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Game-theoretic Research of a Power Plant and a Manufacturer Considering New Energy Consumption

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Abstract. Considering power-sale-side reform and carbon trading, we studies the pricing and emission reduction game between a power plant and a manufacturer. We investigates the optimal emission reduction, retail price and the optimal electricity price with and without power-sale-side reform, and analyzes the influence of electricity price, the carbon trading price, abatement cost coefficient and other factors on the decision-making of the power plant and manufacturer. We find that with the power-sale-side reform liberalized the electricity price, the emission reduction decision of power plant is independent of the carbon trading regulation of different entities; when the electricity price is low, carbon trading regulation will incentive the power plant to improve emission reduction; regardless of the carbon trading regulation is implemented for the manufacturer and the power plant, the retail price of the product decreases (increases) as the electricity price increases, but when the manufacturer is regulated by carbon trading regulation, the retail price decreases as the emission reduction amount of the power plant increases; without power-sale-side reform, if the price of carbon trading rises, power plant will certainly increase emission reductions; with the power-sale-side reform, only under certain conditions, the emission reductions of power plant will increase with the increase in carbon trading prices.

Introduction

To reduce carbon emissions, many countries, such as China has begun to vigorously develop new energy power. However, the technology and stability of new energy power in power generation and transmission causes the cost of per unit power to be higher than that of thermal power. In fact, a large amount of new energy is wasted. For example, a large number of abandoned winds in the northeast and northwest regions of China is wasted. In order to promote the energy production and consumption revolution and promote the construction of ecological civilization, China has promulgated the "Renewable Energy Power Quota and Assessment Measures(draft for comment)" and "Renewable Energy Power Quota and Assessment Method Preparation Instructions", including renewable market entities such as power grid enterprises, other types of distribution power companies (incremental distribution network enterprises with social capital investment), industrial enterprises with self-sufficient power plants, and direct purchase users participating in power market transactions energy and electricity quota system.

The fundamental purpose of the renewable energy power quota system is to promote new energy consumption and achieve carbon emission reduction. This system is similar to the carbon trading system. The state allocates certain quotas to market entities, and various market entities in the same provincial level bear the same quota quotas and participate fairly in the renewable energy power market transactions. In the carbon trading system, two major sources of emission permits are considered, emission cap (referred to as “quota”) imposed by the government, and permits purchased via emission trading. If the quota is insufficient to satisfy the target production, extra permits should be purchased via trading[1]. As the end of June 2019, the cumulative turnover of China's carbon market was 337 million tons, with a turnover of 7.296 billion yuan[2]. Therefore, carbon trading system has an important impact on the operation of the constrained enterprises. Under the national carbon trading market, the operational decisions of power plant will also be significantly affected.

At the same time, the power-sale-side reform of China's power market is gradually advancing. As the development of China's power sales companies is in the initial stage, in order to promote the competition and improve the efficiency of the power market, the National Development and Reform Commission and other departments jointly issued the "Notice on Printing and Distributing the Supporting Documents for the Power System Reform" on November 26, 2015. It involves documents such as the “Implementation Opinions on Promoting the Reform of Transmission and Distribution Price” and the “Implementation Opinions on Promoting the Construction of the Power Market”. According to relevant regulations, manufacturer who meet the market access conditions may directly trade with the power plant, or may choose to trade with the power sales company independently, or choose not to participate in market transactions; the liberalized power generation plan partially forms the price through market transactions. The unopened power generation plan partially implements the electricity price stipulated by the government; the market transaction price can be determined through independent negotiation between the two parties or through centralized matching and market bidding. Therefore, in the future power market, on the one hand, power plant and manufacturer may be bound by the carbon trading system, and they need to adjust carbon emissions through decision-making such as emission reduction and price; on the other hand, in the power market, manufacturer and power plant can negotiate on electricity prices and determine the price of electricity transactions.

Existing research on power-sale-side reform focuses on institutional design and empirical analysis. Bai Yang et al.(2015)[3] reviewed the history of China's power system reform and the difficulties of current power-sale-side reforms, and studied the significance of the power-sale-side reform in shaping market-oriented trading mechanisms, promoting distributed energy development, and responding to demand, and he also proposed the system design and recommendations for China's steadily promoting the power-sale-side reform. Zhang Xiaotong et al.(2016)[4] introduced foreign experience in the market access mechanism, trading mechanism, guaranteed power supply mechanism, replacement of electricity seller mechanism, credit mechanism and other sales market operating mechanisms. Sun Yi et al. (2016)[5] analyzed the is assumed to be the carbon trading price, and the total emission cost of the power plant is $\frac{1}{2}ke^2$, and the notation k denotes the abatement cost coefficient for the power plant. The manufacturer consumes one unit of electricity per unit of product. In order to focus on power generation and emission reduction and product pricing issues, this paper does not consider other costs besides the cost of purchasing electricity.

Assume that the market demand for the product is $D = a - bp$, where a, p and b are the product's potential market demand scale, the product’s retail price, and the impact coefficient of the retail price on the market demand, respectively. At this time, the power demand is also $D = a - bp$. The paper analyzes two game models. Model 1 studies the emission reduction and pricing game between power plant and manufacturer before the power-sale-side reform. Model 2 studies the emission reduction and pricing game between power plant and manufacturer when manufacturer and power plant negotiate to determine the price of electricity transactions directly. The two models are divided into two cases: the carbon trading system for power plant and the carbon trading system for manufacturer. In order to ensure that the models analyzed have the optimal solution, we assume $4k - bp_e{}^2 > 0$.

Problem Analysis

A. Game process between power plant and manufacturer before the power-sale-side reform

Before the power-sale-side reform, the electricity price was fixed, and the power plant and manufacturer could not directly negotiate to determine the price of electricity. At this point, the power plant first decides e units of emission per unit of electricity, and the manufacturer decides the market price of the product in the following order, and purchases the electricity by a exogenous price w from the electricity generated outside the power plant according to the market demand.

a) When implement the carbon trading system for power plant

When the government implements the carbon trading system for power plant, the profit of power plant consists of three parts, namely, the profit of electricity sales, the cost of emission reduction and the income or expenditure related to carbon trading. The profit or expenditure related to carbon trading is $p_e[E-(1-e)(a-bp)]$; the profit of the manufacturer is the cost of purchasing electricity from the sales revenue of the product. Therefore, the objective functions of power plant and manufacturer are shown in equation (1) and (2) respectively.

$$\max_{e} \pi_s(e) = (w-c)(a-bp) - \frac{1}{2}ke^2 + p_e[E-(1-e)(a-bp)] \tag{1}$$

$$\max_{p} \pi_m(p) = (p-w)(a-bp) \tag{2}$$

Using the inverse induction method to solve, first ask the production price response function of the manufacturer. Since $\pi_m(p)$ is a concave function for p, the optimal response function of the retail price according to the first-order condition is: $p=\frac{a+bw}{2b}$. Substitut it into Equation (1), we obtain $\pi_s(e)=(w-c-p_e+p_e e)\frac{a+re-bw}{2}-\frac{1}{2}ke^2+p_eE$. When $\frac{\partial 2\pi_s(e)}{\partial e^2}=rp_e-k<0$, $\pi_s(e)$ is a concave function about e. According to the first-order condition, the most effective emission reduction can be obtained. Combined with (3), the game equilibrium at this time can be obtained as follows:

$$\begin{cases} e^{s*} = \dfrac{p_e(a-bw)}{2k} \\ p^{s*} = \dfrac{a+bw}{2b} \end{cases} \tag{3}$$

At this time, the product market demand is $D^{s*}=\frac{a+bw}{2}$. By substituting e^{s*} and p^{s*} into equations (1) and (2), the optimal profits of power plant and manufacturer can be obtained.

b) when implementing the carbon trading system for manufacturer

We assum that the government's emission reduction target remains unchanged. That is, the carbon quota is still E when the manufacturer constrained by the carbon trading regulation. Also, we assum that the manufacturer does not invest in emission reduction. Thus, the profit of the power plant is only generates from selling electricity, and the manufacturer’s profit consists of the profit of saelling products and the income or expenditure generated from carbon trading. The objective functions of power plant and manufacturer are shown in equation (4) and (5), respectively.

$$\max_{e} \pi_s(e) = (w-c)(a-bp+re) - \frac{1}{2}ke^2 \tag{4}$$

$$\max_{p} \pi_m(p) = (p-w-p_e+p_e e)(a-bp+re)+p_eE \tag{5}$$

Since $\pi_m(p)$ is concavein p , according to the first-order conditions, the optimal response function of the retail price can be obtained as follows: $p=\frac{a+bw+bp_e(1-e)}{2b}$. By substituting it into equation (4), the power plant’s profit function can be written as $\pi_s(e)=(w-c)\frac{a-b(w+p_e)+bp_e e}{2}-\frac{1}{2}ke^2$. $\pi_s(e)$ is concave in e .According to the first-order condition, the optimal emission reduction level can be obtained. Then, the game equilibrium can be obtained as

$$\begin{cases} e^{m*} = \dfrac{(w-c)bp_e}{2k} \\ p^{m*} = \dfrac{2k(a+bw+bp_e)-(w-c)(bp_e)^2}{4kb} \end{cases} \tag{6}$$

The market demand at this time is $D^{m*} = \dfrac{4ka - 2k(a+bw+bp_e)+(w-c)(bp_e)^2}{4k}$. By substituting e^{m*} and p^{m*} into equations (4) and (5), the optimal profits of power plant and manufacturer can be obtained.

Theorem 1: (1) $w \le \dfrac{a+bc}{2b}$ then $e^{s*} \ge e^{m*}$, otherwise, $e^{s*} < e^{m*}$; (2) when $w ? c \quad \dfrac{2k}{bp_e}$ (or $p_e \le \dfrac{2k}{b(w-c)}$), $p^{m*} \ge p^{s*}$, otherwise $p^{m*} < p^{s*}$; (3) $D^{m*} - D^{s*} < 0$.

Theorem 1 shows that when the electricity price is low, the implementation of carbon trading system for power plant is beneficial to reduce the carbon emission per unit of electricity. Also, when the electricity price is low, the retail price is higher and the market demand is lower when the manufacturer is carbon constrained than those when the power plant is carbon constrained.

B. game between power plant and manufacturer after the power-sale-side reform

With the power-sale-side reform the power plant decides the emission reduction e and price w per unit power first, and then the manufacturer decides the market price p of the product.

a) when implementing the carbon trading system for power plant

With electricity selling side reform, the objective functions of power plant and manufacturer are shown in equation (7) and (8) respectively.

$$\max_{w,e} \pi_m(w,e) = (w-c)(a-bp) - \frac{1}{2}ke^2 + p_e[E-(1-e)(a-bp)] \tag{7}$$

$$\max_{p} \pi_m(p) = (p-w)(a-bp) \tag{8}$$

By using the backward induction method, the optimal response function of p can be obtained as $p = \dfrac{a+bw}{2b}$. Furthermore, we obtain the equilibrium as equation (9) when $4k - bp_e{}^2 > 0$.

$$\begin{cases} e^{s'*} = \dfrac{2ap_e - p_e(a+bc+bp_e)}{4k-bp_e{}^2} = \dfrac{p_e(a-bc-bp_e)}{4k-bp_e{}^2} \\ w^{s'*} = \dfrac{2k(a+bc+bp_e)-bp_e ap_e}{4bk-(bp_e)^2} \\ p^{s'*} = \dfrac{k(3a+bc+bp_e)-bp_e ap_e}{4bk-(bp_e)^2} \end{cases} \tag{9}$$

The market demand for the product is $D^{s'*} = \dfrac{k(a-bc-bp_e)}{4k-bp_e{}^2}$. By substituting the optimal decision into equations (7) and (8), we have the optimal profits of power plant and manufacturer.

b) when implementing the carbon trading system for manufacturer

With power-sale-side reform, the objective functions of the power plant and manufacturer when the manufacturer is carbon constrained are shown in equation (10) and equation (11), respectively.

$$\max_{w,e} \pi_m(w,e) = (w-c)(a-bp) - \frac{1}{2}ke^2 \tag{10}$$

$$\max_{p} \pi_m(p) = (p-w)(a-bp) + p_e[E-(1-e)(a-bp)] \tag{11}$$

Using the inverse induction method, we have the optimal response function of p as $p = \frac{a+bw+bp_e(1-e)}{2b}$, and the equilibrium as equation (12) when $4k - bp_e^2 > 0$.

$$\begin{cases} e^{m'*} = \dfrac{p_e(a-bp_e-bc)}{4k-bp_e^2} \\ w^{m'*} = \dfrac{2k(a-bp_e)+(2k-bp_e^2)bc}{b(4k-bp_e^2)} \\ p^{m'*} = \dfrac{a(2k-bp_e^2)+k(a+bp_e+bc)}{b(4k-bp_e^2)} \end{cases} \tag{12}$$

At this point, the market demand for the product is $D^{m'*} = \frac{k(a-bp_e-bc)}{4k-bp_e^2}$. Substitut the optimal decision into equations (10) and (11), we have the optimal profits of the power plant and manufacturer.

Theorem 2: (1) $e^{m'*} = e^{s*}$, $p^{m'*} = p^{s*}$, $D^{m'*} = D^{s*}$; (2) when $k \le \frac{(a-bc)p_e}{4}$ (or $p_e \ge \frac{4k}{a-bc}$), $w^{m'*} \ge w^{s*}$, otherwise, $w^{m'*} < w^{s*}$.

Theorem 2 (1) shows that after the electricity selling side reform, when the manufacturer can directly negotiate with the power plant to determine the electricity transaction price, the carbon trading system for both the power plant and the manufacturer can achieve the same emission reduction effect, and the product retailers and market demand at this time remain unchanged. Theorem 2 (2) shows that, after the electricity selling side reform, the manufacturer can directly negotiate with the power plant to determine the electricity trading price. If the power plant has a higher emission reduction efficiency or a higher carbon trading price, the electricity price will be higher when the manufacturer is constrained by the carbon trading regualtion.

Theorem 3: whether with the reform of electricity selling side or not, (1) whether the manufacturer or the power plant is constrained by the carbon trading regualtion, $\frac{\partial p}{\partial w} > 0$; (2) when the manufacturer is constrained by the carbon trading regualtion, $\frac{\partial p}{\partial w} < 0$.

Theorem 3 shows that the higher the price of electricity, the higher the retail price of the product, whether the carbon trading system is implemented for the manufacturer or the power plant. But when it comes to carbon trading, retail prices fall as power producers cut emissions. By analyzing the game equilibrium of the above four cases, theorem 4 can be obtained.

Theorem 4: (1) before the electricity selling side reform, $\frac{\partial e^{m*}}{\partial p_e} \ge 0$, $\frac{\partial e^{s*}}{\partial p_e} \ge 0$; (2) after the electricity selling side reform, if $a - bc - 2bp_e \ge 0$ so $\frac{\partial e^{m'*}}{\partial p_e} = \frac{\partial e^{s'*}}{\partial p_e} \ge 0$; Otherwise, $\frac{\partial e^{m'*}}{\partial p_e} = \frac{\partial e^{s'*}}{\partial p_e} \ge 0$ if $k \le \frac{bp_e^2(a-bc)}{4(2bp_e-a+bc)}$, $\frac{\partial e^{m'*}}{\partial p_e} = \frac{\partial e^{s'*}}{\partial p_e} < 0$ if $k > \frac{bp_e^2(a-bc)}{4(2bp_e-a+bc)}$.

Theorem 4 shows that before the reform of electricity selling side, as long as the carbon trading price increases, power plant will definitely increase emission reduction; After the reform of electricity selling side, if the potential market demand of products a is large enough and can be guaranteed $a-bc-2bp_e \geq 0$, power plant will increase emission reduction as long as the carbon trading price increases. If the potential market demand for the product a is not large enough and $a-bc-2bp_e < 0$, only the power plant will increase the emission reduction when their emission reduction efficiency is high enough.

Conclusion

Considering power-sale-side reform, carbon trading and new energy consumption, the implementation of carbon trading system for different decision-making bodies and the influence of electricity selling side reform on power industry emission reduction are studied. We find that when the electricity price is low, implementing the carbon trading system for power plant is beneficial to reduce the carbon emission per unit of electricity, but when the electricity price is low, implementing the carbon trading system for manufacturer' product retail price is higher, and implementing the carbon trading system for manufacturer' product market demand is lower. After the electricity selling side reform, the carbon trading system for both power plant and manufacturer can achieve the same emission reduction effect, and the product retailers and market demand remain unchanged at this time. If the emission reduction efficiency of power plant is higher or the carbon trading price is higher, the electricity price of the carbon trading system for manufacturer will be higher. The higher the electricity price is, the higher the retail price will be. However, when the carbon trading system is implemented for the manufacturer, the retail price will decrease with the increase of emission reduction of the power plant. Before the power-sale-side reform, as long as the carbon trading price rises, power plant will definitely increase emission reduction; After the reform of electricity selling side, only under certain conditions, the emission reductions of power plant will increase with the increase in carbon trading prices.

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