Equilibrium Decision Making in Power Supply Chain Network Based on RPS Considering Tradable Green Certificates

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Abstract. The development of renewable energy has attracted widespread attention in the context of the synergistic promotion of the "dual carbon" policy and the power market-oriented reform. Based on this, this paper focuses on the coupling of renewable energy portfolio standard (RPS) and tradable green certificates to participate in the power market. The network equilibrium model of power supply chain considering green certificate trading under RPS is established, and the equilibrium state of power supply chain is obtained by using Nash equilibrium and variational inequality theory, which is solved by using modified projection algorithm. The results show that: the stricter RPS restricts the flow and profit of the power supply chain, but favors the consumption of renewable energy; the social benefit increases and then decreases with the increase of RPS, and there exists a value of RPS that makes the social benefit optimal during the implementation of the RPS policy.

Keywords: Renewable Portfolio Standard, tradable green certificates, power supply chain, network equalization.

1. Introduction

Against the backdrop of the transformation of the global energy structure towards decarbonization, renewable energy has become an important measure for countries to address environmental challenges and safeguard energy security. Driven by the policy, green certificates cover all renewable energy power generation projects, and clarify the interface mechanism between green certificate issuance, trading and quota system assessment. The synergistic mechanism of renewable portfolio standard (RPS) and tradable green certificates (TGC) in China has been developing rapidly, but there are still problems, such as: the difference of the main body responsible for the consumption of electricity and TGC market, and the reasonable allocation of RPS between regions. Therefore, the research on the participation of RPS and TGC in the power market is of great significance to promote China's power reform of marketization and energy transition strategy.

The synergistic mechanism of RPS and TGC restructures the revenue distribution mechanism of the power system through the dual-track system of "mandatory constraints + marketization". Researchers have proposed various models to study the effects of RPS and TGC on the power system [1-2]. For example, some scholars decompose the effect of RPS into substitution effect, tax effect output effect, and establish a general equilibrium model considering RPS policy. The results show that a stricter RPS can either bring resource benefits or enhance emission reduction, but not both at the same time [3]. In addition, researchers used evolutionary game theory and system dynamics to study the behavior of power generation companies under RPS. They found that an increase in the level of penalties motivates power producers to accept the RPS as soon as possible and promotes the transaction size of the TGC, but too low a quota requirement should be avoided [4]. Using system dynamics, scholars constructed market trading models with benchmark feed-in tariffs and market-based feed-in tariffs, respectively, and investigated how RPS stimulates and guides demand-side green certificate trading to increase the utilization level of renewable power generation [5]. The researchers considered the power seller as the main body of renewable energy consumption responsibility, and considered the inclusion of biomass power projects in TGC trading, and established a literature on the trading structure of the day-ahead spot market under RPS [6]. In addition, scholars have shown keen interest in the interplay between the pricing strategies of members within the electricity supply chain, which has led to significant progress in the development of coordination mechanisms [7-9].

The above studies have explored the influence of RPS and TGC mechanisms on power system flow or members' decision-making from various angles, however, the coupling of RPS and TGC with power market mechanisms and the study on the mutual game relationship between members of different tiers of the power supply chain network (PSCN) are still insufficient. Therefore, this paper establishes a PSCN equilibrium model under the consideration of RPS and TGC synergistic mechanism, obtains the equilibrium conditions of the PSCN by combing the optimal decisions of members of different tiers, and solves the problem by using the modified projection algorithm, which finally leads to the analysis of equilibrium supply chain flows as well as social benefits.

2. Model Assumptions

2.1 Behavior of generators

In this study, renewable energy generator i can sell green certificates to power supplier k to gain revenue, and the objective of all generators is to maximize the total profit. The objective function and constraints faced by the power generators can be expressed as follows:

$$MAXG_i = \sum_{k=1}^{K} q_{ik}\rho_{ik} - \sum_{k=1}^{K} c_i(q_{ik}) - \sum_{k=1}^{K} f_i(q_{ik}) + \sum_{n=1}^{N} q_{vik}\rho_{vik} - \sum_{n=1}^{N} c_{vik}(q_{vik}) \tag{1}$$

$$MAXG_j = \sum_{k=1}^{K} q_{jk}\rho_{jk} - \sum_{k=1}^{K} c_j(q_{jk}) - \sum_{k=1}^{K} f_j(q_{jk}) \tag{2}$$

The constraints are: $0 \le \sum_{k=1}^{K} q_{ik} \le a_i, 0 \le \sum_{k=1}^{K} q_{jk} \le b_j, \sum_{k=1}^{K} q_{ik} \ge \sum_{k=1}^{K} q_{vik}$

Eq. (1) is the objective function of the conventional power producer, whose first term is the revenue of the conventional power producer j, and $q_{jk}\rho_{jk}$ denotes the product of electricity quantity and electricity price. The last two terms denote its transaction and generation costs. In Eq. (2), the first three terms are similar to Eq. (1), the fourth term denotes the revenue from the sale of green certificates, and the fifth term denotes the transaction cost of green certificates. The a_i and b_j in the constraints denote the generation capacity constraints of the two power producers. The last constraint indicates that the flow of green certificates of the renewable energy generator is greater than or equal to its renewable energy generation capacity. Assuming that generators compete non-cooperatively under Nash conditions, their optimal behavior can be described as a variational inequality satisfying the following conditions: $\sum_{i=1}^{I}\sum_{k=1}^{K}\left[\frac{\partial c_i(q_{ik}^*)}{\partial q_{ik}} + \frac{\partial f_i(q_{ik}^*)}{\partial q_{ik}} - \rho_{ik}{}^* + \lambda^{1i*} - \lambda^{2*}\right] \times [q_{ik} - q_{ik}^*] + \sum_{j=1}^{J}\sum_{k=1}^{K}\left[\frac{\partial c_j\left(q_{jk}^*\right)}{\partial q_{jk}} + \frac{\partial f_j\left(q_{jk}^*\right)}{\partial q_{jk}} + \lambda^{1j*} - \rho_{jk}^*\right] \times [q_{jk} - q_{jk}^*] + \sum_{i=1}^{I}\sum_{k=1}^{K}\left[\frac{\partial c_{vik}(q_{vik}^*)}{\partial q_{vik}} - \rho_{vik}{}^* + \lambda^{2*}\right] \times [q_{vik} - q_{vik}^*] + \sum_{i=1}^{I}\left[a_i - \sum_{k=1}^{K} q_{ik}^*\right] \times [\lambda^{1i} - \lambda^{1i*}] + \sum_{j=1}^{J}\left[b_j - \sum_{k=1}^{K} q_{jk}^*\right] \times [\lambda^{1j} - \lambda^{1j*}] + \sum_{i=1}^{I}\left[\sum_{k=1}^{K} q_{ik}^* - \sum_{k=1}^{K} q_{vik}^*\right] \times [\lambda^2 - \lambda^{2*}] \ge 0, (q_{vik}^*, Q1^*, Q2^*, \lambda^{1i*}, \lambda^{1j*}, \lambda^{2*}) \in K^1 = R_+^{IK\times IK\times JK\times I\times J\times I}$.

2.2 Behavior of power suppliers

The objective function and constraints faced by power supplier k are shown below:

$$MAXS_k = \sum_{n=1}^{N} q_{kn}\rho_{kn} - \sum_{i=1}^{I} q_{ik}\rho_{ik} - \sum_{j=1}^{J} q_{jk}\rho_{jk} - \sum_{n=1}^{N} f_k(q_{kn}) - \sum_{n=1}^{N} c_k(q_{kn}) - \sum_{k=1}^{K} q_{vik}\rho_{vik} - \sum_{i=1}^{I} c_{vki}(q_{vik}) \quad (3)$$

The constraints are: $\sum_{i=1}^{I} q_{ik} + \sum_{j=1}^{J} q_{jk} \geq \sum_{n=1}^{N} q_{kn} \geq 0$,$\sum_{i=1}^{I} q_{vik} \,/\, \sum_{n=1}^{N} q_{kn} \geq RPSk$

In Eq. (3), the first term represents the revenue earned by the power supplier from the sale of electricity. The $\sum_{i=1}^{I} q_{ik}\rho_{ik}$ and $\sum_{j=1}^{J} q_{jk}\rho_{jk}$ denote the cost of purchasing electricity from the generator by the supplier k. The fourth and fifth terms denote the operation and transaction costs, respectively. The fourth and fifth terms denote the operating and transaction costs, respectively, while the last term denotes the green certificate transaction cost. The first constraint denotes the flow conservation constraint of the power supplier. The last constraint denotes the number of green certificates q_{vik} purchased by power supplier k from the renewable energy generator needs to satisfy the prescribed $RPSk$ constraint. Suppose that all power suppliers compete in a non-cooperative manner. Then, the optimality conditions for all power suppliers can be formulated as the following variable inequality formula: $\sum_{i=1}^{I}\sum_{k=1}^{K}[\rho_{ik}{}^{*} - \lambda^{3*}] \times [q_{ik} - q_{ik}^{*}] + \sum_{j=1}^{J}\sum_{k=1}^{K}[\rho_{jk}{}^{*} - \lambda^{3*}] \times [q_{jk} - q_{jk}^{*}] + \sum_{k=1}^{K}\sum_{n=1}^{N}\left[\frac{\partial c_k(q_{kn}^{*})}{\partial q_{kn}} + \frac{\partial f_k(q_{kn}^{*})}{\partial q_{kn}} - \rho_{kn}{}^{*} + \lambda^{3*} + \lambda^{4*} \times RPSk\right] \times [q_{kn} - q_{kn}^{*}] + \sum_{i=1}^{I}\sum_{k=1}^{K}\left[\rho_{vik}{}^{*} + \frac{\partial c_{vki}(q_{vik}^{*})}{\partial q_{vik}} - \lambda^{4*}\right] \times [q_{vik} - q_{vik}^{*}] + \sum_{k=1}^{K}\left[\sum_{i=1}^{I} q_{ik}^{*} + \sum_{j=1}^{J} q_{jk}^{*} - \sum_{n=1}^{N} q_{kn}^{*}\right] \times [\lambda^{3} - \lambda^{3*}] + \sum_{k=1}^{K}\left[\sum_{i=1}^{I} q_{vik}^{*} - \sum_{n=1}^{N} q_{kn}^{*} \times RPSk\right] \times [\lambda^{4} - \lambda^{4*}] \geq 0$, $(Q1^{*}, Q2^{*}, Q3^{*}, q_{vik}^{*}, \lambda^{3*}, \lambda^{4*}) \in K^2 = R_{+}^{IK\times JK\times KN\times IK\times K\times K}$.

2.3 Behavior of power suppliers

Decision-making behavior in demand markets n:

$$\rho_{kn}^{*} + c_{nk}(q_{kn}^{*}) \begin{cases} = \rho_d^{*}, q_{kn}^{*} > 0 \\ \geq \rho_d^{*}, q_{kn}^{*} = 0 \end{cases} \quad (4)$$

$$d_n(\rho_d^{*}) \begin{cases} = \sum_{k=1}^{K} q_{kn}^{*}\,, \rho_d^{*} > 0 \\ \leq \sum_{k=1}^{K} q_{kn}^{*}\,, \rho_d^{*} = 0 \end{cases} \quad (5)$$

Eq. (4) indicates that in equilibrium, if the demand market purchases power from the supplier, the sum of the price charged by the supplier and the transaction costs borne by the customer will be no higher than the price the customer is willing to pay. Otherwise, there will be no trading volume in the demand market. Eq. (5) shows that if the price of electricity that users are willing to pay is positive, the sum of power flows from the supplier to the demand market is equal to the actual demand, otherwise the supply of power exceeds the actual demand in the demand market. The equilibrium condition can be obtained by expressing it in the form of a variable inequality: $\sum_{k=1}^{K}\sum_{n=1}^{N}[\rho_{kn}^{*} + c_{nk}(q_{kn}^{*}) - \rho_d^{*}] \times [q_{kn} - q_{kn}^{*}] + \sum_{n=1}^{N}\left[\sum_{k=1}^{K} q_{kn}^{*} - d_n(\rho_d^{*})\right] \times [\rho_d - \rho_d^{*}] \geq 0$, $(Q3^{*}, \rho_d^{*}) \in K^3 = R_{+}^{KN\times N}$.

2.4 Equilibrium conditions of the electricity supply chain network

Under RPS regulation, the equilibrium state of the power supply chain network considering TGC must satisfy the consistency of power transaction flows between different tiers and satisfy the optimality conditions for all generators i and j, supplier k and demand market n. Accordingly, finite dimensional variational inequalities are given to control the conditions for the equilibrium of the power supply chain network: $\sum_{i=1}^{I}\sum_{k=1}^{K}\left[\frac{\partial c_i(q_{ik}^*)}{\partial q_{ik}}+\frac{\partial f_i(q_{ik}^*)}{\partial q_{ik}}+\lambda^{1i*}-\lambda^{2*}-\lambda^{3*}\right]\times[q_{ik}-q_{ik}^*]+\sum_{j=1}^{J}\sum_{k=1}^{K}\left[\frac{\partial c_j(q_{jk}^*)}{\partial q_{jk}}+\frac{\partial f_j(q_{jk}^*)}{\partial q_{jk}}-\lambda^{3*}+\lambda^{1j*}\right]\times[q_{jk}-q_{jk}^*]+\sum_{k=1}^{K}\sum_{n=1}^{N}\left[\frac{\partial c_k(q_{kn}^*)}{\partial q_{kn}}+\frac{\partial f_k(q_{kn}^*)}{\partial q_{kn}}+c_{nk}(q_{kn}^*)-\rho_d^*+\lambda^{3*}+RPSk\times\lambda^{4*}\right]\times[q_{kn}-q_{kn}^*]+\sum_{i=1}^{I}\sum_{k=1}^{K}\left[\frac{\partial c_{vik}(q_{vik}^*)}{\partial q_{vik}}+\frac{\partial c_{vki}(q_{vik}^*)}{\partial q_{vik}}+\lambda^{2*}-\lambda^{4*}\right]\times[q_{vik}-q_{vik}^*]+\sum_{n=1}^{N}\left[\sum_{k=1}^{K}q_{kn}^*-d_n(\rho_d^*)\right]\times[\rho_d-\rho_d^*]+\sum_{i=1}^{I}\left[a_i-\sum_{k=1}^{K}q_{ik}^*\right]\times[\lambda^{1i}-\lambda^{1i*}]+\sum_{j=1}^{J}\left[b_j-\sum_{k=1}^{K}q_{jk}^*\right]\times[\lambda^{1j}-\lambda^{1j*}]+\sum_{i=1}^{I}\left[\sum_{k=1}^{K}q_{ik}^*-\sum_{k=1}^{K}q_{vik}^*\right]\times[\lambda^{2}-\lambda^{2*}]+\sum_{k=1}^{K}\left[\sum_{i=1}^{I}q_{ik}^*+\sum_{j=1}^{J}q_{jk}^*-\sum_{n=1}^{N}q_{kn}^*\right]\times[\lambda^{3}-\lambda^{3*}]+\sum_{k=1}^{K}\left[\sum_{i=1}^{I}q_{vik}^*-RPSk\times\sum_{n=1}^{N}q_{kn}^*\right]\times[\lambda^{4}-\lambda^{4*}]\geq 0,\forall(Q1^*,Q2^*,Q3^*,q_{vik}^*,\rho_d^*,\lambda^{1i*},\lambda^{1j*},\lambda^{2*},\lambda^{3*},\lambda^{4*})\in K^4=R_+^{IK\times JK\times KN\times IK\times N\times I\times J\times I\times K\times K}$.

3. Example Analysis

According to the simulation example of RPS implementation in a province, there are two renewable energy generators, one traditional generator, two power suppliers and two demand markets in this PSCN. The cost function and parameters are set as follows: the generation cost function is expressed as: $f_i(q_{ik})=e_1q_i^2+0.005(q_iq_{I-i}+q_iq_j),(i=1,e_1=0.2;i=2,e_1=0.25)$, $f_j(q_j)=0.5q_j^2+0.005(q_jq_i+q_jq_{I-i}),(j=1)$; transaction costs are: $c_{i,j}(q_{ik,jk})=0.01q_{ik,jk}^2+0.1q_{ik,jk},(i=1,2;j=1)$; the supplier's operating costs are: $f_k(q_k)=0.01q_k^2,(k=1,2)$, and the demand market bears the transaction costs: $c_{nk}(q_{kn})=q_{kn}+5$; capacity constraints are: $a_1=150,a_2=120,b_3=300$; and the demand function of the market is: $d_{n1}=1500-2\rho_d-\rho_{D-d}$, $d_{n2}=1300-1.8\rho_d-\rho_{D-d}$. The evaluation metrics involved in this study include social benefits (*TSB*), environmental benefits (*EB*), total supply chain profit (*TP*), and consumer surplus (*CS*). Considering that *TP* consists of all power generators and suppliers' profits, *CS* consists of all demand market consumer surplus, and EB is related to conventional energy generation, $EB=100000-0.85q_{jk}^2$, where *TSB*=*EB*+*CS*+*TP*.

Table 1. PSCN effects under RPS alteration

Parameters	RPS					
	0.60	0.62	0.64	0.66	0.68	0.70
Q1	270.633	270.588	270.568	270.524	270.480	270.433
Q2	191.404	176.562	162.603	149.501	137.166	125.540
Q3	461.894	446.952	432.935	419.753	407.330	395.617
q_{vik}	270.405	270.355	270.309	270.273	270.231	270.179
ρ_{d1}	422.978	425.468	427.806	430.001	432.070	434.021
ρ_{d2}	381.765	384.433	386.938	389.290	391.506	393.597
ρ_d	402.372	404.951	407.372	409.645	411.788	413.809
TP	158462.870	156488.703	154367.993	152126.591	149797.934	147411.350
CS	28545.232	26764.197	25145.959	23673.514	22327.323	21095.211
EB	68859.837	73501.911	77526.105	81001.985	84007.705	86603.778
TSB	255867.939	256754.811	257040.057	256802.090	256132.961	255110.338

Table 1 gives the impact of RPS target adjustment on the PSCN equilibrium decision. When RPS grows, power suppliers need to expand TGC purchases, but there is a limitation on the number of TGCs that renewable generators can trade over time, which leads to an oversupply of TGCs over a short period of time, which has a significant impact on the equilibrium decisions of PSCN members. Specifically, when the RPS is more stringent, power suppliers consider changing their decision scheme to reduce the requirement to achieve the RPS by purchasing less conventional generation *Q2*. This affects the total trading flow *Q3* of the PSCN, but the active TGC market ensures that renewable energy generators are motivated to generate. As a result, conventional energy generation is ultimately subject to the flow-tightening effect generated by the RPS constraint, which relatively boosts the market share of renewable generation. From the perspective of demand market tariff prices, it can be found that the tariffs ρ_{d1} as well as ρ_{d2} in both demand markets increase with the increase of RPS and the increase is close to each other.

The average tariff ρ_d in the demand market is affected by the RPS with an upward trend, which leads to an unfavorable impact on the consumer surplus *CS*. Analyzing from the perspective of profit *TP*, it can be found that stricter RPS standards significantly reduce *TP* by reducing overall flows, while the benefits from higher electricity prices are not sufficient to compensate for the losses. However, it can be found that the environmental benefit *EB* shows a steady increase in the process. Analyzing from the perspective of the overall social benefit *TSB*, there is a tendency for *TSB* to increase and then decrease as RPS rises, achieving a maximum at RPS of 0.64 and a minimum at RPS of 0.7. The results seem to be different from intuition, and one might think that the social benefits should be better under the more stringent RPS criterion. However, in this paper, the relationship between *TSB* and RPS is not simply linear, but rather coupled by the impacts on *TP*, *CS* and *EB* under equilibrium decisions with different RPS. Therefore, policy makers can realize the process of promoting renewable energy consumption to ensure the maximum social welfare by weighing the pros and cons and finding the synergistic point of economic development and environmental benefits.

4. Summary

This paper establishes a network equilibrium model of the power supply chain based on the consideration of the coupling of quota system and green certificate trading, and obtains the equilibrium state of the model through the Nash equilibrium and the theory of variational inequality, and solves it by using the modified projection algorithm. The results of the study show that: firstly, stricter RPS constraints cause tightening of power market flows, and profits are adversely affected, but this process can increase the market share of renewable power; secondly, an increase in RPS raises the average price of electricity, which leads to a decrease in consumer surplus in the demand market but a significant increase in the environmental benefit; furthermore, the social benefit tends to increase and then decrease in the process of the RPS growth. There exists a value of RPS that optimizes the social benefits. Accordingly, the government can realize the trade-off between economic development and environmental protection goals through the change of RPS, and ensure the optimal social welfare in the path of achieving the growth of consumption.

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