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Market Power and Technology Diffusion in an Energy-Intensive Sector Covered by an Emissions Trading Scheme

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Abstract: The emissions trading scheme (ETS) has been long advocated to address climate change not only because it is cost effective but also because it can provide economic incentives for the adoption of new technologies. The emissions abatement of the energy-intensive sector covered by ETS is of great significance for the whole nation to attain sustainable and low-carbon development, especially for developing countries. This paper investigates the effect of market power in the emissions trading market on the diffusion of a new emissions abatement technology when firms in the energy-intensive sector interact in an imperfectly competitive output market. In the model, each firm needs to determine the optimal time to adopt the new emissions abatement technology, taking into account its benefits and costs, as well as its rival's strategic behavior. With this framework, the results suggest that firms will delay adoption of the new emissions abatement technology in the presence of market power. Moreover, when the output demand is larger and more elastic, emissions abatement technology diffusion will occur earlier. It implies that the technology diffusion in the weak elastic sector, such as the Chinese iron and steel sector, may have more barriers than that in the strong elastic sector, such as the Chinese nonferrous metals sector.

Keywords: market power; emissions trading scheme; technology adoption; strategic behavior; energy-intensive sector

1. Introduction

Economists have long advocated an emissions trading scheme (ETS) to fight against climate change not only because it is cost effective but also because it can provide economic incentives for the adoption of new emissions abatement technologies. Moreover, these economic incentives may be the most crucial approaches to ensure the attainment of the deep carbon dioxide (CO_2) emissions reduction target in the long term [1]. However, in common with many other commodity markets, the emission trading market has also been affected by market power, and several dominant firms play a key role in permit prices [2–6]. Following Hahn's seminal article [7], there is substantial theoretical literature analyzing the issues of market power in the permits market. Developing a dominant firm–competitive fringe model, Hahn concluded that the dominant firm will use its market power to manipulate the permit price. Based on Hahn's model framework, Westskog extended to multiple agents with market power [8], and other articles considered the output market and noted that the dominant firm will exercise its market power to raise its rivals' cost [9,10]. This main finding has also been demonstrated by other scholars [5,11–14]. In the context of international ETS, the issue of market power in the permits market has been recognized to be a challenging potential problem [15,16]. Furthermore, several laboratory experiments have provided evidence that the exercise of market power can be rather extreme when taking into account both permit and output markets [17–19]. Additionally, to reduce the efficiency loss in the permits market affected by market power, some scholars focus on related policy design [20,21].

As a consequence, the market efficiency will be distorted due to the presence of market power, especially considering the output market. Thus, there would be strategic behaviors in the ETS market that make the equilibrium price deviate from the marginal abatement cost. Moreover, these strategic behaviors further have influence on a firm's decision-making of technology renewal. Hence, compared with a perfect emission trading market, it is worthwhile to study whether or not ETS increases the economic incentive for technology adoption in the imperfectly competitive permit market. Therefore, this key issue needs to be urgently investigated, providing policymakers more understanding and facilitating referencing in ETS policy development.

The effect of market power in the emission trading market on technology adoption has not been extensively studied in the literature. Scholars compared taxes and ETS in terms of motivating investment in environmental research and development (R&D) [22–24]. However, our paper focuses on the design of ETS rather than on the policy choice between ETS and taxes. More specifically, compared with a perfect emission trading market, do firms delay (or accelerate) the adoption of emissions abatement technologies in the presence of market power? Studying this point has important policy implication since ETS is typical in the real world. Nowadays a great number of countries or regions, including the European Union, Norway, Switzerland, Australia, Canada, New Zealand, Japan, Korea, and India, have set up their own national or regional ETS or intend to do so [25,26]. Specially, China, the largest emitter in the world, has already implemented the emission trading pilot in its seven regions and started the world's largest carbon trading system on 19 December 2017.

To our knowledge, there is a limited number of studies investigating this problem [27,28], but the result has been a matter of debate. André and Arguedas [27] did not consider the output market and found that technology adoption is related to the initial distribution of permits. That implies that the output market is completely competitive. In fact, most firms with market power in the permits market often engage in an imperfectly competitive output market such as power sector [11,12,29] or iron and steel sector [28,30]. With the development of the microgrid [31–37], many renewable-energy power generation companies will also engage in imperfectly competitive output markets in the future. Hence, it is necessary to explicitly take into account the output market. Wang et al. [28] assumed that all firms have market power in the permits market and noted that market power can accelerate technology adoption. Differing from this literature, we use the dominant firm–competitive fringe model to describe an imperfect emissions trading market structure. Moreover, Wang et al. [28] considered the adoption of end-of-pipe technologies, while we pay attention to energy-saving technologies. In fact, energy-saving technologies are more common than end-of-pipe technologies for curbing carbon emissions, since the end-of-pipe technology (i.e., carbon capture and storage technology) is extremely expensive and has not been widely applied in reality. Additionally, Wang et al. [28] assumed zero costs of production, while we take into account the constant marginal production cost in our model. This makes it more general because that would allow for the possibility to do sensitivity analysis with respect to production cost parameters.

To investigate the issues that raised above, and motivated by these research gaps, this paper presents a general model of the diffusion of a new emissions abatement technology when firms take part in imperfect competition in the output market. In particular, consider an energy-intensive sector that is composed of two representative heterogeneous firms—a dominant firm (or some collusion firms) with market power in the permits market and a price-taking fringe. Based on a classical framework [38], this paper makes the extension by introducing heterogeneous firms to describe the situation where market power in the emissions trading market does exist. Assume that the R&D of new technology is exogenous, when a new emissions abatement technology appears in the market, each firm needs to decide when to adopt it. Each firm makes the decision based on the discounted cost of adopting new emissions abatement technology and the behavior of its competitor. On the one hand, a firm can earn great profits at the cost of the other firms when it adopts the new emissions abatement technology before its competitor. On the other hand, it may save cost if the firm adopts the new technology later. This is because the discounted cost of adopting new technology may decrease over time. Therefore, the firm must balance the costs and benefits of delaying adoption, as well as take into account its competitor's strategic behavior.

The main contribution of this paper is twofold. First, this study contributes to the literature by investigating the effect of market power on the adoption of emissions abatement technologies. As mentioned, the issue has not been extensively studied in the literature and there are only two studies investigating the impact of market power in carbon ETS on technology adoption. However, the result has been a matter of debate. Through theoretical analysis and numerical simulation, we found that firms will delay the adoption of new emissions abatement technology in the presence of market power. Second, from the point of industry level, we explored emissions abatement technology diffusion in China's energy-intensive sectors covered by ETS. This analysis was motivated by the fact that policy makers ultimately must assess and design an ETS policy by the degree to which ETS provides economic incentive for new technology diffusion into the industry. Furthermore, the energy-intensive sector contributes large amounts of carbon emissions and its emissions abatement is of great significance for the whole nation to attain sustainable and low-carbon development, especially for developing countries. The result shows that when the output demand is larger and more elastic, emissions abatement technology diffusion will occur earlier.

2. Materials and Methods

Suppose in an energy-intensive sector, a pair of representative heterogeneous firms, which consist of a dominant firm (firm 1) with market power in permits market and a price-taking fringe (firm 2), is producing a homogeneous good (e.g., iron and steel or cement). The linear inverse demand function is given by:

$$P = P(Q) = a - b(q_1 + q_2),\ a,\ b > 0, \tag{1}$$

where q_1 and q_2 denote the output level of firm 1 and firm 2, respectively. The production cost function $c(q_i)$ for firms is assumed to be of linear form, i.e., $c(q_i) = c_i q_i$, $c_i > 0$, $i = 1,2$, where c_i is the production cost coefficient, that is, the marginal production cost is constant in this study. The production of goods q_i $(i = 1,2)$ generates carbon emissions e_i $(i = 1,2)$ as a by-product with intensity $k_i > 0$ $(i = 1,2)$. Following the previous literature [28,39–44], we consider a linear production function $q_i = k_i e_i$ in the case of the current technology and the emissions intensity of the output is k_0 $(k_0 > k_i,\ i = 1,2)$ in the case of the new emissions abatement technology. Thus, firms adopting the new technology use less energy per unit of output and therefore generate less emissions per unit of output. The cost function $\rho(t)$ of adopting the new technology is expressed as $\rho(t) = Ke^{-(\delta+\theta)t}$ [39], where K is a positive parameter, t is the date of adoption of the firm, δ is the discount rate, and θ is the diffusion rate. The strategic behaviors between firm 1 and firm 2 are described by the following two-stage mechanism, and the schematic of the study framework is depicted in Figure 1.

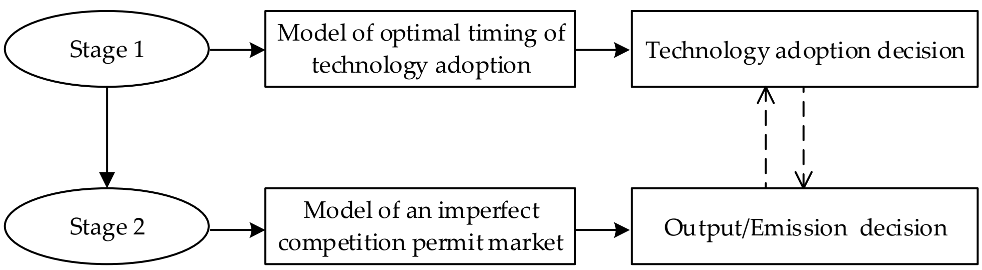

Figure 1. The schematic of the study framework.

Stage 1: Model of optimal timing of technology adoption. At any instant, each firm can either adopt the new technology or postpone the adoption decision. Hence, each firm needs to determine the optimal time to adopt the new technology, taking into account its benefits and costs, as well as its competitor's strategic behavior.

Stage 2: Model of an imperfect competition permit market. Given the emissions abatement technology, firms make output and emissions decisions to maximize profits. This stage is described as a leader–follower model.

The two-stages mechanism plays out backwards, since firms' decisions in stage 2 affect their technology adoption decision.

2.1. Model of an Imperfect Competition Permit Market

Firms are subject to tradable permits regulation that sets up a binding cap on aggregate emissions and look for the output and the emissions that maximize profits. The emissions cap E is equal to $(1-\lambda)\cdot E_0$, where E_0 is the total emissions in the absence of an environmental policy and λ is the percent of emissions reduction. The solution process of E_0 can be found in Appendix A.

Acting as a Stackelberg leader, the dominant firm 1 announces first how many permits to trade and how much output to bring to the output market. Having observed that, the fringe firm 2 chooses its output and clears the permits market.

Firm 1 solves the problem:

$$\pi_1 = \underset{e_1}{Max}[(a-b(k_1e_1+k_2e_2))k_1e_1 - c_1(k_1e_1) - p(e)(e_1-\varepsilon_1)], \tag{2}$$

and firm 2 solves the problem:

$$\pi_2 = \underset{e_2}{Max}[(a-b(k_1e_1+k_2e_2))k_2e_2 - c_2(k_2e_2) - p(e)(e_2-\varepsilon_2)], \tag{3}$$

where $p(e)$ is the permit price, ε_1 and ε_2 are the quantity of emissions permits freely received by firm 1 and firm 2, respectively, based on the grandfathering or benchmarking method allocation. Moreover, firms comply with the environmental regulation in this study.

The problem is solved by backward induction. Firm 2 takes $p(e)$ as given, as a follower, and maximizes π_2. According to the first order conditions (FOCs), we have:

$$p(e) = bk_2(2k_2-k_1)e_1 - 2bk_2^2E + (a-c_2)k_2, \tag{4}$$

As a leader, firm 1 maximizes π_1. The FOCs and permit market clearing condition yields the emissions levels of firms:

$$e_1 = \frac{(a-c_1)k_1-(a-c_2)k_2}{b(2k_1^2-3k_1k_2+4k_2^2)} + \frac{k_2(2k_2-k_1)(\varepsilon_1+E)}{2k_1^2-3k_1k_2+4k_2^2}, \tag{5}$$

$$e_2 = \frac{(a-c_2)k_2-(a-c_1)k_1}{b(2k_1^2-3k_1k_2+4k_2^2)} + \frac{2(k_2^2-k_1k_2+k_1^2)E-k_2(2k_2-k_1)\varepsilon_1}{4k_2^2-3k_1k_2+2k_1^2}. \tag{6}$$

Then, the outputs levels of firms:

$$q_1 = \frac{(a-c_1)k_1^2-(a-c_2)k_1k_2}{b(2k_1^2-3k_1k_2+4k_2^2)} + \frac{k_1k_2(2k_2-k_1)(\varepsilon_1+E)}{2k_1^2-3k_1k_2+4k_2^2}, \tag{7}$$

$$q_2 = \frac{(a-c_2)k_2^2-(a-c_1)k_1k_2}{b(2k_1^2-3k_1k_2+4k_2^2)} + \frac{2k_2(k_2^2-k_1k_2+k_1^2)E-k_2^2(2k_2-k_1)\varepsilon_1}{4k_2^2-3k_1k_2+2k_1^2}, \tag{8}$$

and the permit price $p(e)$ is given by:

$$p(e) = \frac{k_2(2k_1k_2 - k_1^2)(a - c_1) + k_2(2k_2^2 - 2k_1k + 2k_1^2)(a - c_2)}{2k_1^2 - 3k_1k_2 + 4k_2^2} + \frac{bk_2^2(2k_2 - k_1)^2(\varepsilon_1 + E)}{2k_1^2 - 3k_1k_2 + 4k_2^2} - 2bk_2^2E \quad (9)$$

Taking the partial derivative of a, b, and E, we have the following:

$$\frac{\partial p}{\partial a} = \frac{k_2(2k_2^2 + k_1^2)}{2k_1^2 - 3k_1k_2 + 4k_2^2} = \frac{k_2(2k_2^2 + k_1^2)}{(k_1 - 2k_2)^2 + k_1^2 + k_1k_2} > 0,$$

$$\frac{\partial p}{\partial b} = \frac{k_2^2(2k_2 - k_1)^2(\varepsilon_1 + E)}{2k_1^2 - 3k_1k_2 + 4k_2^2} - 2k_2^2E < -2k_2^2E\frac{(k_1^2 + k_1k_2)}{(k_1 - 2k_2)^2 + k_1^2 + k_1k_2} < 0,$$

$$\frac{\partial p}{\partial E} = \frac{bk_2^2(2k_2 - k_1)^2}{2k_1^2 - 3k_1k_2 + 4k_2^2} - 2bk_2^2 = -bk_2^2\frac{(2k_2 - k_1)^2 + 2k_1^2}{(k_1 - 2k_2)^2 + k_1^2 + k_1k_2} < 0.$$

Hence, the permit price $p(e)$ is increasing in a and decreasing in b, E. That implies that the permit price is larger if the output demand is larger and more elastic and greater stringency of the environmental policies is implemented.

To compare the difference of technology adoption in the imperfect competition permits market and perfectly competitive permits market, the corresponding problem in the perfect competition permits market should been solved. If the emission trading market is perfectly competitive, all market participants are price takers. That is, both firms make their output and emissions decisions simultaneously taking the permit price as given. Then the equilibrium permit price p_c is given by:

$$p_c = \frac{(a - c_1)k_2 + (a - c_2)k_1}{2} \cdot \frac{k_1k_2}{k_1^2 + k_2^2 - k_1k_2} - \frac{3bE}{2} \cdot \frac{k_1^2k_2^2}{k_1^2 + k_2^2 - k_1k_2}. \quad (10)$$

The proofs of the results in the perfectly competitive permits market can be found in Appendix B.

2.2. Model of Optimal Timing of Technology Adoption

Based on the classical framework [38], this paper makes an extension by introducing heterogeneous firms to describe the situation where market power in the emission trading market does exist. Let t_1 and t_2 be the adoption dates of firms 1 and 2, respectively. Then, we can make a summary of the profit opportunities described above in Table 1.

Table 1. The profit opportunities of firms.

Adoption Dates t	The Profit of Firm 1	The Profit of Firm 2
$0 \le t \le \min\{t_1, t_2\}$	π_1^{NA}	π_2^{NA}
$t_1 \le t \le t_2$	π_1^1	π_2^1
$t_2 \le t \le t_1$	π_1^2	π_2^2
$\max\{t_1, t_2\} \le t < \infty$	π_1^A	π_2^A

In order to be a perfect equilibrium, the following assumptions illustrate the relative magnitudes of profits.

Assumption 1. $\pi_i^i > \pi_i^A > \pi_i^j > 0$, $\pi_i^i > \pi_i^{NA} > \pi_i^j > 0$, $i,\ j = 1, 2$, $i \neq j$.

This assumption implies that profit to the firm is greatest when it has adopted the new emissions abatement technology but the other has not. Moreover, the next greatest profits come up in the case where firms both have adopted (or no firm has yet adopted). Finally, the profit opportunity for a firm is least when the other has adopted the new emissions abatement technology but it has not.

Assumption 2. $\pi_i^i - \pi_i^{NA} > \pi_i^A - \pi_i^j, i, \ j = 1, 2, i \neq j.$

That is, the increase in revenue when one is first exceeds the increase in revenue when one is second.

Assumption 3. $\rho''(t) > \delta(\pi_i^i - \pi_i^0)e^{-\delta t}, i = 1, 2.$

That is, the decrease in the adoption costs $\rho(t)$ cannot continue indefinitely, which rules out infinity. This assumption also makes sure that the firm's objective function is strictly concave and each firm has the optimal date of adoption.

Similar to what was shown by Reinganum [38], the payoffs to two firms are defined as follows.

Definition 1. *The payoff to firm 1 is*

$$V_1(t_1, t_2) = \begin{cases} f_1^1(t_1, t_2) & if\ t_1 \leq t_2 \\ f_1^2(t_1, t_2) & if\ t_1 > t_2 \end{cases}, \tag{11}$$

where

$$f_1^1(t_1, t_2) = \int_0^{t_1} \pi_1^{NA} e^{-\delta t} dt + \int_{t_1}^{t_2} \pi_1^1 e^{-\delta t} dt + \int_{t_2}^{+\infty} \pi_1^A e^{-\delta t} dt - \rho(t_1),$$

and

$$f_1^2(t_1, t_2) = \int_0^{t_2} \pi_1^{NA} e^{-\delta t} dt + \int_{t_2}^{t_1} \pi_1^2 e^{-\delta t} dt + \int_{t_1}^{+\infty} \pi_1^A e^{-\delta t} dt - \rho(t_1).$$

Definition 2. *The payoff to firm 2 is*

$$V_2(t_1, t_2) = \begin{cases} f_2^1(t_1, t_2) & if\ t_2 \leq t_1 \\ f_2^2(t_1, t_2) & if\ t_2 > t_1 \end{cases}, \tag{12}$$

where

$$f_2^1(t_1, t_2) = \int_0^{t_2} \pi_2^{NA} e^{-\delta t} dt + \int_{t_2}^{t_1} \pi_2^2 e^{-\delta t} dt + \int_{t_1}^{+\infty} \pi_2^A e^{-\delta t} dt - \rho(t_2),$$

and

$$f_2^2(t_1, t_2) = \int_0^{t_1} \pi_2^{NA} e^{-\delta t} dt + \int_{t_1}^{t_2} \pi_2^1 e^{-\delta t} dt + \int_{t_2}^{+\infty} \pi_2^A e^{-\delta t} dt - \rho(t_2).$$

Without loss of generality, we will handle firm 1's optimal timing of technology adoption problem, and the corresponding results for firm 2 can be solved the same way.

Note that $V_1(t_1, t_2)$ is continuous in t_1 (for fixed t_2) and is not differentiable at $t_1 = t_2$. As a matter of fact, the left-hand derivative at t_2 is $f_{11}^1 = (\pi_1^{NA} - \pi_1^1)e^{-\delta t_2} - \rho'(t_2)$, while the right-hand derivative at t_2 is $f_{11}^2 = (\pi_1^2 - \pi_1^A)e^{-\delta t_2} - \rho'(t_2)$. Furthermore, it is not difficult to show that $f_1^1(t_1, t_2)$ and $f_1^2(t_1, t_2)$ are strictly concave by Assumption 3. Therefore, there exist t_1^1 and t_1^2, which maximize $f_1^1(t_1, t_2)$ and $f_1^2(t_1, t_2)$, respectively. It follows that first-order conditions for $f_1^1(t_1, t_2)$ and $f_1^2(t_1, t_2)$ are given by:

$$(\delta + \theta)Ke^{-(\delta+\theta)t_1^1} - (\pi_1^1 - \pi_1^{NA})e^{-\delta t_1^1} = 0, \ (\delta + \theta)Ke^{-(\delta+\theta)t_1^2} - (\pi_1^A - \pi_1^2)e^{-\delta t_1^2} = 0.$$

That is,

$$t_1^1 = \frac{1}{\theta} \ln \frac{(\delta + \theta)K}{\pi_1^1 - \pi_1^{NA}}, \ t_1^2 = \frac{1}{\theta} \ln \frac{(\delta + \theta)K}{\pi_1^A - \pi_1^2}. \tag{13}$$

Furthermore, it is easy to show that $t_1^1 < t_1^2$ by Assumption 2.

Lemma 1. *$\exists \widetilde{t_1} \in (t_1^1, t_1^2)$ such that $f_1^1(t_1^1, t_2) \le f_1^2(t_1^2, t_2)$ as $t_2 \le \widetilde{t_1}$, and vice versa.*

Proof. See Appendix C. □

Theorem 1.

$$R_1(t_2) = \begin{cases} t_1^2 & t_2 < \widetilde{t_1} \\ \left\{t_1^1, t_1^2\right\} & t_2 = \widetilde{t_1} \\ t_1^1 & t_2 > \widetilde{t_1} \end{cases}, \tag{14}$$

where the mapping R_1 is firm 1's best response correspondence.

Proof. See Appendix C. □

For firm 2, we can derive some similar conclusions by the same way.

Lemma 2. *$\exists \widetilde{t_2} \in (t_2^1, t_2^2)$ such that $f_2^1(t_1, t_2^1) \le f_2^2(t_1, t_2^2)$ as $t_1 \le \widetilde{t_2}$, and vice versa, where*

$$t_2^1 = \frac{1}{\theta} \ln \frac{(\delta + \theta)K}{\pi_2^2 - \pi_2^{NA}}, \; t_2^2 = \frac{1}{\theta} \ln \frac{(\delta + \theta)K}{\pi_2^A - \pi_2^1}. \tag{15}$$

Proof. See Appendix C. □

Theorem 2.

$$R_2(t_1) = \begin{cases} t_2^2 & t_1 < \widetilde{t_2} \\ \left\{t_2^1, t_2^2\right\} & t_1 = \widetilde{t_2} \\ t_2^1 & t_1 > \widetilde{t_2} \end{cases}, \tag{16}$$

where the mapping R_2 is firm 2's best response correspondence.

Proof. See Appendix C. □

Theorem 3.

(1) If $\widetilde{t_2} > t_1^2$ or $\begin{cases} \widetilde{t_2} < t_1^2 \\ \widetilde{t_1} < t_2^1 \end{cases}$, then there exists a unique Nash equilibrium (t_1^1, t_2^2).

(2) If $\begin{cases} t_2^1 < \widetilde{t_1} < t_2^2 \\ t_1^1 < \widetilde{t_2} < t_1^2 \end{cases}$ or $\begin{cases} t_2^1 = \widetilde{t_1} \\ \widetilde{t_2} \le t_1^2 \end{cases}$ or $\begin{cases} t_1^1 \le \widetilde{t_2} \\ \widetilde{t_1} = t_2^2 \end{cases}$, then there exist two Nash equilibria (t_1^1, t_2^2) and (t_1^2, t_2^1).

(3) If $\widetilde{t_1} > t_2^2$ or $\begin{cases} \widetilde{t_1} < t_2^2 \\ \widetilde{t_2} < t_1^1 \end{cases}$, then there exists a unique Nash equilibrium (t_1^2, t_2^1).

Proof. See Appendix C. □

Additionally, the proposed study framework can be extended from the following aspects. First, to obtain a closed-form solution, two representative asymmetric firms are considered in our model. It would be even more general to study the situation where finite multiple heterogeneous firms are included in the ETS. Second, our model is suitable for a single sector. It will be meaningful to extend our model to multiple sectors. Third, our model is operated under environmental certainty. It will be interesting to extend our study framework in environmental uncertainty, such as economic uncertainty (e.g., the output demand is always changing in the future) and technological uncertainty (e.g., the arrival time of new emissions abatement technologies is uncertain).

3. Results

In this section, we select the Chinese iron and steel sector as a case study to illustrate several key analytical results, and the main reasons are as follows. First, the market structure of China's iron and steel sector is imperfect competition [28,30,43,44]. Second, among all the sources of CO_2 emissions in China, the iron and steel sector plays a crucial role. Furthermore, the iron and steel sector is one of the first eight key emissions sectors to be included in the national carbon emissions trading market.

Following Zhu et al. [44], let $P(Q) = 7191 - 5.2(q_1 + q_2)$ be the demand curve, the production cost coefficients of the firms are $c_1 = 2374$ and $c_2 = 3543$, respectively. The emissions intensity of the output is $k_1 = 0.60$ and $k_2 = 0.47$ in the case of the current technology, respectively. The diffusion rate in adoption cost $\theta = 0.038$ [39]. Moreover, the positive parameter K in the adoption cost is equal to one million and the emissions intensity of output K_0 in the case of the new emissions abatement technology is assumed to be 0.8. Additionally, the percentage of emissions reductions λ is set as 0.1, and the discount rate δ used here is 0.05. Table 2 describes all the parameters used in the numerical simulation.

For the sake of convenience in writing, we name the imperfectly competitive permits market as market 1 and the perfectly competitive permits market as market 2. Additionally, the software used in our study is MATLAB and the version is R2015b. We believe that most computers meet this condition.

Table 2. Parameters used in the numerical simulation.

Parameters	Dimension	Description	Value	Source
a		Parameters in linear inverse demand function	7191	[44]
b			5.2	
c_1	(yuan/tSteel)	Firm 1's production cost coefficient	2374	
c_2	(yuan/tSteel)	Firm 2's production cost coefficient	3543	
k_1	(tSteel/tCO_2)	Firm 1's initial emissions intensity	0.6	
k_2	(tSteel/tCO_2)	Firm 2's initial emissions intensity	0.47	
k_0	(tSteel/tCO_2)	Emissions intensity of the new technology	0.8	Given
K	(million yuan)	The parameter of investment cost	1	Given
θ		The diffusion rate	0.038	[39]
λ		Percentage of emissions reductions	0.1	Given
δ		The discount rate	0.05	Given

3.1. The Effect of Output Market

Changes in the output market are described by changes in parameters a and b in this study. Figures 2 and 3 show the effect of the output market on technology adoption, and the following conclusions can be drawn. First, firms adopt the new emissions abatement technology earlier when the output demand is larger (larger a) or more elastic (smaller b). Second, compared to market 2, both firms adopt the new emissions abatement technology later in market 1. That is, firms both delay the adoption of the new emissions abatement technology in the presence of market power. Third, when the product demand is larger or more elastic, technology diffusion will occur earlier. The analysis is as follows. On the one hand, given the parameter b, the higher the output demand in the output market (larger a), the higher the output levels of the firms will be. Hence, the firms adopt the new emissions abatement technology earlier to meet the higher level of emissions. On the other hand, given the parameter a, the initial level of carbon emissions is higher if the output demand is more elastic (smaller b). Therefore, this could cause the greater stringency of the environmental policies required, which leads to an increase in the adoption benefits and speed up the adoption of new technology.

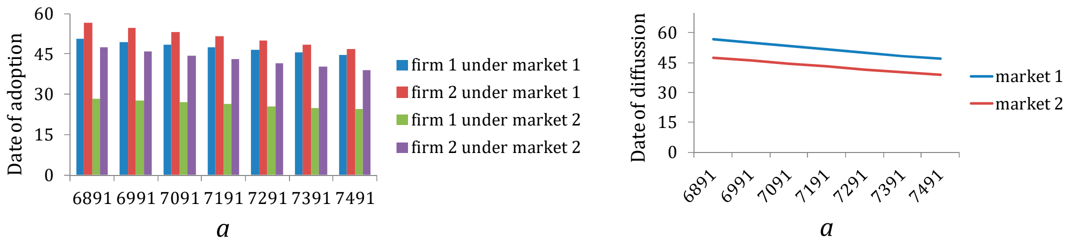

Figure 2. Changes in the parameter a of demand function and technology adoption.

Figure 3. Changes in the parameter b of demand function and technology adoption.

3.2. The Effect of Production Cost

The difference between the production cost of firm 1 and 2 (i.e., $c_2 - c_1$) is shown by changing the marginal production cost of firm 1 and keeping the marginal production cost of firm 2 constant. As shown in Figure 4, the following conclusions can be drawn. First, compared to market 2, the firms adopt the new emissions abatement technology later in market 1. In other words, both firms delay the adoption of the new emissions abatement technology in the presence of market power. Second, for a smaller difference between the production costs of firms 1 and 2 (larger c_1), the firm that first adopts the new technology switches from firm 1 to firm 2, and then the difference between the adoption date of firm 1 and 2 gradually becomes smaller and then becomes larger.

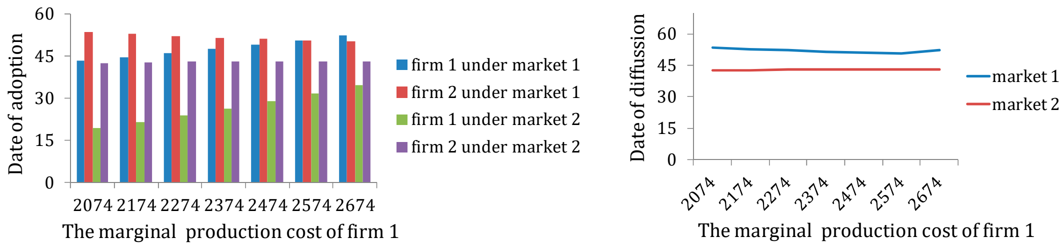

Figure 4. Changes in the marginal production cost and technology adoption.

3.3. The Effect of Emissions Reduction Target

Changes in the emissions reduction target are described by changes in the parameter λ. More specifically, the higher the percent of emissions reduction (larger λ), the larger the emissions reduction target will be (smaller E). As shown in Figure 5, the following conclusions can be drawn. First, as expected, the firms adopt the new emissions abatement technology earlier when the emissions reduction target is larger. Therefore, implementing larger emissions reduction target will induce an earlier diffusion of emissions abatement technology. Second, compared to market 2, firms adopt the new emissions abatement technology later in market 1. In other words, both firms delay the adoption of the new emissions abatement technology in the presence of market power. Third, with a larger emissions reduction target (larger λ), the difference between the adoption date of firms under market 1 and market 2 gradually becomes smaller.

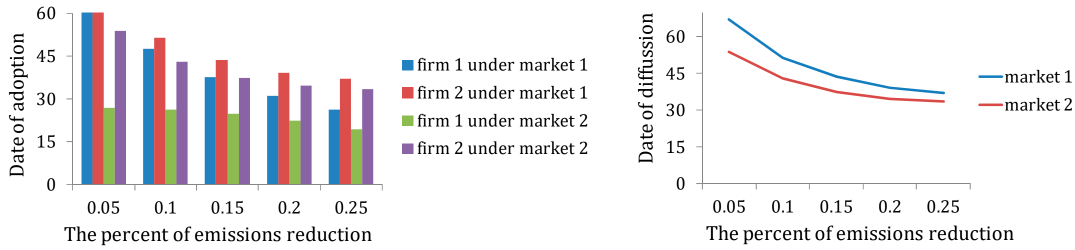

Figure 5. Changes in the percent of emissions reduction and technology adoption.

4. Discussion

4.1. Changes in Social Welfare

Social welfare contains four parts: Consumer surplus (CS), firm's profits (FP), emissions damages, and investment costs (IC). The aggregate damage caused by the total emissions E is equal to $\gamma E^2/2$, $\gamma > 0$ [28,39]. Hence, the emissions damages stay constant throughout the sequence of adoption in different market structures since emissions are capped before adoption starts. Let $Q(i)$ represent the total output in the case where i $(i = 1, 2)$ firms have adopted the new emissions abatement technology in the market and $(2 - i)$ firms still use current technology. In addition, it is easy to show that the consumer surplus is given by $Q^2(i) \cdot b/2$ because the demand curve is defined by $P(Q) = a - bQ$.

Hence, if i firms have adopted the new emissions abatement technology in the market, then the social welfare is given by $W(i) = Q^2(i) \cdot b/2 + \pi_1 + \pi_2 - \gamma E^2/2 - Ke^{-(\delta+\theta)t_i}$. Let $W_1(i)$ and $W_2(i)$ be the social welfare when the firms participate in market 1 and 2, respectively. Then, changes in social welfare $\Delta W(i) = W_1(i) - W_2(i)$ can be expressed as

$$\Delta W(i) = \underbrace{\left[{Q^2}_1(i) - {Q^2}_2(i)\right] \cdot b/2}_{\Delta CS(i)} + \underbrace{\left[\pi'_1 + \pi'_2 - \pi_1 - \pi_2\right]}_{\Delta FP(i)} - \underbrace{\left[Ke^{-(\delta+\theta)t'_i} - Ke^{-(\delta+\theta)t_i}\right]}_{\Delta IC(i)}.$$

where t'_i, t_i are the date of adoption in market 1 and 2; π'_1, π_1 are the profits of firm 1 in market 1 and 2; and π_2, π'_2 are the profits of firm 2 in market 1 and 2, respectively.

Tables 3 and 4 show changes in the consumer surplus ΔCS, changes in the firm's profits ΔFP, changes in the investment costs ΔIC, and changes in the social welfare in different market structures.

From Tables 3 and 4, two main conclusions can be drawn. First, the social welfare in an imperfect competition permits market is larger than that in firms in a perfect competition permits market. The analysis is as follows. When only one firm is using the new technology in the market, changes in social welfare primarily relied on the investment cost. This is because the investment cost of the firm that first adopted the new technology was high. As shown in Section 3.1, firms delay the adoption of the new emissions abatement technology in the presence of market power. Thus, the substantial reduction in investment costs leads to an increase in social welfare. When firms both are using the new technology in the market, changes in social welfare are mainly dependent on the firm's profits. This is because the investment cost declines quickly with time and technological diffusion. Thus, the increase in the firm's profits brings about the social welfare increase.

Second, the larger the output demand (larger a) or the more elastic the output demand (smaller b), the greater the changes in social welfare. As shown in Section 3.1, firms adopt the new technology earlier when the output demand is larger. Therefore, the sooner the adoption, the larger the changes in investment costs will be and, hence, the greater the changes in social welfare.

Table 3. Changes in a and social welfare.

a	6891	6991	7091	7192	7291	7391	7491
$\Delta CS(1)$	414	426	426	426	426	425	425
$\Delta FP(1)$	48,642	46,486	45,767	45,049	44,331	43,614	42,898
$\Delta IC(1)$	−71,379	−75,291	−79,222	−83,375	−87,785	−92,265	−96,938
$\Delta W(1)$	120,435	122,203	125,415	128,850	132,542	136,304	140,261
$\Delta CS(2)$	0	0	0	0	0	0	0
$\Delta FP(2)$	83,220	83,220	83,220	83,220	83,220	83,220	83,220
$\Delta IC(2)$	−8489	−9502	−10,635	−11,847	−13,250	−14,763	−16,430
$\Delta W(2)$	91,709	92,722	93,855	95,067	96,470	97,983	99,651

Table 4. Changes in b and social welfare.

b	4.6	4.8	5.0	5.2	5.4	5.6	5.8
$\Delta CS(1)$	377	393	409	426	442	459	475
$\Delta FP(1)$	50,925	48,803	46,851	45,049	43,380	41,831	40,389
$\Delta IC(1)$	−110,840	−100,390	−91,363	−83,375	−76,399	−70,255	−64,805
$\Delta W(1)$	162,142	149,586	138,623	128,850	120,220	112,545	105,669
$\Delta CS(2)$	0	0	0	0	0	0	0
$\Delta FP(2)$	94,075	90,155	86,549	83,220	80,138	77,276	74,611
$\Delta IC(2)$	−15,819	−14,281	−12,982	−11,847	−10,915	−9992	−9239
$\Delta W(2)$	109,894	104,440	99,531	95,067	91,053	87,268	83,850

Note. Changes in consumer surplus are shown as zero when two firms are using the new technology because its absolute value was too small (less than e^{-10}).

4.2. Comparison with Related Studies

As mentioned in the introduction, there are only two studies investigating this problem [27,28], However, the result has been a matter of debate. André and Arguedas [27] assumed that the output market is completely competitive and minimized the cost. That is, they did not consider the impact of the output market on technology adoption. However, several scholars confirmed that the exercise of market power can be rather extreme when taking into account both permit and output markets [17–19]. Furthermore, most firms with market power in a permits market often engage in an imperfectly competitive output market in the real world, such as the power sector [11,12,29] and the iron and steel sector [28,30]. Therefore, it is necessary to explicitly consider the output market when studying this problem.

Wang et al. [28] supposed that all firms have market power in a permits market and focused on the effect of production capacity on technology adoption. Our paper differs from this literature in several respects. First, we use the dominant firm–competitive fringe model to describe an imperfect emissions trading market structure. More specifically, we study the cases of a dominant firm with market power in a permits market and a price-taking firm. Second, Wang et al. [28] considered the adoption of end-of-pipe technologies, while our paper pays attention to the adoption of energy-saving technologies. In fact, energy-saving technologies are more common than end-of-pipe technologies for curbing carbon emissions, since the end-of-pipe technology (i.e., carbon capture and storage technology) is extremely expensive and has not been widely applied in reality. Furthermore, several authors have found that there might be potential differences between the adoption of the two types of abatement technologies by using empirical approaches [45–47]. For example, Frondel et al. [46] found that cost savings are more important for the energy-saving technologies, while policy stringency is more important for the end-of-pipe technologies. Hence, the impact of market power on two completely different emissions abatement technologies is clearly distinct, and a firm's investment behaviors regarding these two technologies are also distinct. Third, Wang et al. [28] assumed zero costs of production, while we take into account the constant marginal production cost in our model. This makes it more general because that would allow for the possibility to do sensitivity analysis with respect to production cost parameters.

4.3. Limitations and Further Research

For mathematical tractability, there are several limitations in our study. First, the assumption of a constant marginal production cost might be rigorous. It would be even more general if production cost had a generic (not necessarily linear) shape. Second, a better data source, which is used for calibrating the key parameters in the model, would help to obtain more accurate findings. Third, the case of perfect compliance is studied, and the firm's non-compliance behavior has not yet been considered.

The issue of technology adoption in the presence of market power is rather sophisticated. In reality, a firm will face various uncertainties when makes the adoption decision, mainly including economic uncertainty (e.g., the output demand is always changing in the future) and technological uncertainty (i.e., the arrival time of new emissions abatement technologies is uncertain). Therefore, to heighten its applicability and provide policymakers with more insights on this issue, the study framework could be extended in uncertainty environments. On the other hand, our model is suitable for a single sector. In fact, many sectors will be covered in the carbon ETS. Hence, it will be meaningful to extend our model to multiple sectors. These points are the main suggestions for future research.

Finally, our model can be applied to analyze other sectors with high market concentration covered in the carbon ETS. Furthermore, the proposed analytical framework can also be extended to the setting where the agents are located in different countries, not just heterogeneous firms, and the governments are usually bound by international climate agreements such as the Paris Agreement. In this context of international ETS, China and the U.S. may have market power in the international carbon market, because they are the two countries with the most carbon emissions in the world. Therefore, to promote the adoption of new emissions abatement technologies, these countries should be set a relatively high emissions reduction target on specific time horizons.

5. Conclusions

This paper provides an analytical framework to investigate the effect of market power in the emission trading market on the diffusion of a new emissions abatement technology when firms interact in an imperfectly competitive output market. This study shows that firms will delay the adoption of the new emissions abatement technology in the presence of market power. Moreover, when the output demand is larger and more elastic technology diffusion will occur earlier. This implies that the technology diffusion in the weakly elastic sector, such as the Chinese iron and steel sector, may have more barriers than that in the strong elastic sector, such as the Chinese nonferrous metals sector. However, it should be noticed that the social welfare in an imperfect competition permits market is larger than that of firms in a perfect competition permits market throughout the sequence of adoption. A better understanding of the effects of market power on cost-effectiveness and technology diffusion would be helpful in designing better carbon ETS and related regulatory policies, especially for a country where the carbon market is still in its early stage. Therefore, in order to speed up technological diffusion and attain sustainable and low-carbon development, the policymaker should pay more attention to the market structure of sector covered in the ETS. Furthermore, the regulator can enhance supervision for the key firms to cope with the side effects of market power.

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

Appendix A The Solution Process of E_0 in the Absence of Environmental Policy

Firms choose the output levels to maximize profits. Firm 1 solves the problem:

$$\pi_1 = \underset{e_1}{Max}[(a - b(k_1e_1 + k_2e_2))k_1e_1 - c_1(k_1e_1)],$$

and firm 2 solves the problem:

$$\pi_2 = \underset{e_2}{Max}[(a - b(k_1e_1 + k_2e_2))k_2e_2 - c_2(k_2e_2)].$$

According to the FOCs, we obtain the following:

$$e_1 = \frac{a - 2c_1 + c_2}{3bk_1},\ e_2 = \frac{a - 2c_2 + c_1}{3bk_2}$$

Therefore, the total emissions in the absence of environmental policy is given by:

$$E_0 = e_1 + e_2 = \frac{a(k_1 + k_2) - c_1(2k_2 - k_1) + c_2(k_2 - 2k_1)}{3bk_1k_2}$$

Appendix B The Results in the Perfectly Competitive Permits Market

Firms are price takers in a perfectly competitive permits market. That is, both firms make their output and emissions decisions simultaneously taking the permit price as given.

Firm 1 solves the problem:

$$\pi_1 = \underset{e_1}{Max}[(a - b(k_1e_1 + k_2e_2))k_1e_1 - c_1(k_1e_1) - p_c(e_1 - \varepsilon_1)],$$

and firm 2 solves the problem:

$$\pi_2 = \underset{e_2}{Max}[(a - b(k_1e_1 + k_2e_2))k_2e_2 - c_2(k_2e_2) - p_c(e_2 - \varepsilon_2)],$$

where p_c is the equilibrium permit price, ε_1 and ε_2 are the quantity of emissions permits freely received by firm 1 and firm 2, respectively.

According to the FOCs, we have the following:

$$e_1 = \frac{a - c_1}{3bk_1} + \frac{k_1 - 2k_2}{3bk_1^2k_2}p_c,\ e_2 = \frac{a - c_2}{3bk_2} + \frac{k_2 - 2k_1}{3bk_1k_2^2}p_c.$$

Since $e_1 + e_2 = E$, the equilibrium permit price p_c is given by:

$$p_c = \frac{(a - c_1)k_2 + (a - c_2)k_1}{2} \cdot \frac{k_1k_2}{k_1^2 + k_2^2 - k_1k_2} - \frac{3bE}{2} \cdot \frac{k_1^2k_2^2}{k_1^2 + k_2^2 - k_1k_2}.$$

Hence, the emissions levels of the firms are

$$e_1 = \frac{1}{6b} \cdot \frac{(a - c_1)(2k_1 - k_2) + (a - c_2)(k_1 - 2k_2)}{k_1^2 + k_2^2 - k_1k_2} - \frac{E}{2} \cdot \frac{k_2(k_1 - 2k_2)}{k_1^2 + k_2^2 - k_1k_2},$$

$$e_2 = \frac{1}{6b} \cdot \frac{(a - c_1)(k_2 - 2k_1) + (a - c_2)(2k_2 - k_1)}{k_1^2 + k_2^2 - k_1k_2} - \frac{E}{2} \cdot \frac{k_1(k_2 - 2k_1)}{k_1^2 + k_2^2 - k_1k_2}.$$

Then, the outputs levels of the firms are

$$q_1 = \frac{1}{6b} \cdot \frac{k_1(2k_1 - k_2)(a - c_1) + k_1(k_1 - 2k_2)(a - c_2)}{k_1^2 + k_2^2 - k_1k_2} - \frac{E}{2} \cdot \frac{k_1k_2(k_1 - 2k_2)}{k_1^2 + k_2^2 - k_1k_2},$$
$$q_2 = \frac{1}{6b} \cdot \frac{k_2(a - c_1)(k_2 - 2k_1) + k_2(a - c_2)(2k_2 - k_1)}{k_1^2 + k_2^2 - k_1k_2} - \frac{E}{2} \cdot \frac{k_1k_2(k_2 - 2k_1)}{k_1^2 + k_2^2 - k_1k_2}.$$

Appendix C

Proof of Lemma 1. Let $\gamma(t_1^1, t_1^2, t_2) = f_1^1(t_1^1, t_2) - f_1^2(t_1^2, t_2)$, then we can get

$$\gamma(t_1^1, t_1^2, t_1^1) = f_1^1(t_1^1, t_1^1) - f_1^2(t_1^2, t_1^1) < 0,$$
$$\gamma(t_1^1, t_1^2, t_1^2) = f_1^1(t_1^1, t_1^2) - f_1^2(t_1^2, t_1^2) > 0.$$

Since $\partial\gamma/\partial t_2 = \left[(\pi_1^1 - \pi_1^{NA}) - (\pi_1^A - \pi_1^2)\right]e^{-\delta t_2} > 0$, it follows by the intermediate value theorem and the monotonicity of γ in t_2 that there exists a unique $\widetilde{t_1} \in (t_1^1, t_1^2)$ such that $f_1^1(t_1^1, t_2) \leq f_1^2(t_1^2, t_2)$ as $t_2 \leq \widetilde{t_1}$, and vice versa. □

Proof of Theorem 1. (i) Case 1: $t_2 < \widetilde{t_1}$

$\forall t_1 \leq t_2$,
$$V_1(t_1^2, t_2) = f_1^2(t_1^2, t_2) > f_1^1(t_1^1, t_2) \geq f_1^1(t_1, t_2) = V_1(t_1, t_2).$$
$\forall t_1 \geq t_2,\ t_1 \neq t_1^2$,
$$V_1(t_1^2, t_2) = f_1^2(t_1^2, t_2) > f_1^2(t_1, t_2) = V_1(t_1, t_2).$$

Thus $R_1(t_2) = t_1^2$.

(ii) Case 2: $t_2 = \widetilde{t_1}$

$\forall t_1 \leq t_2,\ t_1 \neq t_1^1$,
$$V_1(t_1^1, \widetilde{t_1}) = f_1^1(t_1^1, \widetilde{t_1}) > f_1^1(t_1, \widetilde{t_1}) = V_1(t_1, \widetilde{t_1}).$$
$\forall t_1 \geq t_2,\ t_1 \neq t_1^2$,
$$V_1(t_1^2, \widetilde{t_1}) = f_1^2(t_1^2, \widetilde{t_1}) > f_1^2(t_1, \widetilde{t_1}) = V_1(t_1, \widetilde{t_1}).$$
Since $f_1^1(t_1^1, \widetilde{t_1}) = f_1^2(t_1^2, \widetilde{t_1})$, thus $R_1(t_2) = \left\{t_1^1, t_1^2\right\}$.

(iii) Case 3: $t_2 > \widetilde{t_1}$

$\forall t_1 \leq t_2,\ t_1 \neq t_1^1$,
$$V_1(t_1^1, t_2) = f_1^1(t_1^1, t_2) > f_1^1(t_1, t_2) = V_1(t_1, t_2).$$
$\forall t \geq t_2$,
$$V_1(t_1^1, t_2) = f_1^1(t_1^1, t_2) > f_1^2(t_1^2, t_2) \geq f_1^2(t_1, t_2) = V_1(t_1, t_2).$$

Thus $R_1(t_2) = t_1^1$. □

Proof of Lemma 2. Let $\eta(t_1, t_2^1, t_2^2) = f_2^1(t_1, t_2^1) - f_2^2(t_1, t_2^2)$, then we can get

$$\eta(t_2^1, t_2^1, t_2^2) = f_2^1(t_2^1, t_2^1) - f_2^2(t_2^1, t_2^2) < 0,$$
$$\eta(t_2^2, t_2^1, t_2^2) = f_2^1(t_2^2, t_2^1) - f_2^2(t_2^2, t_2^2) > 0.$$

Since $\partial\eta/\partial t_1 = \left[(\pi_2^2 - \pi_2^{NA}) - (\pi_2^A - \pi_2^1)\right]e^{-\delta t_1} > 0$, it follows by the intermediate value theorem and the monotonicity of η in t_1 that there exists a unique $\widetilde{t_2} \in (t_2^1, t_2^2)$ such that $f_2^1(t_1, t_2^1) \le f_2^2(t_1, t_2^2)$ as $t_1 \le \widetilde{t_2}$, and vice versa. □

Proof of Theorem 2. (i) Case 1: $t_1 < \widetilde{t_2}$

$\forall t_2 \le t_1$,

$$V_2(t_1, t_2^2) = f_2^2(t_1, t_2^2) > f_2^1(t_1, t_2^1) \ge f_2^1(t_1, t_2) = V_2(t_1, t_2).$$

$\forall t_2 \ge t_1$, $t_2 \ne t_2^2$,

$$V_2(t_1, t_2^2) = f_2^2(t_1, t_2^2) > f_2^2(t_1, t_2) = V_2(t_1, t_2).$$

Thus $R_2(t_1) = t_2^2$.

(ii) Case 2: $t_1 = \widetilde{t_2}$

$\forall t_2 \le t_1$, $t_2 \ne t_2^1$,

$$V_2(\widetilde{t_2}, t_2^1) = f_2^1(\widetilde{t_2}, t_2^1) > f_2^1(\widetilde{t_2}, t_2) = V_2(\widetilde{t_2}, t_2).$$

$\forall t_2 \ge t_1$, $t_2 \ne t_2^2$,

$$V_2(\widetilde{t_2}, t_2^2) = f_2^2(\widetilde{t_2}, t_2^2) > f_2^2(\widetilde{t_2}, t_2) = V_2(\widetilde{t_2}, t_2).$$

Since $f_2^1(\widetilde{t_2}, t_2^1) = f_2^2(\widetilde{t_2}, t_2^2)$, thus $R_2(t_1) = \left\{t_2^1, t_2^2\right\}$.

(iii) Case 3: $t_1 > \widetilde{t_2}$

$\forall t_2 \le t_1$, $t_2 \ne t_2^1$,

$$V_1(t_1, t_2^1) = f_2^1(t_1, t_2^1) > f_2^1(t_1, t_2) = V_2(t_1, t_2)$$

$\forall t_2 \ge t_1$,

$$V_2(t_1, t_2^1) = f_2^1(t_1, t_2^1) > f_2^2(t_1, t_2^2) \ge f_2^2(t_1, t_2) = V_2(t_1, t_2).$$

Thus $R_2(t_1) = t_2^1$.□

Proof of Theorem 3. According to Theorems 1 and 2, the best-response correspondences R_1 and R_2 are shown in Figures A1 and A2, respectively.

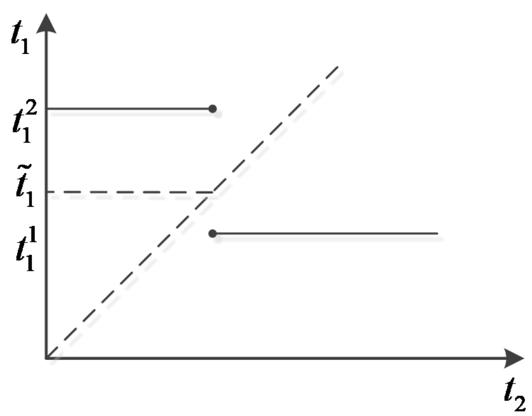

Figure A1. Firm 1's best-response correspondence.

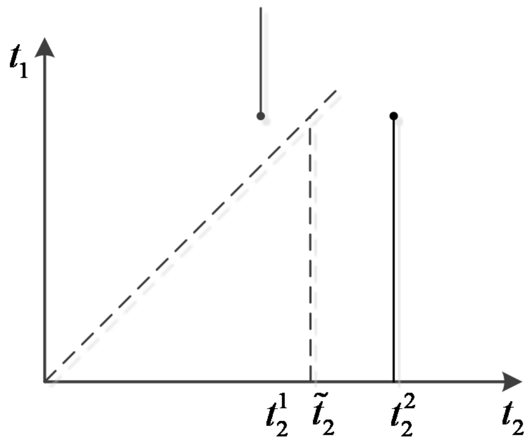

Figure A2. Firm 2's best-response correspondence.

As shown in Figure A3, it is not difficult to show that there is only one intersection between them if $\widetilde{t_2} > t_1^2$ or $\begin{cases} \widetilde{t_2} < t_1^2 \\ \widetilde{t_1} < t_2^1 \end{cases}$.

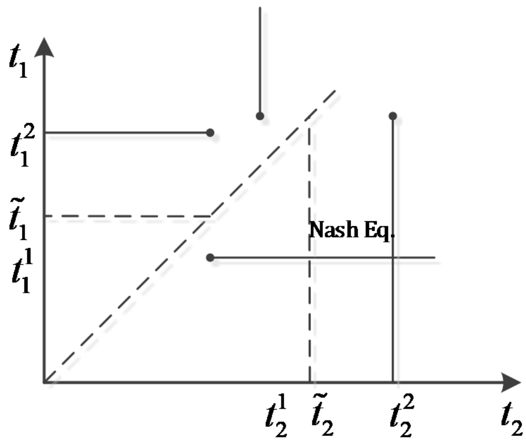

Figure A3. Part (1) in Theorem 3.

That is, if $\widetilde{t_2} > t_1^2$ or $\begin{cases} \widetilde{t_2} < t_1^2 \\ \widetilde{t_1} < t_2^1 \end{cases}$, then there exists a unique Nash equilibrium (t_1^1, t_2^2).

As shown in Figure A4, it is easy to obtain Parts (2) and (3) in Theorem 3 in the same way. □

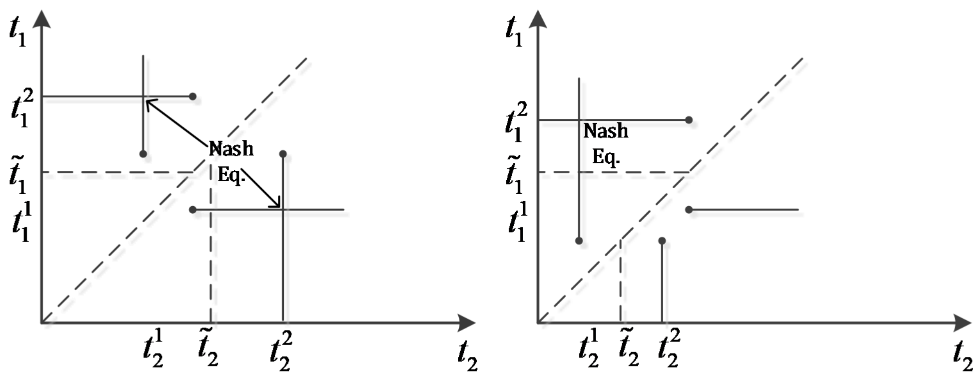

Figure A4. Parts (2) and (3) in Theorem 3.

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