le g_{ims} \le \overline{g}_{ims}, \qquad m = 1, \cdots, M; s = 1, \cdots, S \tag{3}$$

$$0 \le r_{im} \le \overline{r}_{im}, \qquad m = 1, \cdots, M \tag{4}$$

$$\sum_{i=1}^{I}\sum_{m=1}^{M} r_{im} = \sum_{j=1}^{J}\sum_{n=1}^{N} t_{jn}\,. \tag{5}$$

Here, the objective function (1) represents the profit of renewable energy generator i. Specifically, the first term $\sum_{s=1}^{S}\sum_{m=1}^{M} P_s(w_s)g_{ims}$ denotes the total revenue of generator i, the second term $\sum_{m=1}^{M} f_{im}(g_{im})$ and the third term $\sum_{s=1}^{S}\sum_{m=1}^{M} c_{ims}(g_{ims})$ denote the electricity generation cost and transaction cost of generator i, the fourth term $\alpha\sum_{m=1}^{M} r_{im}$ denotes the revenue that generator i receives from selling green certificates. For example, Iberdrola in Spain, a renewable energy company based in Europe, generates electricity from wind and solar power and receives corresponding green certificates when it performs relatively well in terms of power output. These certificates are sold to conventional energy generators to help them meet their carbon neutrality targets. Through such transactions, Iberdrola not only finances renewable energy generation, but also contributes to global carbon reduction. Constraint condition (2) indicates that, for each power plant, the generator generates the same amount of electricity as the electricity sold by all suppliers trading. Constraint condition (3) indicates that the limits of achievable generation output, and that the generation capacity possesses an upper limit of generation, subject to various conditions such as renewable energy resource endowment, maturity of generation technology, installed capacity, renewable energy consumption problems, and so on. In order to promote the active generation of electricity by renewable energy generators and to avoid passive shutdowns, a lower limit value for the amount of electricity is established. Constraint condition (4) indicates that a limit on the quantity of green certificates to be allocated for issuance, as the generation of renewable energy generators in the electricity market determines the upper limit on the quantity of green certificates, which must be not less than zero. Condition (5) states that in the green certificate trading system, the green certificates sold by renewable energy producers are equal in number to those bought by conventional energy producers.

4.2 Equilibrium model of conventional energy generators

Conventional energy generators enter the green trading certificate market and determine the green certificate transaction fee based on the quantity of green certificates t_{jn} they need to purchase. Since the green certificates price is α, αt_{jn} is green certificates purchase cost for a conventional energy generator. Under the green certificate trading market regulations, every conventional energy generator has polluting emissions, and the government mandates that it must have a certain number of green certificates to offset polluting emissions. Conventional energy generators purchase green certificates, and the shortfall is subject to a certificate penalty. Let $\pi\sum_{n=1}^{N}(\bar{t}_{jn}-t_{jn})$ be the penalty fee of the conventional energy generator j on green certificate trading. From the above discussion, the mathematical optimization model for conventional energy generator j can be constructed as

$$(\mathrm{P}_j) \quad \max_{g_{jns},\, g_{jn},\, t_{jn}} \sum_{s=1}^{S}\sum_{n=1}^{N} P_s(w_s)g_{jns} - \sum_{n=1}^{N} f_{jn}(g_{jn}) - \sum_{s=1}^{S}\sum_{n=1}^{N} c_{jns}(g_{jns}) - \alpha\sum_{n=1}^{N} t_{jn} - \pi\sum_{n=1}^{N}(\bar{t}_{jn}-t_{jn}) \tag{6}$$

$$\text{s.t.} \quad \sum_{s=1}^{S} g_{jns} = g_{jn}, \qquad n=1,\cdots,N \tag{7}$$

$$\underline{g}_{jns} \le g_{jns} \le \overline{g}_{jns}, \qquad n=1,\cdots,N;\ s=1,\cdots,S \tag{8}$$

$$0 \le t_{jn} \le \bar{t}_{jn}, \qquad n=1,\cdots,N \tag{9}$$

$$\sum_{i=1}^{I}\sum_{m=1}^{M} r_{im} = \sum_{j=1}^{J}\sum_{n=1}^{N} t_{jn}\,. \tag{10}$$

Here, function (6) represents the conventional energy generator j's profit. Specifically, the first term $\sum_{s=1}^{S}\sum_{n=1}^{N}P_s(w_s)g_{jns}$ denotes the total revenue of generator j, the second term $\sum_{n=1}^{N}f_{jn}(g_{jn})$ and the third term $\sum_{s=1}^{S}\sum_{n=1}^{N}c_{jns}(g_{jns})$ denote the electricity generation cost and the transaction cost of generator j, the fourth term $\alpha\sum_{n=1}^{N}t_{jn}$ denotes the cost of purchasing green certificates, and the last term $\pi\sum_{n=1}^{N}(\bar{t}_{jn}-t_{jn})$ denotes the penalty cost of conventional energy generators regarding green certificate transactions. Constraint conditions (7) and (8) have the same interpretation as constraint conditions (2) and (3). Constraint condition (9) indicates that the quantity of green certificates to be purchased by a conventional energy generator cannot be exceeded than the number of certificates required by the government. Conventional energy generators are purchasing green certificates to compensate for their carbon emissions in an effort to make a green transition. The initiative aims to enhance corporate image and reduce adverse environmental impacts. By purchasing green certificates, they set an example of sustainable development in the electricity market and provide support for the development of renewable energy. Enterprises should be aware of their responsibility to protect the environment and actively strive to transition to green energy. Constraint condition (10) has the same interpretation as constraint condition (5).

5 Model analysis and solution

For the optimization model P_i of renewable energy generator i, in this paper, we assume that the price function $P_s = a_s - b_s\left(\sum_{i=1}^{I}\sum_{m=1}^{M}g_{ims}+\sum_{j=1}^{J}\sum_{n=1}^{N}g_{jns}\right)$, where the parameters a_s, $b_s>0$. Assume that the generation cost function $f_{im}(g_{im})=\frac{1}{2}\beta_{im}g_{im}^2$ is a quadratic function with respect to g_{im}, where the parameter $\beta_{im}>0$. Suppose that the transaction cost function $C_{ims}(g_{ims})=\frac{1}{2}\theta_{ims}g_{ims}^2$ is a quadratic function on g_{ims}, where the parameter $\theta_{ims}>0$. It is easy to see that the model P_i is a convex optimization model and the model solution can be equivalently transformed into the KKT condition.

For the optimization model P_j of conventional energy generator j, assume that the generation cost function $f_{jn}(g_{jn})=\frac{1}{2}\beta_{jn}g_{jn}^2$ is a quadratic function with respect to g_{jn}, where the parameter $\beta_{jn}>0$. Suppose that the transaction cost function $C_{jns}(g_{jns})=\frac{1}{2}\theta_{jns}g_{jns}^2$ is a quadratic function on g_{jns}, where the parameter $\theta_{jns}>0$. It is easy to see that the model P_j is a convex optimization model and the model solution can be equivalently transformed into the KKT condition. For the optimization model P_i, let δ_{ims}, ϵ_{ims}, τ_{im} , θ_{im}, σ_{im} and ρ be the Lagrange multipliers corresponding to all constraint conditions of model P_i, then the Lagrange function is

$$
\begin{aligned}
&L_i(g_{ims}, g_{im}, r_{im}; \delta_{ims}, \epsilon_{ims}, \tau_{im}, \theta_{im}, \sigma_{im}, \rho)\\
&\quad = -\sum_{s=1}^{S}\sum_{m=1}^{M} P_s(w_s) g_{ims} + \sum_{m=1}^{M} f_{im}(g_{im}) + \sum_{s=1}^{S}\sum_{m=1}^{M} c_{ims}(g_{ims}) - \alpha \sum_{m=1}^{M} r_{im}\\
&\quad + \sum_{s=1}^{S}\sum_{m=1}^{M} \delta_{ims}(g_{ims} - \overline{g}_{ims}) + \sum_{s=1}^{S}\sum_{m=1}^{M} \epsilon_{ims}\left(\underline{g}_{ims} - g_{ims}\right)\\
&\quad + \sum_{m=1}^{M} \tau_{im}(r_{im} - \overline{r}_{im}) + \sum_{m=1}^{M} \theta_{im}(-r_{im})\\
&\quad + \sum_{m=1}^{M} \sigma_{im}\left(\sum_{s=1}^{S} g_{ims} - g_{im}\right) + \rho\left(\sum_{i=1}^{I}\sum_{m=1}^{M} r_{im} - \sum_{j=1}^{J}\sum_{n=1}^{N} t_{jn}\right).
\end{aligned}
$$

Define $L_i = L_i(g_{ims}, g_{im}, r_{im}; \delta_{ims}, \epsilon_{ims}, \tau_{im}, \theta_{im}, \sigma_{im}, \rho)$. Since P_i is a convex optimization model, solving the Nash equilibrium challenge is tantamount to solving the subsequent mixed complementarity problem:

$$
\begin{cases}
\nabla_{(g_{ims}, g_{im}, r_{im})} L_i = 0, i = 1, \cdots, I; m = 1, \cdots, M; s = 1, \cdots, S\\
\delta_{ims} \ge 0, g_{ims} - \overline{g}_{ims} \le 0, \delta_{ims}\left(g_{ims} - \overline{g}_{ims}\right) = 0, i = 1, \cdots, I; m = 1, \cdots, M; s = 1, \cdots, S\\
\epsilon_{ims} \ge 0, \underline{g}_{ims} - g_{ims} \le 0, \epsilon_{ims}\left(\underline{g}_{ims} - g_{ims}\right) = 0, i = 1, \cdots, I; m = 1, \cdots, M; s = 1, \cdots, S\\
\tau_{im} \ge 0, r_{im} - \overline{r}_{im} \le 0, \tau_{im}(r_{im} - \overline{r}_{im}) = 0, i = 1, \cdots, I; m = 1, \cdots, M\\
\theta_{im} \ge 0, -r_{im} \le 0, \theta_{im}(-r_{im}) = 0, i = 1, \cdots, I; m = 1, \cdots, M\\
\sum_{s=1}^{S} g_{ims} - g_{im} = 0, i = 1, \cdots, I; m = 1, \cdots, M\\
\sum_{i=1}^{I}\sum_{m=1}^{M} r_{im} - \sum_{j=1}^{J}\sum_{n=1}^{N} t_{jn} = 0.
\end{cases}
\tag{11}
$$

According to the work of Facchinei and Pang (2003), the Fischer-Burmeister function $\phi(a, b) = a + b - \sqrt{a^2 + b^2}$ satisfies the property that $\phi(a, b) = 0 (\forall a, b \in \mathbb{R}) \Leftrightarrow a \ge 0, b \ge 0, ab = 0$. Then, by using Fischer-Burmeister function, (11) can be equivalently reformed as the following nonlinear equations:

$$
\begin{cases}
\nabla_{(g_{ims}, g_{im}, r_{im})} L_i = 0, i = 1, \cdots, I; m = 1, \cdots, M; s = 1, \cdots, S\\
\delta_{ims} + \overline{g}_{ims} - g_{ims} - \sqrt{\delta_{ims}^2 + (\overline{g}_{ims} - g_{ims})^2} = 0, i = 1, \cdots, I; m = 1, \cdots, M; s = 1, \cdots, S\\
\epsilon_{ims} + g_{ims} - \underline{g}_{ims} - \sqrt{\epsilon_{ims}^2 + (g_{ims} - \underline{g}_{ims})^2} = 0, i = 1, \cdots, I; m = 1, \cdots, M; s = 1, \cdots, S\\
\tau_{im} + \overline{r}_{im} - r_{im} - \sqrt{\tau_{im}^2 + (\overline{r}_{im} - r_{im})^2} = 0, i = 1, \cdots, I; m = 1, \cdots, M\\
\theta_{im} + r_{im} - \sqrt{\theta_{im}^2 + r_{im}^2} = 0, i = 1, \cdots, I; m = 1, \cdots, M\\
\sum_{s=1}^{S} g_{ims} - g_{im} = 0, i = 1, \cdots, I; m = 1, \cdots, M\\
\sum_{i=1}^{I}\sum_{m=1}^{M} r_{im} - \sum_{j=1}^{J}\sum_{n=1}^{N} t_{jn} = 0.
\end{cases}
\tag{12}
$$

Similarly, for the optimization model P_j, let $\delta_{jns}, \epsilon_{jns}, \tau_{jn}, \theta_{jn}, \sigma_{jn}$ $(j = 1, \cdots, J; n = 1, \cdots, N; s = 1, \cdots, S)$ and ϱ be the Lagrange multipliers corresponding to all constraint conditions of model P_j, then the Lagrange function is

$$
\begin{aligned}
&L_i\left(g_{jns}, g_{jn}, t_{jn}; \delta_{jns}, \epsilon_{jns}, \tau_{jn}, \theta_{jn}, \sigma_{jn}, \varrho\right) \\
&\quad = -\sum_{s=1}^{S}\sum_{n=1}^{N} P_s(w_s) g_{jns} + \sum_{n=1}^{N} f_{jn}\left(g_{jn}\right) + \sum_{s=1}^{S}\sum_{n=1}^{N} c_{jns}\left(g_{jns}\right) - \alpha \sum_{n=1}^{N} t_{jn} \\
&\quad + \sum_{s=1}^{S}\sum_{n=1}^{N} \delta_{jns}\left(g_{jns} - \overline{g}_{jns}\right) + \sum_{s=1}^{S}\sum_{n=1}^{N} \epsilon_{jns}\left(\underline{g}_{jns} - g_{jns}\right) \\
&\quad + \sum_{n=1}^{N} \tau_{jn}\left(t_{jn} - \overline{t}_{jn}\right) + \sum_{n=1}^{N} \theta_{jn}\left(-t_{jn}\right) \\
&\quad + \sum_{n=1}^{N} \sigma_{jn}\left(\sum_{s=1}^{S} g_{jns} - g_{jn}\right) + \rho\left(\sum_{i=1}^{I}\sum_{m=1}^{M} r_{im} - \sum_{j=1}^{J}\sum_{n=1}^{N} t_{jn}\right).
\end{aligned}
$$

Define $L_j = L_j(g_{jns}, g_{jn}, t_{jn}; \delta_{jns}, \epsilon_{jns}, \tau_{jn}, \theta_{jn}, \sigma_{jn}, \varrho)$. Since P_j is a convex optimization model, tackling the Nash equilibrium problem corresponds to handling the ensuing mixed complementarity problem:

$$
\begin{cases}
\nabla_{(g_{jns}, g_{jn}, r_{jn})} L_j = 0, j = 1, \cdots, J; n = 1, \cdots, N; s = 1, \cdots, S \\
\delta_{jns} \geq 0, g_{jns} - \overline{g}_{jns} \leq 0, \delta_{jns}(g_{jns} - \overline{g}_{jns}) = 0, j = 1, \cdots, J; n = 1, \cdots, N; s = 1, \cdots, S \\
\epsilon_{jns} \geq 0, \underline{g}_{jns} - g_{jns} \leq 0, \epsilon_{jns}\left(\underline{g}_{jns} - g_{jns}\right) = 0, j = 1, \cdots, J; n = 1, \cdots, N; s = 1, \cdots, S \\
\tau_{jn} \geq 0, t_{jn} - \overline{t}_{jn} \leq 0, \tau_{jn}(t_{jn} - \overline{t}_{jn}) = 0, j = 1, \cdots, J; n = 1, \cdots, N \\
\theta_{jn} \geq 0, -t_{jn} \leq 0, \theta_{jn}(-t_{jn}) = 0, j = 1, \cdots, J; n = 1, \cdots, N \\
\sum_{s=1}^{S} g_{jns} - g_{jn} = 0, j = 1, \cdots, J; n = 1, \cdots, N \\
\sum_{i=1}^{I}\sum_{m=1}^{M} r_{im} - \sum_{j=1}^{J}\sum_{n=1}^{N} t_{jn} = 0.
\end{cases}
\tag{13}
$$

Then, by using Fischer-Burmeister function, (13) can be equivalently reformed as the following nonlinear equations:

$$
\begin{cases}
\nabla_{(g_{jns}, g_{jn}, r_{jn})} L_j = 0, j = 1, \cdots, J; n = 1, \cdots, N; s = 1, \cdots, S \\
\delta_{jns} + \overline{g}_{jns} - g_{jns} - \sqrt{\delta_{jns}^2 + (\overline{g}_{jns} - g_{jns})^2} = 0, j = 1, \cdots, J; n = 1, \cdots, N; s = 1, \cdots, S \\
\epsilon_{jns} + g_{jns} - \underline{g}_{jns} - \sqrt{\epsilon_{jns}^2 + (g_{jns} - \underline{g}_{jns})^2} = 0, j = 1, \cdots, J; n = 1, \cdots, N; s = 1, \cdots, S \\
\tau_{jn} + \overline{t}_{jn} - t_{jn} - \sqrt{\tau_{jn}^2 + (\overline{t}_{jn} - t_{jn})^2} = 0, j = 1, \cdots, J; n = 1, \cdots, N \\
\theta_{jn} + t_{jn} - \sqrt{\theta_{jn}^2 + t_{jn}^2} = 0, j = 1, \cdots, J; n = 1, \cdots, N \\
\sum_{s=1}^{S} g_{jns} - g_{jn} = 0, j = 1, \cdots, J; n = 1, \cdots, N \\
\sum_{i=1}^{I}\sum_{m=1}^{M} r_{im} - \sum_{j=1}^{J}\sum_{n=1}^{N} t_{jn} = 0.
\end{cases}
\tag{14}
$$

By solving the system of nonlinear equations (12) and (14), the Nash equilibrium solution for the competition between renewable energy generators and conventional energy generators is then obtained.

6. Numerical experiments

In this section, we consider two renewable energy generators and two conventional energy generators, each with two power plants, and electric power suppliers supply electricity to the markets served by transmission companies, see Fig. 2.

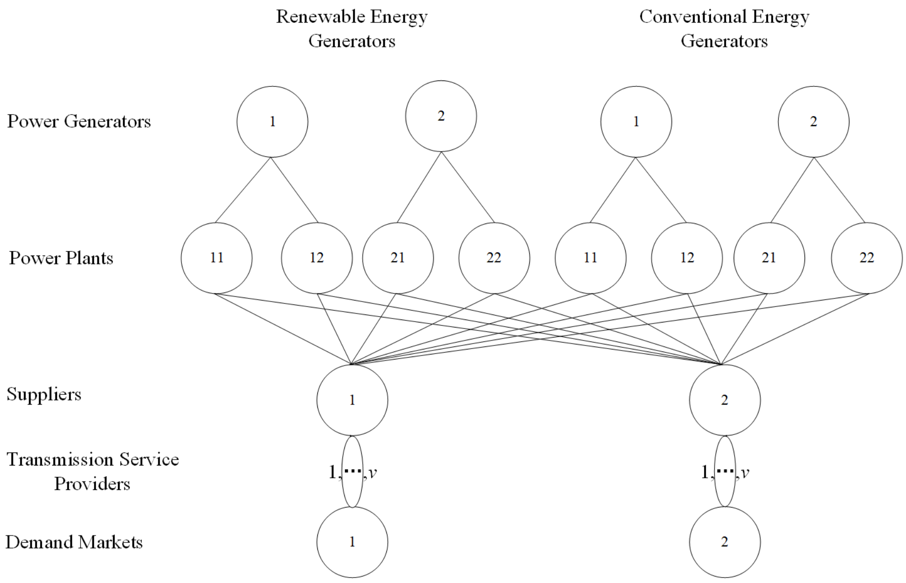

Fig. 2 The network of a specific electric power supply chain

Numerical experiments are carried out using MATLAB software to create a groundwork for decision making for renewable energy generators, conventional energy generators, and government administrators. The parameters' values are set as follows: For each $i = 1, 2$, $m = 1, 2$, $s = 1, 2$, let $\overline{g}_{ims} = 1$, $\underline{g}_{ims} = 0$, $\beta_{im} = 10$, $\theta_{ims} = 10$, $\overline{r}_{im} = 200$, $a_s = b_s = 10$; For each $j = 1, 2$, $n = 1, 2$, $s = 1, 2$, let $\overline{g}_{jns} = 1$, $\underline{g}_{jns} = 0$, $\overline{t}_{jn} = 200$, $\beta_{jn} = 10$, $\theta_{jns} = 10$. Besides, we set $\alpha = 1$, $\pi = 2$.

6.1 Unit price for green certificates

As the cost for fossil-fuel-based producers to attain green certificates is often elevated compared to their market value, this fundamentally reduces the significance of the market price of green certificates in assessing the number of certificates secured by renewable energy producers or the total obtained by conventional energy sources. As depicted in Fig. 3, the demand for green certificates from renewable energy producers remains steady in the market, irrespective of the quantity of certificates generated, due to the government's stipulation on the number of certificates that conventional energy generators must purchase. Green certificates cannot be traded or stockpiled for extended periods; they are like a ticking clock. They are a must-have for the system. Renewable energy producers and conventional energy suppliers play a balancing act, swapping green certificates in lockstep. The market price of green certificates is a non-factor when it comes to how many conventional energy generators buy or how many renewable energy producers create.

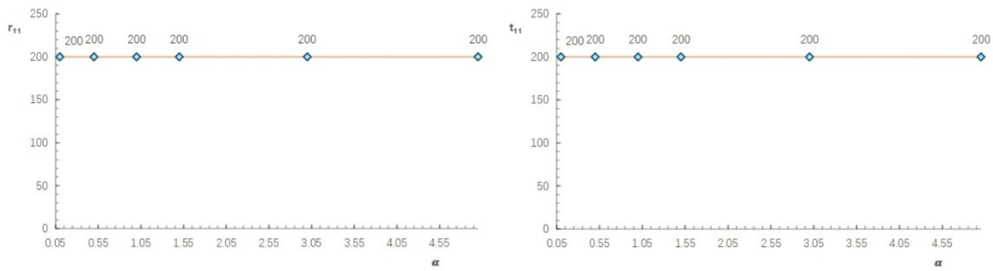

Fig. 3 Influence of unit price for green certificates

In the case of conventional energy producers, the cost of procuring green certificates is invariably lower than the fine incurred for not having enough of them, provided the number of certificates is equal. Consequently, the individual cost of a green certificate does not sway the decision of a typical energy firm to secure the necessary amount to avoid penalties. Thus, irrespective of the green certificate's price per unit, the quantity bought by a conventional power outfit will consistently be the amount they need or the maximum allowable purchase.

6.2 Number of required green certificates

Since the calculations in the experiment about different power plants of different generators are the same, only the data results of the first power plant of the first conventional energy generator are taken, as shown in Fig. 4. We can see that as the government mandates a higher quantity of green certificates for conventional energy producers to buy, there is a corresponding rise in the green certificates acquired by renewable energy sources and those purchased by the traditional energy sector. This increase is proportionate, meaning both rise by the same amount. However, once the required number of green certificates hits a certain point, the numbers of green certificates gathered by renewables and bought by the old-school energy companies max out, and from thereon, the numbers remain static.

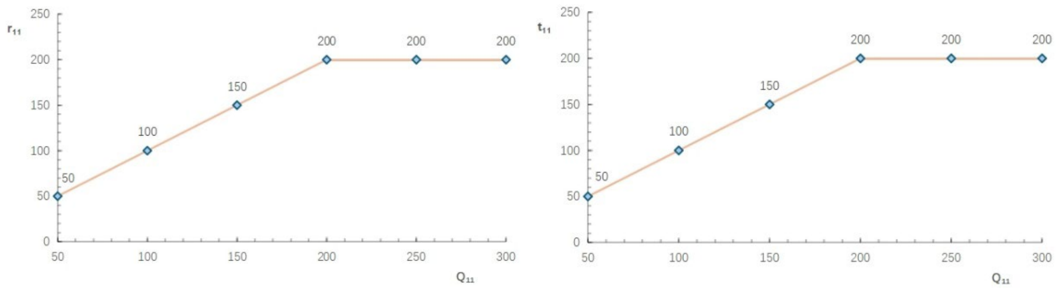

Fig. 4. Influence of number of required green certificates

Observe that the government-mandated minimum number of green certs traditional energy producers need to buy sets the ceiling on how many green certs renewable energy firms can snag. That is, the total number of green certs floating in the electricity marketplace will never exceed the renewable sector's max tally. Under these guidelines, the green certs renewable sources amass and the green certs conventional sources fork over are directly tied to the govt-set minimum green certs the conventional energy companies have to buy. Therefore, in the purchase decision of green certificates for conventional energy producers, conventional energy power producers can either purchase the quantity of green certificates that meets government's requirements when the price is low or the maximum can be purchased in circulation in the market to ensure that they do not pay additional penalties, or purchase and stockpile lower-priced green certificates that can be retained within the limitation period in advance to ensure that they can maximize their own profits.

6.3 Cap on the quantity of traded electricity

As shown in Fig. 5, regardless of whether a renewable energy generator or a conventional energy generator, the amount of power traded between a generator's power plants and suppliers does not affect the amount of power traded by the generator under the maximum profit, and its own power traded tends to be close to the upper or lower limit of the power traded under the maximum profit when the amount of power traded under the maximum profit is not in the range of the upper and lower limits of the power traded. As the renewable energy generator's power plant-supplier trading volume cap increases, the renewable energy generator's trading volume also increases. When the volume of electricity traded under the maximum profit is reached, the volume of electricity traded by renewable energy generators no longer changes, and conventional energy generators follow the same trend as it does.

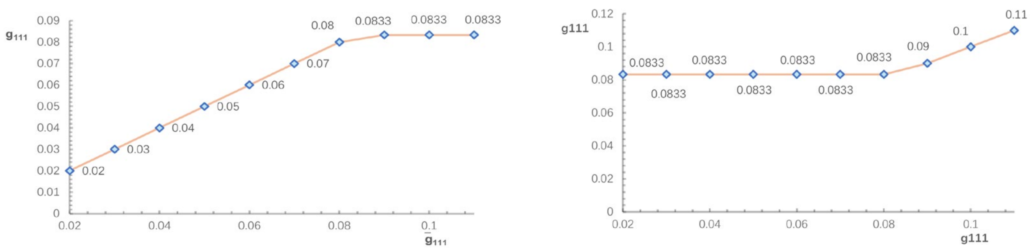

Fig. 5. Influence of cap on the quantity of traded electricity

For power generators, in the process of power trading, there exists a power trading volume that is not determined by their own production level, but by the market supply demand under the maximum profit. Therefore, power generators can find the range of maximum profit power trading volume through the actual power generation demand situation or rigorous data analysis, so as to make a reasonable decision plan.

6.4 Generation cost coefficient of power generators

It can be seen from Fig. 6 that the volume of electricity traded by renewable energy generators decreases as their own generation costs increase. Power generators can increase the volume of electricity traded by improving the level of generation technology and saving on generation costs. When the cost coefficient of renewable energy generators increases, the volume of electricity traded by conventional energy generators gradually increases. That is, when the cost coefficient of power generation of renewable energy power generators is too high, renewable energy power generators will not produce too much power in order to maintain their own profits, and will not reach the volume of power trading under the maximization of profits.

At this time, due to the weakening of competition from conventional energy generators, conventional energy generators will increase their power generation capacity, expanding the volume of electricity traded under maximize profitability.

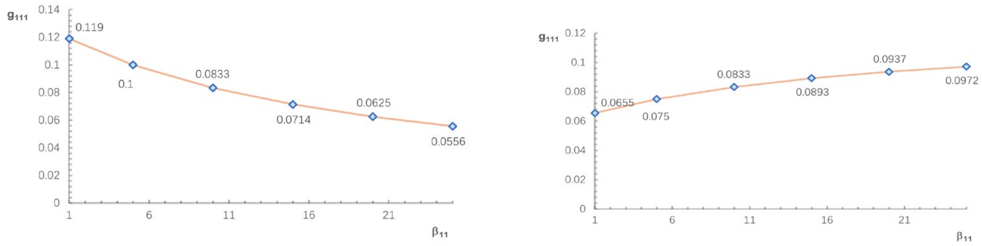

Fig. 6. Influence of generation cost coefficient of power generators

6.5 Cap on the number of green certificates

Per the illustration in Fig. 7, the ceiling on green certificates procured by renewable energy producers aligns precisely with the mandatory quantity that conventional energy producers must acquire, as dictated by the government's regulations. It is quite evident from various sources that there is a mutually reinforcing relationship at play between these two entities. In essence, the renewable energy producer's green certificates and the conventional energy producer's purchased certificates must never surpass the government-defined limit for the conventional energy producer's green certificate purchases and the renewable energy producer's certificate earnings. If one amount is set, the other will be adjusted proportionally to the renewable energy certificates earned and the conventional energy certificates bought.

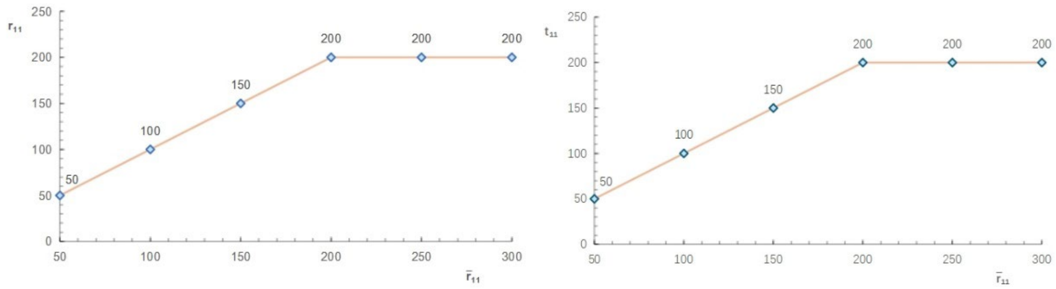

Fig. 7. Influence of cap on the number of green certificates

Hence, when it comes to the issuance of green certificates by a renewable power producer, the producer merely has to secure the appropriate quantity of green certificates, which can be calculated based on the volume of green electricity they produce. They then hand these over to the conventional energy provider. The producer keeps the surplus green certificates within the designated timeframe, and sells them when the market price spikes, thereby guaranteeing they capitalize on their earnings to the fullest.

6.6 Managerial insights

The study establishes a gaming-inspired operational research framework designed to evaluate both renewable and traditional energy producers within the context of green certificate exchanges. Key management insights have been garnered through both theoretical contemplations and quantitative findings.

1) The supply and demand of green certificates are strictly regulated by government policies. For the government, it is important to set an appropriate trading price for green certificates to avoid the price being too low. For conventional energy power producers, implementing carbon reduction should be a top priority, as this is beneficial for both environmental improvement and the long-term development of the business.

2) When the green certificate resources are limited, power generation companies need to optimize resource allocation under resource constraints. For example, conventional energy power producers should purchase a suitable quantity of green certificates with low price to increase their profits. Furthermore, policy changes not only have short-term effects but also impact the long-term strategies of power producers. Therefore, power producers should seek a balance amid policy changes and plan for long-term development accordingly.

3) The supply-demand relationship in the green certificate market is highly dependent on government policy, and policy changes directly influence the production and sales strategies of renewable energy generation. The government should establish reasonable policies regarding green certificates, as this plays a positive role in reducing carbon emissions, promoting green production, and encouraging the production enthusiasm of power producers.

7. Conclusions

The study delves into the strategic choices made by both renewable and traditional energy producers when engaging in green certificate trading. Utilizing a network diagram, we dissect the intricate decision-making mechanisms within the power supply chain. By employing game theory, we establish an equilibrium model that encompasses various power generators. Initially, we showcase that the optimization model adheres to the principle of convexity. By using Karush-Kuhn-Tucker conditions, the Nash equilibrium model can be converted into a mixed complementarity system which can be restructured into a set of nonlinear equations. Both theoretical and numerical investigations underscore the substantial influence of green certificate trading. In particular, there is a scenario where the cost per green certificate does not sway the amount that renewable energy firms get or the volume that fossil fuel generators buy. Moreover, as the demand for green certificates grows and the limit on the total number of certificates rises, both renewable energy providers and conventional energy firms acquire more certificates in tandem.

It is essential to emphasize that this study delves into the competitive interactions of all energy producers in the electricity market under the green certificate policy, including both renewable and conventional energy generators. Future research could explore the competition among power generators under different policy frameworks. Additionally, other roles within the electricity supply chain should also be considered. As a result, it is meaningful to study the whole power supply chain network equilibrium model, which may offer a promising avenue to provide valuable insights and practical applications.

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